Combining Horizontal and Vertical Ground Reaction Force Reduction with Sustainability in Multi-Sport Surfaces

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

Alexander William Walker

BSc, MBA

School of Aerospace Mechanical and Manufacturing Engineering

College of Science Engineering and Health

RMIT University

October 2014
Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis/project is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Alexander William Walker

25/08/2015
# Table of Contents

Table of Contents ........................................ iii  
List of Tables ............................................. viii  
List of Figures ............................................ x  
Acknowledgements .......................................... xv  
Declaration .................................................. Error! Bookmark not defined.  
Abstract ..................................................... xvii  
Publications and Awards .................................... xix  

## Chapter 1

### Introduction

1.1 The research problem and the context  
   1.1.1 Playing surfaces  
   1.1.2 Sustainability  

1.2 Significance of the research  

1.3 Research goals and objectives  

1.4 Research method  

1.5 Limitations of the research  

1.6 Outline and structure of the thesis  

## Chapter 2

### Literature review

2.1 Introduction  

2.2 Sports surface related lower limb injury  
   2.2.1 Injury causation mechanisms  
   2.2.2 Overuse injury on sports surfaces  
   2.2.3 Non-contact injury  
   2.2.4 Surface force reduction and surface stiffness  
   2.2.5 Knee injury  
   2.2.6 Ankle injury  

2.3 Sports surface mechanical behaviour  
   2.3.1 Sports surface friction  
   2.3.2 Surface material and relation to injury risk  
   2.3.3 Surface test devices  

2.4 Sustainable design: Life cycle thinking and closed-loop processes  
   2.4.1 Sustainable indoor sports surfaces  

2.5 Summary  


Chapter 3

Indoor sports surface materials, design and testing protocols

3.1 Introduction

3.2 Natural and synthetic indoor sports surfaces

3.3 Indoor sports surface types and construction
  3.3.1 Classification of sports surfaces
  3.3.2 Hardwood timber sports surface systems
  3.3.3 Pour-in-place synthetic sports surface systems
  3.3.4 Prefabricated sheet synthetic sports surface systems
  3.3.5 Prefabricated tile synthetic sports system
  3.3.6 Sports surface subfloors

3.4 Sports surface selection

3.5 The development of international performance standards for indoor playing surfaces
  3.5.1 DIN 18032 Part 2
  3.5.2 DIN pre-standard 18032 Part 2
  3.5.3 EN14904

3.6 EN14904 performance parameters for sports surfaces
  3.6.1 Mechanical performance
  3.6.2 Safety and biomechanical performance

3.7 Inclined impact test devices

3.8 Conclusion

Chapter 4

Investigation of sustainability in the design and development of sports surfaces

4.1 The need for sustainable design
  4.4.1 Standards, protocols and regulatory compliance in the sports surface industry
  4.4.2 Extended product responsibility
  4.4.3 Design response to the need for environmental and economic sustainability: Life cycle thinking

4.2 Conclusion

Chapter 5

Life cycle assessment: Sports facility design and sports surface selection tool

5.1 Streamlined indoor sports surface life cycle assessment

5.2 Sports surface environmental evaluation using streamlined life cycle assessment
  5.2.1 Conventional surface selection methods based on supplier generated information
  5.2.2 Environmental impact implications of indoor playing surfaces
  5.2.3 Definition of assessment goal and scope
  5.2.4 Streamlined life cycle inventory analysis
  5.2.5 Streamlined life cycle interpretation and discussion

5.3 Sports surface life cycle assessment
  5.3.1 Goals of the study
  5.3.2 Scope of the study
  5.3.3 Sports surface function
  5.3.4 Sports surface functional unit
  5.3.5 System boundaries
  5.3.6 Data quality criteria
  5.3.7 Technology
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.3.8</td>
<td>Initial system boundaries</td>
<td></td>
</tr>
<tr>
<td>5.3.9</td>
<td>Limitations</td>
<td></td>
</tr>
<tr>
<td>5.3.10</td>
<td>Assumptions</td>
<td></td>
</tr>
<tr>
<td>5.3.11</td>
<td>Goal and scope review</td>
<td></td>
</tr>
<tr>
<td>5.3.12</td>
<td>Inventory analysis</td>
<td></td>
</tr>
<tr>
<td>5.3.13</td>
<td>Limitations of life cycle inventory</td>
<td></td>
</tr>
<tr>
<td>5.3.14</td>
<td>Impact assessment</td>
<td></td>
</tr>
<tr>
<td>5.3.15</td>
<td>End-of-life scenarios</td>
<td></td>
</tr>
<tr>
<td>5.4</td>
<td>Floor surface environmental performance</td>
<td>111</td>
</tr>
<tr>
<td>5.4.1</td>
<td>Hardwood timber sports surface heating ventilation and air-conditioning power requirements ºC</td>
<td></td>
</tr>
<tr>
<td>5.4.2</td>
<td>Hardwood timber sports surface</td>
<td></td>
</tr>
<tr>
<td>5.4.3</td>
<td>Pour-in-place synthetic sports surface system life cycle assessment</td>
<td></td>
</tr>
<tr>
<td>5.4.4</td>
<td>Prefabricated sheet synthetic sports surface system life cycle assessment</td>
<td></td>
</tr>
<tr>
<td>5.4.5</td>
<td>Prefabricated tile synthetic sports surface system life cycle assessment</td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>Comparative analysis</td>
<td>131</td>
</tr>
<tr>
<td>5.6</td>
<td>Interpretation</td>
<td>131</td>
</tr>
<tr>
<td>5.7</td>
<td>Conclusion</td>
<td>131</td>
</tr>
</tbody>
</table>

**Chapter 6**

**New sports surface design and development**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Product development</td>
<td>133</td>
</tr>
<tr>
<td>6.1.1</td>
<td>Phase 1: Design brief, research and product definition development</td>
<td></td>
</tr>
<tr>
<td>6.1.2</td>
<td>Phase 2: Idea generation, concept development, analysis, initial prototyping, testing and selection</td>
<td></td>
</tr>
<tr>
<td>6.1.3</td>
<td>Phase 3: Final concept development, final prototype testing and pre-production</td>
<td></td>
</tr>
<tr>
<td>6.2</td>
<td>Phase 1: Design brief, product research and product definition</td>
<td>135</td>
</tr>
<tr>
<td>6.2.1</td>
<td>New sports surface design brief and problem definition</td>
<td></td>
</tr>
<tr>
<td>6.2.2</td>
<td>The product’s conceptual vision</td>
<td></td>
</tr>
<tr>
<td>6.2.3</td>
<td>Key surface functionality</td>
<td></td>
</tr>
<tr>
<td>6.2.4</td>
<td>Sustainable sports surface design</td>
<td></td>
</tr>
<tr>
<td>6.2.5</td>
<td>Taking the product to market</td>
<td></td>
</tr>
<tr>
<td>6.2.6</td>
<td>Improved safety performance</td>
<td></td>
</tr>
<tr>
<td>6.2.7</td>
<td>Improved surface life cycle cost</td>
<td></td>
</tr>
<tr>
<td>6.2.8</td>
<td>Project aim</td>
<td></td>
</tr>
<tr>
<td>6.2.9</td>
<td>Technical challenges to be overcome</td>
<td></td>
</tr>
<tr>
<td>6.2.10</td>
<td>Indoor sports surface product definition</td>
<td></td>
</tr>
<tr>
<td>6.3</td>
<td>Phase 2: Idea generation, concept development, analysis, initial prototyping, testing and selection</td>
<td>152</td>
</tr>
<tr>
<td>6.3.1</td>
<td>Surface function analysis</td>
<td></td>
</tr>
<tr>
<td>6.3.2</td>
<td>Tile sports surface pvees analysis</td>
<td></td>
</tr>
<tr>
<td>6.3.3</td>
<td>Sports floor market segmentation</td>
<td></td>
</tr>
<tr>
<td>6.3.4</td>
<td>Sports surface market</td>
<td></td>
</tr>
<tr>
<td>6.3.5</td>
<td>Analysing customer features and benefits</td>
<td></td>
</tr>
<tr>
<td>6.3.6</td>
<td>Customer benefits analysis</td>
<td></td>
</tr>
<tr>
<td>6.3.7</td>
<td>Sustainable design approaches and considerations</td>
<td></td>
</tr>
<tr>
<td>6.4</td>
<td>Phase 3: Final concept development, final prototype testing and pre-production</td>
<td>174</td>
</tr>
<tr>
<td>6.4.1</td>
<td>Failure modes and effects analysis (FMEA)</td>
<td></td>
</tr>
<tr>
<td>6.4.2</td>
<td>Sports surface innovation</td>
<td></td>
</tr>
<tr>
<td>6.4.3</td>
<td>Innovation through morphological analysis</td>
<td></td>
</tr>
<tr>
<td>6.4.4</td>
<td>Unit cost analysis</td>
<td></td>
</tr>
<tr>
<td>6.5</td>
<td>Conclusion</td>
<td>191</td>
</tr>
</tbody>
</table>
Chapter 7

Structural analysis and manufacturing of modular tile sports surface 193

7.1 Modular tile and connector configuration and material selection 193

7.2 Modular connector material selection for increased horizontal force reduction 195
    7.2.1 Surface isolator material selection
    7.2.2 Tile and connector configuration for optimal part flatness
    7.2.3 Tile and connector rib connection boss configuration
    7.2.4 Playing surface wall thickness
    7.2.5 Tile and connector rib, side wall and boss draft angles and radii
    7.2.6 Tile and connector injection moulding tool design considerations
    7.2.7 Injection moulding tool gate location and size
    7.2.8 Tile and connector injection moulding considerations

7.3 Structural analysis of modular tile and connector 204
    7.3.1 Introduction
    7.3.2 Tile and connector mathematical model construction
    7.3.3 Finite element model
    7.3.4 Analysis and interpretation of FEA results

7.4 Linear surface analysis versus non-linear surface analysis 211
    7.4.1 Surface geometry linearity and non-linearity
    7.4.2 Surface material linearity and non-linearity
    7.4.3 Surface restraint linearity and non-linearity

7.5 Tile and connector support rib design linear static finite element analysis 214
    7.5.1 Static analysis of tile rib structures in horizontal compression
    7.5.2 Tile to connector linkage development and analysis
    7.5.3 Effects of mineral filler additive materials on part stiffness during clipping assembly and disassembly
    7.5.4 Tile and connector loading
    7.5.5 Surface spot impact loading
    7.5.6 Tile and connector support rib design linear static finite element analysis outcomes and recommendations

7.6 Sports surface isolator analysis 227
    7.6.1 Surface isolation
    7.6.2 Surface dampening
    7.6.3 Surface shock isolation
    7.6.4 Viscoelastic materials
    7.6.5 Passively damped surface design
    7.6.6 Surface loading analysis
    7.6.7 Development of final HGRF isolator design configurations

7.7 Conclusion 253

Chapter 8

Exploratory design, assessment and validation 255

8.1 Introduction 255

8.2 Surface exploratory testing 255
    8.2.1 Exploratory test method
    8.2.2 Discussion of results
    8.2.3 Conclusion

8.3 Surface assessment testing 263
    8.3.1 Assessment test method
    8.3.2 Discussion of results
Chapter 8

8.4 Surface validation tests
   8.4.1 Validation test method
   8.4.2 Inclined impact test apparatus for validation of results
   8.4.3 VIITA laboratory testing
   8.4.4 Results and discussion
   8.4.5 Conclusions

Chapter 9

Conclusions and recommendations for future research

9.1 Original contributions
   9.1.1 Background
   9.1.2 Research objective A
   9.1.3 Research objective B
   9.1.4 Research objective C
   9.1.5 Research objective D
   9.1.6 Research objective E

9.2 Recommendations for future research

References
# List of Tables

## Chapter 1

| Table 1.1 | Most common injury types and their approximate cost range per injury in 2006 (Source: Medibank Private Safe Sports Report 2006) | 1 |
| Table 1.2 | Haddon injury intervention matrix (Source: Sports Injury Prevention Task Force May 2013) | 1 |

## Chapter 2

| Table 2.1 | Focus and current status (at thesis submission) of research submitted to peer-reviewed conferences and journals as research papers and book chapters. | 15 |
| Table 2.2 | Summary of the average maximal vertical and braking forces generated at landing at netball (Steele and Milburn 1987) | 33 |
| Table 2.3 | Running parameter averages in percentage body weight (Bagley 1992) | 36 |
| Table 2.4 | Braking parameter averages in percentage body weight (Bagley 1992) | 36 |
| Table 2.5 | Jumping parameter averages in percentage body weight (Bagley 1992) | 36 |

## Chapter 3

| Table 3.1 | European Standard EN 14904 | 69 |
| Table 3.2 | Force reduction (FR) surface types for point elastic, area elastic, mixed elastic and combination elastic sports surface systems (EN14904 2006) | 72 |
| Table 3.3 | Point elastic and area elastic sports surface force reduction classifications, European Standard EN14904 (EN14904 2006) | 73 |
| Table 3.4 | Combined elastic and mixed elastic sports surface force reduction classifications, European Standard EN14904 (EN14904 2006) | 73 |
| Table 3.5 | Vertical deformation surface categories for point elastic and area elastic, mixed elastic and combination elastic sports surface systems (EN14904 2006). | 78 |

## Chapter 5

| Table 5.1 | Manufacture, installation and transport data to site of installation for hardwood timber sports surface | 116 |
| Table 5.2 | Manufacture, installation and transport data to site of installation for a pour-in-place synthetic sports surface | 120 |
| Table 5.3 | Manufacture, installation and transport data to site of installation for a prefabricated sheet synthetic sports surface | 124 |
| Table 5.4 | Manufacture, installation and transport data to site of installation for a prefabricated tile synthetic sports surface | 128 |

## Chapter 6

| Table 6.1 | Proposed point elastic sports surface force reduction classes as described in Figure 6.4 for combined horizontal and vertical force reduction, in respect to the requirements for different sports (Sport England 2007) | 162 |
| Table 6.2 | Customer benefits analysis | 170 |
| Table 6.3 | Sports surface failure modes and effects analysis | 176 |
| Table 6.4 | Sports surface failure severity ratings | 178 |
| Table 6.5 | Sports surface failure occurrence ranking | 178 |
| Table 6.6 | Sports surface failure detection rating | 179 |
Table 6.7  Potential concepts for development 183
Table 6.8  Functional groupings and potential solution modelling approaches 185
Table 6.9  Netball surface manufacturing cost analysis 190

Chapter 7

Table 7.1  Material properties for copolymer polypropylene (Basell Polyolefins 2013) 214
Table 7.2  Spot load analysis for new tile and connector design 226
Table 7.3  Spot load analysis for competitor arch rib tile 226
Table 7.4  Loading per isolator during peak braking on one (IL1) and two (IL2) tiles or connectors 244
Table 7.5  Loading and kinetic energy conditions per isolator during peak braking, on single and double loaded tiles/connectors 247
Table 7.6  Material properties used for Sorbothane polyurethane elastomer in 30, 50 and 70 durometer grades (Sorbothane 2013) 248
Table 7.7  Square isolator design evaluations with durometer 50 and 70 grade material 249
Table 7.8  Disk isolator design evaluations with durometer 50 and 70 grade material 249
Table 7.9  Torus Isolator design evaluations with durometer 50 and 70 grade material 249
Table 7.10  Rectangular isolator design evaluations with durometer 50 and 70 grade material 250
Table 7.11  Rectangular Isolator design evaluations with alternative form factors with durometer 70 grade material 251

Chapter 8

Table 8.1  Summary of the magnitude and rate of loading for vertical and horizontal forces generated by the exploratory incline impact test apparatus (Walker and Subic 2010). 261
Table 8.2  Measurement of isolator stiffness in tile-connector configurations a) and b) 268
Table 8.3  Surface test scenarios 281
Table 8.4  Summary of the mean magnitude and rates of loading for horizontal forces generated by the VIITA in surface test scenarios A to F 289
# List of Figures

## Chapter 2

| Figure 2.1 | Flow-diagram representing the literature review | 14 |
| Figure 2.2 | Extrinsic risk factors for lower extremity injury (Walker 2010) | 18 |
| Figure 2.3 | The four step sequence for injury prevention research (van Mechelen, Hlobil et al. 1992) | 19 |
| Figure 2.4 | Non-contact injuries are common in netball which features sudden leaping, braking, twisting manoeuvres and sudden changes in direction | 22 |
| Figure 2.5 | Posterior view of the knee showing the various ligaments of the knee (Sports Medicine Australia 2006a) | 26 |
| Figure 2.6 | Posterior view of the knee showing meniscus, anterior cruciate ligament and posterior cruciate ligament (Sports Medicine Australia 2006d) | 28 |
| Figure 2.7 | Lateral ligaments of the ankle (Sports Medicine Australia 2006b) | 29 |
| Figure 2.8 | Lateral ligaments of the ankle (Sports Medicine Australia 2006c) | 30 |
| Figure 2.9 | Graph showing features of a typical force-time curve generated at landing in netball (Steele 1990, p. 92) | 33 |
| Figure 2.10 | Conventional ‘sprung’ sports surface vertical ground reaction force | 34 |
| Figure 2.11 | Schematic diagram of the Berlin Artificial Athlete (BAA) | 43 |

## Chapter 3

| Figure 3.1 | Point elastic sports surface | 52 |
| Figure 3.2 | A3 area elastic sports surface | 53 |
| Figure 3.3 | A4 area elastic sports surface | 53 |
| Figure 3.4 | Combined elastic indoor sports surface | 54 |
| Figure 3.5 | Mixed elastic indoor sports surface | 54 |
| Figure 3.6 | Hardwood timber sports surface | 57 |
| Figure 3.7 | Pour-in-place synthetic sports surface | 58 |
| Figure 3.8 | Prefabricated sheet synthetic sports surface | 61 |
| Figure 3.9 | Prefabricated tile synthetic sports surface | 64 |

## Chapter 4

| Figure 4.1 | Conceptual vision for sustainable sports surfaces | 81 |

## Chapter 5

| Figure 5.1 | Life cycle assessment procedure | 90 |
| Figure 5.2 | Stream-lined LCA overview (Sustainable Minds 2011) | 97 |
| Figure 5.3 | Prefabricated tile synthetic sports flooring stream-lined LCA impact overview (Sustainable Minds 2011) | 98 |
| Figure 5.4 | Prefabricated tile synthetic sports flooring stream-lined LCA impact overview (Sustainable Minds 2011) | 99 |
| Figure 5.5 | Prefabricated tile synthetic sports flooring stream-lined LCA impacts by SBOM inputs: Carbon footprint [CO2 eq. kg/functional unit] (Sustainable Minds 2011) | 100 |
| Figure 5.6 | Life cycle assessment procedure: ISO 14044 (Walker 2012) | 105 |
Figure 5.7  Inputs and outputs of the system as elementary flows  107
Figure 5.8  LCA exclusions from the study  108
Figure 5.9  Hardwood timber sports surface installation process  115
Figure 5.10  Hardwood timber sports surface process tree diagram  118
Figure 5.11  Pour-in-place synthetic sports surface installation process  119
Figure 5.12  Pour-in-place synthetic sports flooring process tree diagram  122
Figure 5.13  Prefabricated sheet synthetic sports surface installation  123
Figure 5.14  Prefabricated sheet synthetic sports flooring process tree diagram  126
Figure 5.15  Prefabricated tile synthetic sports surface installation  127
Figure 5.16  Prefabricated tile synthetic sports flooring process network diagram  130
Figure 5.17  Sports surface system comparative analysis  131

Chapter 6
Figure 6.1  Continuous product development methodology (Cooper 2005)  133
Figure 6.3  Indoor sports surface selection criteria (Walker and Subic 2010)  144
Figure 6.4  Proposed point elastic sports surface force reduction classifications for combined horizontal and vertical shock attenuation, including the England Netball Association
recommended force reduction classification and target NT force reduction classification.

Figure 6.5  Function analysis systems technique (FAST) diagram structure (Fowler 1990; Kaufman and Woodhead 2006)

Figure 6.6  Provide low injury risk sports playing surface FAST diagram

Figure 6.7  Provide low injury risk sports playing surface function specification

Figure 6.8  Tile sports surface function peeves analysis

Figure 6.9  Tile sports surface component peeves analysis

Figure 6.10  Tile sports surface manufacturing peeves analysis

Figure 6.11  Major sports floor market segments

Figure 6.12  Sport categories in relation to level of competitive play (Sport England 2012)

Figure 6.13  Sports surface value proposition

Figure 6.14  Paired comparison criteria scoring matrix

Figure 6.15  Conceptual mind map

Figure 6.16  Final iteration of octagonal tile and square connector

Figure 6.17  Four meter X four meter section of sports surface laid utilising the octagonal tile and square connector shown in Figure 6.16

Figure 6.18  Sports surface unit cost analysis structure.

Chapter 7

Figure 7.1  Proposed octagonal modular tile and square connector surface configuration

Figure 7.2  Tile and connector rib thickness configuration

Figure 7.3  Tile and connector boss configuration

Figure 7.4  Tile and connector rib and side wall configuration

Figure 7.5  Ground reaction force vectors

Figure 7.6  von Mises stress plot for a column configuration support structure, based on a competitor tile

Figure 7.7  von Mises stress plot for the proposed new rib configuration support structure under horizontal loading

Figure 7.8  Displacement plot for the proposed new rib configuration support structure under horizontal loading

Figure 7.9  Conventional retaining clip ‘snap hook’ tile to tile (no connector) connection approach

Figure 7.10  Conventional retaining clip approach modelled without and with internal fillets

Figure 7.11  Alternative retaining clip concepts which promote tile displacement and tile to connector engagement

Figure 7.12  Initial design for flexible side-wall hooks engaging laterally on the loop to promote clipping and unclipping for ease of assembly and disassembly

Figure 7.13  Final retaining clip concept analysis

Figure 7.14  Connector underside deformation contours for uniform loading

Figure 7.15  Connector von Mises stress under uniform load

Figure 7.16  Impact crater formed by an inline hockey-stick unit load impact

Figure 7.17  Standard impact in three separate cases as seen from the underside of a tile or connector
| Figure 7.18 | Analysis of a competitor arched rib tile | 226 |
| Figure 7.19 | Compressive stress vs durometer (Sorbothane 2013) | 240 |
| Figure 7.20 | Frequency vs shear modulus (Sorbothane 2013) | 241 |
| Figure 7.21 | Frequency vs tan delta (Sorbothane 2013) | 242 |
| Figure 7.22 | Isolator deformation at 25.06N loading | 251 |

### Chapter 8

| Figure 8.1 | Test types and occurrence in relation to the product development process | 255 |
| Figure 8.2 | Exploratory inclined impact test apparatus (EIITA) schematic and impact test device (Walker and Subic 2010) | 258 |
| Figure 8.3 | Inclined impact test apparatus with spherical and athletic footwear impact heads. | 261 |
| Figure 8.4 | Constructional features of a 10mm thick injection moulded polypropylene modular square tile sports surface, with 6mm thick SBR crumbed rubber shock-pad underlay | 261 |
| Figure 8.5 | Constructional features of a 6mm thick homogenous vinyl sports surface, with 6mm thick SBR crumbed rubber shock-pad underlay | 262 |
| Figure 8.6 | Interconnected modular square tile sports surface allowing a limited amount of horizontal displacement via the tile connections | 263 |
| Figure 8.7 | Surface assessment tests with prototypes in configuration a) the tile-connector interface with the connector moving directly between two tiles, and test configuration b) the tile-connector interface with the connector moving directly onto a tile. | 266 |
| Figure 8.8 | Surface assessment tests with 3D printed ABS prototypes showing top view and ribbed bottom view | 267 |
| Figure 8.9 | VIITA main components shown undergoing laboratory testing in its perpendicular test configuration | 272 |
| Figure 8.10 | Mobile device interface utilising Smartphone GPS, accelerometer and wireless features to systematically set-up, record and store sports surface force reduction impact data | 275 |
| Figure 8.11 | Load cell mounted test foot, which sends impact data to the mobile device via the VIITA head unit | 275 |
| Figure 8.12 | VIITA mounted in inclined test frame | 276 |
| Figure 8.13 | Geometric differences in displacements achieved on a surface composed predominantly from square and octagonal elements | 277 |
| Figure 8.14 | Test foot adaptor with 2000N/mm VIITA spring and tile connector, which reliably links the VIITA with the modular synthetic tiled sports surface | 278 |
| Figure 8.15 | FDM prototypes (Top-left square connector, top-right tile to connector loop interlock mechanism, bottom-left outdoor tile surface version and bottom-right octagonal tile) | 281 |
| Figure 8.16 | Validation Test A - 45 degree inclined impact test centrally positioned on a homogenous hardwood timber court surface | 282 |
| Figure 8.17 | Validation Test B - 45 degree inclined impact test with a centrally positioned tile being impacted directly down-court | 283 |
| Figure 8.18 | Validation Test C - 45 degree inclined impact test with a centrally positioned tile being impacted at 45 degrees across-court | 284 |
| Figure 8.19 | Validation Test D - 45 degree inclined impact test with a peripherally positioned tile being impacted at 45 degrees across-court | 285 |
| Figure 8.20 | Validation Test E - 45 degree inclined impact test with a centrally positioned connector being impacted directly down-court | 286 |
Figure 8.21 Validation Test F- 45 degree inclined impact test with a centrally positioned connector being impacted at 45 degrees across-court 287

Figure 8.22 Typical force-time history for the vertical ground reaction force (Fz), the horizontal anterior-posterior force (Fy) and the horizontal medial-lateral force (Fx) generated by the VIITA. The VIITA can be considered a simplified but repeatable simulation of athlete/surface interaction. 287

Figure 8.23 Comparison of tile test configurations in relation to the homogenous sports surface (Test A) 290

Figure 8.24 Comparison of impact test loading rates with surface test scenario configuration A and surface test scenario configuration B 292

Chapter 9

Figure 9.1 Point elastic sports surface force reduction classifications for combined horizontal and vertical shock attenuation showing the measured performance of the new modular tile surface 304

Figure 9.2 Sports surface test types including surface comparison testing 307

Figure 9.3 Four step sequence for injury prevention research incorporating the proposed surface related injury prevention measures 307

Figure 9.4 Online netball injury reporting form A 310

Figure 9.5 Online netball injury reporting form B 311
Acknowledgements

I would like to express my gratitude to the following people whose assistance has made this thesis possible. My most sincere thanks to:

- My primary supervisor Professor Aleksandar Subic, thank you for your most generous support and encouragement.
- My secondary supervisor Professor Colin Walker, thank you for your extra guidance and advice.
- Professor Franz Fuss, thank you for your extra guidance and advice.
- Dr Dominic Thewlis, thank you for your guidance and access to the University of South Australia Biomechanics and Motor Control Laboratory facilities.

Thanks also to:

- Garry Thomson, Managing Director of Garon Plastics.
- Daryl Wene, Managing Director of Global Plastics Technology.
- Norm Goedheer, National Sales Manager of Herculan Australia.
- Ross James and Daniel Cutting who helped build my final impact test device.

And special thanks to my family and friends for their continued lasting, support and encouragement.

Thanks also to the University of South Australia:

- to the School of Health Sciences at the University of South Australia for providing access to their Human Performance Laboratory, which made the experimental and validation tests possible (Chapter 8)
- to the School of Art Architecture and Design at the University of South Australia for providing access to their Design Workshop, which made the construction of sports surface prototypes and the EIITA, AIITA and VIITA devices used in the tests possible

And thanks last but not least to Barbara Brougham who assisted with the final editing and polishing of the document.
For my Dad
Abstract

Any sports surface which does not adequately attenuate the energy imparted into the surface when an athlete lands or changes direction on the surface, is potentially dangerous. Any material placed between the athlete and the surface, which does not sufficiently ‘decouple’ the athlete from the sports surface through shock attenuation, can cause injury. Despite the risk of injury while participating in sport and the costs associated with rehabilitation, sports related exercise offers huge health and wellbeing benefits to participants and the wider community. In order to preserve good health in an aging population, it is important to enable and encourage participation in physical exercise and recreation by economically providing low injury-risk surfaces on which various sport and recreation activities can take place. Injuries are a major barrier to the maintenance or increased participation in physical activity.

Sprung timber sports playing surfaces are the commonly used throughout most of the developed world and are especially common at higher levels of competitive indoor sport. Although timber is widely recognised as a natural and renewable resource with negative net carbon emissions, there is also the possibility that the environmental burdens created while using, maintaining and ultimately disposing of a wooden playing surface, may outweigh the environmental loads of its synthetic alternatives. The use of life cycle thinking approaches challenge conventional wisdom and aim to expose the true environmental loads over the lifecycle of each surface type considered. Only by using comparative life cycle thinking tools, such as LCA, do the life cycle implications of material/component selection decisions become fully apparent.

The body of work presented in this thesis therefore describes the research for and development of, an innovative sustainable court sports surface. This has been achieved through the design and development of a novel impact attenuating sports surface technology, which permits the mitigation of potentially injurious braking forces and therefore reduces the risk of injury while playing sports such as volleyball, basketball, indoor soccer and netball. In order to develop a more environmentally sustainable sports surface, the full life-cycle costs and life-cycle environmental impacts of the surface are also considered and minimised where possible.

Sport is an important aspect of Australian life and, in particular, it has a significant place in the social structures of our urban and rural communities. Safe, affordable, low environmental impact sports surfaces will encourage sport participation, encourage social interaction, increase access to sports facilities and help individuals maintain physical activity longer in life. The research placed a particular focus on netball, due to its popularity and the high rates of lower limb injury experienced by netball participants.

This research is significant as connections between surface material and injury risk on sports surfaces and surface sustainability have rarely been studied. Despite a wide range of playing surfaces being commercially available, the literature states that there is a lack of evidence connecting to the appropriateness of the playing characteristics of different surface types to distinct sports.
The research outcomes have the potential to reduce the risk of participant injury on sports surfaces across all age groups, lower the associated health costs, increase access to safe, sustainable sports surfaces and ultimately increase the level of sports and physical activity participation.

The original contributions to the field resulting from this research include:

1. the development of a new force reduction test method and its associated test apparatus
2. a new method for interpreting the combined horizontal and vertical force reduction test results generated by the new force reduction test method
3. a means whereby sports surface purchasers and sports arena designers can incorporate a life-cycle thinking approach in their decision making to produce objective, consistent and comprehensive data detailing the environmental impacts and waste implications of their surface selection decisions
4. a novel sustainable modular synthetic horizontal ground reaction force and a vertical ground reaction force attenuating sports surface as the final outcome.
Publications and Awards

The following publications, presentations, book chapters and awards have arisen directly from the work conducted for the thesis.

Refereed journal publications


This paper reviewed the performance of an impact device, to illustrate its effectiveness and validity in determining horizontal and vertical reaction force attenuation and assess its potential to evaluate injury risk on different sports surfaces.

Refereed conference presentations


The broad aim of this paper was to challenge our assumptions by analysing the environmental impacts of natural and artificial grass playing surfaces on climate change, through life cycle assessment.


The aim of this paper was to analyse the environmental impacts of various constructional styles of indoor playing surface on climate change, through the application of life cycle assessment.


This conference paper explores the need develop and refine the data required to make the LCA technique easier to use and the results more precise, such that entire life cycles rather than unconnected elements should become the analytical focus avoiding simplistic answers to what are complex problems.


This paper discusses the development of an angular, mechanical impact device, used to measure the resultant horizontal and vertical forces generated, which can be used to help quantify their injury prevention potential.


This paper discusses a research project which will see the development of an injury trial undertaken to quantify injury rates and describe injury mechanisms, on a broad variety of netball surface types.

This paper provides an overview of the main determining considerations which should be taken into account when selecting an appropriate sports surface for court type sports, in order to reduce the risk of injury to athletes.

**Book chapters**

Walker, A. (2012), Life-cycle thinking, analysis and design, *Designing for zero waste, consumption, technologies and the built environment*, Earthscan, UK.
See also: [www.earthscan.co.uk](http://www.earthscan.co.uk)

See also pp.[www.ttp.net](http://www.ttp.net)

ISWA Publication Award 2012, 2nd Prize, awarded by the International Solid Waste Association (ISWA), Vienna, for *Designing for zero waste*, Routledge (2012).
See also: [www.iswa.org](http://www.iswa.org)
Combining Horizontal and Vertical Ground Reaction Force Reduction with Sustainability in Multi-Sport Surfaces
Chapter 1

Introduction

1.1 The research problem and the context

Over five million Australians suffer sports related injuries each year, with the highest risk age group for injury being 18 to 24 year-olds, and lower limb injuries representing the most common form of injury across all sports and recreational activities. ‘Landing badly’ on a sports surface is the most common cause of injury reported, for both ankle and knee injuries. The most common sports injuries are to the knee (16%) and ankle (11%), followed by general bruising and cuts (8%) and damage to the back (7%). The approximate treatment cost per injury is illustrated in Table 1.1, and the significant role that a sports surface plays in injury intervention is shown in Table 1.2.

Table 1.1 Most common injury types and their approximate cost range per injury in 2006 (Source: Medibank Private Safe Sports Report 2006)

<table>
<thead>
<tr>
<th>Injury Type</th>
<th>Cost Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee</td>
<td>$11,000 to $16,500</td>
</tr>
<tr>
<td>Ankle</td>
<td>$4,400 to $6,600</td>
</tr>
<tr>
<td>Foot and Achilles tendon</td>
<td>$5,500 to $6,600</td>
</tr>
<tr>
<td>Back</td>
<td>$15,750 to $22,000</td>
</tr>
<tr>
<td>Shoulder</td>
<td>$5,500 to $7,700</td>
</tr>
<tr>
<td>Forearm/wrist</td>
<td>$4,400 to $6,600</td>
</tr>
<tr>
<td>Elbow</td>
<td>$4,400 to $6,600</td>
</tr>
</tbody>
</table>

In Australia, no better example of a sport that experiences frequent lower limb injury can be found than netball. Over one million participants play annually, both male and female, with women making up 96% of sporting club membership. Play takes place on non-resilient playing surfaces, such as bitumen, concrete and parquet, and the sport ranks amongst the top sports for injuries in Australia.

Table 1.2 Haddon injury intervention matrix (Source: Sports Injury Prevention Task Force May 2013)

<table>
<thead>
<tr>
<th>Phase</th>
<th>Human</th>
<th>Equipment</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-accident</td>
<td>Accident prevention</td>
<td>Risk awareness</td>
<td>Braces</td>
</tr>
<tr>
<td></td>
<td></td>
<td>preseason conditioning</td>
<td>Proper footwear</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strength training</td>
<td>Playing surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Warm-up</td>
<td></td>
</tr>
<tr>
<td>Injury event</td>
<td>Injury prevention</td>
<td>Fall techniques</td>
<td>Shin guards</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Impact coping techniques</td>
<td>Mouth protection</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Face guards</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Padded goal posts</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Shock absorbing surfaces</td>
</tr>
<tr>
<td>Post-accident event</td>
<td>Injury treatment and rehabilitation</td>
<td>First aid training</td>
<td>First aid equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compliance with ‘return to play rules’</td>
<td>Emergency equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Emergency and rescue services</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Medical care and rehabilitation services</td>
</tr>
</tbody>
</table>

In Australia, no better example of a sport that experiences frequent lower limb injury can be found than netball. Over one million participants play annually, both male and female, with women making up 96% of sporting club membership. Play takes place on non-resilient playing surfaces, such as bitumen, concrete and parquet, and the sport ranks amongst the top sports for injuries in Australia.

Table 1.2 Haddon injury intervention matrix (Source: Sports Injury Prevention Task Force May 2013)

<table>
<thead>
<tr>
<th>Phase</th>
<th>Human</th>
<th>Equipment</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-accident</td>
<td>Accident prevention</td>
<td>Risk awareness</td>
<td>Braces</td>
</tr>
<tr>
<td></td>
<td></td>
<td>preseason conditioning</td>
<td>Proper footwear</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strength training</td>
<td>Playing surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Warm-up</td>
<td></td>
</tr>
<tr>
<td>Injury event</td>
<td>Injury prevention</td>
<td>Fall techniques</td>
<td>Shin guards</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Impact coping techniques</td>
<td>Mouth protection</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Face guards</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Padded goal posts</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Shock absorbing surfaces</td>
</tr>
<tr>
<td>Post-accident event</td>
<td>Injury treatment and rehabilitation</td>
<td>First aid training</td>
<td>First aid equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compliance with ‘return to play rules’</td>
<td>Emergency equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Emergency and rescue services</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Medical care and rehabilitation services</td>
</tr>
</tbody>
</table>
The Victorian Government’s Sports Injury Prevention Taskforce Report (May 2013), noted that the provision of shock absorbing surfaces to sports participants would remove a sport injury related environmental barrier which could be preventing people from leading more active lifestyles.

The current research fills a void which exists in our knowledge about the risk and prevention of injury associated with playing different sports on different types of surfaces, with emphasis on netball as a prime example of a popular sport that poses risks due to the playing surface.

Studies conducted by Monash University’s Accident Research Centre show that netball ranks among the top sports, along with Australian Rules Football, rugby union and league and soccer, for sporting injuries in Australia. In netball, ankle and knee injuries represent more than two thirds of all injuries which require emergency department treatment (Finch, Cassell and Stathakis 1999).

The game involves sprinting and stopping suddenly when passing and catching, as well as pivoting. The haste at which these movements occur affects a variety of muscle activities and the magnitude of the ground reaction forces generated involve both vertical and horizontal components (Ting 1991). The vertical ground reaction forces (VGRF) generated when a netballer is landing range from 3.9 to 4.3 times their bodyweight (BW), while horizontal ground reaction forces, also known as braking forces (BF), range from 4.2 to 4.6 times BW (Steele and Milburn 1987). The magnitude of these horizontal and vertical ground reaction forces, along with their repetitive nature, is believed to contribute to the relatively high incidence of lower limb injury common to netball players (Neal and Sydney-Smith 1992).

1.1.1 Playing surfaces

Sports surfaces are complex structures, often made from many different layers of materials, which contribute to their varied shock attenuating properties. Currently no sports surface has been specifically designed to attenuate the potentially harmful braking forces generated when an athlete stops, turns or lands.

Steele and Milburn (1988) claim that excessive braking forces, such as those experienced while playing netball, subject ligaments and bony or cartilaginous structures to undue stress, especially in the knee joint. Haapasalo et al. (2007), for example, have noted that knee injury risk is ten times higher in recreational and competitive sports than in commuting and lifestyle activities, and epidemiological evidence indicates that 34% to 93% of netball injuries are located from the knee down (McGrath AC 1998).
The logical approach to reducing these stresses would be to attenuate vertical and horizontal reaction forces through appropriate sports surfaces (Steele and Milburn 1988). For example, in 1992, kinetic evaluation of a synthetic modular sports floor tile system was conducted, which concluded that enhanced dissipation of impact forces was evidenced by a reduction in maximum braking force, in comparison to a homogenous vinyl sports surface (Bagley 1992). In addition, the study concluded that at the same time athletic performance could potentially be enhanced, as maximum acceleration was achieved faster during the running and jumping tasks investigated.

The majority of sports surfaces, however, only aim to reduce vertical ground reaction forces (VGRF), as evidenced by the range of test standards that have been developed to measure only VGRF reduction. Horizontal ground reaction force (HGRF) reduction, for example, has been ignored in the development of the European Standard for Sports Hall Floors (EN 14 904), and the standard now adopted uses the Berlin Artificial Athlete as the definitive test apparatus for the determination of force reduction.

This situation reflects the fact that most current sports surfaces have the potential to attenuate only very low levels of HGRF, and it is the frictional characteristics of the shoe and surface interface which determine whether an athlete’s lower limbs are overloaded. In general, sports surface manufacturers regard HGRF as of less concern than providing a surface able to offer sufficient friction to enable traction and prevent accidental slipping (Olsen et al. 2003). The ability of an athlete to achieve faster starting, stopping, landing and turning manoeuvres, however, is extremely important for performance without sacrificing safety.

In recent years, advances in materials technology have played a critical role in the development of most sports (Subic 2007), but despite a diverse range of playing surfaces and materials used in their construction, there is a lack of data related to the appropriateness of the characteristics of various surfaces and specific sports. Netball, for example, is played on a variety of surfaces, such as concrete, bitumen, timber and various synthetic surfaces, but studies of sport surfaces to date have been limited to vague descriptions of ‘natural’ or ‘synthetic’ surfaces, without relating the details of the materials or structural layers, which ultimately contribute to their complex response behaviours. Investigations to date have been carried out on timber and synthetic surfaces and their relationship to knee injury (Olsen et al. 2003), but such studies only make very generalised observations about the material and structural characteristics of the surfaces considered.
1.1.2 Sustainability

Timber indoor sports playing surfaces are the norm throughout most of the developed world and are especially common at higher levels of competitive indoor sport. Although timber is widely recognised as a natural and renewable resource with negative net carbon emissions (Petersen and Solberg 2004), there is also the possibility that the environmental burdens created while using, maintaining and ultimately disposing of a wooden playing surface, may outweigh the environmental loads of its synthetic alternatives (Walker 2012). The use of life cycle thinking approaches challenge conventional wisdom and aim to expose the true environmental loads over the lifecycle of each surface type considered. Only by using comparative life cycle thinking tools
such as LCA, do the life cycle implications of material/component selection decisions become fully apparent.

1.2 Significance of the research

Injury is a major reason why people cease participation in sport and become less active. Surface related ankle and knee injuries make up more than two thirds of all sport injuries and aging limbs are more prone to injury. As people age and their bodies decline in function, physical activity can help to slow that decline. It is important to remain active or even increase activity as people age.

According to the *Sports Injury Prevention Task Force Report* (May 2013), the overall contribution of sport to the community is a very positive one and as a result governments invest in sports based programs in order to improve community health by increasing participation levels. However, the incidence of lower limb injury has increased over the last 10 to 15 years. The Medibank Private *Safe Sports Report* (2006) states that 5.2 million Australians suffer sports related injuries each year, with these injuries costing the Australian community approximately $2 billion in 2005.

Lower limb injuries have been found to be the most common form of injury across court type sports such as volleyball, basketball, netball, tennis and indoor soccer and recreational activities, and ‘landing badly’ on a sports surface is the most common reason for injury reported for both ankles and knees (Medibank 2006).

With increasing age, injury risk rises due to changes in tissue flexibility and self-repair capacity (Medibank 2006) and injury is a major influencing factor for individuals reducing or ending their participation in sport and physical activity.

Despite the risk of injury while participating in sport and the costs associated with rehabilitation, sports related exercise provides significant health benefits to participants and the community. In order to maintain good health in an aging population, it is important to enable and encourage participation in sport and recreation by providing low injury-risk surfaces, on which various sport and recreational activities can take place. Injuries are a major barrier to the maintenance or increased participation in physical activity. The current research is therefore significant, because it has the potential to reduce the risk of injury on sports surfaces across all age groups, lower the associated health costs, estimated to be over $2 billion, and ultimately increase the level of sports and physical activity participation and so improve community health.
The ever-changing nature of sports and the desire to play different sports in many different climactic conditions, has led to sports being played on synthetic surfaces in place of natural surfaces. In recent years, there has been a trend towards the construction of multi-sport facilities, where utilisation is optimised by offering a multitude of different sports, such as netball, basketball, indoor soccer, volleyball, inline hockey and martial arts, all being played on the same surface. Therefore, sports are now increasingly played on a variety of point elastic multi-layer synthetic sports surfaces. Sports surfaces can therefore be highly complex structures, often constructed from many elements which contribute to their compound behaviour. Despite such a wide range of playing surfaces, the literature states that there is a lack of data connecting the suitability of the playing surface behaviours of various sports surfaces for distinct sports. Conventional ‘sprung’ sports surfaces only reduce vertical ground reaction forces (VGRF) as they can only displace vertically, attenuating the downward force applied by an athlete. This dampening effect reduces the energy being returned to the athlete, thus preventing limbs from being overloaded, protecting them from injury. This is perfectly satisfactory if an athlete is stationary and landing on the surface from a static jump. Playing sports and other forms of physical activity, however, normally require an athlete to travel over a sports surface at speed.

Research indicates that the magnitude and repetitive nature of the high braking forces experienced while an athlete starts, stops, turns and jumps on a sports surface, contribute to the incidence of lower limb injury. Research also indicates that horizontal ground reaction forces experienced by an athlete can be even higher than vertical ground reaction forces.

Any non-energy absorbent sports surface is potentially dangerous. Any material installed directly above these surfaces which does not sufficiently isolate the competitor from the surface through shock attenuation, can cause injury. The highest forces are generated when players land on hard, non-resilient surfaces such as bitumen and concrete.

Synthetic modular plastic tile sports surfaces have been a popular alternative to timber sports floors for almost 30 years. These surfaces can be quickly installed to provide a shock absorbent surface for playing a wide variety of indoor and outdoor sports. They are manufactured from injection moulded copolymer polypropylene and are therefore simple and cost effective to manufacture. In
tests, it was discovered that modular tiled surfaces have the potential to dissipate more braking force energy than uniform, homogenous sports surfaces, such as timber, synthetic pour-in-place and synthetic sheet sports surfaces (Walker 2009).

It was concluded that this characteristic may be due to the fact that an interconnected modular tile sports surface allows a limited amount of horizontal movement through the tile connections. This ability for the surface to move slightly horizontally, just as a conventional sprung surface displaces vertically, may reduce the forces returned to an athlete’s lower limbs while braking and reduce potentially injurious loads to the musculoskeletal system.

This property was subsequently optimised through the design and development of a conceptually new, horizontal energy absorbing modular sport surface, which aims to reduce injury from sport and other forms of physical activity. This interlocking surface has the potential to keep people active, more regularly and for longer in their lives which translates ultimately to improving community health and reducing health costs.

Specifying and selecting a sports surface involves the simultaneous evaluation of a multitude of performance factors. Increasingly, environmental impact is becoming an important component of such surface deliberations (Walker 2008). Surface specifiers require objective, consistent and comprehensive data detailing the environmental impacts and waste implications of their selection decisions. A life-cycle thinking approach to the specification of a sports surface therefore involves a process-based analysis, which looks at each individual material and process in the playing surface value chain, including manufacturing, installing, maintaining and ultimately disposing of a variety of materials, depending on the nature of the sports surface (Walker 2008). The research presented in this thesis addressed this knowledge gap by evaluating the materials, structural characteristics and environmental impacts of the major surface types.

1.3 Research goals and objectives
The overarching goal of the current research was the development of novel technologies capable of providing a new generation of shock attenuating sports surfaces, which meet the needs of both athletes and various sports associations, reduce injury rates and improve player performance while being more environmentally sustainable through the application life cycle approaches when
designing. To the best of the researcher’s knowledge, no equally detailed study into the structural categories of sports surfaces is currently available, nor has other research produced analytical tools to simulate the performance of sport surfaces under combined vertical and horizontal loads in order to predict how the surface will behave during player impact.

Therefore, the key themes and associated goals that guided this research were:

1. reducing rates of lower limb sports injury
2. improving sports surface force reduction measurement
3. enhancing environmentally sustainable over the life of a sports surface.

It is clear from the literature that a number of areas require further research in order to advance our understanding of the ways in which sustainable sports surfaces can reduce the damaging effects of athletes braking during play. In addition, we could benefit from greater knowledge about the ways in which these braking forces can be accurately tested in order to evaluate the mechanical behaviour of a surface under the athlete’s braking loading.

The majority of a sports surface’s environmental impacts are ‘locked-in’ at the design stage. Therefore, designers, engineers and architects are in key positions to influence and reduce these impacts, over the life of a sports facility. Life cycle thinking recognises that whole-product life cycles must be considered if the true environmental impact of a sports surface is to be, firstly, understood and then minimised. Embracing the cyclic approaches that have been developed and perfected by nature, where one the waste from one biological process becomes the resource input for another, can help us achieve a more harmonious, future-friendly, resource efficient future.

The gaps in our current knowledge that were addressed by the research described in this thesis are summarised in relation to the following research objectives.

**Research objective A**

Load and loading rates are major contributors to athletic injury because they represent the stress being absorbed by an athlete’s lower limbs that makes them vulnerable to stress fractures, as well as knee and ankle joint injuries. *The current research sought to identify a means by which loading could occur less suddenly, in order to reduce the loading rate and therefore the risk of overloading injury.* A surface that encourages elastic deformation during contact in the horizontal
anterior-posterior direction and the horizontal medial-lateral direction through a process of horizontal deformation and displacement may result in reduced foot and limb loading. This surface should maximise horizontal energy attenuation in order to reduce the risk of injury while at the same time provide satisfactory energy return to avoid player fatigue. **This research is therefore significant as currently no sports surface exists which specifically targets horizontal force reduction.**

**Research objective B**

Current research into sports surfaces indicates that in order to reduce the potential for injury, the logical approach would be to attenuate both vertical and horizontal reaction forces. Most commercially available surfaces however only seek to reduce vertical forces and this is supported by the range of standards and tests that have been developed to only measure vertical ground reaction force reduction.

Modular plastic tile sports surfaces, may as a result of independent lateral movement under the application of load, potentially dissipate more braking forces in comparison to homogenous surfaces. Modular plastic tile surfaces which permit a restricted amount of horizontal movement via the tile connections have the potential to attenuate more braking force in comparison to a homogenous contact layer sports surface. The research reported in this thesis, therefore, sought to develop an optimised high performance modular plastic tile surface which would encourage a limited amount of horizontal movement via optimised tile connections which would allow ease of tile attachment and disengagement. **No sports surface currently exist which permits limited multi-directional lateral surface displacement.**

**Research objective C**

Horizontal ground reaction force reduction measurement has been ignored in the development of the new European Standard for Sports Hall Floors (EN14904 2006) which utilises the Berlin Artificial Athlete as the definitive test for shock absorption. Previous research has argued that a test mechanism should be developed which could vary the stress applied to a surface in order to take into account the non-linear behaviours of different surface types and also that an athlete-surface impact device should be developed where the impact angle can be varied, in order to replicate combined vertical and horizontal loads, which are applied to a surface as an athlete moves over a
sports surface. The current research, therefore, sought to inform the development of a new sports surface test device based upon the Berlin Artificial Athlete, which can strike a sports surface with a known mass at a known angle and to therefore measure the resultant horizontal and vertical forces. These forces can then be interpreted as a surface property such as horizontal force reduction and vertical force reduction.

**Research objective D**

Develop a means whereby results obtained from vertical and horizontal force reduction measurements can be categorised in relation to existing test categories. This is significant as no means to categorise horizontal force reduction currently exists.

**Research objective E**

Research has shown that sports surface specifiers require objective, consistent and comprehensive data detailing the environmental impacts and waste implications of their selection decisions. This process therefore requires a life-cycle thinking approach to the specification of a sports surface, including a process-based analysis, which looks at each individual material and process in the playing surface value chain. The materials and processes to be considered would include anything required to manufacture, install, maintain and ultimately dispose of an indoor sports surface. This research therefore sought to inform an approach where: the societal need and business case for sustainable approaches will be considered through lifecycle thinking methods and data collection processes suitable for the evaluation of a streamlined life-cycle assessment model.
Objective F (Future research flowing from the research)

It is the intention that moving beyond the remit of this thesis, further research will take the form of a sports surface trial.

1.4 Research method

The results of the research will guide the design and development of a novel, sustainable impact absorbing surface, which will allow damaging HGRF and VGRF to be attenuated and therefore reduce the risk of injury while playing sport on the surface. This will require comprehensive testing, modelling and identification of parameters influencing energy attenuation for different sports surface structures.

When overall injury rates on different surface types are documented, injury type and severity are not usually categorised by surface category. Therefore, an important aspect of the current study was the development and analysis of a comprehensive model of injury causation, intrinsic and extrinsic risk factors and surface properties.

Given the nonlinearity and complex construction of sports surfaces, analysis and evaluation of their behaviour was multifaceted. The study involved the:

- testing of current surfaces’ structures under combined vertical and horizontal loads to predict how they will perform during player impact
- development of a number of comprehensive structural dynamic models of sports surfaces, using the finite element method (FEM)
- analysis of the simulated impact shock attenuation and deformation of the sports surfaces, focusing on the effects of material properties, specifically their structure and impact absorption potential
- construction of prototype surfaces which replicate desirable force attenuation properties
- consolidation of the experimental and virtual models into an integrated design, in order to develop innovative design concepts of an adaptive surface capable of producing the required energy attenuation characteristics
- construction of a prototype surface which could be validated through impact testing
  The testing of the new surface was a direct comparison with the existing surfaces used at ETSA Park, Netball SA’s premier facility.
- assessment of the environmental load potential for different constructional styles of sports surface, in order to guide the development process towards a sustainable sports surface.
1.5 Limitations of the research

When reviewing the results of this research, certain limitations need to be taken into account:

- Full in-service testing has not yet been conducted. The work undertaken to date is predominantly theoretical, although the research has been supported where possible with assessment and validation testing, using various forms of constructed prototype.
- Final prototyping and in-service testing of the proposed new modular sports surface is therefore required and will be undertaken if funding is obtained.
- An injury survey will be conducted in regard to the final prototype and will help develop a more complete comprehension of injury causality and will target the multi-factorial aspects of sports injuries. Although sports injury may appear to be initiated by a single event, it more often results from a compound interaction involving intrinsic and extrinsic risk factors. It is the occurrence of both intrinsic and extrinsic risk factors under competitive conditions that makes an athlete vulnerable to injury.

1.6 Outline and structure of the thesis

The thesis consists of the following sections:

**Chapter 1** explains the need for this research and identifies major gaps in the literature. It introduces the research topic by providing background information on the extent of the sports injury problem to the Australian community, the sports primarily involved in high injury rates, the patterns of injury that contribute to injury and the role that sports surfaces play in contributing to injury. This chapter also discusses the limitations of the research and any impacts that these limitations may have on the research findings.

**Chapter 2** is a literature review and introduces current knowledge gaps and uncertainties associated with design for sustainability, sports injury and finite element analytical methods applied to shock isolation and energy dampening. The review examines the current science behind sports injury and the mechanisms leading to injury. The review has assisted in the application of suitable processes and parameters for the environmental modelling and analysis of sports surface environmental impacts and the finite element modelling and analysis of sports surface structures, over the usable life of a conceptually new prefabricated tile synthetic sports surface.

**Chapter 3** describes the materials and structural characteristics used in the manufacture of different types of sports surface, the performance parameters and the international testing protocols which have been adopted for sports surfaces. In addition, the chapter details the mechanical, safety and biomechanical performance characteristics of indoor sports surface construction categories along with their required performance standards.
Chapter 4 discusses the need for more sustainable approaches which should be applied to the design and manufacture of sports surfaces. It addresses the urgent need for sustainable design and the compelling business case for the sports equipment industry to adopt sustainable approaches. The chapter introduces the concepts of lifecycle thinking, closed loop processes and the benefits and limitations of lifecycle assessment.

Chapter 5 describes the data collection methods, processes and lifecycle analysis methods of the quantitative sustainable design phase of the research. The chapter considers the applicability of streamlined lifecycle assessment approaches in relation the sports surface selection process.

Chapter 6 addresses the new sports surface product development process, from design brief, research and product definition development, through idea generation, concept development, analysis, prototyping and testing and onto final concept development. The outcomes noted in this chapter were used to develop mathematical models used in Chapter 7.

Chapter 7 describes the various forms of structural analysis that were undertaken using the finite element analysis method and the analysis and interpretation of the finite element analysis results. In addition, the chapter compares the benefits and limitations of linear analysis versus non-linear approaches and the reasons for adopting alternating approaches where applicable. Detailed consideration of finite element analysis approaches to the design of dampened sports surface structures and the development of isolator configurations are also considered.

Chapter 8 discusses the design and development of a conceptually new inclined impact hammer test device developed for the surface validation tests, which could collect HGRF and VGRH test data. This device was then used for physical design exploratory tests, assessment testing and validation tests that were undertaken on six different configurations of manufacture prototype, in order to validate the design data developed in Chapter 7.

Chapter 9 covers a synopsis of the thesis, innovation, new intellectual property arising from the research and recommendations for future research. The chapter integrates the findings of all research phases and draws final conclusions. The limitations of the findings are discussed with recommendations for further research, with the chapter concluding by outlining future areas of research and revisiting the practical and theoretical contributions of this thesis.
Chapter 2

Literature review

2.1 Introduction

This chapter presents a view of the literature and introduces gaps in our current knowledge, as well as uncertainties associated with design for sustainability, sports injury and energy attenuation in sports surfaces. The review examines the current science behind surface related sports injury and the mechanisms which lead to injury. Reviewing the literature assisted in the identification of suitable processes and parameters for the modelling and analysis of the environmental impacts of sports surfaces, and the force reduction characteristics of sports surface structures over the usable life of a novel, prefabricated tile synthetic sports surface. The specific topics examined and how this literature relates to the research is represented in Figure 2.1.

<table>
<thead>
<tr>
<th>Literature Review Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Sport surface related lower limb Injury</strong></td>
</tr>
<tr>
<td>• Injury causation mechanisms</td>
</tr>
<tr>
<td>• overuse injury on sports surfaces</td>
</tr>
<tr>
<td>• netball non-contact injury</td>
</tr>
<tr>
<td>• surface force reduction and surface stiffness</td>
</tr>
<tr>
<td>• knee injury</td>
</tr>
<tr>
<td>• ankle injury</td>
</tr>
</tbody>
</table>

| **B. Sports surface mechanical behaviour**  |
| • sports surface friction |
| • surface material and relation to injury risk |
| • sports surface test devices |

| **C. Sustainable design**  |
| • life-cycle thinking and closed loop processes |
| • life cycle assessment |
| • sustainable indoor sports surfaces |

Figure 2.1 Flow-diagram representing the literature review

Despite the amount of information available relating to sports injury, only literature directly related to non-contact lower-limb sport injuries was reviewed.

The review provides a comprehensive description of the major characteristics of surface-related sports injury, the mechanisms by which ground reaction forces contribute to netball injury, the mechanical behaviour of sports surfaces and environmentally sustainable approaches to sports surface design.
A series of papers have been published as book chapters or published in peer-reviewed journals and peer-reviewed conferences. Details of the focus and submission of this research are summarised in Table 2.1. The author (A. Walker) was primarily responsible for analysing data and writing the papers. The contribution of the co-author in many of the papers presented and published (A. Subic) was that of editing of the papers and the provision of advice, characteristic of their role as supervisor to this PhD research project. All experimental work was undertaken by A. Walker.

Table 2.1 Focus and current status (at thesis submission) of research submitted to peer-reviewed conferences and journals as research papers and book chapters.

<table>
<thead>
<tr>
<th>Year</th>
<th>Title</th>
<th>Conference/journal/book chapter</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Grass is not always greener: The application of life cycle assessment to natural and artificial turf sports surfaces</td>
<td>STARSS 2007 conference</td>
<td>Presented</td>
</tr>
<tr>
<td>2008</td>
<td>Going green: The application of life cycle assessment tools to the indoor sports flooring industry</td>
<td>APCST 2007 conference</td>
<td>Presented</td>
</tr>
<tr>
<td>2008</td>
<td>When is green really green: Challenging assumptions through the use of life cycle assessment</td>
<td>Solar Cities 2008 conference</td>
<td>Presented</td>
</tr>
<tr>
<td>2009</td>
<td>Horizontal and vertical reaction force testing for synthetic sports surfaces</td>
<td>4th APCST 2009 conference</td>
<td>Presented</td>
</tr>
<tr>
<td>2010</td>
<td>Exploring the relationship between floor type and risk of injury in netball</td>
<td>STARSS 2010 conference</td>
<td>Presented</td>
</tr>
<tr>
<td>2010</td>
<td>Horizontal and vertical reaction force testing for synthetic sports surfaces</td>
<td>Sports Technology</td>
<td>Published</td>
</tr>
<tr>
<td>2012</td>
<td>Life-cycle thinking, analysis and design</td>
<td>Designing for zero waste, book chapter</td>
<td>Published</td>
</tr>
<tr>
<td>2013</td>
<td>Advances in design and materials for indoor sports surfaces</td>
<td>Advances in engineering materials, product and systems design, book chapter</td>
<td>Published</td>
</tr>
</tbody>
</table>

Additional literature reviews are provided as introductory sections to each research chapter in this thesis, relevant to the particular subject area being explored.

2.2 Sports surface related lower limb injury

The Medibank Private Safe Sports Report (2006) states that 5.2 million Australians suffer from sports related injuries per annum, costing the Australian community approximately $2 billion each year. Lower limb injuries are the most common form of injury in all sports and recreational activities, and ‘landing badly’ on a sports surface is the most common cause reported for both ankle and knee injuries (Medibank Private 2006).

Many associations have been made between the mechanical characteristics of sports surfaces and the risk of lower limb injury to athletes. The two most significant forces acting on players’ limbs are the vertical mechanical behaviour of a surface on landing and the horizontal behaviour during
braking (Stiles, James et al. 2009). Repeated impact and the direction of the forces can lead to ligament damage and other forms of lower limb injury (Radin, Ehrlich et al. 1978; Frederick, Clarke et al. 1984; Voloshin, Burger et al. 1985).

During impact with a sports surface, energy is transmitted from the athlete to the playing surface, and the ratio of input energy to returned energy is determined by the stiffness and dampening properties of the materials from which the surface is constructed. A proportion of this energy is dissipated through a process of hysteresis in the form of heat energy, retained through surface deformation, or returned to the athlete as a result of the surface material’s stiffness (Davidson, Wilson et al. 2009).

The attenuation and return of energy can potentially contribute to the athlete’s performance (Baroud, Nigg et al. 1999). Stefanyshyn and Nigg determined that athletic performance can be increased on surfaces which have high stiffness, as these surfaces deform less and return more energy to an athlete (Stefanyshyn and Nigg 2003). Increased surface deformation, on the other hand, may require an athlete to expend more energy, leading to lower efficiency and the early onset of fatigue (Lejeune, Willems et al. 1998; Millet, Perrey et al. 2006).

High forces and loading rates returning energy from a surface with high stiffness back to an athlete unfortunately increase the stress being absorbed by an athlete’s lower limbs and the susceptibility to stress fractures, knee and ankle joint injuries (Grimston, Engsberg et al. 1991; Dura, Hoyos et al. 1999; Butler, Crowell III et al. 2003; Shorten 2003). Sports surfaces characterised by high stiffness have also been implicated as a factor in overuse injuries, such as Achilles tendinitis and shin splints (James, Bates et al. 1978; Ekstrand and Nigg 1989; Reilly and Borrie 1992). Sports surfaces which are more compliant extend the duration of impact over a longer period of time, reducing the loading rate and the risk of overloading injuries (Davidson, Wilson et al. 2009).

Increasing the extent of energy return to an athlete, and the rate at which that energy is returned, from a stiff surface will lead to compensation adjustments by the athlete in order to reduce the effects of the returned forces. These modifications in movement can be perceived as decreases in leg stiffness, velocity or increases in joint flexure when landing and running (Dura, Hoyos et al. 1999). Soreness in lower limb joints and soft tissues can result when players change from a familiar sports surface to an unfamiliar one because of subtle adjustments to their movement. Where
possible, athletes should train on surfaces with similar properties to the surfaces on which they will compete and to which they have adapted (Nigg, Denoth et al. 1984). Ideally, therefore, standard surface types should be maintained across a particular sport.

2.2.1 Injury causation mechanisms

Although an injury may appear to have been caused by a single incident, injury regularly results from the compound interface of a number of intrinsic and extrinsic risk factors. Of the extrinsic risk factors, those relating to the shoe and surface interface would appear to play a potentially significant role in preventing overuse injury of the lower extremity (Strand, Tvedte et al. 1990; Myklebust, Maehlum et al. 1998). The interaction between an athlete, the athlete’s shoe and sports surface all combine with the specific sports activity on that surface to dictate the extrinsic nature of an injury (Walker 2010) as described in Figure 2.2.
Figure 2.2 Extrinsic risk factors for lower extremity injury (Walker 2010)
The presence of intrinsic and extrinsic risk factors prepares an athlete for injury, but the mere presence of these risks is not alone sufficient to produce an injury. It is the sum of all risk factors and the interaction between them that ‘prime’ an athlete for an injury (Murphy, Connolly et al. 2003). Of all extrinsic risk factors, those which relate to the shoe and surface interface would appear to play a potentially significant role in injury prevention (Strand, Tvedte et al. 1990; Myklebust, Maehlum et al. 1997).

Injury prevention research is a four step sequence as described by van Mechelen, Hlobil el al. (1992) and described graphically in Figure 2.3. Firstly, the magnitude of the problem must be identified and described in terms of the incidence and severity of the injury. Secondly, the risk factors and injury mechanisms that play a part in the occurrence of sport injury need to be identified. Thirdly, measures need to be introduced that are likely to decrease the future risk and/or severity of injury, and, finally, the effect of the measures must be evaluated by repeating the first step (van Mechelen, Hlobil et al. 1992).

![Figure 2.3](image)

**Figure 2.3** The four step sequence for injury prevention research (van Mechelen, Hlobil et al. 1992)
2.2.2 Overuse injury on sports surfaces

Overuse injuries generally occur as a result of repetitive microtrauma of the musculoskeletal system, where the repeated application of a force results in a combined fatigue effect in tissue over a period of time (Bruce 1999). Contributing factors to overuse injuries include: 'poor technique', an excessive number of attempts at a particular activity, inappropriate physical conditioning and/or poor body anthropometry or congenital factors that may predispose a person to injury in a particular sport or activity (Nigg 1985; Renstrim and Johnson 1985; Dalton 1992).

Injuries that occur from running can be classified as either acute or chronic. An acute injury can be caused by a single incident, whereas chronic injury results from repeated loading at or even below the loading threshold normally required to cause an acute injury. Examples of chronic, or overuse injuries, include stress fractures, iliotibial band syndrome, Achilles tendonitis, plantar fasciitis, and patellar tendonitis. Many chronic injuries displayed by athletes are caused by, or exacerbated by repeat loading. These injuries may then lead to developmental arthritis, lower back pain, and articular cartilage degeneration (Steele and Milburn 1988). Many overuse injuries result from the mechanical failure of the musculoskeletal system when it responds to repeated and prolonged impacts generated while landing (Francis, Leigh et al. 1988).

Francis, Leigh et al. (1988) assessed the then current standards used for the evaluation and approval of dance surfaces. Survey results from their study indicated that the most common injuries sustained by aerobics dancers and instructors involved the shins and feet. Impact peak has also been linked with overuse injuries, where the higher the impact peak, the greater the occurrence of overuse injuries (Miller 1990).

Sports surface related injuries may be separated into those produced by rapid decelerations, and those produced as a result of overuse. Overuse injuries can result from repeated overloading or multiple microtrauma of the athlete’s limbs, where the repeated application of forces conglomerate
to develop a cumulative weakness in tissues of an athlete’s lower limbs over time (Elliott 1998; McGrath and Ozanne-Smith 1998). Contributing factors to overuse injuries include:

- performance improvement training, where a high number of repetitions of a single activity or manoeuvre are made
- inadequate levels of player fitness for the level of participation required
- inappropriate body shape or genetic factors that may prime an athlete for injury while playing a particular sport.

Surface related overuse injuries therefore normally fall into two categories. The first is related to repetitions of particular activities such as netball running and passing drills, where with each foot contact with the surface, the horizontal and vertical ground reaction forces must be attenuated by the surface or the footwear worn by the athlete. The second category is associated with a large number of repeated manoeuvres, which require high levels of precision and control as can be found in netball shooting practice (McGrath and Ozanne-Smith 1998).

Epidemiological studies conducted by Foster, John et al. (1989) concluded that changes in injury statistics should be carefully assessed following changes in the type of playing surface. Factors, such as technique and physical capacity measured prior to the playing season, and the causes of any subsequent injury, were then related to these changed characteristics (Foster, John et al. 1989; Brukner, Bennell et al. 1995). Such studies are difficult to manage with elite athletes, however. Therefore researchers have measured the forces which act on an athlete during a specific activity as an indicator of the probability of acquiring an overuse injury (Brukner, Bennell et al. 1995).

Overuse injuries resulting from highly repetitive, medium force activities are related to the frictional characteristics of the surface because a high number of cyclic but small loads will cause an injury to both hard and soft tissues (McGrath and Ozanne-Smith 1998). In the case of netball, which is played primarily on non-resilient surfaces where an athlete is required to repeatedly start, stop, turn, jump and land, it is not surprising that injuries occur to lower limbs. In this case, ankle and knee joints are the most common sites of injury, with injuries to the knee being the most disabling (Elliott 1998).

2.2.3 Non-contact injury

Non-contact injury is incurred without an athlete being touched by any other team mate (as in practice) or a competitor. Even in contact sports, non-contact injuries can occur during training
sessions or away from the sporting field. Of the team sports described as non-contact (although it can be demonstrably ‘rough’ unless well-refereed), netball is the most popular team sport in Australia, and is played mainly by females of various ages and skill levels on a wide variety of surfaces. It is also a significant sport for ankle and knee injuries, which make up more than two thirds of all netball injuries requiring emergency department treatment (Cassell, Finch et al. 2004).

The high number of players and the broad variety of court surface types, makes netball an excellent sport in which to test the capacity of a sports surface to mediate injury. The method of receiving a pass in netball, usually comprises of an athlete running to meet the pass and abruptly stopping on either one or two feet. The speed at which these movements occur can affect an array of muscle activities and ground reaction forces. The magnitude of the ground reaction forces generated while performing manoeuvres, in addition to their repetitive nature, add to the comparatively high incidence of lower limb injury common to netball (Neal and Sydney-Smith 1992; Hetherington, King et al. 2009).

Figure 2.4 Non-contact injuries are common in netball which features sudden leaping, braking, twisting manoeuvres and sudden changes in direction

Steele (1990) states that the factor which influences musculoskeletal stress to the greatest extent is a netball player's landing technique. Footfall in all sports is, in fact, a dangerous time for both competitive and non-competitive athletes. During landing, the human body is exposed to large forces and moments that create the potential for injury (McNitt-Gray 1991). This is as true for 100m runners as it is for basketball players, tennis players, or netballers. However, in netball, the
force is exaggerated by the rules of the game, which state that upon receiving the ball, a player must stop within one and a half steps.

The netball footwork rule encourages excessively high braking force manoeuvres (INFA Netball 2007), forcing players to stop suddenly and repeatedly at speed, affecting a range of muscle activity and ground reaction forces. Such excessive braking exposes the ligaments of an athlete’s lower limbs to excessive stress, particularly in the knee, substantially increasing the probability of injury. For example, epidemiological evidence indicates that 34% to 93% of netball injuries are situated from the knee down (Steele and Milburn 1987).

The logical approach to ameliorate injury would therefore be to attenuate the vertical and horizontal reaction forces (Steele and Milburn 1988) through surface design. Most surfaces however only seek to reduce vertical forces and this is supported by the range of standards and tests that have been developed to measure vertical force attenuation only.

2.2.4 Surface force reduction and surface stiffness

An athlete’s interaction with a sports surface while running, landing or falling is complex, and involves both the surface’s stiffness and its ability to reduce any forces applied to the surface. Force reduction measurement consists of the evaluation of the maximum impact force and calculating the force reduction percentage in comparison to a very rigid surface, such as concrete. Therefore, the force reduction characteristic of a sports surface is the ratio of energy returned to the athlete after they have contacted the surface, as a proportion of the energy that the athlete applied to the surface. This ratio is then used as a measure of how well a surface can attenuate energy.

The stiffness of a sports surface on the other hand, is a measure of the hardness or softness of a surface and it characterises a surface’s ability to reduce the severity of an impact. Stiffness is the ratio of the applied force to the amount of deformation occurring in the surface. Stiff surfaces, such as concrete or bitumen deflect very little, even under the application of large loads, whereas a surface material with low stiffness value, such as a synthetic polymeric material, will deflect more easily under load. The energy loss from hard surfaces such as bitumen and concrete are negligible in respect to an athlete, as they are not able to deform such surfaces.

Ground reaction forces can be defined as a vector quantity consisting of magnitude, direction and point of application (Miller 1990). It was through the use of a Kistler Force Platform that Miller’s
(1990) study was conducted. The use of force platforms to measure ground reaction forces has been reported in the literature since the early 1970s (Miller 1990). Typically the magnitude of impact forces increases as the runner’s velocity increases (Wakeling, Von Tscharner et al. 2001).

The three primary measures of a force platform are the vertical ground reaction force, the horizontal anterior-posterior force and the horizontal medial-lateral force.

The measurement of vertical ground reaction forces, particularly loading rate and impact force, form the basis of Miller’s (1990) study. The rate at which the impact peak is reached during the contact phase of a foot strike is termed the loading rate (Wakeling, Von Tscharner et al. 2001). Loading rate is recorded as an absolute figure in Newtons per second (N/S) or this unit can be normalised for comparison purposes into bodyweights per second (bw/s) (Miller 1990). It is, as the term suggests, a measurement of the rate at which a load is exerted after the fall of the athlete’s foot.

Miller (1990) reports on a study that shows a positive correlation between running speed and loading rate, in that the greater the running speed, the greater the loading rate. The propulsive peak is not usually of concern when examining overuse injuries, as this is usually a lower figure than the impact peak, and also occurs over a greater period of time, hence lowering the loading rate for this peak (Hreljac 2004).

2.2.5 Knee injury

The human knee is one of the most complex joints in the body, and knee injury is one of the most common forms of sports injury, with netball experiencing particular high rates of knee injury. Although less frequent than ankle injuries, traumatic knee injury is the most common debilitating netball injury. Knee injuries have been reported to account for approximately 12% to 25% of netball injuries (McGrath and Ozanne-Smith 1998). The knee joint is highly susceptible to injury as a result of its distinct structure and the high loads conveyed into the joint, especially while performing dynamic manoeuvres, such as starting, stopping, turning and landing on a sports surface.

Although knee injury accounts for 12% of the total sports injuries in Australia, it accounts for 25% of all injury costs (Egger 1990). Netball is one of Australia’s most popular participation team sports, and, along with rugby league/union and Australian Rules football, knee injuries frequently occur (Seward 1997). Studies have indicated that knee injuries are second only in occurrence to
ankle injuries in sports such as netball, soccer, rugby union/league, Australian rules football, basketball, handball, volleyball, and badminton (Purdam 1987; Crawford and Fricker 1990; Egger 1990; Ferratti, Papandrea et al. 1990; Backx, Beijer et al. 1991). Estimates have been made that knee injuries per year can cost as much as $8.8 million for Australian Rules football, $11.9 million for Rugby League/Union, and $5.3 million for netball (Egger 1990). The two main forms of knee injury in netball are damage to the anterior cruciate ligament and the meniscus.

**Anterior cruciate ligament (ACL) non-contact injury.** Research from US college sports and European team handball have also shown that female athletes have an increased risk for anterior cruciate ligament (ACL) injuries in comparison to men (McNitt-Gray 1991). The rate of ACL injury is three to five times higher among women in indoor ball games than among men (Olsen, Myklebust et al. 2003). Studies have indicated that there may be a relationship between the shoe-surface interface and injury risk, with most ACL injuries usually occurring during a non-contact foot plant and cut movement, or when landing from a jump shot (Olsen, Myklebust et al. 2003).

The injury mechanism in all cases is a forceful valgus-external or internal rotation with the knee close to extension, and it appears that the ACL tear occurs at the time when the foot is firmly fixed to the floor. Strand et al. 1990 suggests that playing team handball on wooden parquet floors results in a significantly lower ACL injury rate than was experienced on artificial floors. It was suggested that high levels of friction between the shoe and surface increase the injury risk, as the foot appeared to be fixed to the floor at the time of injury.

The most important extrinsic risk factor for ACL injury is the shoe/surface interface (Strand et al. 1990; Myklebust et al. 1997). It has been hypothesised that increases in friction between an athlete’s footwear and playing surface increase the rate of ACL injury. Playing on wooden floors should therefore result in fewer injuries than playing on artificial floors, which tend to have higher levels of friction. To prevent non-contact ACL injuries in team handball and other ball games, some researchers have suggest that all floor types should have as little a shoe/surface friction as possible, but also provide adequate friction to permit optimum playing performance (Olsen, Myklebust et al. 2003). This view seeks to express the ideal balance that is sought between
footwear release to prevent tissue overload, and footwear traction in order to increase athlete acceleration and control.

ACL injury costs involve surgery and rehabilitation as a result of the original injury and ongoing joint problems (Cochrane 2001). An increased likelihood of recurring degenerative joint problems makes ACL injuries costly and debilitating (Cochrane 2001; Noyes 1997; Shelbourne 1991).

![Posterior view of the knee showing the various ligaments of the knee](Sports_Medicine_Australia_2006a)

**Figure 2.5** Posterior view of the knee showing the various ligaments of the knee

**Meniscus non-contact injury.** Meniscus non-contact injuries are common in sports that feature sudden twisting manoeuvres and sudden changes in direction, movements which are typically found in ball games played on courts, such as basketball, volleyball, squash, badminton and netball (Egger 1990).

The knee is a hinged joint and is arranged to perform two major movements, flexion and extension. The menisci are located on the tibial plateau and femur, and there are two menisci within each knee joint, with each semicircular menisci being considerably thicker around the edge than in the centre (Englund, Guermazi et al. 2008). Meniscal tears can occur in isolation or in combination with some form of ligamentous injury. The meniscus in the knee joint is usually damaged by a twisting action of the knee when the joint is slightly bent (Baker and Lubowitz 2012). A partial or total tear of a
meniscus may arise when an athlete suddenly rotates the upper leg while the foot remains fully planted on the sports surface.

Severe pain is normally experienced when a meniscus has been injured, especially when endeavouring to straighten the knee. If a tear is small, the meniscus may stay in contact with the front and back of the knee. However, if the tear is large, the meniscus may only remain in partial contact with the knee (McDermott and Amis 2006). Severe but sporadic pain may follow, with the pain being highly localised to the damaged area of the joint.

Pain results from the meniscal tear becoming trapped between the moveable surfaces of the tibia and femur, preventing full extension of the leg. Swelling may also occur soon after the meniscus has been injured as a result of joint inflammation. Meniscal tears can be degenerative or traumatic. Degenerative tears result from a progressive wearing of the knee joint, often as a result of natural
degradation of the menisci (Rodkey, DeHaven et al. 2008). Traumatic injuries, however, are very common in sports such as netball (Englund, Guermazi et al. 2008).

Figure 2.6  Posterior view of the knee showing meniscus, anterior cruciate ligament and posterior cruciate ligament (Sports Medicine Australia 2006d)

2.2.6 Ankle injury

Ankle injuries regularly occur as a result of a decelerating athlete’s planted foot rolling on a sports surface. High surface frictional forces and the momentum of the athlete combine to cause the tendons in the ankle to become overloaded and when the tendons weaken, the foot begins to roll and over stress the tendons (Harper 1988). Other common examples of this occurrence are when the foot is awkwardly planted during running, landing unbalanced from a jump or stepping onto an irregular surface such as a competitor’s foot (Nussbaim, Sieler et al. 2001). The ankle is the most regularly injured part of the lower limb in netball, with one ankle sprain occurring per 10 000 individuals per day (Ruth 1961). The most frequent netball injury is a sprain of the lateral ankle
ligaments when a player lands on the outer border of the foot, causing the ankle to ‘roll’ in under the leg and stretching or tearing the lateral ligaments of the joint (Brostrom 1964).

**Ankle sprain.** An ankle sprain is caused by the extending or tearing of ligaments around the ankle. The most common sprain, occurring at rates of approximately 90%, is an inversion ankle sprain (Marieb 2008). This injury occurs when the ankle rolls in such a way that the bottom of the foot faces inwards, which causes hyper extension resulting in damage to the ligaments on the lateral side of the ankle (Brooks, Potter et al. 1981). There are three ligaments on the lateral side of the ankle, the anterior talofibular ligament, the calcaneofibular ligament and the posterior talofibular ligament as shown in Figure 2.7 (Marieb 2008). An eversion ankle sprain is less common than an inversion ankle sprain, with the ankle rotating in such a way that the bottom of the foot faces outwards. This causes the medial ligament, the deltoid ligament, to become stretched excessively (Marieb 2008).

![Figure 2.7 Lateral ligaments of the ankle (Sports Medicine Australia 2006b)](image-url)
Surface related Achilles tendinopathy, tearing and rupture. Achilles tendonitis is an overuse injury that is common in sports which involve running and jumping, such as netball. The Achilles tendon is the largest tendon in the human body and comprises the gastrocnemius and the soleus muscles as shown in Figure 2.8 (Mafulli 1999). Most tendon injuries are the result of gradual wear to the tendon from overuse and/or ageing (Strocchi, DePasquale et al. 1991). Athletes who are required to make high repetitions of the same manoeuvre are more likely to damage a tendon (Clement, Taunton et al. 1984).

A tendon injury can happen gradually or suddenly, and a sudden injury of the tendon is more likely to happen if the tendon has become weakened over time (Mafulli 1999). This type of injury does not involve inflammation and is most likely due to a series of micro tears that weaken the tendon. Achilles tendinopathy results from a number of sources which, alone or in combination, may load the tendon excessively. These sources include: increasing training intensity, decreasing recovery time between activities, inadequate or incorrect footwear, excessive pronation, playing on a non-
resilient sports surface, changing the playing surface type without enough time for the athlete to adjust, and inadequate warm up, stretching and cool down (Maffulli 1999).

Achilles tendon ruptures often occur during recreational sports activities that require sudden bursts of activity, including jumping, pivoting, and sprinting, all manoeuvres commonly performed in the sport of netball.

The Achilles tendon can partially tear or completely rupture. While a partial tear presents symptoms similar to tendinopathy, a complete rupture during sports participation causes pain and sudden loss of power and movement (Postacchini and Puddu 1976). Complete rupture is often associated with athletes between the ages of 30 and 50 years old (Strocchi, DePasquale et al. 1991).

2.3 Sports surface mechanical behaviour

The mechanical behaviour of a sports surface describes the reaction of a surface to an applied force. This mechanical behaviour is regularly described in terms of hardness, strength or stiffness, and relate to a surface’s ability to resist deformation (Nigg and Anton 1995). In the case of purely elastic linear behaviour, the strain induced in a sports surface is directly proportional to the applied strain. Thereafter the surface returns to its original shape once the applied stress has been removed.

The majority of sports surfaces however are non-Hookean and are composed of layers of materials which display both linear and non-linear behaviours. Surface hardness refers to the surface’s resistance to permanent deformation (Bartlett and Bussey 2012). The most common forms of loading that a sports surface will experience are vertical compressive forces and horizontal shear forces. The viscoelastic properties of a surface will determine its dynamic behaviour as it experiences combined horizontal and vertical ground reaction forces generated by the athlete during play (Steele and Milburn 1988).

Landing incorrectly on a sports surface is more likely to result in injury as a result of large impact forces and insufficient impact absorption (Lees 1981; McNitt-Gray 1991). In order to stop quickly on a sports surface, an athlete must apply an appropriate opposing horizontal braking force and the faster the athlete wishes to stop, the higher the braking force will be. Peak braking force when netball players stop to receive a pass, for example, range from on average 4.2 to 4.6 times body weight as shown in Table 2.2 (Steele and Milburn 1987). In most of the test conditions researched in 1987 by Steele and Milburn, all breaking forces recorded exceeded their corresponding vertical force. In subsequent research conducted by Steele and Milburn in 1988 with different sports
surface types, there continued a close correlation between the recorded breaking force and vertical force. This research therefore highlights the importance for consideration of breaking force
performance in any sports surface study. A typical ground reaction force graph generated by netball players on landing is shown in Figure 2.9 (Steele 1990).

![Graph showing features of a typical force-time curve generated at landing in netball (Steele 1990, p. 92)](image)

**Table 2.2** Summary of the average maximal vertical and braking forces generated at landing at netball (Steele and Milburn 1987)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Vert. Forces (BW)</th>
<th>Time to Max (ms)</th>
<th>Brk. Forces (BW)</th>
<th>Time to Max (ms)</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barefoot</td>
<td>4.26</td>
<td>18.0</td>
<td>4.23</td>
<td>---</td>
<td>Steele &amp; Milburn</td>
</tr>
<tr>
<td>Shoes A</td>
<td>4.02</td>
<td>22.3</td>
<td>4.56</td>
<td>---</td>
<td>(1987b)</td>
</tr>
<tr>
<td>B</td>
<td>3.92</td>
<td>28.3</td>
<td>4.50</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>3.99</td>
<td>31.7</td>
<td>4.61</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>3.83</td>
<td>23.6</td>
<td>4.02</td>
<td>29.0</td>
<td>Steele &amp; Milburn</td>
</tr>
<tr>
<td>High Pass</td>
<td>3.69</td>
<td>39.5</td>
<td>3.04</td>
<td>23.4</td>
<td>(1986b)</td>
</tr>
<tr>
<td>Footwork</td>
<td>3.51</td>
<td>21.0</td>
<td>2.98</td>
<td>23.3</td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>3.77</td>
<td>24.2</td>
<td>3.80</td>
<td>30.4</td>
<td>Steele &amp; Milburn</td>
</tr>
<tr>
<td>Bitumen</td>
<td>3.50</td>
<td>20.8</td>
<td>3.51</td>
<td>30.0</td>
<td>(1988c)</td>
</tr>
<tr>
<td>Grass A</td>
<td>3.79</td>
<td>25.0</td>
<td>3.44</td>
<td>27.1</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>3.50</td>
<td>25.6</td>
<td>3.14</td>
<td>25.3</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>3.90</td>
<td>26.5</td>
<td>3.81</td>
<td>26.4</td>
<td></td>
</tr>
<tr>
<td>Rubber A</td>
<td>3.83</td>
<td>27.0</td>
<td>3.54</td>
<td>30.1</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>3.74</td>
<td>22.7</td>
<td>3.22</td>
<td>29.5</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>3.91</td>
<td>21.8</td>
<td>3.18</td>
<td>28.7</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>3.59</td>
<td>25.1</td>
<td>3.33</td>
<td>29.4</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>3.71</td>
<td>22.9</td>
<td>2.98</td>
<td>32.8</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>3.84</td>
<td>22.5</td>
<td>3.67</td>
<td>31.3</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>3.74</td>
<td>24.9</td>
<td>3.42</td>
<td>30.8</td>
<td></td>
</tr>
<tr>
<td>Forefoot</td>
<td>3.30</td>
<td>47.4</td>
<td>2.60</td>
<td>22.3</td>
<td>Steele &amp; Milburn</td>
</tr>
<tr>
<td>Heel</td>
<td>4.50</td>
<td>21.0</td>
<td>4.10</td>
<td>26.0</td>
<td>(1989)</td>
</tr>
<tr>
<td>Forefoot</td>
<td>5.70</td>
<td>30.6</td>
<td>2.00</td>
<td>23.9</td>
<td>Steele &amp; Lafoutine</td>
</tr>
<tr>
<td>Heel</td>
<td>5.25</td>
<td>31.2</td>
<td>3.30</td>
<td>30.5</td>
<td>(1996)</td>
</tr>
<tr>
<td>Chest (F)</td>
<td>5.42</td>
<td>32.0</td>
<td>2.83</td>
<td>26.0</td>
<td>Neal &amp; Sydney-Smith</td>
</tr>
<tr>
<td>Chest (H)</td>
<td>3.96</td>
<td>32.0</td>
<td>2.11</td>
<td>28.0</td>
<td>(1992)</td>
</tr>
<tr>
<td>High (F)</td>
<td>4.53</td>
<td>37.0</td>
<td>1.90</td>
<td>17.0</td>
<td></td>
</tr>
</tbody>
</table>

**Abbreviations:** BW = force equal to the number times body weight
H = Heel
F = Forefoot

Page 33
Conventional ‘sprung’ sports surfaces can only reduce vertical ground reaction forces (VGRF). They displace downwards dampening the vertical force applied by an athlete as shown in Figure 2.10. This dampening effect reduces the energy being returned to the athlete, preventing limbs from being overloaded, which could potentially result in injury. This is acceptable if the athlete is not traveling over the surface and landing from a jump. Playing sports or other forms of physical activity, however normally require an athlete to travel over a surface, starting, stopping, turning and jumping while moving.

![Diagram of vertical ground reaction force](image)

**Figure 2.10 Conventional ‘sprung’ sports surface vertical ground reaction force**

Traction on traditional homogenous surface sports surfaces is normally provided by the horizontal shear resistance of the surface layers in response to the athlete braking on the surface. As the contact layer of the surface is uniform and therefore cannot deform to any significant extent, the opportunity for horizontal ground reaction force reduction is limited.

Bagley (1992) tested 14 recreational athletes between the ages of 20 and 45 years old with no history of lower limb injury. The athletes were asked to perform running, braking and jumping manoeuvres on a homogenous linoleum surface and then the manoeuvres were repeated on a modular plastic tile sports surface over a force platform. The recorded forces were then normalised to body weight.
The modular plastic tile sports surface was found to dissipate more impact forces, as evidenced in the reduction in maximum braking force as shown in Tables 2.3, 2.4 and 2.5. In addition, Bagley (1992) observed that an athletic performance could be enhanced on a tiled surface since the data recorded during running and jumping manoeuvres indicated that the time to reach maximum acceleration was achieved faster. A trend towards a pronounced vertical minimum force during jumping manoeuvres on the modular plastic tile surface was noted. This spring-like behaviour
could therefore potentially be exploited if the compliance of the tile surface was matched to the resonance of the athlete’s muscle system (McMahon and Greene 1978; Bagley 1992).

Table 2.3  Running parameter averages in percentage body weight (Bagley 1992)

<table>
<thead>
<tr>
<th>Running (% contact follows magnitude)</th>
<th>Modular polypropylene sport tile</th>
<th>Linoleum (homogenous contact layer surface)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical contact peak</td>
<td>2.00 (13.4)</td>
<td>1.92 (12.4)</td>
</tr>
<tr>
<td>Vertical minimum</td>
<td>1.69 (18.9)</td>
<td>1.56 (18.7)</td>
</tr>
<tr>
<td>Vertical push-off peak</td>
<td>2.46 (42.0)</td>
<td>2.45 (42.1)</td>
</tr>
<tr>
<td>Braking maximum</td>
<td>0.30 (28.7)</td>
<td>0.43 (30.7)</td>
</tr>
<tr>
<td>Acceleration maximum</td>
<td>0.36 (72.5)</td>
<td>0.36 (74.5)</td>
</tr>
<tr>
<td>Mediolateral maximum</td>
<td>0.18 (31.3)</td>
<td>0.19 (26.3)</td>
</tr>
<tr>
<td>Vertical moment maximum (nm)</td>
<td>5.28 (35.8)</td>
<td>10.05 (30.7)</td>
</tr>
<tr>
<td>Cross-over (% contact)</td>
<td>37</td>
<td>39.9</td>
</tr>
<tr>
<td>Duration (sec)</td>
<td>0.245</td>
<td>0.247</td>
</tr>
</tbody>
</table>

Table 2.4  Braking parameter averages in percentage body weight (Bagley 1992)

<table>
<thead>
<tr>
<th>Running (% contact follows magnitude)</th>
<th>Modular polypropylene sport tile</th>
<th>Linoleum (homogenous contact layer surface)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical contact peak</td>
<td>3.18 (0.041)</td>
<td>2.89 (0.037)</td>
</tr>
<tr>
<td>Braking maximum</td>
<td>0.81 (0.046)</td>
<td>0.94 (0.047)</td>
</tr>
</tbody>
</table>

Table 2.5  Jumping parameter averages in percentage body weight (Bagley 1992)

<table>
<thead>
<tr>
<th>Running (% contact follows magnitude)</th>
<th>Modular polypropylene sport tile</th>
<th>Linoleum (homogenous contact layer surface)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical contact peak</td>
<td>3.09 (9.3)</td>
<td>3.24 (9.4)</td>
</tr>
<tr>
<td>Vertical minimum</td>
<td>1.44 (17.9)</td>
<td>1.73 (17.9)</td>
</tr>
<tr>
<td>Vertical push-off peak</td>
<td>2.84 (46.2)</td>
<td>2.78 (44.5)</td>
</tr>
<tr>
<td>Braking maximum</td>
<td>0.51 (18.0)</td>
<td>0.72 (23.7)</td>
</tr>
<tr>
<td>Acceleration maximum</td>
<td>0.49 (76.9)</td>
<td>0.46 (79.8)</td>
</tr>
<tr>
<td>Cross-over (% contact)</td>
<td>31.3</td>
<td>36.3</td>
</tr>
<tr>
<td>Duration (sec)</td>
<td>0.379</td>
<td>0.378</td>
</tr>
</tbody>
</table>

Walker (2009) conducted further research into the braking energy attenuation potential of modular tile sports surfaces. In this research, test subject variability was removed through the design and construction of a test apparatus which could, with a high degree of repeatability, strike a floor at a predetermined impact angle in order to generate an impact force with both horizontal and vertical components.
The magnitude and direction of the ground reaction forces were recorded using a piezoelectric force plate. The study concluded that modular plastic tile surfaces which permit a restricted amount of horizontal movement via the tile connections could attenuate more braking force in than a homogenous contact layer sports surface. The modular plastic tiled surface achieved braking force reductions of 45%, whereas a homogenous surface only achieved a braking force reduction of 2%.

In addition, the modular tile surface achieved a 10% increase in the time taken to reach peak force. It was concluded that these two factors in combination were likely to be instrumental in reducing potentially injurious stress levels to the athlete’s musculoskeletal system (Walker 2009).

A high performance sports surface must therefore a) balance energy attenuation in order to reduce the risk of injury while at the same time providing satisfactory energy return to avoid player fatigue and b) provide adequate friction to avoid slipping while also avoiding the exposure of athletes to overload through high friction levels. Achieving these two incompatible situations is not however considered realisable (Kolitzus 1984).

Baroud, Nigg and Stefanyshyn (1999) determined that during the propulsion phase of running, energy is transferred from the athlete into a sports surface, with this energy being stored in the surface through deformation. A proportion of this stored energy will be dissipated in the form of heat and sound energy, whilst some energy will be returned to the athlete (Baroud, Nigg et al. 1999). Sports floors can be divided into two distinct categories: area elastic and point elastic. Area elastic surfaces distribute the forces resulting from athlete contact with the surface over a large area, whereas point elastic surfaces distribute force over a much smaller area, centred on the point where the impact occurs (de Koning, Nigg et al. 1997).

With both categories of surface, elastic deformation occurs during contact. Through this deformation process, there may be a reduction in athlete loading (Yeadon and Nigg 1987). Wakeling, Von Tscharner, Nigg and Stergiou (2001) also discussed this principle, stating that athlete loading rates can be reduced by the cushioning effects of a shoe or floor (Wakeling, Von Tscharner et al. 2001). In a study conducted on the cushioning relationship between tennis shoes and artificial surfaces, Dixon and Stiles (2003) state that the surface is influential in determining impact absorption (Dixon and Stiles 2003). Baroud, Nigg et al. (1999) determined that as a sports floor can store and return energy to the athlete, it may be possible that the returned energy during
the take-off phase of the stance will contribute to athletic performance. Neal and Sydney-Smith (1992) determined that both vertical and horizontal forces should be quantified, as the more energy absorbed by the surface, the less energy is absorbed by the biological tissues of the body.

Ground reaction forces consist of combinations of vertical forces experienced during jumping and landing, and horizontal forces experienced during starting, stopping and turning. The size of these forces, along with their repetitive character while playing sport, may therefore add to the comparatively high occurrence of lower limb injury in sports such as netball (Neal and Sydney-Smith 1992). Steele and Milburn (1988) claim that high braking forces, such as those experienced while playing netball, subject the ligaments to excessive stress, especially in the knee joint, thus increasing the probability of injury.

The logical approach would therefore be to attenuate both the vertical ground reaction forces and horizontal ground reaction forces (Steele and Milburn 1988). Most surfaces however can only reduce vertical forces and this is corroborated by the extensive range of standards and tests that have been developed to only measure VGRF attenuation (Walker and Subic 2010). HGRF measurement has been ignored in the development of the European Standard for Sports Hall Floors (EN14904 2006), which has adopted the Berlin Artificial Athlete as the definitive test for force reduction measurement. Most sports surface structures attenuate little or no HGRF and the frictional characteristics of the shoe/surface interface determine whether a player’s lower limb is overloaded or not.

The issue of reducing HGRF, as well as attenuating shock spikes in the horizontal direction, has been addressed by sports shoe design. The Adidas ground control system (GCS shoe) with a slightly sliding heel (Adidas 2009) reduces the rate of pronation by an average of 15% and the critical forces on the knees by a significant 30% on average. The barefoot technology shoes Feet You Wear by Adidas, reduced the injury rate per 1000 basketball players from 11.3 to 7.1 in the first season and from 9.8 to 7.3 in the second one (Meeuwisse, Hagel et al. 1998). It cannot be assumed, however, that suitable sports shoes will always be worn while playing sport, whereas a
sports surface which attenuates appropriate levels of shock will always guarantee protection from surface related injury (Walker 2010).

The logical approach would therefore be to attenuate the vertical and horizontal reaction forces (Steele and Milburn 1988). Most surfaces however only seek to reduce vertical forces and this is supported by a range of standards and tests that have been developed to measure vertical force attenuation. Horizontal force reduction has generally been neglected in the development of the European Standard for Sports Hall Floors (EN 14904 2006) which has decided to adopt the Berlin Artificial Athlete as the definitive test for force reduction.

### 2.3.1 Sports surface friction

Friction is an important aspect of sports performance which allows athletes to start, stop, change direction and jump in a controlled manner (Verhelst, Malcolm et al. 2009). Sports surface friction, or traction, is described as the resisting force acting between a sports shoe and a sports surface during motion (Dixon, Batt et al. 1999). In sport, there are two aspects of friction that relate to performance: ‘force-locking connection’ which relates to the specific properties of the contacting surfaces which combine to provide friction, and ‘form-locking connections’ which relate to the contacting surface properties, such as textures positioned on the sole of a sports shoe or the sports surface contact layer (Stuck, Baudzus et al. 1984).

Insufficient traction between a sports surface and an athlete’s shoe during competitive play can result in slipping, reduced performance and may cause the athlete to fall. A portion of shoe/surface movement is, however, beneficial while playing sport in order to prevent an athlete’s limbs from becoming overloaded. The horizontal displacement behaviour of the shoe reduces the level of stress being experienced by an athlete’s lower limbs over time, as injuries such as knee ligament tears have been linked to surfaces which exhibit high levels of friction. High friction levels result in high rotational forces in the knee once the foot is planted, and therefore the potential for ligament damage to the knee increases (Torg and Quedenfeld 1974; Lambson, Barnhill et al. 1996).

Previous research has suggested that there may be an association between the shoe to surface interface and injury risk (Strand, Tvedte et al. 1990), with most injuries occurring during non-contact foot plant and turn manoeuvres, or while landing on a surface from a jump-shot. Frictional forces, however, need to be high enough to allow players to stop and start without slipping, but not so high that they push the player past the physiological limits of the musculoskeletal system (Steele
and Milburn 1988). In general, a surface needs to provide sufficient friction to enable traction and prevent accidental slipping, but not too much to constrain sliding, turning, cause friction burns and bruises or cause joint and ligament injuries (Olsen, Myklebust et al. 2003).

2.3.2 Surface material and relation to injury risk

Despite the practical all-weather advantages of synthetic sport surfaces, some investigations have implicated the increased use of synthetic surfaces as a significant cause of injury in many sports (Myklebust, Maehlum et al. 1998). Researchers have found injury rates for games played on synthetic surfaces to be significantly higher than those played on natural timber surfaces. Studies conducted by Olsen, Myklebust et al. (2003) concluded that the main causes for injury lay in the surface resilience and stiffness, as well as the high frictional forces caused by the shoe/surface interface. This research was however limited in that they applied a very narrow definition for synthetic surfaces, which were predominantly high friction manufactured sheet rubber surfaces and excluded modern sheet vinyl, modular plastic tile and pour-in-place polyurethane surfaces.

Steel and Milburn found that netball court surfaces with high stiffness, constructed from materials such as bitumen and concrete, appeared to generate the greatest risk of injury, whereas more compliant surfaces, such as granulated rubber, generated the lowest average braking forces and increased the time to reach maximum braking force (Steele and Milburn 1988).

There are two main factors implicated in sports surface related injury: the hardness or stiffness of the material from which a surface is constructed and the friction between the sports shoe and sports surface. Material stiffness has been associated with overuse injuries in many sports (Olsen, Myklebust et al. 2003), with high friction also playing an important contributor to the risk of traumatic injury.

Powell and Schootmann found that materials which generated high coefficients of friction between the players shoe and playing surface increased the risk of knee ligament injury. In addition, large frictional forces have been identified as a major contributing factor to the high incidence of knee and ankle injuries (Powell and Schootman 1992). Investigations have demonstrated that the highest frictional forces were generated when players landed on hard surface materials, such as bitumen and concrete. It therefore appears that traditional all-weather netball courts constructed from
bitumen and concrete may encourage more injury than other types of synthetic surface (Steele and Milburn 1987).

Previous studies have also shown that there is a statistically significant association between body part and the type of surface material. Ankle injuries occur most frequently regardless of the surface, More knee injuries occur on bitumen and more ‘other’ injuries occur on synthetic surfaces (Hopper 1986). Apart from the structural characteristics of different surface types, the expectation that an athlete has of a surface can modify their movement patterns and thus influence loading (Nigg, Denoth et al. 1984).

Connections between surface material and injury risk on indoor sports surfaces has however rarely been studied (Walker 2010). Olsen compared the rate of injury to the anterior cruciate ligament (ACL) between artificial and wooden floors in team handball, and found higher ACL risk for female players on artificial floors.

The ever-changing nature of sports and the desire to play different sports in many different climactic conditions has led to sports being played outdoors on synthetic surfaces in place of natural surfaces (McGrath and Ozanne-Smith 1998). Despite the practical all-weather advantages of synthetic sport surfaces, some investigations have implicated increased use of synthetic surfaces as a mechanism of injury in many sports (Myklebust, Maehlum et al. 1998), where researchers found injury rates for games played on synthetic surfaces to be significantly higher than those played on natural timber surfaces. De Koning, Nigg et al. (1997) also state that area elastic surfaces are commonly constructed from wood, whereas point elastic surfaces are constructed generally from synthetic materials.

Some investigations have implicated the use of synthetic surfaces over natural surfaces as the reason for an increase in injury (Steele and Milburn 1988). McGrath & Ozanne-Smith (1998) also reiterate this belief, but they also state that synthetic surfaces which offer cushioning properties may in fact lower the incidence of injury. Investigations have been carried out on timber and synthetic surfaces and their relationship into knee injury (Olsen, Myklebust et al. 2003), but such studies only make generalised comment on the material and structural characteristics of the surfaces under consideration. With the increased use of these synthetic surfaces, the incidence of injury has also increased (Steele and Milburn 1988; McGrath and Ozanne-Smith 1998; Dixon,
Collop et al. 2000). These artificial surfaces include bitumen, concrete, rubber compounds, synthetic grass and polyurethane (McGrath and Ozanne-Smith 1998).

It can therefore be seen from the research, that the materials used in the construction of sports surface are described in only very general, generic terms and the relationship between injury risk and surface types is in many cases contradictory.

2.3.3 Surface test devices

Many surface test methods have been developed in recent years, to assess the playing characteristics of sport surfaces. These tests have been used to measure the overall performance of an athlete’s interactions with a surface and they provide an indication of how a sports surface will perform in relation to a certain standard (Young and Fleming 2007). For these reasons, sports governing bodies and international standards agencies have developed rigorous testing procedures in order to approve and classify surfaces. Within each test standard there is normally at least one component which assesses the impact attenuation of a surface. The purpose for this type of test is to determine the behaviour of a sports surface under load in order to predict how it may perform during player impact with a surface (Walker and Subic 2010).

Tests are performed for a variety of reasons: (i) to measure physical and mechanical properties; (ii) mechanical integrity; (iii) durability, and quality control purposes. However, many tests are performed under conditions that do not involve actual loads and which therefore should not be expected to predict a surface’s effect on athletic performance or injury risk.

A review of the literature indicates that test devices can be divided into two general categories: type 1 test devices that indicate surface condition, and type 2 test devices that endeavour to simulate an aspect of an athlete’s biomechanical interaction with a surface.

Type 1 surface test devices. These devices provide information on a sports surface which is not specific to an athlete’s interaction with a surface, but serve to benchmark a surface’s performance in respect to some other aspect of sport which may be played on the surface, such as rolling load resistance or ball rebound.

Type 2 surface test devices. These devices evaluate specific surface mechanical behaviours and mechanisms related to athletic performance and athlete injury. No test device however can provide a truly accurate simulation of an athlete’s surface interaction due to the highly complex nature of
athlete to surface loading (Nigg 1990). These devices imitate a specific aspect of an athlete’s interaction with a sports surface, such as the type, extent and rate of loading during impact.

**Athlete-surface impact test devices.** This category of test device measures the force reduction that athletes may experience when landing on a sports surface from a vertical jump. The Berlin Artificial Athlete schematic shown in Figure 2.11 was the first widely used impact test device and it is the current industry standard. The apparatus consists of the following main components:

- a dropping mass of 20.0 kg
- a spring, of spring stiffness of 2 MN/m
- a force quantifying device, having a capacity of 10 kN and, the ability to measure forces with an accuracy of 0.1%
- a circular test foot, through which the impact is delivered to the surface being tested, having a diameter of 70 mm and a bottom surface with a radius of 500 mm (Walker and Subic 2010).

In performing the Berlin Artificial Athlete test, the 20.0kg weight is allowed to drop from a height of 55mm onto the spring and the subsequent force applied to the floor is recorded. The amount by which the peak value of the force is lower than the peak value measured when the test is performed on a concrete substrate is then recorded. The force measuring device is connected to a charge
amplifier, signal processor and signal conditioner. The peak impact force measured and forced reduction or energy dissipation is finally presented as a ratio of force reduction in comparison to concrete (Dixon, Batt et al. 1999). An improved version of this test device has been developed, the Advanced Artificial Athlete, which measures surface force reduction and surface deflection (Young and Fleming 2007; International Rugby Board 2011).

The peak force applied by the BAA is dependent on the stiffness of the surface being tested. An impact measured on a very stiff surface, such as concrete, can be as high as 6.9 kN, while a more compliant running track can record 3.9 kN. The legitimacy of using fixed weight devices in order to measure athlete-surface interactions has been questioned as athletes have been observed to adjust their motions in order to react to changes in stiffness exhibited by different surfaces (Ferris, Louie et al. 1998; Kerdok, Biewener et al. 2002; Tillman, Fiolkowski et al. 2002).

However, Meijer et al. (2007) have shown that, in general, athlete impact data measured in human tests is in the same range as that measured by a Berlin Artificial Athlete (Meijer, Kati et al. 2007). On the other hand, situations where an athlete may be able to compensate for changes in surface stiffness do not always present themselves, for example falling on a sports surface or uncontrolled landings. Fixed load devices are therefore appropriate in these uncontrolled situations where injury may result (Dixon, Batt et al. 1999).

Young and Flemming (2007) argue that a test mechanism should be developed which could vary the stress applied to a surface in order to take into account the non-linear behaviours of different surface types, and Walker and Subic (2010) believe that athlete-surface impact devices should be developed where the impact angle can be varied in order to measure the vertical and horizontal loads applied as an athlete moves over a sports surface.

The use of the BAA for the testing of indoor sports surfaces is limited as creating a device which can simulate human impact is difficult due to the biomechanical complexity of an athlete and the corresponding large number of variables involved. This biomechanical variability makes testing
less repeatable and more time-consuming. Consequently, there is a desire for simple but repeatable tests (Young and Fleming 2007).

The general principle behind impact test devices is to strike a sports surface with a known mass and measure the resultant forces. These forces can then be interpreted as a surface property, such as force reduction. Due to the non-linear behaviour of many sports surfaces, the design of a particular test can considerably affect the measured data. Several tests exist for the assessment of indoor and outdoor natural and synthetic sports surfaces. These tests include: ASTM F355-95, F489-96, F1551-94, D2632-96, DIN 18032 and EN14904 and they allow a number of properties to be evaluated under both laboratory and on-site conditions (Walker and Subic 2010).

2.4 Sustainable design: Life cycle thinking and closed-loop processes

The sports surfaces and sports facilities that we design and construct can be either future-friendly, or not. Sports infrastructure can become an environmental trap if they can only operate on large environmental footprints. In contrast, resource-efficient, non-wasteful sports facilities, operating within closed-loop systems where materials continually circulate in a production system and are not lost from the system in the form of waste, can support a high quality user experiences with only a small footprint (Walker 2012). To stabilise temperatures at manageable levels, emissions would need to be stabilised over the next 20 years and fall between 1% and 3% after that. The options for
change could be reduced if consumer demand for heavily polluting products, buildings and services were also reduced (Stern 2006).

The volume of building materials entering the waste stream at end-of-life is ever-increasing. Land-based disposal is by far the most common form of disposal for sports flooring in Australia. National concerns about recycling, disposal capacity, the relatively short operational life expectancy of flooring, combined with a floor structure’s bulk (which makes it difficult and expensive to handle) have contributed to the search for alternate means for recycling or disposal. While most components that make up floor are recyclable or reusable, only a small percentage of waste surface products currently are handled in these ways. Increased recycling and reuse would reduce waste and recover valuable resources while significantly reducing their environmental impact. This project therefore investigated the potential to reduce the environmental footprint of the surface. The environmental footprint of any flooring system can be defined in terms of local, regional and global environmental impacts to which it contributes over its life.

The longer the lifecycles of sports surfaces and sports facilities, the more critical it is to ensure that we are not creating a negative legacy that will damage the social and physical wellbeing of future generations (WWF International 2006). In an ideal world, the life-cycle impacts of all materials and processes used in our manufacturing systems would be fully defined to allow designers to clearly and unequivocally see which design approach is better from an environmental perspective (Walker 2007). Designers, engineers and architects have a history of innovation and are therefore well placed to use life cycle thinking approaches to creatively lock-in positive features and to innovatively lock-out negative impacts at the design stage (Walker 2012).

The challenge of achieving sustainable levels of consumption and production continues to be one of the more persistent targets on the sustainability agenda. The challenge is how to balance consumers’ apparently infinite needs, desires, and aspirations with the earth's finite resources (Walker 2008).

Aligning production and consumption with sustainable levels requires a combination of arrangements on both the supply (technological innovation to produce higher levels of efficiency in surface and facility design) and the demand side (promoting, motivating and regulating consumers to responsible and appropriate levels of consumption) of a market-forces based economic model. While there is considerable progress in the area of technical innovation, demand only appears to be
increasing as consumption levels in both the developed and developing world continue to rise (Dupre 2005).

Sustainable design seeks to use materials, energy and water efficiently, while minimising waste, negative impacts on the natural environment and the quality of human life. Sustainable design considers environmental impacts at every stage of a product or building’s life cycle and seeks to address key environmental issues at their source by locking-in positive environmental attributes, such as durability, water and energy efficiency, and locking-out negative environmental attributes, such as toxic or hazardous substances, waste and obsolescence (Resource Smart Victoria 2005). A cradle-to-cradle sustainable design method would aspire to ensure that nutrients are continuously cycled round manufacturing processes as valuable resources, rather than being used once and then disposed of as valueless waste. This approach encourages designs that ensure that a product’s output resources, such as materials, water and energy, can be reused as another product’s input resources (Braungart and McDonough 2002).

A cyclic system, such as cradle-to-cradle, could potentially create an economy based on spiral loops that minimises material-flows, energy-flows and environmental deterioration without restricting economic growth or social and technical progress (Börlin and Stahel 1989).

2.4.1 Sustainable indoor sports surfaces
The construction industry consumes more of the earth’s resources than any other human activity. The Green Building Council of Australia states that each year the construction of buildings consumes 32% of the world’s resources. In the OECD countries, the sector is responsible for consuming approximately 40% of total energy consumption, with 40% of all waste going to landfill, originating from the construction and demolition of buildings. In Australia, buildings generate more than 40% of all air emissions (Madew 2006). As no other sector imposes a greater burden on the environment, the construction industry should have a greater obligation to do more to improve environmental performance (Walker 2008).

Specifying and selecting a sports surface involves the simultaneous evaluation of a multitude of performance factors. Increasingly, environmental impact is becoming an important component of such surface deliberations (Walker 2008). Surface specifiers require objective, consistent and comprehensive data detailing the environmental impacts and waste implications of their selection.
decisions. A life-cycle thinking approach to the specification of a sports surface therefore involves a process-based analysis, which looks at each individual material and process in the playing surface value chain, including manufacturing, installing, maintaining and ultimately disposing of a variety of materials, depending on the nature of the sports surface (Walker 2008).

The quantity and quality of sports facilities encourage community exchanges, physical activity and ultimately contribute to the health of the community in which they are situated. Timber indoor sports playing surfaces are commonly used throughout most of the developed world and are especially common at the higher competitive levels of indoor sport. Timber is also a renewable resource with negative net carbon emissions (Petersen and Solberg 2004), but there is also the possibility that the environmental burden developed while using, maintaining and ultimately disposing of a wooden playing surface may outweigh the environmental load of the comparable life cycle stages of its synthetic alternatives. Installing and maintaining a sports surface brings with it many heavy environmental burdens, in the form of periodic resurfacing, sealing and disposal (Nebel, Zimmer et al. 2006). The financial cost of installing and maintaining timber playing surfaces has resulted in the increased popularity of synthetic playing surface alternatives.

Conventional approaches to environmental decision making do not always stand up to objective analysis. The automatic presumption that the use of recycled materials will result in reduced environmental loads cannot always be taken for granted. Recycling may be able to reduce landfill, but the process of recycling a given material may consume more energy and impact air quality more harshly than would production from virgin materials (Walker 2008). The issue is not that one environmental impact is more important than the other, but that conventional wisdom can take precedence over factual information in the decision making process. Recycling has always been an accepted method to reduce flows to and from nature, but over time it has taken on a self-propagating impetus of its own (Trusty and Horst 2002).

The use of rapidly renewable materials is encouraged in many environmental rating systems, where the objective is to reduce the use of limited raw materials and long-cycle renewable materials by substituting them with materials which can re-grow relatively quickly. This assumed environmental gain however ignores the potentially negative consequences of pesticide, herbicide, fertiliser and
water use, which may be required for the cultivation of some rapidly renewable materials. These are highly complex issues which can only be effectively quantified through the use of life cycle assessment (Trusty and Horst 2002).

2.5 Summary
Sports surface selection processes require an objective and comprehensive means of evaluating the environmental credentials of different surface types. Life-cycle thinking approaches which consider each individual material and process in the playing surface value chain, including the materials and energy consumed and wastes and emissions generated during manufacturing, installation, maintaining and ultimately disposing of a sports surface should all be included.
Chapter 3

Indoor sports surface materials, design and testing protocols

3.1 Introduction

Natural, synthetic, and combinations of natural and synthetic materials, are widely used in contemporary sports surfaces designed to deform under load, increasing athletic performance while reducing the risk of injury. The wide variety of indoor sports flooring systems designed to achieve these goals are generally separated into two major categories: area-elastic sports surfaces and point-elastic sports surfaces. Area elastic sport surface structures attenuate vertical ground reaction forces by allowing deformation over a comparatively large area, whereas point elastic surfaces deform over a relatively small area close to the point of impact in response to applied forces. Sports surfaces are therefore extremely complicated arrangements of materials, which contribute to a surface’s complex mechanical behaviour.

Viscoelastic materials are used in order to reduce the amplitude of the shock to the athlete’s limbs during competitive play and in order to understand the cushioning properties of these materials, it is necessary to consider the structural aspects of the various material combinations found in contemporary sports surfaces. In this chapter we discuss different types of sports surface material, how they are configured and used and how effectively they reduce the risk of injury to an athlete.

Advances in the design of indoor sports surfaces have been closely related to the engineering of new materials, which are able to improve performance while providing high levels of safety to the athlete playing sport on the surface. Desirable surface characteristics vary from sport to sport, depending on the nature of the activity. As far as is practical, however, it is preferable to have a common surface which meets the needs of a broad range of sports in a multi-sport or multi-functional facility, although sports such as gymnastics, judo or yoga, where there is a high degree of upper-body contact with a surface, will normally require the use of additional portable gymnastics mats placed on top of the sports surface.

The performance requirements of court sport surfaces are different from track sports surfaces due to the broad range of evasive and attacking manoeuvres common to games played in court areas, although both types of surface require to protect athlete’s limbs during competition. Natural and synthetic surfaces such as timber, ceramic, concrete, and various forms of multi-layered polymeric
surface are all used in the construction of sporting facilities, and can be complex surfaces, with multifaceted behavioural characteristics (Walker and Subic 2010). As sports surfaces are typically installed on a specially prepared subfloor, it can prove difficult to install different surface types in buildings if the space, is not designed to complement, the requirements of each playing surface type.

Despite the wide range of surfaces available, there is a lack of scientific evidence regarding the relationships between surface performance characteristics and the requirements of a particular sport. Ball sports usually involve the athlete starting, stopping, turning, jumping and landing at speed and there is a range of muscle activity and ground reaction forces that is characteristically repetitive, contributing to the frequency of lower limb injury. These forces must be therefore be minimised, while playing performance should be maximised. This chapter explores the different performance requirements for indoor sports surfaces and the ways in which these requirements can be met through advances in both design and materials.

3.2 Natural and synthetic indoor sports surfaces

The constantly changing nature of sports and the desire to play sports under many different conditions have led to the increased use of synthetic surfaces in addition to natural surfaces. In recent years, there has been a trend towards the development of multi-sport facilities, where facility utilisation can be optimised by offering many different sports which can be played on the same surface. This approach may not however be appropriate from health or ecological perspectives, due to the diverse environmental impact implications imposed by different surface choices and the safety needs of different sports. Natural sports surfaces include materials such as timber, natural rubber and linoleum whereas synthetic sports surfaces can be defined as any highly processed manufactured surface on which sports are played. These surfaces are generally constructed from layers of suitably processed materials and can include surfaces such as concrete, composition fibre block, pour-in-place synthetic sports flooring, prefabricated sheet synthetic sports flooring and prefabricated tile synthetic sports flooring. Synthetic surfaces differ greatly in both material type and structure from natural surfaces and these differences provide each surface with its own unique environmental performance characteristics.
3.3 Indoor sports surface types and construction

Multi-sport indoor facilities have provided the opportunity for many different sports to be played in a single venue on the same surface. Natural timber flooring or synthetic flooring systems constructed from layers of processed material, including concrete, composition fibre block, pour-in-place synthetic sports flooring, prefabricated sheet synthetic sports flooring and prefabricated tile synthetic sports flooring, differ greatly in both material type and structure from natural surfaces, but every surface, natural or synthetic, exhibits its own unique playing performance characteristics.

3.3.1 Classification of sports surfaces

There are four distinct categories of flooring system recognised by the international standard EN14904: (i) point elastic (type P); (ii) mixed elastic (type M); (iii) area elastic (type A); and (iv) combined elastic (type C).

**Point elastic systems.** Point elastic systems (Figure 3.1) are typically sports surfaces which have been installed directly over a concrete substrate. As the name implies, there is only a small contact area and displacements and deformations are limited to this point, during an impact on the surface. Some hardwood timber and wood composition sports surfaces also fall into this category, where the surface materials are placed directly onto the sub-floor, with or without an underlay.

![Point elastic sports surface](image)

**Figure 3.1** Point elastic sports surface

Prefabricated sheet, pour-in-place and tile synthetic sports surfaces normally fall into the point elastic category (EN14904 surface types P1, P2 and P3). These systems usually feature thermoplastic elastomeric or rubber underlay material layers installed directly under the playing
surface and are attached directly onto the sub-floor. If shock absorbing materials are not installed under the playing surface layer, the system’s performance would likely to be outside the scope of the acceptable standards.

**Area elastic systems.** Area elastic systems (Figures 3.2 and 3.3), as the name implies, are systems where an area considerably greater than the applied-force contact location is put into motion as the result of an athlete impact with a sports surface. Hardwood timber and wood composition sports surfaces generally fall into this category, where surface materials have a sprung undercarriage sub-structure positioned between the contact layer and the sub-floor, as shown in the figures.
**Combined elastic systems.** Combined elastic systems are synthetic sports surfaces which have been installed directly over a resilient undercarriage sub-structure positioned between a synthetic surface and the sub-floor (Figure 3.4). These aspects embody an amalgamation of area elastic flooring systems and point elastic flooring systems, where the point elastic structure acts as the athlete-contacting surface. These surfaces are likely to be hardwood timber and prefabricated sheet systems, with a sprung undercarriage positioned between them and the sub-floor.

![Combined elastic indoor sports surface](image1)

**Mixed elastic systems.** Mixed elastic systems are surfaces which have characteristics of both area elastic and point elastic sports flooring systems, with mixed elastic M3 and M4 category surfaces often constructed from multi-layered prefabricated sheet systems with thick elastomeric foam underlays.

![Mixed elastic indoor sports surface](image2)
3.3.2 Hardwood timber sports surface systems

Timber is one of the most commonly used materials, for the construction of shock absorbent indoor sports surfaces. Early ‘cushioned’ indoor sports surfaces, were either constructed from earthen materials, or hardwood timber plank structures mounted on joists. ‘Sprung floors’ were then developed which incorporated coil or leaf spring elements into the supporting structure, but these surfaces tended to return too much energy, causing the surface to ‘spring back’ and vibrate. This deficiency was later overcome with the introduction of semi-sprung surfaces, which dampen the ‘spring’ effect of earlier fully-sprung surfaces. The use of sprung floors grew significantly in the 1920s, with the development of public dance halls, but it wasn’t until the 1936 Berlin Olympics that the first commercial use of sprung floors featured for use in sports.

Hardwood timber sports surface systems such as the system shown in Figure 3.6, can be manufactured in a variety of constructional configurations supported on resilient shock absorbent elastomeric pads. Timber is also commonly used as the structural support mechanism for most combined elastic systems. Timber can also be laid on top of closed cell foam sheet materials to form point elastic ‘floating’ surfaces and installed in finished or unfinished conditions. Timber grain quality is selected on the basis of colour uniformity, with the more commonly used timber species being oak, maple and beech, which are selected for their colour consistency, toughness and dimensional stability.

Although timber is a highly durable construction material, it is hydroscopic and must be maintained within controlled temperature and humidity levels. Water penetration of a timber sports surface is the most common cause of surface failure. When timber is installed over a subfloor, either directly onto the subfloor or supported above the subfloor, it must be protected from moisture which may be present in the subfloor, with the installation of a moisture barrier membrane, positioned between the concrete sub-floor and timber surface components. Surface expansion and contraction, which can result from varying temperature and humidity conditions, must be controlled with expansion gaps located at walls and other obstructive features in the surface.

Hardwood timber sports surfaces generally fall into three main constructional categories of surface:

- portable floors which are described as ‘floating’ sports surface systems
- permanent floors which are described as ‘fixed’ sports surface systems, as they have some form of permanent attachment to the subfloor, in either a ‘sleeper’ or a ‘fixed/floating’ surface system


Sleeper construction timber sports surfaces are normally constructed from 25mm thick solid timber supports or engineered plywood laminated supports, which are then laid directly onto a concrete subfloor. The supports run perpendicular to the orientation of the hardwood planks and are spaced anywhere from 100mm to 300mm apart.

- anchored resilient floors, physically attached to a concrete subfloor, but using a combination of shock absorbing elements with varying degrees of resiliency

   Anchored resilient components include wood substrates, channel systems, pads and elastomeric-type cushions, and feature fixings that allow vertical displacement and the ability for the surface to return elastically to its original position immediately after an impact.

Hardwood timber sports surfaces are commercially available in three plank styles:

- random length strips which are separate pieces of flooring, typically 60mm and 90mm wide, with lengths varying between 400mm and 2400mm

- finger jointed strips which consist of a number of random-length strip sections, joined at the manufacturing plant to form timber boards

   In both random length and finger jointed cases, the timber strips are normally 19mm or 21mm thick, are installed in staggered arrangements, with each strip overlapping the adjacent strip and fastened onto the subfloor with staples or steel clips, depending on the recommended fastening system for the chosen subfloor.

- parquet flooring manufactured to form square sheets over a range of sizes

   Individual parquet picket widths can range from 22mm to 29mm, and picket lengths range from 140mm to 300mm. The minimum thickness of parquet flooring is 8mm. The discrete parquet-picket elements, when combined into panels, are either assembled together using wire, mesh or tape attached to the rear of each panel.

Portable timber sport floors are typically assembled in 1200mm X 2400mm sheet panels. Each manufacturer of portable floors normally has a proprietary method of locking the sheet panels together, but all are based on the principle of arranging the panels in a specified order and locking adjacent panels together. Portable floors are assembled commencing with the starting panel positioned in one corner or the centre of the playing surface. The position of the commencing panel is determined during the initial installation and its position is permanently marked on the concrete sub-floor, so that subsequent installations are positioned identically.
3.3.3 Pour-in-place synthetic sports surface systems

Pour-in-place surfaces such as the surface shown in Figure 3.7, are normally composed of polymeric thermoset polyurethane materials, which are mixed on-site at the installation site and ‘poured’ to form a continuous seamless playing surface. Underlay materials are attached to the subfloor prior to the poured layers being applied and can be formulated from rubberised or closed cell foam materials, which attenuate vertical shock and form a point elastic surface. Polyurethane materials are then added on top of the underlay and can include many discrete poured layers in order to achieve the required performance and visual characteristics of the surface, with the final poured layer ranging from 1mm to 4mm thick. This type of surface is usually considered to be a point elastic surface, but meshed materials can be included in its construction, to produce a mixed elastic surface. Similar to prefabricated sheet synthetic sports surfaces and prefabricated tile synthetic sports surfaces, a pour-in-place surface can be installed over a sprung timber structure, in order to produce a combined elastic system.

Pour-in-place synthetic floors are a popular choice for school gymnasiums, principally due to their resiliency and slip resistance. Their installation, however, releases volatile organic compounds which do not comply with many national and international green building codes. Pour-in-place synthetic floors take a number of days to install, as several layers of polyurethane are poured on top of each other and each layer is required to cure fully, before the next layer can be added. Coloured layers are applied to the top layer before full curing has occurred, and then one or more topcoats of sealer are added. The surface’s appearance can be modified with the addition of different topcoats, in order to make the surface smooth or textured. The more textured the surface, however, the more dirt can be retained in the surface, requiring additional and more complicated cleaning processes. Despite the durability of this surface type, pour-in-place synthetic surfaces do not always bond strongly to subfloors that are not completely flat. In addition, if excessive levels of moisture are present in the subfloor, they can be prone to cracking if moment occurs in the subfloor.
Full-depth polyurethane floors are composed totally of polyurethane that has been mixed and poured directly over the subfloor in multiple layers, until a specific thickness has been achieved. The finished sports surface can be smooth or it can have a variety of surface textures applied during the final pour. All of the flooring layers are poured at the point of application after mixing, resulting in a uniform, seamless surface. Game lines are finally added utilising polyurethane game line coatings, once the base polyurethane layers have completely cured. Full-depth polyurethane systems may be installed over new substrates, including asphalt, concrete or wood, or over old surface systems, including vinyl composition tiles, acrylic surfaces and pre-existing polyurethane floors. Where full-depth polyurethane floors are installed over existing flooring systems, specialised bonding agents may be required, matched to the surface which is to be covered. Even when installed over new substrates, a primer layer may be necessary to act as a bonding agent, to insure adequate adhesion.

Sandwich pour-in-place synthetic sports floors utilise a prefabricated underlay, which is fully adhered, partially adhered or loose-laid over the subfloor. The underlay is sealed with a layer of highly viscous polyurethane resin that is mixed and poured in one or more layers until a specified thickness is achieved. Except for the underlay, the surface components are fluid and applied in situ at the time of installation, resulting in a seamless surface.

Figure 3.7 Pour-in-place synthetic sports surface
3.3.4 Prefabricated sheet synthetic sports surface systems

Prefabricated sheet synthetic sports flooring systems such as the system shown in Figure 3.8, are sports floors manufactured from rubber or polymer compounds and either cast, extruded, rolled, cut or pressed into sheets of a single thickness, width and length. Thickness, width and length may vary between types of prefabricated sheet and sport application and the sheets are normally bonded to the subfloor with an adhesive compound. The structure of the prefabricated sheet material may be composed of solid or granulated particles and combined with a chemical binder, or two or more sheets may be laminated together to form a single sheet, with the finished surface being smooth or textured.

Linoleum, polyvinylchloride (PVC), rubber and other composite sheet materials are commonly used as prefabricated sheet sports surfaces. These materials provide a broad range of visual and performance features and have the benefit of being quick to install. Individual rolls of sheet material, range in size from 1200mm to 2000mm wide and once unrolled, can reach the full length of the playing surface. Sheets are adhered directly to the subfloor, and the individual abutting sheet seams can be chemically welded or heat welded together to provide a close-to-seamless join.

**Synthetic sheet surfaces.** Synthetic sheet surfaces are normally used in combination with rubberised or closed cell foam backed or underlay materials, which help attenuate shock, vibration and noise. The backing/underlay material contributes to a sensation of compliance underfoot, which is important where sports which feature a high degree of user/surface contact, such as martial arts. Without foam backing, underlay or supporting substructure, surfaces rely heavily on the quality of the subfloor on which they are laid and care must be taken to avoid exposing any irregularities which may be present in the underlying surface.

As these surfaces lack an undercarriage system, prefabricated sheet synthetic sports surfaces do not achieve elevated force reduction levels which are achievable with hardwood timber sports surfaces, but they are however a cost effective alternative for multi-sport facilities, that do not necessarily require high performance playing surfaces.

**Rubber and polyvinylchloride (PVC) prefabricated sheets.** Rubber and PVC prefabricated sheet synthetic sports surfaces are commercially available in a wide range of colours and surface textures, allowing the installation of sports surfaces that require contrasting colours in order to
define playing surface boundaries and sport specific features such as basketball keys. This reduces the quantity of paint which may be required to be applied to the surface, and therefore the amount of repainting required in order to maintain the surface at an acceptable visual standard. As the coloured pigments are dispersed through the material thickness, high wear areas or damaged areas are less noticeable. Prefabricated sheet sports surfaces are commercially available in thicknesses, typically from 3mm to 6mm, therefore allowing facility designers to select surfaces that can have a range of force reduction and sound absorption characteristics.

If a prefabricated sheet synthetic sports surface becomes detached from its subfloor, as a result of moisture ingress into the surface or if the surface is accidentally gouged, the surface can be repaired by cutting and removing the defective sheet material within the damaged area and patching the section with new sheet materials. The replacement sheet surface will be able to be bonded to the original material, although colour variation may be evident, depending on the age of the original surface and how well the colour of the replacement materials can be matched to the original surface.

Depending on the type of sheet surface material utilised, no additional surface coatings may be necessary. Sheet materials can be formulated to closely match the coefficients of friction found in the surface of hardwood timber sports surfaces. A polyurethane finish is however normally recommended to reduce scuffing and to facilitate the daily cleaning requirements of softer PVC surfaces. When refinishing a PVC surface, a chemical etch is recommended in order to prepare the surface for a fresh coat of polyurethane surface coating.

**Rubber tile prefabricated sheets.** Rubber tile prefabricated sheet synthetic sports surface systems are flooring systems that are manufactured from rubber compounds such as neoprene, ethylene propylene diene monomer (EPDM) and styrene-butadiene rubber (SBR). The rubber component of the surface can formed from either virgin or recycled materials and can be made into sheets and then cut into tiles, or cast into tile shapes. Tile forms are generally 1m x 1m square or less, bonded to the substrate with adhesive and the finished product can have a smooth or textured finish.

**Polyvinyl chloride (PVC) prefabricated sheets.** Polyvinyl chloride (PVC) prefabricated sheet synthetic sports surface systems are manufactured either totally or partially from polyvinyl chloride. They may be solid PVC or they may incorporate a shock absorbent backing layer, bonded
to a thinner PVC wear layer, with the backing material made from cellular foam, rubber or some other resilient material. These floors are usually bonded to the substrate, but they may also be partially adhered or loose-laid. The free edges of the flooring system can be welded together with heat or a chemical bond, to form a uniform seamless surface and the resulting floor may have a smooth or textured finish.

3.3.5 Prefabricated tile synthetic sports system

Polypropylene prefabricated tile synthetic sports surfaces such as the surface shown in Figure 3.9, were commercially introduced to the sports industry as a permanent high performance outdoor sports surface in the mid-1970s, but they are now also extensively used as an indoor sports surface. Prefabricated tile synthetic sports surfaces do not achieve the force reduction standards currently met by hardwood timber sports surfaces, which have sophisticated undercarriage systems, but they again can be a cost-effective alternative for multi-sport facilities which do not require high performance surfaces.

The tiles are loose-laid and may be installed over a resilient underlay and feature an ‘open’ grid playing surface for outdoor use and a solid ‘closed’ playing surface for indoor use. Prefabricated
synthetic tiles are made from injection-moulded polypropylene and normally snap together via a ‘hook and loop’ locking mechanism.

Several manufacturers offer square modular plastic tiles with sides that typically measure 250mm, 300mm or 460mm and are normally 10mm to 13mm thick, with the top 3mm of the tile’s thickness forming the playing surface and the bottom 9mm serving as a support structure, in the form of column legs. The floating characteristics of this surface type allow them to be installed, repaired and quickly replaced, without the use of adhesives or highly skilled personnel.

The repair process can be quickly performed, allowing the sports facility schedule to remain unaltered with minimal disruption. In addition, a modular plastic sports surface can be disassembled, moved and relayed over a variety of subfloor types. Concrete is the preferred subfloor material, but tile surfaces can be laid on top of existing sheet surfaces, pour-in-place surfaces, and if there is no significant moisture damage, a pre-existing hardwood timber sports surface. Many modular prefabricated tile synthetic sports surfaces can be pre-assembled into pallet size sheets of tiles at the time of manufacture, and are installed over 3mm, 5mm, 7mm or 10mm thick recycled-rubber underlays that add shock and sound absorption properties to the surface.

Tile sports surfaces have proven to be highly effective in sports facilities, where recurrent moisture problems or high humidity issues may prohibit the use of hardwood timber sports surfaces, pour-in-place or prefabricated sheet surfaces. Moisture will not damage a polypropylene tile surface which makes it suitable for areas which are prone to inundation.

Modular tile surfaces can also be used as permanent or portable playing surfaces. Rented sports facilities therefore have the option of being able to remove a modular tile sports surface, upon termination of a lease or provide a resale value for the surface. Manufacturers of these surfaces have developed wood grain surface textures, solid and mixed colour injection moulded tiles. These hardwood-resembling sport floor tiles have also become an accepted option for use in dance studios and aerobics centres. Other recent innovations in the modular tile sports surface industry include the introduction of enhanced interlocking features, lighter and more flexible tiles and the addition of corporate logos through the use of in-mould film technologies.
A prefabricated tile surface’s low-maintenance characteristics often give the false impression that little maintenance is required, but modular tile surfaces will lose their colour and visual integrity as a result of improper or inconsistent maintenance. Manufacturers recommend that sports facility owners take the same preventive maintenance measures that they would with any other sports surface, such as restricting the consumption of food and beverages in close proximity to the playing surface, insisting that appropriate footwear is worn and the use of mats outside of the activity area, to allow users to remove dirt and other debris from their shoes prior to accessing the sports surface.

Modular tile sports surfaces are normally not made from post-consumer recycled materials due to the mixed pigments that are normally present in recycled polypropylene, but a modular floor can be easily recycled at the end of its own life cycle, and provide the opportunity for the surface to be recovered, recycled and then remoulded into a new tile surface. This is due to the known material composition of the recovered surface, which is normally copolymer polypropylene with ultraviolet and flame retardant additives.

3.3.6 Sports surface subfloors
Subfloor characteristics tend to be common across all styles of indoor sports surface. The ultimate success of a durable sports surface lies in the strength and integrity of the subfloor upon which the sports surface is installed. There are two main forms of sports subfloor constructed for most indoor sports surface categories in Australia:

- post-tension concrete
- reinforced concrete.
A *post-tension concrete subfloor* is constructed by forming a concrete slab with steel tension wires strategically positioned within the slab, to ‘pull’ the slab elements together. This subfloor construction technique is virtually crack resistant and is the preferred method of sports floor base construction. If ground movement occurs, the tension cables keep the slab unified and the surface free from cracks, which could affect the overlying surface. This subfloor type is suitable for all sport surface categories under consideration in this study.

A *reinforced concrete construction subfloor* utilises steel reinforcement bars in a concrete slab. Expansion joints are created usually between individual sport courts or at the court centre line, to allow a limited amount of controlled movement in the base, in order to prevent cracking. This method of concrete construction is strong, but does not exhibit the same level of resistance to cracking found in a post-tension system. This base type is suitable for pour-in-place, prefabricated sheet and prefabricated tile synthetic sports floors, but not hardwood timber surfaces.

For the purposes of the current study, it was assumed that post tension concrete base construction was used for all surfaces under consideration. The subfloor could therefore be excluded from comparisons, as it was common to all four flooring styles being investigated.

### 3.4 Sports surface selection
The specification and selection of a sports surface involves the simultaneous evaluation of a multitude of factors:

- safety
- ecological footprint
- cost/lifecycle cost
- multi-sport/utilisation level
- performance
- approvals
- aesthetics
- durability
- ease of installation
- maintenance.

Although the advantages of synthetic sport surfaces are clear from many years of installation and use (e.g. springiness, resilience, ease of maintenance, attractiveness, durability), there is a lack of information available to assist sports associations select surfaces suited to the particular needs of individual sports. The selection of an appropriate playing surface involves the consideration of numerous factors, including the life-cycle impacts of a particular surface.

The prime consideration when selecting a surface, however, should be the health, safety and well-being of the players who will use the surface. The mechanical properties of the playing surface, which include both the contact surface layer and the underlying layers, must be compatible with the physical movements and loads exerted on the surface by an athlete, otherwise the surface will be of little benefit to the sport or the sportsperson in terms of play or injury prevention. Many synthetic surfaces, however, have been developed with minimal consideration of the external loads and other injury risk factors which are experienced by athletes while playing, with emphasis being predominantly placed on their durability.

3.5 The development of international performance standards for indoor playing surfaces

Many of the materials found in playing surfaces are both stress and strain dependent, making the analysis and evaluation of their performance highly complex. In order to improve our understanding of sports surfaces and to help quantify their performance characteristics a series of
mechanical tests have been developed. The impact test method involves striking a sports surface with a known mass and measuring the resultant forces and displacements. These forces can then be interpreted as a surface property, such as force reduction or vertical deformation.

The performance classification of a surface is normally controlled by a sport governing body or a standards agency, in order to ensure that it meets the performance and safety requirements for a particular sport. Due to the non-linear behaviour of many sports surfaces, the design of a particular test can considerably affect the measured data. Within each test standard, there is normally at least one test which seeks to evaluate the impact attenuation characteristics of a playing surface in order to predict how it will perform during an athlete’s impact on the surface.

Surface-to-athlete interactions are highly complex scenarios to model and replicate, as many independent factors influence these interactions, including footwear, athlete characteristics and surface properties. The level of shock attenuation provided by a sports floor has been defined as the effectiveness of the surface to reduce the magnitude of the impact peak (Nigg and Anton 1995). It is generally assumed that any non-resilient material, such as concrete, will provide less force attenuation than a relatively resilient material, such as rubber, and therefore could be potentially more damaging to the athlete.

However, it has been concluded by many researchers that athletes have the ability to make kinematic adaptations during running in order to compensate for low levels of shock attenuation which may be provided by a shoe and surface. Testing surfaces using real athletes would have the advantage of measuring actual interactions between the surface and the athlete. Unfortunately, inconsistencies between individuals and the time taken to set-up and analyse tests mean that the results are not repeatable, nor are they cost effective to perform, meaning they are neither feasible nor reliable. Furthermore, to effectively simulate human impact on a sports surface, high biomechanical fidelity is required. The need to replicate complex human action makes testing less repeatable and more time-consuming, and consequently there is a need for simple, repeatable test.

Force reduction is the mechanical property which is used to evaluate the ability of a sports surface to decrease impact related forces, in comparison to impacts on non-resilient surfaces such as concrete. The DIN pre standard 18032 Part 2 was introduced in 2001, as an enhancement to the 1991 version of DIN 18032 Part 2, by the German standardisation body (Deutsches Institut fuer
In 2006, the EN14904 athletic floor performance standard was adopted by the European Union through the European Committee for Standardization (Comité Européen de Normalization) and this standard now replaces DIN 18032 Part 2. This marked the end of more than 20 years of DIN 18032 Part 2 criteria having been the performance standard in Europe and North America.

In comparison to DIN 18032 Part 2, test requirements for EN14904 properties were developed in order to promote increased European Union uniformity in the indoor sports system market, while allowing the acceptance of a much wider range of sports surface types. From a technical perspective, the EN14904 force reduction test procedure uses alternative software adjustments in comparison to the DIN 18032 Part 2 test procedure, which can affect force reduction results by up to 5%. It is therefore not surprising to have lower EN force reduction percentage results in comparison to DIN results (DIN18032-II1991). This method permits targeted use sports floors, such as basketball and volleyball sport courts, to be specified with performance criteria that are more appropriate for their ultimate intended use. Under the DIN standard, the acceptance criteria had constricted performance criteria that removed known high-performance sports floor systems from classification.

3.5.1 DIN 18032 Part 2
DIN 18032 Part 2 was a test standard that was developed for the performance evaluation of indoor sports surfaces, created by the Deutsches Institut fuer Normung in 1991, and was commonly used in the European and North America sports industries. This standard was initially established only for use by the Germans sports industry, and aimed to address both mechanical and biomechanical properties and included ball rebound, rolling load behaviour, area indentation, force reduction, vertical deflection and slip resistance in its classification structure (DIN18032-II 1991). The standard differentiated various types of indoor sports surface and outlined dissimilar performance criteria contingent on the surface type. The standard however did not provide guidelines for maximum allowable variance at testing points and only overall system averages were considered.

3.5.2 DIN pre-standard 18032 Part 2
The DIN pre-standard 18032 Part 2 was introduced as an improvement to the previous 1991 version of DIN 18032 Part 2. The revised version of the standard combined additional
requirements that called for maximum acceptable variances at specific points and more rigorous ranges of acceptability (DIN18032-II 2001).

3.5.3 EN14904

EN14904 is an indoor sports surface standard which was developed by the European Union’s Committee for Standardization, Comité Européen de Normalization, and was approved in 2006 as a replacement for DIN 18032 Part 2. The European Committee for Standardization (CEN) is a European business catalyst whose mission is to enable global trading and improve the welfare of European citizens by removing trade barriers for European stakeholders, such as the European sports industry and other sport stakeholder groups. The standard includes the same performance properties featured in both versions of DIN 18302 Part 2, but categorises performance characteristics by technical and safety criteria (EN14904 2006). In comparison to DIN 18032 Part
2, the testing requirements for EN14904 properties were developed to promote increased uniformity in the measured requirements for indoor sports surface systems.

While the EN14904 standard permits an extensive series of performance levels, the standard correspondingly affords a process where surfaces with comparable performance characteristics may also be grouped and categorised. This process is achieved via the non-compulsory ‘types’ inventory situated within Appendix B of EN14904. There is however no conclusive evidence to support the argument that any specific EN14904 performance level can differentiate a safe sports surface from an unsafe sports surface. Under the DIN 18032-2 standard, a sports surface either passed or failed testing, while with the introduction of the EN14904 standard, manufacturers are now encouraged to develop surfaces that provide performance characteristics that have been optimised for an explicit sport or market. Manufacturers can now design surfaces that would previously have failed DIN 18032-2 but which now are able to address the broader requirements of the EN14904 standard. Table 3.1 shows the broad range of performance requirements for the European Standard EN 14904.

<table>
<thead>
<tr>
<th>EN 14904</th>
<th>Category</th>
<th>Standard</th>
<th>Requirement</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Properties</td>
<td>vertical deformation</td>
<td>EN 14809</td>
<td>≤ 3.5</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>force reduction (minimum)</td>
<td>EN 14808</td>
<td>25% &lt; FR &lt; 75% (Range plus or minus 5% of average)</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>friction coefficient</td>
<td>EN 13036-4</td>
<td>80-110</td>
<td>-</td>
</tr>
<tr>
<td>Technical characteristics</td>
<td>ball rebound (minimum)</td>
<td>EN12235</td>
<td>≥ 90</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>indentation resistance</td>
<td>EN 1516</td>
<td>≤ 0.5</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>wheel resistance (rolling load)</td>
<td>EN 1569</td>
<td>≥ 1500</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>abrasion resistance</td>
<td>EN ISO 5470-1</td>
<td>≤ 1000</td>
<td>mg</td>
</tr>
<tr>
<td></td>
<td>gloss</td>
<td>EN ISO 2813</td>
<td>≤ 30</td>
<td>mg</td>
</tr>
<tr>
<td></td>
<td>flatness</td>
<td>EN 13036-7</td>
<td>≤ 6mm/3m</td>
<td>-</td>
</tr>
<tr>
<td>Classification</td>
<td>fire rating</td>
<td>EN 13501-1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>formaldehyde emission</td>
<td>EN 717-1/2</td>
<td>≥ E1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>pentachlorophenol emission</td>
<td>E 12673</td>
<td>≤ 0.1</td>
<td>%</td>
</tr>
</tbody>
</table>

### 3.6 EN14904 performance parameters for sports surfaces

The performance characteristics of a sports surface will vary from sport to sport due to the particular modes of interaction, the ball, the athletes and the nature of the surface. The selection of a surface for a sports facility will be influenced by commercial pressures on the club and the
manufacturers, who constantly try to better their designs to gain a competitive advantage over their competitors (Walker and Subic 2010).

Performance standards, testing and compliance are the main methods of ensuring that sport requirements are matched to the various commercial surfaces available. The European standard EN14904 has sought to unify sport surface performance standards across Europe and all of the national standards organisations in the European Union are obliged to conform to this unified standard. As many European countries were involved in the development of the EN14904 standard, it has been developed to accommodate an extensive range of sport types, user needs and economic conditions.

The EN14904 standard specifies that a surface which is utilised in a 'multi-sport' application, is one on which more than one sport can be played. There are however also sport-specific standards which have been developed, and in some cases these sport specific standards can take precedence over the EN14904 standard, where a particular sport may dominate a multi-sport facility. The performance characteristics of surfaces classified under the EN14904 standard fall into mechanical, safety and biomechanical performance categories.

3.6.1 Mechanical performance

Rolling load behaviour. Rolling load is the ability of a sport surface to withstand general loads commonly applied to a playing surface in a sports facility. The rolling load test is performed with a load of 1500 N and loading is delivered through a single test wheel. The surface should exhibit no indication of damage once the tests have been completed. The residual deformation of the surface must be less than 0.5 mm 15 to 20 minutes after the test has been completed.

Ball rebound. Ball rebound is the ‘pace’ or the extent to which a ball will rebound from a sports surface. This test evaluates the suitability of a surface primarily for basketball. The ball rebound value is the rebound height achieved from a surface, articulated as a percentage of the rebound height attained from a non-resilient surface such as concrete. The ensuing equation is used to calculate the ball-rebound value.

\[
\text{Ball-rebound} = \left(\frac{\text{Rebound height from sport surface}}{\text{Rebound height from concrete}}\right) \times 100 \quad \text{Eq. 3.1}
\]

The rebound height is calculated from the top of the playing surface, to the bottom of the ball and the recorded heights from this test will typically range from 80% to 100%. Higher ball rebound
values indicate sports surfaces that induce greater rebound heights, normally described as more ‘lively’. A sports surface should have an average ball rebound height greater than or equal to 90%, and no individual point on a sports surface should produce values which vary by more than ± 3% from the average value.

**Area indentation.** Area indentation is the degree to which a sports surface can control the transfer of energy from an athlete into a sports surface, during an impact, such as footfall. This aspect was formally measured in DIN 18032-2, but is no longer considered relevant in the EN14904 standard. Sport surfaces that diffuse impact energy over a large area do poorly with this test, while sports surfaces that restrict impact energy to a compact area do well. Area indentation is frequently the more difficult of the mechanical performance criteria to express, but its intention is to ensure that manoeuvres undertaken at one point on a sports surface will have a nominal effect on competitive play at another point on the surface. Area indentation is normally assessed at the same time that vertical deflection is measured.

### 3.6.2 Safety and biomechanical performance

**Force reduction.** Force reduction, which is also frequently referred to as impact attenuation, assesses the capacity of a sport surface to reduce maximum impact forces, in comparison to an impact on a non-resilient surface such as concrete. This property is a robust indicator of the level of comfort that will be delivered by a sports surface to an athlete. This property has the strongest biomechanical basis of all of the properties contained within the EN14904 standard. The impact period is approximately equal to the duration when ‘passive’ impact peaks normally occur. Passive impact peaks are the localised maximum forces which occur prior to the athlete’s body being able to respond to a landing impact, through the response of their neuromuscular system.

The most commonly used surface performance testing device, and the current industry standard, is the Berlin Artificial Athlete (BAA). The BAA test device consists of a 20±0.1 kg mass, which is released to fall onto a spring with a stiffness of 2000±60kNm-1, from a height of 55±0.25mm. The spring is mounted on top of a load cell which has a capacity of 10 kN. The load cell is then connected to an amplifier, signal processor and signal conditioner. The peak impact force is measured at impact and force reduction can then be calculated as the percentage force reduction, in
comparison to an unyielding surface such as concrete. The maximum impact force can then be calculated from the following equation:

\[
F_{\text{max}} = mg \left( 1 + \sqrt{1 + \frac{2h k}{mg}} \right)
\]

Where:
- \( F_{\text{max}} \) = Maximum force measured by the load cell in N
- \( m \) = The mass of the weight in kg
- \( g \) = Acceleration due to the effects of gravity, 9.81 m/s\(^2\)
- \( h \) = Drop height in m
- \( k \) = Spring rate in N/m

(Demker 2009) \hspace{1cm} \text{Eq. 3.2}

Force Reduction, \( R \), can then be calculated from the following equation:

\[
R = \left( 1 - \frac{F_t}{F_r} \right) \times 100
\]

Where:
- \( F_t \) = Maximum peak force in N
- \( F_r \) = Reference force as measured on concrete

(Demker 2009) \hspace{1cm} \text{Eq. 3.3}

Force reduction describes how a sports surface attenuates impact energy, compared to a non-resilient surface such as concrete. Three test impacts are recorded at each test-point on a surface and an average is calculated from the second and third impacts. Where \( F \) Sport Surface is the maximum impact force generated on the sports surface and \( F \) Concrete is the maximum impact force generated on concrete, \( FR \) is the Force Reduction of the structure articulated as a percentage. Average force reduction values recorded will normally be in the range of 25% to 75% and no individual point on a sports surface may vary by more than ± 5% from the average value.

Table 3.2 indicates the possible force reduction classifications for area elastic, point elastic, mixed elastic and combination elastic sports surface systems.

\[\text{Table 3.2} \hspace{1cm} \text{Force reduction (FR) surface types for point elastic, area elastic, mixed elastic and combination elastic sports surface systems (EN14904 2006)}\]
<table>
<thead>
<tr>
<th>Type</th>
<th>Point elastic systems</th>
<th>Area elastic systems</th>
<th>Mixed elastic systems</th>
<th>Combination elastic systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25 ≤ FR &lt; 35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>35 ≤ FR &lt; 45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>45 ≤ FR &lt; 75</td>
<td>40 ≤ FR &lt; 55</td>
<td>45 ≤ FR &lt; 55</td>
<td>45 ≤ FR &lt; 55</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>55 ≤ FR &lt; 75</td>
<td>55 ≤ FR &lt; 75</td>
<td>55 ≤ FR &lt; 75</td>
</tr>
</tbody>
</table>

Table 3.3 and 3.4 indicate the combined vertical deformation and force reduction classifications for point elastic, area elastic mixed elastic and combination elastic sports flooring systems.

**Table 3.3**  
Point elastic and area elastic sports surface force reduction classifications, European Standard EN14904 (EN14904 2006)

**Table 3.4**  
Combined elastic and mixed elastic sports surface force reduction classifications, European Standard EN14904 (EN14904 2006)
The EN14904 standard addresses the need for testing uniformity by including a wider range of surface types in the standard, and it has also provided manufacturers a means by which they can justify the development and improvement of surface systems that previously would not have complied with the DIN 18032-2 standard. However, there are no guarantees that a system which can comply with the requirements of a performance standard will result in reduced injury rates on a particular surface.

Every movement made by an athlete on a sports surface requires the athlete to expend energy. A sports surface which can return part of that energy has the potential to enhance the performance of an athlete and all compliant sports surfaces have the potential to return energy. When an athlete makes contact with a sports surface, energy passes from the athlete into a compliant surface where it is stored in the form of surface deformation. When the athlete then leaves the surface, energy is returned to the athlete as the deformed surface begins to recover. Energy transmission into and out of the surface can therefore potentially have a significant impact on the athlete’s performance.

The quantity of energy returned from a sports surface is dependent on its material composition and structural characteristics. The larger the force, the more the surface will deform and the greater the potential for energy to be stored and released (Stefanyshyn and Nigg 2003).

\[ E_{surface} = \frac{1}{2} kx^2 \]

Where:
- \( k \) = Material Stiffness
- \( x \) = Deformation

(Stefanyshyn and Nigg 2003) Eq. 3.4

As a result of this relationship, as stiffness increases deformation will diminish. This relationship relates to the energy that can be returned if it is treated as an elastic system. If plastic deformation occurs there will be little or no rebound. The more compliant the surface, the greater the potential for deformation and the larger the amount of energy which can be stored. In addition, energy will be lost as it is transformed into heat, vibration and sound. The energy returned to the athlete will therefore always be less than the energy initially transferred by the athlete to the surface. Energy return is only relevant, therefore, if it is potentially substantial enough to enhance performance. For
an athlete to benefit from returned energy, the reaction forces from the surface must be applied at the correct location, in a suitable direction, at the appropriate time and at a suitable frequency (Nigg and Segesser 1988). In practice this is difficult to achieve, as location, direction, time and frequency are sport-dependent and a surface structure suitable for movements and motions typical of one sport may be quite unsuitable for another.

Friction and slip resistance. A sports surface’s coefficient of friction is an assessment a surface’s ability to resist the sliding of an athlete over the surface. For most sports, the degree of friction between the athlete’s shoes and the sports surface needs to be high enough to prevent unintentional slipping, but not so high as to restrict foot movement, either in a constant direction, when turning, or prevent the controlled sliding of the foot when necessary.

Despite the practical advantages of synthetic sports surfaces, some investigations have implicated the increased use of synthetic surfaces as a causative mechanism of injury in many sports (Myklebust, Maehlum et al. 1998), where researchers found injury rates for games played on synthetic surfaces to be significantly higher than those played on natural timber surfaces. The study conducted by Olsen et al. (2003) concluded that the main causal factor was not just surface resilience and stiffness, but rather the high frictional forces caused by the shoe/surface interface.

The results of injury studies comparing synthetic to natural surfaces must be interpreted cautiously, however, as the terms synthetic or artificial become rather nebulous, due to the extreme variety of surface types now commercially available which include various combination configurations.

Another surface injury type related to friction is abrasion, which can result in burns and lacerations to the athlete’s skin. Surfaces which are rough possess a high degree of friction, and can cause serious damage to the skin if the player is in sliding-contact with the surface. The frictional properties of a surface can also vary over time if the contact layer of the surface alters as a result of ultraviolet degradation, temperature, moisture, humidity, cleaning and routine maintenance. High traffic areas of the surface, such as in a goal mouth, can become ‘polished’ and result in a reduction in surface roughness, and hence reduce friction levels.

Regardless of the type of sport being played, a sports surface should afford a constant balance of shoe release as opposed to traction. The capacity for an athlete to run at high speed on a sports surface necessitates secure grip at the time of acceleration. Equally, to brake and rapidly change direction requires the surface to respond to those forces and permit the athlete’s foot to release or
swivel. An unsafe surface holds the athlete’s shoe and prevents its release from the surface. This failure to release during a turn can lead to physical overloading and lower extremity injury.

**Slip resistance.** Slip resistance is the friction property of a sports surface, which has a number of performance and biomechanical implications. When slip resistance on a sports surface is too low, players will slide excessively during competitive play and the athlete will find it difficult to change direction in a controlled manner. Conversely, when slip resistance is too high, the magnitude of forces being conveyed through the joints while braking, acceleration or changes in direction is increased, also increasing the chances of injury.

Slip resistance values may alter as a result of maintenance practices. Surface cleaning materials can occasionally alter the frictional properties of a sports surface as a result of unintended chemical reactions or surface contamination that leave low friction residues on the surface. Slip resistance is measured using a pendulum device which uses a standardized piece of rubber mounted onto a pendulum device, which is set up to travel across a flooring surface. Low friction surfaces produce readings close to zero, and higher friction surfaces impede the motion of the pendulum arm, giving results above zero, where an average Pendulum Test Value (PTV) will normally be in the range 80 to 110. Individual test points on a surface may vary, by no more than ±4 points from the average value.

**Vertical deformation.** Vertical deformation is the ability of a surface to deflect during impact, from a biomechanics perspective. High vertical deflection levels can cause an athlete to become unbalanced when running and jumping on a surface. Extreme deformation can result in dangerously high forces being generated in the limbs of an athlete and can lead to knee and ankle injuries. The BAA is also used to measure vertical deformation in addition to force reduction, except that the spring stiffness used in this test is adapted to 40±1.5N/mm and the drop height is modified to 120±0.25 mm. These conditions result in a theoretical maximum force of 1.58 kN
The vertical deformation, $D$ values are expressed in millimetres of deformation, and are obtained from the following equation:

$$D = \left(\frac{1500N}{F_{max}}\right) \times f_{max}$$

Where:

- $F_{max} =$ Maximum force created during impact (peak value) in N
- $f_{max} =$ Maximum deformation at the point of impact in mm

(Demker 2009)  

Eq. 3.5

Table 3.5 shows the optional vertical deformation classifications for point elastic, area elastic, mixed elastic and combination elastic sports flooring systems.

<table>
<thead>
<tr>
<th>Type</th>
<th>Point elastic surface systems</th>
<th>Area elastic surface systems</th>
<th>Mixed elastic surface systems</th>
<th>Combination elastic surface systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>StVv &lt; 2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>StVv &lt; 3.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>StVv &lt; 3.5</td>
<td>1.8 ≤ StVv &lt; 3.5</td>
<td>StVv &lt; 3.5</td>
<td>1.8 ≤ StVv &lt; 3.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.5 ≤ VDp &lt; 2.0</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>2.3 ≤ StVv &lt; 5.0</td>
<td>StVv &lt; 3.5</td>
<td>2.3 ≤ StVv &lt; 3.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.5 ≤ VDp &lt; 2.0</td>
</tr>
</tbody>
</table>

VDp represents the vertical deformation aspect of the point elastic component of a combined elastic sports flooring system.

3.7 Inclined impact test devices

Walker and Subic developed an inclined impact test device which can repeatedly strike a floor with a 20 kg weight at a predetermined angle, from a vertical height of 55mm in accordance with current force reduction test requirements specified in the EN14904 standard (Walker and Subic 2010). These aspects will be described in detail, in Chapter 8.

3.8 Conclusion

The changing character of sports has led to sports being played on an expansive range of synthetic and natural playing surfaces. In recent years, there has been a trend towards the creation of multi-sport facilities, where facility utilisation is optimised by offering a variety of sports played on just a few surface types. This integrated approach may not however always be appropriate, due to the varied mechanical, safety, biomechanical performance needs of different sports. In response to
these diverse needs, manufacturers have responded by designing and developing an ever increasing range of sports surface structures.

In order to improve our understanding of these complex structures and to help quantify their performance characteristics and therefore their suitability for different sports, mechanical tests have been developed to simulate and evaluate their mechanical, safety and biomechanical performance. This is a dynamic area, where developments in materials technology are constantly driving innovation.
Investigation of sustainability in the design and development of sports surfaces

4.1 The need for sustainable design

Typically, 80% of a product’s environmental impact is established at the design stage (European Commission 2010), and engineers and designers have the opportunity to intervene early in the design process to maximise the environmental performance of the products and buildings they are responsible for designing. Engineers, industrial designers, architects, product planners and marketers are in key positions to influence and reduce these impacts, often through straightforward methods.

A well-designed product tends to embody a balanced combination of the following qualities: usefulness, ease of use, desirability, producibility, differentiation, profitability and sustainability. This is equally applicable to the selection of a well-designed sports surface, but what makes a particular sports surface environmentally sustainable and how do we compare the relative sustainability of diverse types of sports surface?

Sustainable design approaches attempt to use materials, energy and water efficiently while minimising waste, negative impacts on the natural environment and on the quality of human life. Sustainable design considers environmental impact at every stage of a product or building’s life cycle, and seeks to address key environmental issues at their source by locking-in positive environmental features, such as durability, energy and water efficiency; and by locking-out
negative environmental attributes, such as toxic or hazardous substances, waste and obsolescence (Resource Smart Victoria 2005) (Figure 4.1).

Other key characteristics of sustainable design include:

- sustainable design objectives incorporated into organisational business strategies
- involvement of all company functions, as well as external entities in the organisation’s supply chain in achieving sustainable outcomes
- design decisions being based upon measurable data and environmental assessment tools.

![Conceptual vision for sustainable sports surfaces](image)

4.4.1 Standards, protocols and regulatory compliance in the sports surface industry

Environmentally preferable purchasing initiatives introduced by government purchasing agencies and large retailers such as Wal-Mart, Tesco and Marks and Spencer, are redefining which products are authorised to be part of their supply chains. The combined effects of green product interest, eco-labelling and supply chain eco-discipline are making certifiably sustainable products the norm for access to distribution networks. In 2009, for example, Wal-Mart brought together 1,500 of its main suppliers and associates and announced plans for a worldwide Sustainable Product Index (SPI). The SPI requires suppliers to become involved in a range of eco-initiatives covering plans
for greenhouse gas emission abatement, waste reduction, responsible sourcing of raw materials and responsible and ethical manufacturing practices (Walmart 2009).

In 2006, Marks and Spencer launched the Look Behind the Label (LBL) initiative, which marketed the environmental and ethical benefits of its products (Marks & Spencer 2006). The success of LBL led to the introduction of Plan A, an even more ambitious set of sustainability targets covering climate change, waste, natural resource depletion, fair trading and health and wellbeing. Marks and Spencer announced that Plan A’s eco-efficiency goals had saved the company approximately 50 million pounds in the 2009/10 financial year(Marks & Spencer 2010).

In the US, the Environmental Protection Agency (EPA) has instituted Environmentally Preferable Purchasing (EPP) programs to assist the federal government to ‘buy green,’ and comply with green purchasing requirements and use the US federal government's substantial purchasing power to stimulate market demand for green products and services. Environmentally Preferable denotes ‘products or services that have a lesser or reduced effect on human health and the environment when compared with competing products or services that serve the same purpose’ (United States Environmental Protection Agency 2008) This assessment applies to all stages of a product or service’s life-cycle. The program assists businesses and consumers to:

- locate and assess information concerning environmentally beneficial products and services
- ascertain government environmental purchasing requirements
- evaluate the costs and benefits of environmentally beneficial purchasing options
- control environmental buying processes.

In the context of the adoption of these standards and practices in the government and commercial sector, many international sports surface manufacturers are embracing sustainability in order to reduce the commercial risks associated with life cycle resource input price volatility (access to energy, water and raw materials) and output waste price volatility (waste management), tightening environmental legislation, market demands for ‘greener’ products and services, and the introduction of carbon abatement taxation schemes. Carbon taxes and emissions trading schemes are being implemented globally in an attempt to reduce energy consumption patterns through higher energy pricing and material costs.

Furthermore, the European Union has demonstrated that governments can and will tackle sustainability issues through the legal system. In Europe, a series of protocols, directives and
regulations have been introduced to drive sustainable approaches through the life cycles of certain damaging categories of product. The regulatory systems which have had a particularly strong effect have been: the Waste Electrical and Electronic Equipment (WEEE), the Restriction on Hazardous Substances (RoHS) and the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), the latter two being most relevant to the sports surface industry.

New directives related to the composition of sports surfaces, control access to attractive European markets (Day 2005). The link between effective sustainable design and product-oriented regulatory compliance is now well established and ‘regulatory tracking’ is a key requirement in the design of sports surfaces in order to minimise commercial risk, and European environmental regulation is now more generally driving opportunities for major sustainable design initiatives in the packaging, IT, consumer electronics, white goods, building product and flooring industries.

In the context of the present study, these material reformulations have had important, direct impact on surface performance properties, such as force reduction, as plasticisers are added to polymers in order to increase the polymer's ductility and ease of processing. Among phthalate based plasticisers, for example, the orthophthalates have now been restricted in the European Union, and more recently in North America (Versar 2010). Plasticiser additives cause a reduction in the cohesive intermolecular forces present along polymer chains in the production material. The polymer chains can then move more freely relative to each other, and the resultant stiffness of the polymer is reduced. Toxic plasticisers are now being replaced by alternative materials which have a reduced impact on surface performance.

For commercial and safety reasons, therefore, the floor design central to the research for this thesis had to include features reflecting the product life cycle in response to the environmental sensitivity of the market, as well as improved injury prevention for athletes.

4.4.2 Extended product responsibility

Sustainable design is now more commonly associated with higher levels of surface quality, products which are less likely to result in consumer and environmental harm, and surfaces that specifiers can feel less guilty about using. Companies are using a widening set of eco-labels and green marketing approaches to differentiate their products as ‘green’ and to build trust and lasting connections with consumers. One such label commonly used in the floor surface industry is the Nordic Ecolabel or Nordic Swan, the official sustainability eco-label used in Nordic countries. This
is achieved through a voluntary regulatory system where surface manufacturers agree to follow certain environmental criteria as outlined by Nordic Ecolabeling. Environmental criteria include environmental, quality and health aspects.

Extended product responsibility business models through product leasing or product take-back schemes can also alert a company to a customer’s interest in making a repeat purchase. In 2005, General Electric (GE) announced the launch of their Ecomagination program and by 2008 (General Electric 2007), Ecomagination revenues had risen by 21% above their 2007 sales performance figures. Ecomagination is GE’s major sustainability program, covering its products, services and operations. The Ecomagination Product Review (EPR) process provides full third-party verification of GE’s environmental performance claims, relative to baseline measures such as benchmarking against competitors’ best products and compliance with European regulatory standards (General Electric 2010).

In 1973, Interface Inc. recognised that there was an unmet need for modular floorcoverings which can be flexibly used in the contemporary office environment. To meet this need, a company was formed to produce and market modular floor surfaces. With the company’s later acquisition of Heuga Holdings, one of the world’s oldest manufacturers of carpet tiles, Interface then became the world leader in carpet tile manufacture and distribution. In 1994, Interface recognised that broadloom carpet disposal was becoming a growing environmental concern, given the lack of recycling in the floor-covering industry and the vast amounts of waste carpet being directed to landfill. Interface started to change the way that their carpet products were manufactured and recycled. The program that was initiated was called Mission Zero, with the goal of eradicating any undesirable impact that the business had on the environment by the year 2020. Central to this goal was the company’s efforts to reduce their reliance on non-renewable raw materials. With this aim, the ReEntry carpet recycling program was implemented.

The environmental impact of carpet yarn and backing can be significantly reduced by recycling carpet at the end of its life and in order to do this, Interface developed a suite of carpet tile recycling technologies. ReEntry was the world’s first carpet tile recycling program, closing the loop on the use of non-renewable raw materials and fuel. This program also accepts carpet tiles from other manufacturers, with most vinyl backed tiles being used for recycling into new carpet tiles. Carpet
tiles with bitumen and other types of backing material are also reconditioned and reused in the second hand carpet market (Interface 2011).

4.4.3 Design response to the need for environmental and economic sustainability: Life cycle thinking

Surface developments that improve energy efficiency and decrease direct energy use make sports surfaces more cost effective for consumers to use, as can be seen with the trend towards reduced power consumption products in the white goods and brown goods industries. In addition, reduced sports surface thermal cycling rates can increase the reliability of sports flooring products, which are normally degraded over time as a result of large changes in temperature. Reducing the heating, ventilating and air conditioning demands in downstream products like sports surfaces and upstream sports facility structures, can ultimately reduce running costs to the consumer (Kwon, Yim et al. 2005).

Product life cycle thinking recognises that whole product life cycles must be considered if the true environmental impacts of a product or system are to be understood and then minimised. Even the most valued of surfaces such as timber, have a life cycle that should not be ignored by the sports surface designer, who is ultimately responsible for more than just player safety. Some sports surfaces are indirectly more energy intensive in the use phases of their lifecycles than others. Some are more toxic and some are more wasteful.

Issues with timber. Timber, for example, is a popular sports surface. It is a hydroscopic material, and when exposed to fluctuating temperatures and humidity levels, the surface will release or absorb moisture until it reaches equilibrium with its immediate environment. As timber absorbs water, the addition of moisture causes wood to expand, while the loss of moisture will cause timber to contract. The recommended environment in which a timber sports surface should be installed and maintained, requires an air temperature of between 13 and 24 degrees centigrade, and relative humidity between 35% and 50% (Maple Flooring Manufacturers Association 2011).

These tightly controlled temperature and humidity operational requirements will in most cases require the application of an energy intensive humidity and ventilation air conditioning (HVAC) system for the space in which the surface will be installed over the life of the surface. If the environmental conditions are not tightly controlled, a timber sports surface will continue to react to variations in its environmental conditions over its life, resulting in dimensional changes to its
structure. If conditions are not tightly controlled, timber will react to changing environmental conditions in the following ways:

- The appearance of ‘separations’ or cracks during dry conditions is normal and predictable. These cracks will typically close as humidity increases. The use of humidification/dehumidification systems to maintain suitable humidity levels will reduce these effects.
- Surface ‘squeaking’ can also be initiated by expansion and contraction cycles and can again be minimised by maintaining the surface in an unchanging internal environment.
- Surface ‘dishing’ over the width of a section of flooring is caused by moisture unevenness through the thickness of the surface where the moisture content is more pronounced on the bottom surface of a timber section than on the top surface of a timber section, causing the bottom surface to expand and the top surface to contract. The moisture source must therefore be removed before the surface will recover. (Maple Flooring Manufacturers Association 2011)

Unstable environmental conditions may in extreme cases cause permanent damage to the surface beyond repair, or render the surface unsafe for continued sporting use.

**Other considerations in a life cycle.** Just as avoiding controlled climate situations, such as those for timber, can reduce energy requirements and cost, reducing the volume, weight and embodied energy captured in the materials required for a sports surface, while maintaining or lengthening its serviceable life, can reduce the cost of manufacture and the quantity of waste produced over a surface’s lifecycle. Waste is not only generated at the surface’s highly visible end-of-life, but also at every stage of the surface’s extensive life cycle. The volumes of waste generated during raw material extraction, processing, product manufacture and distribution can be many times the volume of waste eventually materialised at the surface’s end-of-life.

Using recycled materials in a surface can reduce costs, absorb waste generated by other products and ultimately help reduce the quantity of waste going to landfill. Lighter product weights, smaller overall dimensions and reductions in the quantity of packaging used, can all help to reduce a product’s freight costs, the cost of repair, packaging and other associated impacts (Kobayashi and Kobayashi 2005).

The requirement for specialised handling and disposal can be eliminated if hazardous materials are avoided throughout a surface’s lifecycle. Modular plastic sports surface manufacturers traditionally
offered a 10 year warranty period. Through redesign, higher specification sports surface products have been able to extend many warranty periods to 15 years without significantly increasing the unit weight per square meter of a sports surface.

Alternatively, dematerialisation, the process of making the same quality product while using less or alternative materials can be utilised as an alternative sustainable design strategy. This process can be achieved by using existing materials in a more eco-efficient manner or by replacing an inefficient material or process with more eco-efficient alternatives. Dematerialisation not only allows a manufacturer to reduce material costs, but also minimise the raw material extraction, processing energy, emissions, transportation costs and waste generated at each stage along the supply chain and over the life of a surface.

During the course of this study, design for sustainability was one of the core research areas. The approaches adopted were achieved through ‘product stewardship’ and ‘cradle to cradle’ sustainable design strategies, which will be discussed in more depth in Chapter 5.

4.2 Conclusion
Surface manufacturers and businesses can reduce costs, produce a better product and increase profits through the design not only of their product, but of their product’s manufacture. Designing more sustainable products and buildings begins with the introduction of life cycle thinking approaches at the beginning of the design process. The majority of a product’s environmental impacts are ‘locked-in’ at the design stage; therefore, engineers and designers are in key positions to influence and reduce these impacts over a sports surface or sport facility’s life. Life cycle thinking recognises that whole-surface life cycles must be considered if the true environmental impacts of a sports surface are to be understood and then minimised. Embracing the cyclic approaches that have been developed and perfected by nature, where the waste from one biological process becomes the resource input for another can help us achieve more harmonious, future-friendly outcomes. The concept is described more fully in Chapter 5.
Chapter 5

Life cycle assessment: Sports facility design and sports surface selection tool

It is no longer satisfactory to simply focus on the object being designed when a designer’s decisions ultimately influence the entire product system being developed. Ideally, the full life cycle impacts of all materials and processes used in the design of a sports surface would be fully understood, allowing the developer to clearly see which material or process is less damaging; but this unfortunately is not always the case. The introduction of more sustainable approaches to the design process is often restricted by a lack of accurate environmental data. In addition, it is difficult to calculate the impacts of multifaceted production processes from within dynamic evolving designs, where concepts are constantly changing as a design develops.

This issue has encouraged the development of streamlined life cycle assessment tools, which allow for the rapid environmental evaluation of alternative design concepts which are being generated within the design process. These tools can help identify problematic ecological areas within evolving designs, allowing targeted eco-design strategies to be employed. These same approaches can be used to evaluate the ecological appropriateness of different sports surface types, as part of a rational, structured sports surface selection process.

Could, therefore, a streamlined LCA approach provide impact results of sufficient accuracy to allow them to be used as a reliable decision-making tool in the selection process for the purchase of a sustainable sports surface within a sustainable sports facility? A comparative study was conducted to evaluate the outcomes of using streamlined LCA approaches, as part of the research reported in this thesis.

The consumption of materials and energy globally is increasing, while resources irreversibly diminish and waste streams and emissions increase. Greater attention is therefore now being given to the materials and processes that we use to create our cities, with emphasis on sustainable materials and processes. This chapter explores the practicality of using life cycle assessment in the design of a sustainable sports facility and the design and selection of a sustainable sports surface. This study therefore aims to provide a comprehensive description of the main determining factors which should be taken into account when selecting an appropriate sports surface for court sports in order to reduce the life cycle impacts of surface selection in relation to sports facility design.
5.1 Streamlined indoor sports surface life cycle assessment

Life cycle assessment seeks to emulate the ‘cradle-to-grave’ or ‘cradle-to-cradle’ implications of any product or service, and informs the development of strategies to direct the abatement of environmental impacts. It is therefore vital to implement life cycle strategies as early as possible within the design process (Kobayashi 2006). Eco-design is defined as a process of ‘systematic incorporation of environmental factors into product design and development’ (Tukker, Eder et al. 2001). To effectively implement eco-design, all product or building lifecycle stages need to be taken into consideration (Verkuijl 2006).

Life cycle thinking contemplates all stages of the product lifecycle from raw material extraction, manufacturing, distribution, use and disposal (Cooper 2005). As such, life cycle assessment can be used to calculate environmental impacts over a product's life cycle (Nielsen and Wenzel 2002). LCA is therefore a valuable tool which can be used to develop reliable information on the extent of any environmental impacts generated.

However, LCA can also be a complex, time consuming and expensive tool to implement, as it is necessary to compile large amounts of data related to the materials and processes which are used in the manufacture of a product (Cooper 2005). This problem has encouraged the development of ‘streamlined’ LCA tools, which allow the evaluation of various concepts during the design process.
Ecologically optimised concepts can be compared against each other, to identify opportunities for eco-innovation and to select a final design direction (Stevels, Boks et al. 2007).

Ideally, an LCA which involves less effort, time and cost, but which can still achieve reliable results, would be regarded as a highly desirable environmental assessment tool. Streamlined LCA is a technique which has been developed to make this type of analysis more achievable. As such, streamlined LCAs are used where only the more significant key attributes of materials or processes are included. In this process, elements which can be omitted within the LCA are identified without impairing the overall result. This may involve adjusting the project’s system boundaries or the scope of the assessment, so that the stages of the life cycle under analysis which make only small contributions to the project’s environmental impacts can be ignored. The recurring life cycle assessment process is shown in Figure 5.1.

![Life cycle assessment procedure](image)

The reliable identification of the elements which can be safely ignored without increasing the uncertainty of the result of the analysis is of considerable importance. In order to do this, the stated purpose of the LCA must be carefully considered within the ‘goal and scope’ phase. Given the growing importance of carbon in global economies and its implications for climate change, CO$_2$. 

water use and single score impact values are frequently used as alternative measures to reporting a broader range of environmental impacts, such as acidification, ecotoxicity, eutrophication and other LCA impact categories. Streamlined LCA techniques also make estimates and assumptions based on common LCA data for the various materials and processes more generally utilised in industry.

5.2 Sports surface environmental evaluation using streamlined life cycle assessment

A sports surface is arguably the most significant building element incorporated within a sport and recreation facility, as this is the component which comes into most direct contact with the facility’s primary user, the sports participant. The sports surface is therefore subjected to most wear, often requiring remediation, removal and replacement a number of times during the life of a sports facility.

Specifying and selecting a sports surface normally involves the simultaneous evaluation of a multitude of performance factors. Increasingly, environmental impact is becoming an important component of these considerations as buildings strive to become more sustainable. Designers require objective, consistent and comprehensive data detailing the environmental impacts and waste implications of their selection decisions. This approach involves a process-based analysis, which looks at each individual material and process in the playing surface’s value chain (Walker 2008). Sports surface selection criteria normally include, the purchase cost/life cycle cost, sport type/utilisation level, athlete safety, playing performance, required approvals systems, aesthetics, surface durability, ease of installation, maintenance and more commonly now the sports surface’s environmental footprint.

5.2.1 Conventional surface selection methods based on supplier generated information

The process of designing a building involves the consideration of a vast range of materials and building components, with component suppliers making competing claims for the environmental credentials of their products or services. Claims extolling the green virtues of one aspect of a materials life cycle may however ‘mask’ the negative elements of another lifecycle stage. In addition, viewing each building element in isolation ignores the interconnected and interdependent nature of the building’s components, within the structure’s life cycle. If a ‘more sustainable sport
and recreation centre’ were to be developed, how would the designer decide which sports surface should be used within the facility when:

- Hardwood timber sports flooring suppliers commonly claim that wood is the only natural resource that is at once renewable, recyclable, biodegradable and re-usable (Maple Flooring Manufacturers Association 2011). These claims however ignore the regular use of toxic oil or water based urethane finishes, which are required to provide a resilient and durable playing surface.

- Pour-in-place synthetic sports flooring suppliers make claims that their products have become more environmentally responsible through the elimination of mercury and lead from their polyurethane components, making disposal of these floors less of an environmental burden. The vast majority of these surfaces however are still ultimately consigned to landfill at their end-of-life.

- Prefabricated sheet synthetic sports flooring suppliers claim that vinyl is a harmless material widely utilised in numerous industries, although there is still considerable debate in respect to the environmental and health implications from the use of chemical additives, such as phthalate plasticisers and organotins. It has been found that organotins affect the immune system of laboratory animals, whilst phthalates display a wide range of toxicities (Allsopp, Santillo et al. 2000).

- Prefabricated tile synthetic sports flooring suppliers claim that this style of flooring is 100 percent recyclable, with some surfaces being verified as ‘zero waste’, and that they are immune to moisture damage which is a common problem with other styles of sports floor. These claims however ignore the oil extraction, resource depletion, the energy implications of the injection moulding processes used to manufacture the tiles and the shorter life expectancy for this category of surface (Sport Court 2013).

These ‘green’ claims make the selection process extremely difficult and may result in poor decision making, in the absence of more reliable environmental information. Green rating systems such as LEED (The Leadership in Energy and Environmental Design) and Green Star can assist by encouraging the selection of flooring systems which have low emitting VOCs, or those which are rapidly renewable or those which have recycled content. Determining which flooring systems are the most eco-friendly within the overall context of the structure in which they are to be installed and used over the entire life of the proposed structure can be challenging, however.

5.2.2 Environmental impact implications of indoor playing surfaces

Timber indoor sports playing surfaces are the norm throughout most of the developed world and are especially common at higher levels of competitive indoor sport. Although timber is widely

92
recognised as a renewable resource with negative net carbon emissions (Petersen and Solberg 2004), there is also the possibility that the environmental burdens created while using, maintaining and ultimately disposing of a wooden playing surface, may outweigh the environmental loads of its synthetic alternatives.

Installing and maintaining a sports surface brings with it many heavy environmental burdens in the form of periodic resurfacing, sealing and ultimate disposal (Nebel, Zimmer et al. 2006). The financial cost of installing and maintaining timber playing surfaces is resulting in the increased popularity of synthetic playing surface alternatives. Synthetic surfaces are continuing to gradually replace timber in many parts of the world, as synthetic surfaces avoid many of timber’s drawbacks.
5.2.3 Definition of assessment goal and scope

The purpose of the LCA undertaken during the current study was to assess and evaluate the environmental impacts of alternative constructional styles of indoor sports flooring surface, each with a different life expectancy, over the 50 year anticipated life of a sports facility. The commercial construction classifications of the flooring were:

- hardwood timber sports flooring
- pour-in-place synthetic sports flooring
- prefabricated sheet synthetic sports flooring
- prefabricated tile synthetic sports flooring

The anticipated life expectancy of each surface listed is determined by the normal commercial warranty period provided by the manufacturers of each surface type. The life cycle of a sports flooring product can be divided into four main life cycle stages:

- floor production (resource extraction, processing of raw materials, manufacture and surface installation)
- floor transport (moving the various components of the surface, to the point of installation)
- floor use (use and maintenance of the surface, including periodic resurfacing and facility climatic control)
- floor disposal and replacement (removal, disposal and multiple replacement of the surface at the end of its useful life, over the life of the sports facility).

If it is assumed that a sports facility will last approximately 50 years, then two timber surfaces, three and one-third pour-in-place surfaces, three and one-third synthetic sheet surfaces and five tile sports surfaces may be needed over the extended life of the facility. Most modern building structures are typically designed for a 50 year life span. Therefore, for sports surface comparison purposes, given that each indoor surface type has a different typical life expectancy, a sports facility with a service life expectancy of 50 years was assumed. The sports surface life-cycle data could therefore be normalized to a per-square-meter-per-year basis, over a 50 year period. Each life cycle stage may consist of a number of processes, with each process using one or more inputs from previous processes, and can deliver outputs to one or more following processes. Each input can be followed upstream to its origin and each output downstream to its end.
It is widely assumed that as wood is the result of a living carbon sequestrating system, it will be more environmentally benign than the various hydrocarbon based synthetic alternatives. The truth of this assumption is of considerable interest to designers, and it is possible that quantitative life cycle assessment could provide the proof they require. The aim of the current study was to use streamlined LCA single score values to determine the emissions produced by the specification of different constructional styles of sports surface. The baseline measure was emissions per one square meter of playing surface per hour of service provided over the life of a facility (Walker 2012). This streamlined exercise was simplified in the following ways:

- The environmental impact of daily/weekly surface cleaning, subsurface base manufacture and installation and game line marking processes were omitted, as these processes are replicated using similar materials and processes for all of the surface types under consideration.
- In each case, specific manufacturer data or manufacturer association data were chosen as the main sources of LCA inventory data.
- Only indoor playing surfaces were considered in the study.
- The scope was limited to single score CO₂ equivalent data.
- Transportation inputs were based on freight types and distances from the various manufacturing plant locations to the proposed point of installation in Adelaide, South Australia.

5.2.4 Streamlined life cycle inventory analysis

A streamlined online LCA tool was used to define each flooring surface’s bill of materials (BOM) and then data on the environmental load was gathered for each surface life cycle. In this study, the necessary information was gathered from company literature, other LCA studies and the online LCA tool’s Ecoinvent materials and processes database. The various inputs required for each of the flooring styles under investigation were multiplied by the life expectancy factor assigned to that surface. This multiplication factor would therefore take into account the additional material, process and transportation resources required for surfaces which have shorted life expectancies and which would have to be replaced more frequently. Simple online tools such as the one used in this study can be quickly and effectively used by a designer to capture and analyse the complex array of inventory data required for the LCA.
5.2.5 Streamlined life cycle interpretation and discussion

This method of assessment effectiveness varies according to the subject matter, type of analysis required, the quality of the data used and complexity of the environmental assessment undertaken. The successful use of such tools depends on their successful incorporation into the design team and design process.

Considering the complexity of some sports surface structures, and the uncertainties associated with long facility life cycles, streamlined methods using simple metrics are likely to be more preferable, when comparing design decisions for use in specific design phases. LCA results alone, however, should never lead designers and architects to make their final choices, as a surface’s performance requirements, cost, durability, sporting tradition and aesthetic expectations must also be taken into account. In addition, one should always be careful in drawing firm conclusions from a single case study, such as the one presented in this research, as the data incorporated into a study will vary greatly from one geographic and climatic location to the next, and different assessment methods and tools may give different and even contradictory answers (Jonsson 2000).

The streamlined LCA inline tool, Sustainable Minds, was implemented in this approach. Sustainable Minds is a web-based, streamlined LCA application which can be used to investigate the environmental impacts of current and future products. The application takes designers through each stage of a product’s life cycle in order to model new product variants and highlight the elements triggering possible environmental damage and can identify the points in the surface’s lifecycle where they arise.

Figure 5.2 shows an overview of the study, indicating the reference lowest impact Prefabricated Tile Synthetic Sports Flooring system, in comparison to each other surface’s environmental performance improvement. Figure 5.3 shows an impact overview, indicating the ecological damage impact categories for each surface under consideration.
<table>
<thead>
<tr>
<th>Reference, Lowest Impact</th>
<th>Impacts / functional unit mPts/func unit</th>
<th>CO₂ eq. kg / functional unit CO₂ eq. kg/func unit</th>
<th>Performance improvement from reference mPts</th>
<th>Performance improvement from reference %</th>
<th>Units of SVC deliveredSvc. Units</th>
<th>Assessment type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prefabricated Tile Synthetic Sports Flooring</td>
<td>6.8</td>
<td>4.9</td>
<td></td>
<td></td>
<td>50</td>
<td>Estimate</td>
</tr>
<tr>
<td>Hardwood Timber Sports Flooring: No HVAC</td>
<td>18</td>
<td>2.1</td>
<td>-11</td>
<td>-160%</td>
<td>50</td>
<td>Estimate</td>
</tr>
<tr>
<td>Hardwood Timber Sports Flooring: With HVAC</td>
<td>27</td>
<td>6.1</td>
<td>-20</td>
<td>-300%</td>
<td>50</td>
<td>Estimate</td>
</tr>
<tr>
<td>Prefabricated Sheet Synthetic Sports Flooring</td>
<td>40</td>
<td>2.2</td>
<td>-33</td>
<td>-490%</td>
<td>50</td>
<td>Estimate</td>
</tr>
<tr>
<td>Pour-in-Place Synthetic Sports Flooring</td>
<td>61</td>
<td>2.5</td>
<td>-54</td>
<td>-790%</td>
<td>50</td>
<td>Estimate</td>
</tr>
</tbody>
</table>

Figure 5.2 Stream-lined LCA overview (Sustainable Minds 2011)
Figure 5.3 Prefabricated tile synthetic sports flooring stream-lined LCA impact overview (Sustainable Minds 2011)
Figure 5.4 shows total impacts in millipoints (mPts) of each surface system by life cycle stage. The life cycle stages with high scores can be identified, compared and targeted to improve the overall environmental performance.

Figure 5.4  Prefabricated tile synthetic sports flooring stream-lined LCA impact overview (Sustainable Minds 2011)
Figure 5.5 Prefabricated tile synthetic sports flooring stream-lined LCA impacts by SBOM inputs: Carbon footprint [CO2 eq. kg/functional unit] (Sustainable Minds 2011)
Alternatively, results can be viewed by carbon footprint. In this view, the best and worst performing surfaces in terms of total impacts in millipoints (mPts) per functional unit were considered. This represents the total quantity of global warming gasses created over the life cycle of each surface. The impact units are represented in kilograms (kgs) of carbon dioxide (CO$_2$) equivalent. Sustainable ‘hot spots’ (materials, manufacturing processes, power, water and other consumables, end of life methods and transportation activities with high scores) can be identified, allowing the designer to seek alternatives approaches in order to reduce global warming impacts.

The single score result developed by performing this assessment using Sustainable Minds software, would appear go against ‘conventional wisdom’, as the timber sports surface featured in this analysis would appear to have a significantly larger ecological footprint than a polypropylene prefabricated tile synthetic sports surface (Figure 5.3), even when five prefabricated tile surfaces are supplied over the 50 year life of the facility, in comparison to the two timber surfaces over the same period.

The timber surface however does perform better than both the prefabricated sheet and pour-in-place synthetic sports surfaces under the same conditions. Figures 5.4 and 5.5 show a comparison of the prefabricated tile synthetic sports surface, with a hardwood timber sports surface with and without the use of heating, ventilating, and air conditioning (HVAC) equipment. HVAC equipment is normally required during the use phase of a timber sports surface. The analysis was also undertaken without the use of HVAC equipment, in order to highlight the normally ‘obscured’ role that electrical power for climate control equipment plays in the resultant use-phase impacts of timber surfaces.

Without due consideration of the energy consumed and therefore CO$_2$ emitted during the ‘use phase’ of a timber flooring system may lead the designer to make less sustainable choices. Both the prefabricated sheet and pour-in-place synthetic sports surfaces perform reasonably well in respect to CO$_2$ impacts in comparison to the prefabricated tile surface.

HVAC equipment is recommended for use with timber sports surfaces, as timber is a hygroscopic material. Moisture absorption causes timber to expand, whereas moisture loss causes timber to contract. In order to avoid damaging a timber sports floor, manufacturers recommend that timber
sports surfaces are maintained at a temperature between 13°C to 24°C and humidity levels between 40% and 60% (Maple Flooring Manufacturers Association 2011).

Good airflow should also be maintained over and under the surface, otherwise the timber strips may shrink and crack due to low timber moisture content or cup due to high moisture content. The extent to which HVAC is required will obviously vary depending on the prevailing climatic conditions in the geographic region of surface installation. Synthetic surfaces on the other hand require no temperature or humidity control, other than what is required for player comfort.

The high end-of-life impacts of the pour-in-place surface system are of particular note, as they are significantly higher than all other system types. This is primarily due to the human toxicity potential of the surface’s polyurethane component materials being disposed to landfill.

Only by using comparative life cycle thinking tools such as LCA, do the life cycle implications of material/component selection decisions become fully apparent.

5.3 Sports surface life cycle assessment

Sports surfaces should ideally be manufactured using materials and techniques that minimise the waste and emissions produced over their entire life cycle and minimise the materials and energy consumed over the whole life cycle. There are many different environmental considerations that can be assessed during the selection process for a sustainable sports surface, including the use of resources, manufacturing, indoor air quality, energy consumption, use of rapidly renewable or recycled materials, the ability to recycle, and safe disposal. A positive contribution at one life cycle stage may however lead to a negative impact in another. Manufacturing and maintaining a sports surface, brings with it considerable environmental loads over its life, in the form of periodic resurfacing, sealing and disposal. The environmental and financial cost of installing and maintaining hardwood timber sports surfaces has resulted in the increased popularity of synthetic indoor playing surface alternatives. Synthetic surfaces are therefore continuing to gradually replace timber in many parts of the world as synthetic surfaces avoid many of timber’s drawbacks.

Indoor synthetic sports surfaces are a class distinct from timber sports floors used for similar purposes. These surfaces are generally assembled from a assortment of synthetic materials, some of which include styrene-butadiene rubber (SBR) or ethylene propylene diene monomer (EPDM) rubber, polychloroprene (neoprene), polyurethane, polypropylene, polystyrene, polyvinyl chloride,
nylon, or any number of petroleum derivative compounds that are either poured-in-place or prefabricated into some standard form, including sheets, rolls and tiles. These floors are considered ‘point elastic’, and deform under a single point when compressed. Therefore they rely on some
measure of resilience from the synthetic material to give the flooring system its shock absorbing characteristics.

Whether timber or synthetic, shock absorbing sports flooring has become the norm in gymnasiums, since these surfaces reduce the amount of energy which will be returned to an athlete, and therefore reduce the risk of injury. Older sports facilities use harder surfaces, such as vinyl tiles or timber parquet installed directly onto the concrete sub floor, which can be damaging to athletes’ knees and ankles. Apart from them being less expensive to install, these hard surfaces were thought to be better suited for multisport applications.

The purpose of the current study was to use life cycle assessment techniques in order to evaluate the comparable environmental loads and potential impacts associated with the provision of alternative indoor sports surface construction types. The life cycle assessment was used to analyse the environmental loads and potential impacts over each surface system’s life cycle from cradle to grave, from raw material extraction, through production, use and eventual end of life. The data developed from the current study will be used in conjunction with surface safety data to better inform stakeholders on the sustainability benefits (social, environmental and economic benefits) of each type of flooring examined. The program of work was undertaken in four distinct phases, in order to achieve the requirements of the international and the joint Australian/New Zealand standards for environmental management and life cycle assessment, including:

- AS/NZS ISO 14041:1999 Goal and Scope Definition and Inventory Analysis
- AS/NZS ISO 14042:2001 Lifecycle Impact Assessment
- AS/NZS ISO 14043:2001 Lifecycle Implementation

The four phases of study were:

- goal and scope definition
- inventory analysis
- life cycle impact assessment
- life cycle interpretation.
Figure 5.6 provides an explanation of the four phases of the lifecycle assessment procedure.

![Life cycle assessment procedure: ISO 14044 (Walker 2012)](image)

### 5.3.1 Goals of the study

In this part of the study, the aim was to consider community needs in response to various surface options available for use in the design of a sustainable sports facility; analyse the life cycle issues associated with each surface option; conduct a life cycle assessment on each surface type under review; and produce recommendations based on the outcomes of the life cycle assessment.

The specification and selection of a sports surface involves the simultaneous evaluation of a multitude of factors as described in section 3.4.

The goal of the current study involving life cycle assessment of various sports surfaces was to unambiguously state the intended application, the reasons for undertaking the study and the anticipated recipient of the information flowing from the study. This aspect intended to inform all subsequent phases of the life cycle assessment, as the goal of the study was to determine the most sustainable sports flooring option for a ‘green’ sports facility:

- to identify the major environmental loads and impacts associated with hardwood timber sports flooring, pour-in-place synthetic sports flooring, prefabricated sheet synthetic sports flooring and prefabricated tile synthetic sports flooring over each product’s life cycle
- to compare each flooring system in order to evaluate the relative significant environmental loads and impacts of each system and form a detailed understanding of the environmental benefits and drawbacks of each type of surface system within the context of its lifecycle.
5.3.2 Scope of the study

The scope of the study included the following elements:

- the functions of the flooring system, the functional unit and the reference flow
- product system and system boundaries
- description of data categories
- criteria for initial inclusion of data inputs and outputs
- data quality requirements.

Life cycle assessment is recognised as an iterative technique and therefore various facets of the scope required adjustment as data were accrued in order to meet the original goal established for the study. Any modifications were addressed in the subsequent phases of the program of work.

The life cycle assessment considered the impacts of:

- hardwood timber sports flooring, with and without the use of heating, ventilation and air conditioning (HVAC) equipment
- pour-in-place synthetic sports flooring
- prefabricated sheet synthetic sports flooring
- prefabricated tile synthetic sports flooring.

The surfaces listed were assessed as alternative playing surfaces over a comparable 50 year period.

5.3.3 Sports surface function

The primary functions of a sports surface can be defined as: to enclose a space, to support equipment, to facilitate human sport activities, to enhance sporting performance and to minimise the risk of sport participant injury. All additional functions were ignored for the purposes of the LCA.

5.3.4 Sports surface functional unit

The functional lifetime used for the LCA was one square meter of playing surface per hour of service provided. The functional lifetimes of each surface type under consideration were:

- hardwood timber sports surface (25 year average expected life).
- pour-in-place synthetic sports surface (15 year average expected life).
- prefabricated sheet synthetic sports surface (15 year average expected life).
- prefabricated tile synthetic sports surface (10 year average expected life).
Sports surface failures are generally caused by poor adhesion to the subfloor, shrinkage/cracking, expansion/buckling or aesthetic deterioration, when the playing surface of a sports hall deteriorates visually. High impact wear can result in ‘crazing’ and thinning of the top surface of a sports floor, although this form of deterioration does not necessarily affect the safety, performance or any other primary function of the surface. Resurfacing the floor can extend the life of the surface until the visual quality of the playing surface again worsens.

Industry standard warranty data collected for each flooring system indicates the average manufacturer guaranteed performance life for each flooring system. In the sports flooring industry, hardwood timber sports surfaces typically claim a 25 year average warranty period; pour-in-place synthetic sports flooring a 15 year average warranty period; prefabricated sheet synthetic sports flooring a 15 year average warranty period; and prefabricated tile synthetic sports flooring a 10 year average warranty period. Based on the surface function and functional lifetime described for each surface type, the functional unit of the LCA was defined as the surface area for the warrantee period of use required to provide a surface to the sports facility over the anticipated life of the facility, i.e. one square metre of sports surface delivered over a 50 year period.

5.3.5 System boundaries
The study covered all life cycle stages for each flooring system under investigation and excluded only those processes which are replicated in all four surface systems. Figure 5.7 illustrates the life cycle stages considered for each product system and the inputs and outputs as elementary flows.

![Figure 5.7](image-url) Inputs and outputs of the system as elementary flows
A number of processes were identified for exclusion from the system boundaries for the four flooring systems under investigation in order to simplify the study and emphasise the comparative aspects of each system.

<table>
<thead>
<tr>
<th>Excluded processes</th>
<th>Rational for exclusion from the study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily/weekly surface cleaning</td>
<td>The environmental impact of daily/weekly surface cleaning is replicated for all surface types under consideration, regardless of the constructional style.</td>
</tr>
<tr>
<td>Sub-surface</td>
<td>Subsurface base manufacture &amp; installation is common to all surface types under consideration.</td>
</tr>
<tr>
<td>Game line-making</td>
<td>Each surface will require similar applications of polyurethane game lines, in relation to the range of sports which will be played on each surface, and will require repainting after similar periods of use.</td>
</tr>
<tr>
<td>Lighting</td>
<td>Each internal space will require similar levels of illumination.</td>
</tr>
<tr>
<td>Background temperature control</td>
<td>Each internal space will require similar levels of background heating for player comfort.</td>
</tr>
</tbody>
</table>

**Figure 5.8** LCA exclusions from the study

### 5.3.6 Data quality criteria

The life cycle assessment was required to demonstrate the use of qualified data supplied by accredited sources. Data provided in the *Simapro* EcoInvent databases was accepted as qualified, where it applied to specific conditions. Information and technologies that were not available that could have influenced the reproducibility of the findings, such as the specific energy requirements for HVAC control, were investigated and noted.

### 5.3.7 Technology

Each of the surfaces that was analysed uses well established manufacturing technologies and limited automation. Comparisons were therefore not weighted for technology, as weighting could conceal opportunities for improvement.

### 5.3.8 Initial system boundaries

ISO 14040 requires that an analysis of the energy and material flows be undertaken within the scope of the study. The analysis was undertaken during the inventory analysis phase and added to the scope prior to the impact assessment. Capital goods, i.e. equipment and infrastructure used in each stage of the life cycle, were not included in the LCA. In the case of the injection moulding process necessary for the manufacture of the prefabricated tile synthetic sports surface, the tool required to produce the injection moulded tile component was included in the study, as it is closely linked to the production of this part. However, injection moulding machines were not included, as they would also be used to produce other components and products unrelated to the analysis.
5.3.9 Limitations
None of the flooring systems analysed are manufactured in Australia. Product is transported by sea and road, and travels long distances to regional areas of Australia. Limitations therefore included the impacts of road transport to allow for the packaged weight of each system. Consideration was given to the actual location of the surface manufacturers to ensure that the limitations did not skew the results obtained. Two alternative waste scenarios were considered where applicable: recycling and landfilling.

5.3.10 Assumptions
It was assumed for the study that each surface to be analysed was used at least once each day and would require cleaning weekly. Any specific maintenance required was included in the use phase of the life cycle assessment. This arrangement was particularly important whenever evidence supported the assumption that the surface substrates did not remain waterproof throughout the functional 50 year lifetime of the facility. All fittings and fixtures were assumed to be outside the scope of the LCA but the method of attaching the surface to the subfloor varied, and was considered in the LCA if they were found to have a significant effect on the results obtained during the initial analysis.

5.3.11 Goal and scope review
The initial goal and scope report formed an interim guide for the LCA to progress to the inventory analysis phase. While the goal directed the life cycle assessment to its completion, the scope varied as the data was collected and a better understanding of each of the systems under assessment was obtained. The goal was used to review the continued relevance of the scope at each stage of the life cycle assessment. Any elaborations, additions or exclusions to the scope were documented and reported.

5.3.12 Inventory analysis
Life cycle inventory analysis is concerned with the data gathering and calculation procedures for the life cycle assessment. Data were estimated and/or retrieved from the Ecoinvent datasets available in Sustainable Minds, using the following assumptions:

- Material waste during production would be recycled.
- All transportation in Europe would be by rail.
- All transportation in North America would be by rail.
- All transportation in China would be by rail.
- All transport within Australia would be by road.
- All intercontinental transport would be by container ship.

5.3.13 Limitations of life cycle inventory

System functions are limited to the practical aspects of installing a sports surface. This disregards aesthetics and perceived value based on human interaction in the process. Aesthetic factors are important motivators for the purchase and early disposal of a flooring surface. The aesthetic aspects of wear were therefore acknowledged as a contributor to the functional life of each sports flooring system under analysis. Excessive use for non-sporting applications may shorten the life of a surface, and relate to the surface’s durability.

System boundaries are influenced by available data. The study was intended to be a full scope limited-depth life cycle assessment and, as such, all stages of the life cycle of the product have been considered and minimal processes excluded. The processes that were excluded were identified as contributing very little to the overall result of the flooring system comparisons or were replicated across all of the surfaces considered.

5.3.14 Impact assessment

Each hardwood timber, pour-in-place, prefabricated sheet and prefabricated tile sports surface system scrutinised using LCA was considered from an environmental perspective, using impact categories and category indicators linked to the life cycle inventory. This phase of the study provided information for the following lifecycle interpretation phase.

The life cycle analysis software, Sustainable Minds, was used for the life cycle inventory analysis phase. Sustainable Minds is a lifecycle assessment application which permits the modelling of flooring products or sports facility systems from a lifecycle perspective and is fully integrated with the Ecoinvent database. Ecoinvent datasets include comprehensive international lifecycle inventory databases, covering topics such as agriculture, energy supply, transport, biomaterials, bulk chemicals, construction materials, packaging materials, metals, metals processing, electronics and waste treatment.
5.3.15 End-of-life scenarios

The end-of-life scenarios included in the models developed were based on documented current disposal practices in South Australia. Only one end-of-life scenario was modelled for the hardwood timber, pour-in-place synthetic and prefabricated sheet synthetic sports flooring systems and this disposal method, was disposal to landfill. Although hardwood flooring can potentially be recycled for use in other timber products, there is no evidence that this outcome is routinely practised in Australia at present. Once the timber strip has been sanded down to the tongue and groove interlock feature, it cannot generally be reused as a timber flooring product. In addition, the polyurethane top coat applied to the surface of a timber sports surface effectively renders the timber unusable for recycling into other timber-based products due to contamination.

Two end-of-life scenarios were modelled for the prefabricated tile synthetic sports flooring system, and these were disposal to landfill and processing into repelletised polypropylene, which can then be used for the production of new prefabricated tile synthetic sports flooring products. It should be possible to recycle a high proportion of the flooring material, given the large volume of co-polymer polypropylene used in each sports surface, known installation locations and the recognised grades of material used in the surface’s manufacture. A conservative assumption of 75% reuse has therefore been incorporated in the modelled end-of-life scenario, with the remaining material being disposed of in landfill.

5.4 Floor surface environmental performance

The environmental performance characteristics over the entire lifecycle of each surface type were evaluated. A major differentiating factor in respect to the surfaces studied was the need for hardwood timber sports surfaces to be installed within a humidity and temperature controlled environment, due to their hydroscopic nature. This requirement is unique to this type of surface.

5.4.1 Hardwood timber sports surface heating ventilation and air-conditioning power requirements °C

To reduce the risk of damage to a hardwood timber sports surface, it must be maintained at a temperature of between 13°C and 27°C and humidity levels of 40% to 60% (Maple Flooring Manufacturers Association 2011). These temperature and humidity limits need to be maintained otherwise the timber strips may shrink and crack (low moisture conditions) or expand and cup.
(high moisture conditions). Synthetic surfaces, on the other hand require little or no temperature or humidity control, other than that which is required for adequate player comfort.

The estimated heat load on a typical 800m$^2$ gymnasium building space, maintained at a target interior temperature of 25°C in summer (with a 35°C exterior ambient temperature) and a target interior temperature of 18°C in winter (with a 7°C exterior ambient temperature), and approximately 50% relative humidity is: summer = 130kW and winter = 110kW.

The building material assumptions in the current study were based on a facility featuring solid concrete walls, a flat iron roof with R3.0 insulation and an external perimeter wall of 120m (external dimensions of 40m x 30m). No allowance was made for the solar load on the structure resulting from glass windows and additional air conditioning needs for user comfort, as it was assumed that the power load would be the same for both synthetic and timber sports surface situations.

To obtain results for estimated peak energy consumption, a minimum air conditioning equipment energy efficiency ratio/coefficient of performance (EER/COP) of 2.75 was assumed. Therefore, by dividing peak heat load by the assumed performance ratio:

- Summer peak energy consumption \( \frac{130kW}{2.75} = 47kW/hr \)
- Winter peak energy consumption \( \frac{110kW}{2.75} = 40kW/hr \)

Both the EER and COP ratios were determined by the amount of heating and cooling generated by an HVAC system, in comparison to 1kW of energy consumed by the system.

Peak load estimates depend on building construction variations and changes in ambient temperature, i.e. 40°C temperature peaks in summer and 3°C temperature lows in winter. In addition, power consumption is also related to equipment running times and the use of energy saving systems, such as fresh-air bypass and heat extraction ventilators, many of which are now standard in contemporary Australian sports facilities. The estimate for the overall power consumption during a 12 month period would therefore be as follows:

Summer consumption based on a three month period with approximately:
- two months at 100% of estimated summer load
- one month at 115% of estimated summer load (to accommodate for 40°C peaks)
47kW/hr x 100% x 12 hours x 60 days = 33,840kW/hrs
47kW/hr x 115% x 12 hours x 30 days = 19,458kW/hrs
Total = 53,298kW/hrs

Autumn consumption based on a three month period with approximately:

- one month at 85% of estimated summer load
- one month at 50% of estimated summer load
- one month at 50% of estimated winter load

47kW/hr x 85% x 12 hours x 30 days = 14,382kW/hrs
47kW/hr x 50% x 12 hours x 30 days = 8,460kW/hrs
40kW/hr x 50% x 12 hours x 30 days = 7,200kW/hrs
Total = 30,042kW/hrs

Winter consumption based on a three month period with approximately:

- two months at 100% of estimated winter load
- one month at 150% of estimated winter load (to accommodate for 3°C lows)

40kW/hr x 100% x 12 hours x 60 days = 28,800kW/hrs
40kW/hr x 150% x 12 hours x 30 days = 21,600kW/hrs
Total = 50,400kW/hrs

Spring consumption would be based on a three month period with approximately:

- one month at 85% of estimated summer load
- one month at 50% of estimated winter load
- one month at 50% of estimated summer load

47kW/hr x 85% x 12 hours x 30 days = 14,382kW/hrs
40kW/hr x 50% x 12 hours x 30 days = 7,200kW/hrs
47kW/hr x 50% x 12 hours x 30 days = 8,460kW/hrs
Total = 30,042kW/hrs

The above assumes a minimum of a 12 hour HVAC operation per day (50% duty cycle 24hr/day) and a 30 day month.

Therefore the total estimated annual HVAC power consumption for an 800m² sports facility is 163,782kW/hrs. This figure, however, will vary according to building construction, leakage and usage patterns. The HVAC energy required to stabilise 1m² of hardwood timber sports surface over the 50 year anticipated life of the sports facility would therefore be:

163,782kW/hr / 800m² = 204.73 kW/hr/m²
204.73 kW/hr/m² x 50 years = 10,236kW/hr
5.4.2 Hardwood timber sports surface

Table 5.1 lists the foreground data collected for unit processes included in the hardwood timber sports surface system boundary for one square meter of playing surface supplied twice. The data also includes estimates for HVAC power use. The data was entered into Sustainable Minds and a unit process network tree was generated. A cut-off threshold of 5% was applied to limit the network display in order to emphasise those processes contributing more heavily to environmental loads.
### Table 5.1  Manufacture, installation and transport data to site of installation for hardwood timber sports surface

#### Surface Manufacture and Installation:

<table>
<thead>
<tr>
<th>Surface sub-assembly or part</th>
<th>Material</th>
<th>Material manufacturing process</th>
<th>Qty (kg/m²) (kg/2m²)</th>
<th>Origin</th>
<th>Distance by road (km 1) (km 2)</th>
<th>Distance by sea (km 1) (km 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waterproof vapour barrier membrane</td>
<td>0.15mm polyethylene low density lap joined</td>
<td>Extrusion and then calendaring</td>
<td>0.150 (1) 0.300 (2)</td>
<td>Springfield Illinois</td>
<td>800 (1) 1600 (2)</td>
<td>-</td>
</tr>
<tr>
<td>Shock pad</td>
<td>57mmx76mmx16mm PVC Cushion Pad</td>
<td>Cast</td>
<td>0.250 (1) 0.500 (2)</td>
<td>Naperville Illinois</td>
<td>609 (1) 1218 (2)</td>
<td>-</td>
</tr>
<tr>
<td>Sleeper/batten</td>
<td>38mm x 64mm softwood (spruce, pine or hemlock) 305mm centers. (0.022m³/m² at 0.700 10³ kg/m³)</td>
<td>Rough cut</td>
<td>1.702 (1) 3.405 (2)</td>
<td>Mercer Wisconsin</td>
<td>30 (1) 60 (2)</td>
<td>-</td>
</tr>
<tr>
<td>Wood preservative</td>
<td>Alkaline copper quaternary</td>
<td>Dip treated</td>
<td>0.150 (1) 0.300 (2)</td>
<td>Dover Delaware</td>
<td>1852 (1) 3704 (2)</td>
<td>-</td>
</tr>
<tr>
<td>Staples</td>
<td>51mm 16 SWG stainless steel</td>
<td>Wire Drawn Steel</td>
<td>0.550 (1) 1.100 (2)</td>
<td>Ningbo China</td>
<td>1872 (1) 3.744 (2)</td>
<td>19635 (1) 39270 (2)</td>
</tr>
<tr>
<td>Flooring Strip/sports board</td>
<td>Northern Hard Maple 20mmx57mm (0.02m³/m² at 0.750 10³ kg/m³)</td>
<td>Cut</td>
<td>15.000 (1) 30.000 (2)</td>
<td>Mercer Wisconsin</td>
<td>110 (1) 220 (2)</td>
<td>-</td>
</tr>
<tr>
<td>Seal and Finish</td>
<td>2 pack polyurethane 0.5mm</td>
<td>Pour-in-place 0.5mm</td>
<td>0.500 (1) 1.000 (2)</td>
<td>Springfield Illinois</td>
<td>800 (1) 1600 (2)</td>
<td>-</td>
</tr>
<tr>
<td>Transportation Pallet</td>
<td>Timber (Pine) (25kg) One pallet holds 50m² of flooring</td>
<td>Milled, cut and nailed</td>
<td>0.500 (1) 1.000 (2)</td>
<td>Mercer Wisconsin</td>
<td>20 (1) 40 (2)</td>
<td>-</td>
</tr>
<tr>
<td>Stretch-wrap</td>
<td>Polyethylene, Low Density</td>
<td>Calendaring</td>
<td>0.010(1) 0.020 (2)</td>
<td>Lebanon, PA, USA</td>
<td>1709 (1) 3418 (2)</td>
<td>-</td>
</tr>
</tbody>
</table>

#### Surface Use (HVAC):

<table>
<thead>
<tr>
<th>Type of consumption</th>
<th>Name</th>
<th>Consumption process</th>
<th>Qty (kW-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power use</td>
<td>Electricity consumption</td>
<td>Electricity, 120V, US</td>
<td>NA</td>
</tr>
</tbody>
</table>
## Surface End-of-Life:

<table>
<thead>
<tr>
<th>Surface sub-assembly or part</th>
<th>Material</th>
<th>End of life (EOL) method</th>
<th>Qty (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waterproof Vapor barrier membrane</td>
<td>0.15mm polyethylene low density lap joined</td>
<td>Landfill</td>
<td>0.150 (1) 0.300 (2)</td>
</tr>
<tr>
<td>Shock pad</td>
<td>57mmx76mmx16mm PVC Cushion Pad</td>
<td>Landfill</td>
<td>0.250 (1) 0.500 (2)</td>
</tr>
<tr>
<td>Sleeper/batten</td>
<td>38mm x 64mm softwood (spruce, pine or hemlock) 305mm centers</td>
<td>Recover and reuse</td>
<td>1.702 (1) 3.405 (2)</td>
</tr>
<tr>
<td>Wood preservative</td>
<td>Alkaline copper quaternary</td>
<td>Landfill</td>
<td>0.150 (1) 0.300 (2)</td>
</tr>
<tr>
<td>Staples</td>
<td>51mm 16 SWG stainless steel</td>
<td>Landfill</td>
<td>0.550 (1) 1.100 (2)</td>
</tr>
<tr>
<td>Flooring Strip/sports board</td>
<td>Northern Hard Maple 20mmx57mm</td>
<td>Recover and reuse</td>
<td>15.000 (1) 30.000 (2)</td>
</tr>
<tr>
<td>Seal and Finish</td>
<td>2 pack polyurethane 0.5mm</td>
<td>Landfill</td>
<td>0.500 (1) 1.000 (2)</td>
</tr>
<tr>
<td>Transportation Pallet</td>
<td>Timber (Pine) One pallet holds 50m2 of flooring</td>
<td>Recover and reuse</td>
<td>0.500 (1) 1.000 (2)</td>
</tr>
<tr>
<td>Stretch-wrap</td>
<td>Polyethylene, Low Density</td>
<td>Calendaring</td>
<td>0.010 (1) 0.020 (2)</td>
</tr>
</tbody>
</table>

## Surface transport of surface components from point of manufacture to point of installation:

<table>
<thead>
<tr>
<th>Surface sub-assembly or part</th>
<th>Material Qty (kg/m²)</th>
<th>Transportation mode</th>
<th>Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardwood Timber Sports Surface</td>
<td>18.813 (1) 37.625 (2)</td>
<td>Rail- Mercer Wisconsin to New York</td>
<td>1872 (1) 3,744 (2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oceanic freighter- New York to Melbourne</td>
<td>18398 (1) 36796 (2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Truck 20-28t- Melbourne to Adelaide</td>
<td>728 (1) 1456 (2)</td>
</tr>
</tbody>
</table>

Point of Manufacture: , Mercer, Wisconsin, USA

Point of Installation: Adelaide, South Australia, Australia
Figure 5.10  Hardwood timber sports surface process tree diagram
5.4.3 Pour-in-place synthetic sports surface system life cycle assessment
For the purposes of the study LCA, data were obtained from Herculan Sports Flooring for the manufacture of their most common sandwich pour-in-place synthetic sports surface compounds, supplied from Meerkerk, The Netherlands for final installation in Adelaide, South Australia, Australia.

Table 5.2 lists the foreground data collected for unit processes included in the pour-in-place synthetic sports surface system boundary for one square meter of playing surface supplied 3.3 times. The data were entered into Sustainable Minds and a unit process network tree was generated. A cut-off threshold of 5% was applied to limit the network display in order to emphasise those processes contributing more heavily to environmental loads.
Table 5.2  Manufacture, installation and transport data to site of installation for a pour-in-place synthetic sports surface

<table>
<thead>
<tr>
<th>Surface sub-assembly or part</th>
<th>Material</th>
<th>Material manufacturing process</th>
<th>Qty (kg/m²) (kg/3.3m²)</th>
<th>Origin</th>
<th>Distance by road (km)</th>
<th>Distance by sea (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pour-in-place synthetic sports surface</td>
<td>8.18 kg/m² 12mm thick</td>
<td>Multilayered pour-in-place</td>
<td>8.180 (1) 26.994 (3.3)</td>
<td>Meerkerk, The Netherlands</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Polyurethane top coat</td>
<td>Polyurethane 1.0mm thick</td>
<td>Two pack polyurethane pour-in-place</td>
<td>1.050 (1) 3.465 (3.3)</td>
<td>Meerkerk, The Netherlands</td>
<td>0 (1)</td>
<td>0 (3.3)</td>
</tr>
<tr>
<td>Polyurethane self-levelling layers</td>
<td>Polyurethane 2mm thick</td>
<td>Two pack polyurethane pour-in-place</td>
<td>2.100 (1) 6.930 (3.3)</td>
<td>Meerkerk, The Netherlands</td>
<td>0 (1)</td>
<td>0 (3.3)</td>
</tr>
<tr>
<td>Pore-Filler</td>
<td>Polyurethane 0.5mm thick</td>
<td>Two pack polyurethane pour-in-place</td>
<td>0.525 (1) 1.732 (3.3)</td>
<td>Meerkerk, The Netherlands</td>
<td>0 (1)</td>
<td>0 (3.3)</td>
</tr>
<tr>
<td>Rubber cushion underlay</td>
<td>Granulated car tyre- styrene-butadiene 8mm</td>
<td>Calendaring</td>
<td>4.400 (1) 14.520 (3.3)</td>
<td>Geretsried, Germany</td>
<td>853 (1)</td>
<td>2815 (3.3)</td>
</tr>
<tr>
<td>Adhesive (backing to concrete)</td>
<td>Two pack elastomeric polyurethane adhesive 3M CR-20 0.5 thick</td>
<td>Two pack polyurethane pour-in-place</td>
<td>0.105 (1) 0.347 (3.3)</td>
<td>St. Paul, Minneapolis USA</td>
<td>1910 USA (1)</td>
<td>6303 USA (3.3)</td>
</tr>
<tr>
<td>Transportation Pallet Underlay</td>
<td>Timber (Pine) (25kg)</td>
<td>Milled, cut and nailed</td>
<td>0.813 (1) 2.707 (3.3)</td>
<td>Meerkerk, The Netherlands</td>
<td>20 (1)</td>
<td>66 (3.3)</td>
</tr>
<tr>
<td>Stretch-wrap</td>
<td>Polyethylene, low density</td>
<td>Calendaring</td>
<td>0.010 (1) 0.033 (3.3)</td>
<td>Geertruidenberg, The Netherlands</td>
<td>29 (1)</td>
<td>96 (3.3)</td>
</tr>
</tbody>
</table>

### Surface use

<table>
<thead>
<tr>
<th>Type of consumption</th>
<th>Name</th>
<th>Consumption process</th>
<th>Qty (kW-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power use</td>
<td>Electricity consumption</td>
<td>Electricity, 120V, US</td>
<td>NA</td>
</tr>
</tbody>
</table>
## Surface end-of-life

<table>
<thead>
<tr>
<th>Surface sub-assembly or part</th>
<th>Material</th>
<th>End of life (eol) method</th>
<th>Qty (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PU top coat, self-levelling layers, pore-filler and adhesive</td>
<td>Polyurethane elements</td>
<td>Landfill</td>
<td>3.780 (1) 12.474 (3.3)</td>
</tr>
<tr>
<td>Rubber cushion underlay</td>
<td>Granulated car tyre- styrene-butadiene</td>
<td>Landfill</td>
<td>4.400 (1) 14.520 (3.3)</td>
</tr>
<tr>
<td>Transportation pallet underlay</td>
<td>Timber (pine) (25kg)</td>
<td>Recovered and reused</td>
<td>0.813 (1) 2.707 (3.3)</td>
</tr>
<tr>
<td>Stretch-wrap</td>
<td>Polyethylene, low density</td>
<td>Landfill</td>
<td>0.010 (1) 0.033 (3.3)</td>
</tr>
</tbody>
</table>

## Surface transport of surface components from point of manufacture to point of installation

<table>
<thead>
<tr>
<th>Surface sub-assembly or part</th>
<th>Material qty (kg/m2); (kg/3.3m2)</th>
<th>Transportation mode</th>
<th>Distance (km1); (kn3.3)</th>
<th>Point of manufacture, Meerkerk, the Netherlands</th>
<th>Via Herculan Australia, Brisbane, Queensland, Australia</th>
<th>Point of installation: Adelaide, South Australia, Australia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pour-in-place synthetic sports surface</td>
<td>9.003 (1) 29.710 (3.3)</td>
<td>Truck 20-28t Meerkerk to Rotterdam</td>
<td>48 (1) 158 (3.3)</td>
<td>Point of manufacture, Meerkerk, the Netherlands</td>
<td>Via Herculan Australia, Brisbane, Queensland, Australia</td>
<td>Point of installation: Adelaide, South Australia, Australia</td>
</tr>
</tbody>
</table>

| | Oceanic freighter- Rotterdam to Brisbane | 22750 (1) 75075 (3.3) | | | | |
| | Truck 20-28t- Brisbane to Adelaide | 2059 (1) 6795 (3.3) | | | | |
Figure 5.12 Pour-in-place synthetic sports flooring process tree diagram
5.4.4 Prefabricated sheet synthetic sports surface system life cycle assessment

For the purposes of the LCA undertaken in this study, a polyvinyl chloride (PVC) prefabricated sheet synthetic sports surface was selected, given the market dominance for this type of sheet surface. Data were obtained from the Gerflor Flooring Group for the manufacture of the surface in Villeurbanne Cedex, France and installation in Adelaide, South Australia, Australia.

![Figure 5.13 Prefabricated sheet synthetic sports surface installation](image)

Table 5.3 lists the foreground data collected for unit processes included in the prefabricated sheet synthetic sports surface system boundary for one square meter of playing surface supplied a total of 3.3 times. The data were entered into Sustainable Minds and a unit process network tree was generated. A cut-off threshold of 5% was applied to limit the network display in order to emphasise those processes contributing more heavily to environmental loads.
### Table 5.3  Manufacture, installation and transport data to site of installation for a prefabricated sheet synthetic sports surface

<table>
<thead>
<tr>
<th>Surface sub-assembly or part</th>
<th>Material</th>
<th>Material manufacturing process</th>
<th>Qty (kg/m2) (kg/3.3m2)</th>
<th>Origin</th>
<th>Distance by road (km)</th>
<th>Distance by sea (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prefabricated sheet synthetic sports surface (Gerflor Taraflex Multi-use 6.2)</td>
<td>PVC 4.2 kg/m²  6.2mm thick  1.5m x 20.5m Roll</td>
<td>Calendaring</td>
<td>4.2 (1)  13.860 (3.3)</td>
<td>Villeurbanne Cedex France</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Polyurethane top coat</td>
<td>Polyurethane 1mm thick (1050 kg/m²)</td>
<td>Two pack polyurethane pour-in-place after sheet material laying</td>
<td>1.050 (1)  3.465 (3.3)</td>
<td>Villeurbanne Cedex France</td>
<td>25 (1)  82.5 (3.3)</td>
<td></td>
</tr>
<tr>
<td>PVC wear layers</td>
<td>PVC sheet 2.1mm thick</td>
<td>Calendaring</td>
<td>2.484 (1)  8.197 (3.3)</td>
<td>Villeurbanne Cedex France</td>
<td>0 (1)  0 (3.3)</td>
<td></td>
</tr>
<tr>
<td>Pigment</td>
<td>PVC Organic Colorant (3%)</td>
<td>Extrusion</td>
<td>0.086 (1)  0.283 (3.3)</td>
<td>Tossiat France</td>
<td>69 (1)  228 (3.3)</td>
<td></td>
</tr>
<tr>
<td>Flame and smoke suppressant with UV inhibitor</td>
<td>PVC FR w/ Smoke Suppressant (10%).</td>
<td>Extrusion</td>
<td>0.286 (1)  0.942 (3.3)</td>
<td>Tossiat France</td>
<td>69 (1)  228 (3.3)</td>
<td></td>
</tr>
<tr>
<td>Foam cushion backing</td>
<td>Polyurethane foam</td>
<td>Calendaring</td>
<td>0.249 (1)  0.822 (3.3)</td>
<td>Bad Berleburg Germany</td>
<td>823 (1)  2716 (3.3)</td>
<td></td>
</tr>
<tr>
<td>Glass fibre mesh</td>
<td>Glass fibre mesh 0.1 thick</td>
<td>Woven</td>
<td>0.045 (1)  0.148 (3.3)</td>
<td>Beijing China</td>
<td>138 Ch (1)  455 Ch (33)  663 Eur (1)  2188 Eur (3.3)  20739 (1)  68439 (3.3)</td>
<td></td>
</tr>
<tr>
<td>Adhesive (backing to concrete)</td>
<td>Two pack elastomeric Polyurethane adhesive 3M CR-20 0.1 thick</td>
<td>Two pack polyurethane pour-in-place</td>
<td>0.105 (1)  0.347 (3.3)</td>
<td>St. Paul, Minneapolis USA</td>
<td>1910 USA (1)  6303 USA (3.3)  663 Eur (1)  2188 Eur (3.3)  5778 (1)  19067 (3.3)</td>
<td></td>
</tr>
<tr>
<td>Transportation pallet underlay</td>
<td>Timber (Pine) (25kg)  One pallet holds 30.75m² of flooring</td>
<td>Milled, cut and nailed</td>
<td>0.813 (1)  2.707 (3.3)</td>
<td>Villeurbanne Cedex France</td>
<td>20 (1)  66 (3.3)</td>
<td></td>
</tr>
<tr>
<td>Stretch-wrap</td>
<td>Polyethylene, Low Density</td>
<td>Calendaring</td>
<td>0.010 (1)  0.033 (3.3)</td>
<td>Cedex France</td>
<td>343 (1)  1132 (3.3)</td>
<td></td>
</tr>
</tbody>
</table>

### Surface use

<table>
<thead>
<tr>
<th>Type of consumption</th>
<th>Name</th>
<th>Consumption process</th>
<th>Qty (kW-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power use</td>
<td>Electricity consumption</td>
<td>Electricity, 120V, US</td>
<td>NA</td>
</tr>
</tbody>
</table>
## Surface end-of-life

<table>
<thead>
<tr>
<th>Surface sub-assembly or part</th>
<th>Material</th>
<th>End of life (EOL) method</th>
<th>Qty (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PU Top coat, backing and adhesive</td>
<td>Polyurethane</td>
<td>Landfill</td>
<td>1.404 (1) 4.633 (3.3)</td>
</tr>
<tr>
<td>PVC wear layers, pigment, flame, smoke and UV inhibitors</td>
<td>PVC</td>
<td>Landfill</td>
<td>2.856 (1) 9.425 (3.3)</td>
</tr>
<tr>
<td>Glass fibre mesh</td>
<td>Glass</td>
<td>Landfill</td>
<td>0.045 (1) 0.148 (3.3)</td>
</tr>
<tr>
<td>Transportation Pallet Underlay</td>
<td>Timber (Pine) (25kg)</td>
<td>Recovered and reused</td>
<td>0.813 (1) 2.707 (3.3)</td>
</tr>
<tr>
<td>Stretch-wrap</td>
<td>Polyethylene, Low Density</td>
<td>Landfill</td>
<td>0.010 (1) 0.033 (3.3)</td>
</tr>
</tbody>
</table>

## Surface transport of surface components from point of manufacture to point of installation

<table>
<thead>
<tr>
<th>Surface sub-assembly or part</th>
<th>Material qty (kg/m²) (kg/3.3m²)</th>
<th>Transportation mode</th>
<th>Distance (km1) (kn3.3)</th>
<th>Point of manufacture, Point of Installation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Rail- Villeurbanne to Le Havre</td>
<td>663 (1) 2188 (3.3)</td>
<td>Point of Manufacture , Villeurbanne Cedex France</td>
</tr>
<tr>
<td>Prefabricated Sheet Synthetic Sports Surface</td>
<td>5.128 (1) 16.922 (3.3)</td>
<td>Oceanic freighter- Le Havre to Melbourne</td>
<td>21481 (1) 70887 (3.3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Truck 20-28t- Melbourne to Adelaide</td>
<td>728 (1) 2402 (3.3)</td>
<td>Point of Installation: Adelaide, South Australia, Australia</td>
</tr>
</tbody>
</table>
Figure 5.14 Prefabricated sheet synthetic sports flooring process tree diagram
5.4.5 Prefabricated tile synthetic sports surface system life cycle assessment

For the purposes of this LCA, data were obtained from Sport Court for the manufacture of the polypropylene tile sports surface, supplied from Salt Lake City, Utah, USA and installation in Adelaide, South Australia, Australia.

Table 5.4 lists the foreground data collected for unit processes included in the prefabricated tile synthetic sports surface system boundary for one square meter of playing surface supplied five times. The data were entered into Sustainable Minds and a unit process network tree was generated. A cut-off threshold of 5% was applied to limit the network display in order to emphasise those processes contributing more heavily to environmental loads.
## Table 5.4 Manufacture, installation and transport data to site of installation for a prefabricated tile synthetic sports surface

<table>
<thead>
<tr>
<th>Surface sub-assembly or part</th>
<th>Material</th>
<th>Material manufacturing process</th>
<th>Qty (kg/m²) (kg/5m²)</th>
<th>Origin</th>
<th>Distance by road</th>
<th>Distance by sea</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(km 1)</td>
<td>(km 1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(km 5)</td>
<td>(km 5)</td>
</tr>
<tr>
<td>254mm X 254mm injection moulded polypropylene tile (Sportcourt Response)</td>
<td>Polypropylene copolymer</td>
<td>Injection moulding</td>
<td>3.01 (1)</td>
<td>Salt Lake City, Utah, USA</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Polypropylene copolymer- Huntsman PP AP 5325-HS (87%)</td>
<td>Extrusion</td>
<td>2.62 (1)</td>
<td>Dayton, Texas, USA</td>
<td>2401 (1)</td>
<td>12005 (5)</td>
</tr>
<tr>
<td></td>
<td>Polypropylene colour pigment</td>
<td>Extrusion</td>
<td>0.09 (1)</td>
<td>Muttenz, Switzerland</td>
<td>718 Eur (1)</td>
<td>3590 (5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3493 USA (1)</td>
<td>17465 USA (5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6126 (1)</td>
<td>30630 (5)</td>
</tr>
<tr>
<td></td>
<td>Polypropylene flame and smoke suppressant with UV inhibitor</td>
<td>Extrusion</td>
<td>0.30 (1)</td>
<td>Muttenz, Switzerland</td>
<td>718 Eur (1)</td>
<td>3590 (5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3493 USA (1)</td>
<td>17465 USA (5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6126 (1)</td>
<td>30630 (5)</td>
</tr>
<tr>
<td>Tile injection moulding tool</td>
<td>P20 tool steel (0.8X0.8X0.6=0.384) (SG of steel is 7.8) 3.000kg</td>
<td>Smelting/machining</td>
<td>0.032 (1)</td>
<td>Ningbo, China</td>
<td>3493 (1)</td>
<td>17465 (5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19635 (1)</td>
<td>98175 (5)</td>
</tr>
<tr>
<td>3mm Rubber underlay</td>
<td>Granulated car tyre- styrene-butadiene</td>
<td>Calendaring</td>
<td>1.65 (1)</td>
<td>Lebanon, PA, USA</td>
<td>3330 (1)</td>
<td>16650 (5)</td>
</tr>
<tr>
<td>Transportation pallet tile surface</td>
<td>Timber (Pine) (25kg)</td>
<td>Milled, cut and nailed</td>
<td>0.250 (1)</td>
<td>Salt Lake City, Utah, USA</td>
<td>20 (1)</td>
<td>100 (5)</td>
</tr>
<tr>
<td>Stretch-wrap</td>
<td>Polyethylene, low density</td>
<td>Calendaring</td>
<td>0.010 (1)</td>
<td>Bristol, PA, USA</td>
<td>3467 (1)</td>
<td>17335 (5)</td>
</tr>
<tr>
<td>Transportation pallet underlay</td>
<td>Timber (Pine) (25kg)</td>
<td>Milled, cut and nailed</td>
<td>0.250 (1)</td>
<td>Lebanon, PA, USA</td>
<td>3330 (1)</td>
<td>16650 (5)</td>
</tr>
<tr>
<td>Stretch-wrap</td>
<td>Polyethylene, low density</td>
<td>Calendaring</td>
<td>0.010 (1)</td>
<td>Lebanon, PA, USA</td>
<td>3330 (1)</td>
<td>16650 (5)</td>
</tr>
<tr>
<td>Type of consumption</td>
<td>Name</td>
<td>Consumption process</td>
<td>Qty (kW-hr)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------</td>
<td>-----------------------------</td>
<td>-----------------------------</td>
<td>-------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power use</td>
<td>Electricity consumption</td>
<td>Electricity, 120V, US</td>
<td>NA</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface end-of-life</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface sub-assembly or part</td>
<td>Material</td>
<td>End of life (EOL) method</td>
<td>Qty (kg)</td>
</tr>
<tr>
<td>Polypropylene tile</td>
<td>Polypropylene</td>
<td>90% Recycle 10% Landfill</td>
<td>13.55 0.51</td>
</tr>
<tr>
<td>3mm Rubber underlay</td>
<td>Granulated car tyre-styrene-butadiene</td>
<td>Reuse first installation for all 5 surfaces. After final use, underlay will be sent to landfill.</td>
<td>1.65 (1 only)</td>
</tr>
<tr>
<td>Pallet</td>
<td>Timber (pine)</td>
<td>Recovered and reused</td>
<td>0.250 (1) 0.250 (1)</td>
</tr>
<tr>
<td>Stretch-wrap</td>
<td>Polyethylene, low density</td>
<td>Polyethylene landfill (5 tile trips and 1 underlay trip)</td>
<td>0.010 (1) 0.060 (6)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface transport of surface components from point of manufacture to point of installation</th>
<th>Surface sub-assembly or part</th>
<th>Material qty (kg/m²) (ky/5m²)</th>
<th>Transportation mode</th>
<th>Distance (km¹) (km5)</th>
<th>Point of manufacture: Salt Lake City, Utah, USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface sub-assembly or part</td>
<td>Material qty (kg/m²) (ky/5m²)</td>
<td>Transportation mode</td>
<td>Distance (km¹) (km5)</td>
<td>Point of installation: Adelaide, South Australia, Australia</td>
<td></td>
</tr>
<tr>
<td>Prefabricated tile synthetic sports surface tiles and underlay (underlay, pallet and stretch wrap delivered once)</td>
<td>5.12 (1) 19.76 (5)</td>
<td>Rail: Salt Lake City, Utah to New York</td>
<td>3493 (1) 17480 (5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oceanic freighter: New York to Melbourne</td>
<td>18398 (1) 91990 (5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Truck 20-28t: Melbourne to Adelaide</td>
<td>728 (1) 3640 (5)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 5.16  Prefabricated tile synthetic sports flooring process network diagram
5.5 Comparative analysis

The five surface systems under analysis were compared against various impact categories to assess the relative impacts of each system, as shown in Figure 5.17.

![Bar chart showing comparative analysis of sports surface systems](image)

**Figure 5.17** Sports surface system comparative analysis

5.6 Interpretation

The interpretation phase of the study consisted of three elements:

- review of the goal and scope definition, inventory analysis and impact assessment to identify significant issues
- evaluation against the identified goal and scope to assess the need for modification, based on the significant issues identified
- conclusions and recommendations for use in product development.

5.7 Conclusion

Timber indoor sports playing surfaces are the norm throughout most of the developed world and are especially common at higher levels of competitive indoor sport. Although timber is widely recognised as a natural and renewable resource with negative net carbon emissions (Petersen and Solberg 2004), there is also the possibility that the environmental burdens created while using, maintaining and ultimately disposing of a wooden playing surface, may outweigh the environmental loads of its synthetic alternatives. When installed and used in the South Australian context, the hardwood timber sports surface with HVAC has greater impacts than all other surfaces.
assessed and the greatest contributors to the environmental impact categories applied during the study were the as a result of electrical power use consumed during the use phase. The use of life cycle thinking approaches challenge conventional wisdom and aim to expose the true environmental loads over the lifecycle of each surface type considered. Only by using comparative life cycle thinking tools such as LCA, do the life cycle implications of material/component selection decisions become fully apparent.

Through LCA, the lowest environmental impacts were recorded by the prefabricated tile synthetic sports surface. The environmental credentials of this style of surface were further enhanced, as explained in the next chapter, through the development of a more rugged, durable, stronger surface while attempting to increase the expected life for the surface from 10 years to 15 years. The adoption of a cradle to cradle business model was also adopted, as will be explained.
New sports surface design and development

6.1 Product development

Effective product development methods centre on the ways in which the research and development activity can be effectively planned, controlled and implemented. The process can be regarded as a sequence of activities and decisions which progress a problem solving process from the initial identification of the problem, through to a final implementable design solution.

The process of design is fundamentally an iterative method, which comprises the articulation of the problem which is to be solved, collecting and codifying pertinent information, the divergent exploration of potential problem solutions, convergence towards a favourable solution, and finally the detailed implementation and optimisation of the design solution.

A typical new product development method normally consists of six sequential phases, as detailed in Figure 6.1. The process is normally represented diagrammatically with overlapping phases to illustrate the iterative character of the product development process (Cooper 2005). The design activity itself can be regarded as the development processes which occur over phases one, two and three.

![Continuous Product Development Process](image)

**Figure 6.1** Continuous product development methodology (Cooper 2005)
Most organisations engaged in new product development have a range of concurrent exploratory projects, which are essential to guarantee that a sustainable flow of new product ideas is constantly being created for the organisation to exploit. In addition, it is vitally important that these ideas are continually evaluated and screened against commercial metrics to ensure that only projects which have acceptable levels of risk, and projects which meet organisational commercial expectations, advance to the next phase (Walker 2014). This chapter will detail the first three phases of the new product development process for a conceptually new, more sustainable, safer sports surface.

6.1.1 Phase 1: Design brief, research and product definition development

Also known as the project-feasibility stage, the first phase of the new product development process aims to establish the commercial and technical feasibility of a project and establish measurable criteria for success. This phase necessitates a broad understanding of the needs and desires of potential users and customers, the environment and conditions of use and the benefits which will be conveyed to users by a new sports surface design. The primary output from this phase is normally a comprehensive product definition which describes the attributes of the new surface, in addition to a clearly articulated business case to in order to validate any required financial investment.

6.1.2 Phase 2: Idea generation, concept development, analysis, initial prototyping, testing and selection

Having specified the prospective product opportunity and having defined the desirable attributes of a successful sports surfacing solution as detailed in the product definition, the conceptual design phase aims to generate divergent concepts describing potential surface solutions. During this phase, product architecture and usability issues are established.

6.1.3 Phase 3: Final concept development, final prototype testing and pre-production

Conceptual filtering is then applied to the design process in order to determine which of the various emerging ideas best satisfies the product definition established in Phase 1. Once a superior approach has been identified, it must be converted into a manufacturable and commercial reality. This aspect is usually one of the most time consuming phases, as high fidelity prototypes and production tools may be required.

It is critical that during this phase, the concept does not diverge too far from the agreed product definition, since detailed engineering and design decisions will be made.
6.2 Phase 1: Design brief, product research and product definition

This phase of the methodology seeks to:

- define in detail the design brief and the problem to be addressed and the conceptual vision for the project
- identify aspects of required key functionality and sustainability requirements
- describe the sports surface market and the competition
- determine the anticipated competitive advantage
- identify the customer safety performance requirements
- calculate the life-cycle costs
- ascertain the technical challenges in undertaking the project and product definition.

6.2.1 New sports surface design brief and problem definition

The design brief is a key document in any design process, as it is required to articulate the problem to be solved and establish the objectives, scope and the ambitions of the new project. There is no single established technique which can be used to create an optimal design brief, and it can be as detailed or minimal as is required for the problem under investigation.

The design brief articulates the primary vision that the playing surface must achieve. It expresses the problem definition, objectives, goals and functions of the required floor and does not normally contain precise limits. The brief outlines the product’s aims and should be as explicit as possible, without designating solutions or restricting the creative scope of potential design solutions. The design brief is an initial starting point from which the undefined aspects of the sports surface and market can be acknowledged, researched and then acted on.

A short brief can be effective when market and user specifics are undefined and the organisation desires the design team to investigate and identify market conditions, as well as conceptualise potential product solutions. When the project requires incremental innovation, based around recognised technologies, market conditions and consumers, it is often appropriate to develop an extremely detailed brief, as is the case in this study.

Over five million Australians suffer sports related injuries each year, with lower limb injuries comprising the most common form of injury across all sports and recreational activities, with ‘landing badly’ on a playing surface being the most common method of injury reported for both ankles and knees (Medibank Private 2006). Netball is the most popular team sport in Australia and
it is played predominantly by females on non-resilient, hard playing surfaces and ranks amongst the top sports for sporting injuries in Australia (McGrath and Ozanne-Smith 1998). The product development project described in this dissertation was designed to fill a void which exists in our knowledge about the injury risks associated with playing sport on different surface types and materials, and the desired outcome of the current study was the creation of a conceptually new surface which will reduce the injury risk to athletes.

Sports surfaces are complex structures, often made from many different layers of materials, which contribute to their composite behavior. These materials exhibit in many cases non-linear characteristics, making the analysis and evaluation of their behavior highly complex. This study involved the simulation of new sport surface structures under combined vertical and horizontal loads in order to determine their behaviour during player impact. The capacity to understand the behaviour of the surface determined the potential configurations that could be used in order to reduce injury rates and improve player performance.

The outcomes of the current study will advance our knowledge of injury risks associated with playing sports on different sports surfaces and guide decision making when developing new sports facilities, in order to better manage injury risk. The goal of the current research was to create a new sports surface technology to serve as a catalyst for a new generation of sports surface products. The discovery of this new knowledge and its quantification will enable the development of a new generation of shock attenuating sports surface which meets the needs of both athletes and governing sports associations.

Any non-energy absorbent surface is potentially dangerous. Any material put directly onto these surfaces which does not sufficiently ‘decouple’ the athlete from the sports surface through shock attenuation can cause injury. In addition, high frictional forces have been acknowledged as a significant cause of ankle and knee injuries. Investigations have demonstrated that the highest frictional forces are generated when players land on hard surfaces, such as bitumen and concrete. It therefore appears that traditional all-weather netball courts made from bitumen and concrete may encourage more injury, in comparison to other synthetic surfaces (Steele and Milburn 1987). Previous studies have also shown that there is a statistically significant link between body part and
surface type. Ankle injuries occur most frequently regardless of the surface type. However, more hand injuries are recorded on grass, more knee injuries on bitumen and more other injuries on synthetic surfaces (Hopper 1986).

Despite the risk of injury while participating in sport and the costs associated with rehabilitation, sports-related exercise offers huge health and well-being benefits to participants and the wider community. In order to preserve good health in an aging population, it is important to enable and encourage participation in sport and recreation by providing facilities, such as low injury risk surfaces, on which various sport and recreation activities can take place. Injuries are a major barrier to the maintenance of physical activity. This design project is therefore significant because it has the potential to reduce the risk of participant injury on sports surfaces across all age groups, lower the associated health costs and ultimately increase the level of sports and physical activity participation.

The attenuation of the horizontal ground reaction forces (HGRF) on sports surfaces is anticipated to contribute to the following:

- a reduction in joint and ligament injuries
- athletes will be able to turn faster and slide when required, as well as an improvement in their performance
- maintain levels of sport and recreational activity in urban and rural communities for longer.

6.2.2 The product’s conceptual vision

An innovative sustainable impact absorbing sports surface was developed during this project, which allows damaging braking/deceleration forces to be attenuated and so reduce the chance of injury. The full life-cycle costs and life-cycle environmental impacts of the surface were considered and minimised where possible. The product could potentially be manufactured and distributed in Australia, ultimately replacing competing synthetic sports surfaces, which are predominantly imported from Europe and North America.

The surface and its associated intellectual property could also be exported, particularly to North America, where modular tile synthetic sports surfaces are well accepted in the market. Sport is an important part of Australian life and is a particularly important social element of our rural communities. A safe, affordable, low environmental impact sports surface will encourage sport
participation, encourage social interaction, increase access to sports facilities and help individuals maintain physical activity longer. Life cycle assessment modelling has demonstrated that modular tile surfaces have the potential to exhibit lower environmental impacts, in comparison to competing synthetic and timber-based sports surfaces.

### 6.2.3 Key surface functionality

Investigations conducted by Walker and Subic as part of this research demonstrated that prefabricated tile synthetic sports flooring has the potential to attenuate horizontal ground reaction forces (Walker and Subic 2010). A key functional aspect of the current proposal therefore was to enhance the HGRF attenuating characteristic through the addition of shock dampening elements into interconnected tile junctions. Such an arrangement allows a restricted amount of horizontal movement via the tile connections. This horizontal surface displacement ultimately reduces the forces experienced by the lower limb while braking and may reduce potentially injurious stress to the musculoskeletal system. In the tests conducted previously on modular tile surfaces, the modular tiled surfaces were found to dissipate more braking force than homogenous vinyl surfaces. In addition, there was an increase in the time to reach peak HGRF, which represents a more gradual loading of the musculoskeletal system (Walker and Subic 2013). These two factors in combination, when enhanced with the introduction of dampening elements into the interconnected tile junctions, is expected to reduce potentially injurious stress levels to the athlete.

### 6.2.4 Sustainable sports surface design

The design process adopted for this study sought to employ sustainable design approaches throughout the new product development process. Outcomes were pursued which aimed to use materials, energy and water efficiently, and minimise waste and negative impacts on the natural environment for the benefit of the communities in which the sports surfaces are placed.

Sustainable design considers environmental impacts at every stage over the life of a sports surface, including the materials and energy consumed over its life and the wastes and emissions produced over its life. Using a sustainable sports surface design strategy it was possible to lock in positive environmental features (durability, recycled materials, design for disassembly, recycling and/or remanufacturing, water and energy efficiency) and lock-out negative environmental features (avoiding the specification of toxic or hazardous substances, eliminating or reducing consumables).
The whole surface life cycle was considered in order to produce a sustainable product, by applying analytical tools to quantify the environmental impact of the surface over its lifetime.

6.2.5 Taking the product to market

It is anticipated that the primary market for a new low injury-risk sports surface would be sports facility specifiers, architects, school principals, local government, facility owners, sports associations and athletes.

Market competition. The ever-changing nature of sports and the desire to play different sports in many different climactic conditions has led to sports being played on synthetic surfaces in place of natural surfaces. In recent years, there has been a trend towards the creation of multi-sport facilities, where a facility is optimised by using it for a multitude of different sports, such as netball, basketball, indoor soccer, volleyball, inline hockey and martial arts. Sports are therefore now played on a variety of synthetic sports surfaces.

Despite such a wide range of playing surfaces, the literature states that there is a lack of information about the appropriateness of different surfaces for different sports. In Australia, the main indoor sports surface competitors are manufacturers and distributors of pour-in-place, sheet vinyl and timber sports surfaces.

Anticipated competitive advantage. The new product system developed during this project is a sports surface system that provides a safe, low cost, durable, sustainable and high performance playing surface for a wide variety of sports. This was attained by using the geometry of the tiles to mitigate the high horizontal ground reaction forces generated in playing sports such as netball. Research into the market for this type of product concluded that there are four main areas which are not being adequately addressed by currently available products. These aspects are: the need for multipurpose/multi-sport surfaces (including sporting and non-sport usage); improved safety performance (force reduction, stiffness and friction); improved environmental performance (minimising the materials and energy consumed and waste and emissions generated over the surface’s life); and improved surface life cycle (cradle-to-cradle). These competitive advantages were the primary drivers of this project.
6.2.6 Improved safety performance

The Medibank Private *Safe Sports Report 2006* states that 5.2 million Australians suffer sports related injuries each year, with these injuries costing the Australian community approximately $2 billion in 2005. Lower limb injuries were found to be the most common form of injury across all sports and recreational activities, and ‘landing badly’ on a sports surface was the most common method of injury reported for both ankle and knee injuries.

With increasing age, injury risk rises due to changes in tissue flexibility and repair capacity (Medibank Private 2006), and injury is a major factor in the reduction of physical activity among older Australians. Netball is still predominantly played on hard, rigid surfaces, which offer very
low levels of shock absorption and protection to the athlete. There is therefore a great need for alternative surface materials and designs, which can offer improved levels of participant safety.

6.2.7 Improved surface life cycle cost

Most prefabricated synthetic tile sports flooring systems currently available in the Australian market are prohibitively expensive. Through improved manufacturing efficiency and lower freight costs due to localised manufacture, the proposed product can be priced much more affordably.

The surface developed during this project is a multipurpose floor, encouraging higher levels of use in the facility. The proposed system uses a large 500mm tile format, which is more efficient to injection mould and quicker to install or remove than the more common 254mm and 305mm square tile formats. One of the key goals of the project was to increase the durable life of the new tile system from 10 years to 15 years through improved structural design.

6.2.8 Project aim

The focus of the project was the development of a conceptually new sustainable sports surface with the capacity to reduce the number and severity of injuries resulting from player/surface interaction. The research also sought to improve athletic performance while reducing the likelihood of injury. Surface benefits would include:

- increased levels of sports participation and enjoyment of sport
- reduced period and type of sports injury treatment required
- less time lost through injury
- reduced risk of giving up sport through injury
- reduced environmental footprint in comparison to other surfaces currently available in the Australian, North American and European markets.

6.2.9 Technical challenges to be overcome

The current study encompassed four main technical objectives:

- to develop a high performance modular plastic sports floor tile which adequately addresses athlete safety, multi-propose/multi-sport use, improved environmental performance and reduced surface life cycle impacts
- to develop a floor tile which minimises the cooling distortion stresses currently found in modular plastic sport tile surfaces, resulting in a flatter playing surface
- to develop a floor tile which can resist structural loads to increase its performance life from 10 to approximately 15 years
to develop a modular plastic joining connector which links the floor tiles together and locally attenuates the potentially physically damaging horizontal braking forces exerted on the floor by an athlete when they suddenly change direction or brake during competitive play or while training.

To address the specific issues relating to the floor’s technical challenges, the following major development activities were undertaken:

**Mathematical modelling.** Three dimensional mathematical models were developed using a high end modeller with all draft and split faces represented within the models. Defeated versions of these models were developed, allowing 3D meshes to be generated from this data, which allowed subsequent simulation studies to be conducted.

**Finite element analysis.** As the new prefabricated synthetic tile sports flooring system will be subjected to high dynamic and static forces over its service life, it was important to confirm that failure resulting from overstretching would not occur. It was critical, therefore, that the stresses did not exceed the recommended design limits for the materials used.

Firstly, mathematical models of the floor components were described by the generation of 3D mesh models developed using CAD data and combine with the properties of the proposed surface materials. A series of simulations were then performed in order to determine the surface’s load bearing and force attenuation potential. The outcomes of this analysis are detailed in Chapter 7.

### 6.2.10 Indoor sports surface product definition

The creation of a concise and timely product definition is a critical stage in the development of any new product. The product definition articulates the multidimensional aspects of the whole product which should be materialised through the design process, and deals with functionality, manufacturability, distribution, service, support and end-of-life.

In addition, the product definition should deliver comprehensive, quantifiable and explicit details about what the new product must achieve, without creating superfluous constraints or proposing potential solutions, which may limit creativity. The definition of an appropriate sports surface can be challenging. It is therefore important that sports surfaces should only be specified after suitable consideration of all surface variables and their relation to injury risk has taken place. Figure 6.3 details ten major surface selection criteria with associated sub-criteria, which should ideally be taken into consideration while defining the performance requirements of a sports surface. The
selection criteria detailed in Figure 6.3 were established after detailed consultation with the national sales manager of Herculan Australia.
Figure 6.3  Indoor sports surface selection criteria (Walker and Subic 2010)
Although all surface selection criteria were considered to some extent during the design process for the current study, as the primary focus of the research task was principally to minimise injury and
maximise environmental performance and surface economics, the product definition was centred principally on:

- multipurpose/multi-sport use (sporting and non-sport usage needs)
- mechanical/safety performance (horizontal and vertical force reduction)
- environmental performance (minimisation of materials & energy consumed and waste and emissions generated, over the surface’s life)
- life cycle cost considerations (cradle to cradle).

**Multipurpose sport use.** The ever-changing character of sport and the need to play sports under different competitive conditions has led to the development of a wide variety of synthetic and natural surfaces. The sport and recreation industry in recent years has seen the development of a trend towards the construction of multi-sport facilities, in which the use of the sporting surface is optimised by having a single synthetic sports surface capable of satisfying a variety of needs.

From an injury prevention perspective, however, it is unlikely that any sports surface can accommodate every type of sporting activity with equal success, which is why some sports facilities feature more than one surface type. Selecting an appropriate indoor sports surface requires a comprehensive understanding of all the varied sporting and non-sporting events that will be conducted at the facility. Regardless of the sport to be played, the health, safety and comfort of the surface’s users should be a major concern when developing a sports surface.

When injury results, it is likely to be a result of the complex interaction of surface stiffness, resilience and frictional properties, in combination with the surface, athlete and environmental factors. Optimum surface characteristics vary from sport to sport, but the consequences of selecting an inappropriate surface on the health and safety of the surface’s users must always be a major concern. A truly multipurpose sports surface should be capable of meeting the sporting needs of netball, basketball, martial arts, floorball, volleyball, soccer, inline hockey, and the non-sport needs of dance, school examinations and various non-sporting community uses. However, specific performance standards have been developed for many sports, and in some instances it may be appropriate for sport specific standards to take precedence over EN14904 in specialist facilities, or where a particular sport is given priority in a multi-sport facility.

A customisable multi-sport surface, which is ‘tuneable’ to meet the needs of certain categories of sporting use, is described by the following EN performance categories:
- P0- Surfaces outside the EN 14904 standard but which are suitable for sporting and non-sporting uses requiring low levels of force reduction, such as bowls, carpet bowls, inline hockey, concerts and non-sporting community activities.
- P1- Surfaces within the EN 14904 standard complying with the P1 force reduction category which are suitable for boxing, indoor cricket, movement, dance, keep-fit classes and netball.
- P2- Surfaces within the EN 14904 standard which comply with the P2 force reduction category and which are suitable for futsal and box lacrosse.
- P3- Surfaces within the EN 14904 standard complying with the P3 force reduction category and which are suitable for badminton, basketball, handball, korfball and volleyball. (EN14904 2006; Sport England 2007)

**Mechanical/safety performance.** The mechanical properties of a playing surface, which include both the contact surface layer and the underlying materials, should be compatible with the types of physical movement and loads exerted on the surface by an athlete, otherwise there will be an increase in the injury risk to the athlete. Insufficient attenuation of the forces being applied to the surface can result in damage to the soft tissues of the lower limb. In addition, the high frictional forces generated during braking can subject the ligaments of the lower limb to excessive stress and increase the potential for ligament damage. High frictional forces have been implicated as a significant contributing factor to the high occurrence of lower limb injury in many sports, as well as causing skin damage from abrasion when falling on a high friction surface. These damaging forces can be reduced by specifying a surface which meets the specific demands of a particular sport or group of similar sports.

As the current EN classification system only addresses vertical force reduction and not horizontal force reduction, there is a clear need for an extension to the system which also addresses the requirements of horizontal ground reaction force reduction. To this extent, the data expressed in Tables 3.3 and 3.4 are combined and expressed as a coordinate system, where percentage horizontal ground reaction force reduction is featured on the x axis, and percentage vertical ground reaction force reduction is featured on the y axis. For the purposes of the study, netball will be targeted and the design process should therefore aim to achieve a sports surface which is customisable in order to achieve a specific range of horizontal and vertical force reduction classifications over the NO and NP range of Netball England classifications, with an optimal ‘two dimensional’ performance target for the new surface being NT, HGRFR (20% minimum and 30%...
maximum) and VGRFR (20% minimum and 30% maximum), which spans both the NO and NP categories.

Figure 6.4 represents a series of extrapolated combined horizontal ground reaction force reduction (HGFR) and vertical ground reaction force reduction (VGRF) classifications based on the EN 14904 standard, where the horizontal axis represents HGRF and the vertical axis represents VGRF. Given that Steele and Millburn (1988) concluded that a shod athlete with a mass of 65kg and a height 165 cm could apply forces of:

\[
\begin{align*}
\text{HGRF} &= 2470\text{N to 2700N} \\
\text{VGRF} &= 2295\text{N to 3530N}. \quad \text{(Steele and Milburn 1988)}
\end{align*}
\]

Given the relative comparability of horizontal and vertical ground reaction forces measured by Steele and Milburn, it would be reasonable to expect the horizontal and vertical force reduction components similarly. NT therefore represents the target classification for netball for which the new surface was designed.

![Figure 6.4](image-url)  
Proposed point elastic sports surface force reduction classifications for combined horizontal and vertical shock attenuation, including the England Netball Association recommended force reduction classification and target NT force reduction classification.
Existing modular tile systems which use different thicknesses of rubber underlay (3mm, 5mm, 7mm and 10mm) are currently capable of achieving VGRFR results of:

- (3mm) – 20% - 25% (outside EN 14904)
- (5mm) – 25% - 30% (P1)
- (7mm) – 30% - 35% (P1)
- (10mm) – 35% - 40% (P2)

(Sport Court 2013)

It will therefore be possible to achieve the target NT VGRFR (20% minimum and 30% maximum) utilising 3mm or 5mm rubber underlays. The NT HGRFR (20% minimum and 30% maximum) component was achieved through other means as described later in this chapter.

**Environmental performance.** A factor often neglected, but of primary concern to the health, safety and comfort of athletes involved in sports, is the tendency for some sports surfaces to absorb and then transmit heat to the athlete. The air temperature immediately above the surface of a sports floor can therefore be greatly increased, due to some surface materials absorbing and then radiating infrared energy. This is particularly important with outdoor surfaces, which are in direct sunlight. Problems such as heat prostration can become concerns for athletes playing on hot surfaces, as this condition can result in a loss of concentration, dehydration and impaired performance. Heat prostration is obviously of greater concern with sports played in hot climates such as Australia.

While the appearance of a sports surface may not necessarily directly impact an athlete’s performance, colour choice will allow the facility’s designer to create the preferred ambiance for the internal spaces in the structure. Furthermore, the durability of particular aspects, such as painted game line surfaces, surface borders and basketball keys, in addition to surface textures in the sports floor itself, must to be evaluated. Different colours of surface may deteriorate at different rates, depending on the ultraviolet stability of the materials used, the degree of natural light striking the surface and surface traffic. For the majority of indoor sports, a matte or low reflectance surface is favoured, as this will make sports surface line-marking more discernible and reduce levels of reflection for athletes. A matt surface permits the utilisation of higher levels of natural light and lowers the sport facility’s power consumption requirements, in order to illuminate the sports surface.
A sports hall’s lighting level must be bright enough to safely accommodate a wide range of ball, racket and stick sports. At the same time, lighting levels should prevent athletes from being blinded while attempting lay-up or setting manoeuvres while playing volleyball. Indirect lighting can be selected to mitigate this problem, even though it is less energy efficient and more complicated to construct, as it requires highly reflective ceilings and equipment and structural elements to be positioned to avoid casting shadows. The use of natural light in order to reduce energy costs can complicate the lighting process, as the weather will begin to influence lighting levels.

Colour also plays a significant role in sport surface design, with the increasing coverage of televised indoor court sports such as netball. With synthetic sports surfaces, colour is not restricted to the traditional natural colours of timber. The majority of synthetic sports surfaces can be used to create a homogeneous, uniform surface and do not contain the arbitrary irregularities found in many natural playing surfaces. Random visual irregularities in the playing surface can diminish the level of contrast between the ball, shuttle-cock or puck and surface, impairing the capacity of an athlete to observe a ball during rapid competitive play and causing fatigue through eyestrain. In addition, excessive glare from natural or artificial light sources reflecting from a playing surface can also reduce the ability of an athlete to detect a ball. Appropriate surface colours, contrast and reflectivity levels should therefore all be considered when selecting an appropriate sport surface to ensure player comfort, safety and wellbeing.

It is important to ensure that the sports surface manufacture, cleaning and maintenance requirements minimise emissions and harmful waste materials, as well as the consumption of energy and non-renewable resources by:

- using manufacture and construction materials which are nontoxic and can be recycled
- minimising transportation distances
- minimise the energy and water profile of the flooring system over its entire life cycle
- surface durability
- minimising the use of any energy required to maintain the usable playing environment in the form of lighting, heating, cooling and humidity control. For example, the Maple Flooring Manufacturers Association recommends that an indoor relative humidity between 40% and 60% should be maintained throughout the year when a timber sports floor is installed, to prevent damage to the surface. Specialised HVAC controls are generally not required if
synthetic surfaces are installed other than for player comfort (Maple Flooring Manufacturers Association 2011).

The sports surface should ideally be manufactured using raw materials and manufacturing processes that minimise waste and maximise the good stewardship of natural resources. There are many environmental considerations. Focus on the use of resources, manufacturing, indoor air quality, energy consumption, use of sustainable or recycled materials, ability to recycle later, and disposal are common examples. A positive contribution to any one consideration may however lead to a negative outcome in another.

The sturdiness of a sports surface is mainly determined by its capability to adequately manage the mechanical loads and abrasion to which it is exposed. Normal non-athletic uses include the movement of portable basketball backstops, ladders or lifting equipment used to maintain lighting or hanging banners. The rolling and static loads delivered by the use of retractable seating must also be taken into account while determining the mechanical strength requirements of a sports surface. Non-sporting use, including the movement of tables and chairs on the sports surface and can result in considerable point-loads. The multi-directional start and stop nature of competitive sport movements on a sport surface will result in increased wear of the floor surface and the line marked surfaces. Inline hockey activity will increase wear of the floor, as will ordinary foot traffic in non-sport shoes. Inline hockey is the most challenging sport in terms of durability for most sports surfaces. Striking the surface with hockey sticks substantially increases the risk for the surface to become scratched or punctured.

A sports surface’s specified use will determine its ultimate maintenance requirements. The varied use of synthetic surfacing and its ability to meet the needs of a variety of sporting and non-sporting activities means more regular maintenance may be required, than that required for a natural timber surface designed for a single purpose. Most synthetic surfaces require weekly or biweekly scrubbing with a manufacturer-specified cleaning product. Floors should be scrubbed with a non-alkaline cleaning product immediately after non-athletic activities.

As timber is a hydroscopic material, it requires an additional level of attention. Liquid spills on timber surfaces need to be immediately removed, scuffs and marking removed, and HVAC levels carefully monitored. Bi-annual recoating is also necessary.
Maintenance needs can differ considerably for different types of surface, and the manufacturer’s maintenance instructions for daily, weekly and monthly cleaning need to be considered prior to choosing a specific flooring product. Generally, however, the same daily and weekly principles are followed in each surface case. Good maintenance includes cleaning and repairing game lines, punctures or structural damage, the intermittent application of repair coatings or the sanding and resurfacing an entire sports surface needs to be fully considered within the context of a long-term maintenance plan.

The surface should be constructed from materials which are easily recovered, reused and possibly resold as a second-hand surface or recycled into a new surface.

Where possible, a service oriented, extended product responsibility business model should be adopted. A leasing strategy, where the surface remains the ownership of the leasing organisation would encourage the company to maximise the life expectancy and recover the surface from the installation site at the end of its useful life.

6.3 Phase 2: Idea generation, concept development, analysis, initial prototyping, testing and selection

During this phase of the research plan a range of processes was explored and creative approaches developed relating to the established product definition. Specifically, function analysis, peeves analysis, market segmentation, customer benefits analysis and sustainable design approaches were all considered.

6.3.1 Surface function analysis

The analysis of product functions is an effective analytical technique which can be used to identify the functional methods required to satisfy user needs without the need to focus on existing components or mechanisms, and, if necessary, identifying and eliminating unnecessary functions and components. When developing a new product, it is commonplace to consider the redesign of the product’s individual components and mechanisms in order to address specific needs. The product then evolves generally without the consideration of alternative approaches, although
alternatives could potentially perform the required function equally well, at reduced cost or functionally better (Fowler 1990).

In a sports surface function analysis, each functional aspect is described with a verb and a noun descriptor combination. Intermittently, three word combinations may be required, but the simplicity of the verb/noun technique contributes to the conceptual value of such an analysis by encouraging the unearthing of unconventional alternative approaches. Functional relationships are structured by commencing the process by defining the basic or highest order need, which directly satisfies the customers’ needs. This process is recognised by questioning ‘How is customer need satisfied?’

In the current study, the highest order function was defined as, ‘Provide a low injury risk sports playing surface’. In this case, the primary functions supporting the highest order function would be to ‘attenuate horizontal ground reaction forces’, ‘attenuate vertical ground reaction forces’, ‘allow tile interconnection’ and ‘allow grip’. These functions will allow the product to operate as anticipated and are the most important functions required by the surface.

Secondary functions then support the primary function to work, as very few products could exist with just a basic function alone. Secondary functions can be identified by looking at main product assemblies or component clusters and describing the function or functions that they then perform, again without naming components. Function specification is then used to define what must be delivered and the technical requirements or performance limits required for each function.

![Function analysis systems technique (FAST) diagram structure](https://example.com/figure6.5.jpg)

**Figure 6.5** Function analysis systems technique (FAST) diagram structure (Fowler 1990; Kaufman and Woodhead 2006)

Functional analysis systems technique diagramming is an important step in the selection of those features of the design problem requiring specific innovation, and confirms that the most critical
aspects of the surface needs are addressed first and are given the most consideration (Kaufman and Woodhead 2006). Other potential benefits which can be gained from conducting a surface function analysis and FAST diagram include:

- the grouping of associated functions, which can identify surface configurations that can be redesigned with greater simplicity
- providing a structured approach to problem solving to ensure that all significant functions have been fully addressed in the study
- specifying the precise relationships of all functions in the surface’s product architecture
- developing a hierarchy of functions, which clearly highlights the relative importance that design intervention makes to the surface’s overall functionality.

![FAST Diagram](image)

**Figure 6.6** Provide low injury risk sports playing surface FAST diagram
### Functions

<table>
<thead>
<tr>
<th>Verb</th>
<th>Noun</th>
<th>Primary</th>
<th>Secondary</th>
<th>Function Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attenuate</td>
<td>HGRF</td>
<td></td>
<td></td>
<td>combined VGRF/HGRF resultant force of 6.0 times body weight,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>representing a force of $= 6BW \times 65kg \times 9.81 = 3.826kN$.</td>
</tr>
<tr>
<td>Allow</td>
<td>horizontal tile movement</td>
<td></td>
<td></td>
<td>the largest gap which the customer group will accepting is 2mm.</td>
</tr>
<tr>
<td>Allow</td>
<td>gap expansion</td>
<td></td>
<td></td>
<td>0mm to 2mm</td>
</tr>
<tr>
<td>Allow</td>
<td>gap contraction</td>
<td></td>
<td></td>
<td>2mm to 0mm</td>
</tr>
<tr>
<td>Allow</td>
<td>horizontal force dampening</td>
<td></td>
<td></td>
<td>$R_y = 4.243BW$ or $2.706kN$.</td>
</tr>
<tr>
<td>Attenuate</td>
<td>VGRF</td>
<td></td>
<td></td>
<td>combined VGRF/HGRF resultant force of 6.0 times body weight,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>representing a force of $= 6BW \times 65kg \times 9.81 = 3.826kN$.</td>
</tr>
<tr>
<td>Allow</td>
<td>vertical tile movement</td>
<td></td>
<td></td>
<td>2mm</td>
</tr>
<tr>
<td>Allow</td>
<td>vertical force dampening</td>
<td></td>
<td></td>
<td>$R_z = 4.243BW$ or $2.706kN$.</td>
</tr>
<tr>
<td>Allow</td>
<td>tile interconnection</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Allow</td>
<td>tile movement</td>
<td></td>
<td></td>
<td>2mm to 0mm</td>
</tr>
<tr>
<td>Allow</td>
<td>thermal expansion &amp; contraction</td>
<td></td>
<td></td>
<td>0 to 37 degrees Centigrade</td>
</tr>
<tr>
<td>Allow</td>
<td>horizontal and vertical colour change</td>
<td></td>
<td></td>
<td>square or octagonal</td>
</tr>
<tr>
<td>Allow</td>
<td>grip</td>
<td></td>
<td></td>
<td>80-110</td>
</tr>
</tbody>
</table>

---

**Figure 6.7** Provide low injury risk sports playing surface function specification

### 6.3.2 Tile sports surface peeves analysis

Peeves are irritations experienced by product users but often not reported formally. In many instances, the annoyances are not reported by users because it is assumed that the issue would be rectified if there were a solution available to be implemented, such as having sore joints and muscles after playing sport. This is generally accepted as a by-product of participating in vigorous physical exercise. Peeves can however correspond to a large series of minor design issues, which
have been left unaddressed by the surface manufacturer, and can therefore present an abundant source of design opportunities (White 1992).

In carrying out the data gathering process, casual user interviews were conducted with facility staff and sport participants at Puckhandlers Stadium, which was using a Sport Court Response 6.0 surface. Kemalex Plastics (floor tile manufacturer) staff were also interviewed. The data revealed areas where surface solutions were not providing the necessary levels of satisfaction for the user. Typical peeve comments are listed below.

**Functional Peeves (Tile)**

*Surface becomes slippery when wet.*

*Some floors are too quiet. Players like to hear where the opposition are on the court.*

*Raised corners on tile surfaces can influence ball/puck travel over the surface.*

*Knees become sore and swollen after playing on some surfaces.*

*Ankle roll-over when stopping or landing while travelling at speed over the court.*

*No colour separation for in-play areas of the surface.*

*Game-lines are not obvious and confusing.*
<table>
<thead>
<tr>
<th>Functional Peeves</th>
<th>Effect</th>
<th>Cost</th>
<th>Causes</th>
<th>Overcome By</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not enough grip</td>
<td>Falling injury</td>
<td>Medical costs, lost income through injury, reduced participation in sport</td>
<td>Coefficient of friction insufficient</td>
<td>Investigate alternative textures and friction coatings.</td>
</tr>
<tr>
<td>Slippy when wet</td>
<td>Falling injury</td>
<td>Medical costs, lost income through injury, reduced participation in sport</td>
<td>Coefficient of friction changing when wet</td>
<td>Investigate alternative textures and coatings.</td>
</tr>
<tr>
<td>Too quiet</td>
<td>Can't hear where other players are</td>
<td>Lower playing performance</td>
<td>Surface does not reverberate</td>
<td>Increase surface 'suspension'</td>
</tr>
<tr>
<td>Raised corners</td>
<td>Ball/puck can deflect from original path</td>
<td>Lower playing performance</td>
<td>Surface is not flat</td>
<td>Remove 90 degree corners and Improved part design</td>
</tr>
<tr>
<td>Sore knees</td>
<td>Repetitive stress injury</td>
<td>Condition may become chronic, Medical costs, lost income through injury, reduced participation in sport</td>
<td>High braking forces when stopping or landing</td>
<td>Attenuate braking forces</td>
</tr>
<tr>
<td>Ankle roll-over</td>
<td>Damaged ligaments</td>
<td>Recovery periods or surgery required, medical costs, lost income through injury, reduced participation in sport</td>
<td>High friction coupled with high braking forces</td>
<td>Reduce coefficient of friction and braking forces</td>
</tr>
<tr>
<td>Game lines not obvious</td>
<td>Confusion during play</td>
<td>Lower playing performance</td>
<td>Many lines to be aware of</td>
<td>Can game lines be switched on and off</td>
</tr>
<tr>
<td>No colour delineation</td>
<td>Confusion during play</td>
<td>Lower playing performance</td>
<td>Floor is uniform in colour and game lines are coloured</td>
<td>Metric tile is developed which can have a H&amp;V laying pattern</td>
</tr>
</tbody>
</table>

**Figure 6.8**  
**Tile sports surface function peeves analysis**

**Component Peeves (Tile)**

*Suits imperial surface dimensions but not metric surface systems. Most existing tile surfaces are 10 or 12 inches square.*

*Tiles do not remain flat, especially when conditions are hot.*

*Tiles distort when temperatures are high.*

<table>
<thead>
<tr>
<th>Component Peeves</th>
<th>Effect</th>
<th>Cost</th>
<th>Causes</th>
<th>Overcome By</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not metric</td>
<td>Tile surfaces do not always suit metric courts</td>
<td>Tiles have to be cut to suit reducing floor quality</td>
<td>Most tile surfaces are manufactured in the US</td>
<td>Develop metric (0.5m) tile</td>
</tr>
<tr>
<td>Tiles do not remain flat</td>
<td>Lifting corners create shallow pyramids on surface</td>
<td>Lower playing performance</td>
<td>Differential shrinkage over material flow lengths</td>
<td>Developing a tile with uniform material flow lengths</td>
</tr>
<tr>
<td>Tiles lift off substrate</td>
<td>Tiles buckle as they experience thermal expansion</td>
<td>Can present tripping hazard or close the facility</td>
<td>Plastic tiles expand and contract at higher rates than substrate materials</td>
<td>Create means to absorb dimensional changes</td>
</tr>
</tbody>
</table>

**Figure 6.9**  
**Tile sports surface component peeves analysis**
Manufacturing peeves (Tile)
Requires operator to assemble tile sheets at the injection moulding machine where space is limited. Tiles require to be cooled in groups of 10, to allow parts to cool adequately prior to assembly into sheets. Tile shift easily once stacked onto a pallet and the pallet is moved. This also limits the number of sheets which can be stacked onto a pallet. Certain inorganic pigments and additives can increase the effect of shrinkage and stiffness of the moulded tiles. Tile sheets require nonstandard pallets to be used.

<table>
<thead>
<tr>
<th>Manufacturing Peeves</th>
<th>Effect</th>
<th>Cost</th>
<th>Causes</th>
<th>Overcome By</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limited space at moulding machine</td>
<td>Difficulty removing loaded pallets</td>
<td>Reduction in manufacturing efficiency</td>
<td>Limited space in vicinity of injection moulding machine</td>
<td>Reconfigure assembly area or change machine</td>
</tr>
<tr>
<td>Tile cooling space</td>
<td>Production bottle-neck/tiles being assembled early</td>
<td>Reduction in manufacturing efficiency</td>
<td>Limited space in vicinity of injection moulding machine</td>
<td>Cooling rack/robotic sequenced insertion into cooling rack</td>
</tr>
<tr>
<td>Tiles shift on pallets</td>
<td>Tile loads become unstable and load can be lost</td>
<td>Damaged/lost tiles and pallet needs to be restacked</td>
<td>Poor tile/pallet interface due to shrink-wrap non-contact area</td>
<td>Improve the interface or interconnection where tiles meet pallet</td>
</tr>
<tr>
<td>Pigment changing mechanical properties</td>
<td>Tiles distort and will not flatten after cooling</td>
<td>Tile ‘cupping’ and floor will not be flat</td>
<td>Use of organic pigments</td>
<td>Trial each pigment prior to moulding production quantities</td>
</tr>
<tr>
<td>Non-standard pallets</td>
<td>Special pallets need to be manufactured</td>
<td>Cost of non-standard non-returnable pallets</td>
<td>Imperial tiles using metric pallets</td>
<td>Change to metric tiles to allow use of metric pallets</td>
</tr>
</tbody>
</table>

Figure 6.10 Tile sports surface manufacturing peeves analysis

The peeves analysis when reversed into opportunities as opposed to problems serves as a means by which to identify features that are important to users and other stakeholders, and generates a variety of potential ideas for incorporation into the conceptual development process.

6.3.3 Sports floor market segmentation
In all markets, diverse groups of customers have dissimilar needs. The market for sports flooring systems can be divided into separate segments, comprising clusters of users and customers who have similar requirements, characteristics and desires (Dickson and Ginter 1987). In a well-defined surface market segment, customers can be regarded as having a comparable response to the marketing mix (surface attributes, promotional approach, pricing policy and place of purchase).
The major customer segments for an indoor sports surface would include the major groupings shown in Figure 6.11.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Description of usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local government</td>
<td>Community sports centre with multi-use/multi-sport applications</td>
</tr>
<tr>
<td>Private gymnasium</td>
<td>Specific sport usage</td>
</tr>
<tr>
<td>School hall/gymnasium</td>
<td>Multi-use/multi-sport purposes</td>
</tr>
<tr>
<td>University gymnasium</td>
<td>Multi-use/multi-sport purposes</td>
</tr>
<tr>
<td>Sport association</td>
<td>Specific sport usage</td>
</tr>
<tr>
<td>Military hall</td>
<td>Multi-use/multi-sport purposes</td>
</tr>
</tbody>
</table>

**Figure 6.11** Major sports floor market segments

These segments can be further subdivided into the classifications shown in Figure 6.12 in relation to the different levels of competitive play and training that may take place on each sports surface. These classifications can generally be categorised as international, premier, club and community.

<table>
<thead>
<tr>
<th>Category</th>
<th>Level of competitive play</th>
</tr>
</thead>
<tbody>
<tr>
<td>International</td>
<td>The lowest level of international competition. Surfaces are intended for county premier league and county first team use.</td>
</tr>
<tr>
<td>Premier</td>
<td>Premier/national league club, competing in regional or interstate competitions. Surfaces are intended for state premier league and county first team use only.</td>
</tr>
<tr>
<td>Club</td>
<td>Local club competing in district and state league competitions. Intended for local league, school, recreation and community use.</td>
</tr>
<tr>
<td>Community</td>
<td>School and community use, where there is no formal competitive structure. Intended for local league, school, recreation and community use.</td>
</tr>
</tbody>
</table>

**Figure 6.12** Sport categories in relation to level of competitive play (Sport England 2012)

In respect to the multi-sport/multi-use market for sports surfaces, the school gym sport floor market would present the highest growth potential, as most primary and secondary schools have at least one school hall/gymnasium. This market has grown significantly in size since the implementation of the Federal Government’s Nation Building Economic Stimulus Plan in 2009, which has funded approximately 24,000 infrastructure projects for approximately 9,500 schools (DEEWR 2010), significantly increasing the number of school halls in Australian schools, all of which will have ongoing sports surface maintenance and replacement needs. According to the pour-in-place surface
installer, Herculan Australia, this market segment normally requires surfaces that can generally claim the following attributes delivered by their products:

- **multipurpose/multi-sport including exam and community use**
- **safer, by reducing repetitive stress injury by attenuating vertical ground reaction forces**
- **high levels of friction, to reduce the risk of falling injuries and skin abrasion**
- **low life cycle cost**
- sustainable, low impact in comparison to other sports surfaces
- durable, with a minimum playing life of 15 years
- simple and quick to clean
- simple to maintain and repair with minimal down-time
- simple to install and remove
- colour variety, to meet a variety of interior architecture treatments
- moisture resistant
- fungus and mildew resistant
- no or minimal climate control required in comparison to other sports surfaces, reducing energy usage and running costs
- looks good and stays looking good over the playing life of the surface.

(Herculan Australia 2010)

This market will have children ranging in age from 4 to 18 years old playing on school hall sports surfaces. Their developing bones and joints have a particularly demanding need for surfaces which protect limbs from repetitive stress overloading.

Market segmentation and positioning are significant aspects of new product development and are vital to ensure that the product attributes and benefits concur with the requirements of each of the objective user groups. Market segmentation can be regarded in four phases:

- defining the indoor sports surface market
- market segmentation- school sports hall/community level
- opportunity target- high injury risk, high levels of participation, netball
- flooring solution position- customisable surface which can be adjusted to meet the needs of a broad variety of high participation sports which can be used in a multi-sport/multipurpose environment.

Market knowledge is an important input to the development of the product definition and market research assists product developers visualise the motivations of different groups of users. For all surface types and markets, different groups of customers will have different force reduction needs.
Table 6.1 Proposed point elastic sports surface force reduction classes as described in Figure 6.4 for combined horizontal and vertical force reduction, in respect to the requirements for different sports (Sport England 2007)

<table>
<thead>
<tr>
<th>VHGRFR Classification</th>
<th>Proposed HGRFR</th>
<th>Proposed VGRFR</th>
<th>Sport</th>
</tr>
</thead>
<tbody>
<tr>
<td>PO netball outdoor</td>
<td>10% to 30%</td>
<td>20% to 30%</td>
<td>netball</td>
</tr>
<tr>
<td>PO NT</td>
<td>20% to 30%</td>
<td>20% to 30%</td>
<td>netball</td>
</tr>
<tr>
<td>P1HV</td>
<td>25% to 35%</td>
<td>25% to 35%</td>
<td>tennis, bowls, inline hockey</td>
</tr>
<tr>
<td>P1HV³V</td>
<td>35% to 45%</td>
<td>25% to 35%</td>
<td>NA</td>
</tr>
<tr>
<td>P1HV²V</td>
<td>45% to 75%</td>
<td>35% to 45%</td>
<td>box lacrosse</td>
</tr>
<tr>
<td>P1HV²V</td>
<td>25% to 35%</td>
<td>35% to 45%</td>
<td>NA</td>
</tr>
<tr>
<td>P1HV³V</td>
<td>25% to 35%</td>
<td>45% to 75%</td>
<td>martial arts, Table tennis,</td>
</tr>
<tr>
<td>P2HV</td>
<td>35% to 45%</td>
<td>35% to 45%</td>
<td>handball, korfball, futsal</td>
</tr>
<tr>
<td>P2HV³V</td>
<td>45% to 75%</td>
<td>35% to 45%</td>
<td>NA</td>
</tr>
<tr>
<td>P2HV²V</td>
<td>35% to 45%</td>
<td>45% to 75%</td>
<td>dance &amp; KEEP-FIT, VOLLEYBALL</td>
</tr>
<tr>
<td>P3HV</td>
<td>45% to 75%</td>
<td>45% to 75%</td>
<td>badminton, basketball</td>
</tr>
</tbody>
</table>

6.3.4 Sports surface market

It is estimated that there are over 4,500 multi-sport halls in England. This represents approximately 2.7 million m² of sports surface. The vast majority (83%) are small halls with three to four badminton courts (Sport England 2012). This Figure is approximately twice that for Australia, which has slightly less than half the population of England, but slightly higher levels of sport participation. It is impossible to segment a market unless it is first clearly defined. The way in which a market is defined influences the approach to its segmentation. The school hall/gym market, the target market for the proposed new surface, is the largest market for sports floors in Australia,
with primary schools having 1.9 million enrolments and secondary schools having 1.4 million enrolments in 2008 (DEEWR 2010).

### 6.3.5 Analysing customer features and benefits

Customers not only want surfaces which are reasonably priced, but they also require a sports surface that is useful, that functions as promised, is usable, desirable, well differentiated from competing surfaces and sustainable. In addition to these customer-oriented requirements, the manufacturer needs a surface which is easy to produce and profitable. A well-designed sports surface should combine the following valuable qualities (Figure 6.13).

- **usefulness**
  The surface should be highly functional. It should work well and function as promised and it should do what it is expected to do and satisfy an appropriate level of performance. Many commercially available surfaces however do not provide the athlete with appropriate levels of force reduction, which can result in injury to knees, ankles and lower backs when these surfaces are used over a prolonged period of time.

- **usability**
  The surface should be safe and have appropriate ergonomics, considering how, where, how often and which sports will be played on the surface and the way in which it is installed, maintained, repaired and removed at its end of life.

- **desirability**
  The surface should have an appropriate aesthetics/visual impact/colour, which complements the sports facility in which it is placed, over the useable life of the surface. What is acceptable will depend on the characteristics of the market (local government sport centre, school hall, private gym) and the particular sports which are to be serviced. Features which appear to be acceptable are also dependent upon other competitive and complementary products, such as the other architectural elements in the interior of the building and complementary sports equipment. It is important that the surface aesthetics are suitable for the market, users and use environment.

- **manufacture**
  The surface must be capable of achieving an economic volume of manufacture, using appropriate materials and production processes, considering the impact on the association of new parts, assemblies and assembly processes. Producible surfaces combine optimisation of assembly and manufacture, with modularity and platform strategies, and will be mindful of its environmental impacts over its entire life-cycle. It should be designed for ease of manufacture, assembly, installation and disassembly.
- **profitability**
  The surface should meet user and market needs (price, place, promotion and product), represent good value for money and it must result in adequate business rewards, measured in terms of market share, profit, turnover or sales volume.

- **differentiation**
  The benefits of good design are seen in well differentiated surfaces. To this extent, the surface should be original and innovative. Differentiation can be achieved through it being able to satisfy the user’s core needs in novel ways, by achieving superiority in the surface’s physical attributes or by providing prominent support services around the physical product system, for example, a product stewardship business model. The surface should have a competitive advantage and preferably a sustainable competitive advantage potentially through the generation of protectable intellectual property.

- **sustainability**
  The surface should exert the minimum possible impact on the environment, while exceeding the safety requirements for this category of product. The surface should also promote high levels of participation through reduced injury rates.
Figure 6.13  Sports surface value proposition
Within the design process, attention should focus on two distinct areas: a) providing the lowest cost components to carry out the necessary functions for surface value in use, and b) providing features/benefits which make the product acceptable in use, when compared with competing flooring systems.

### 6.3.6 Customer benefits analysis

Functions can be relatively easily identified and costed, but product features and benefits are not cost-measurable, in that they are a measure of how well the product functions as perceived by the customer. In the design process, initial emphasis is placed upon the mechanical excellence of the surface’s components to provide user acceptance. A customer features analysis can be used to determine which features and benefits are important to sports surface users, as these factors will influence sales, continued customer satisfaction and recommendations to other potential customers. Another aspect of the features/benefits analysis is to make comparisons between competitor’s
strengths and weaknesses and to highlight areas where design effort and resources should be concentrated (Gale 1994).

An obvious source of feature listing is a customer sales brochures and company websites. An additional source of reference can be obtained through trade journals and trade websites, which can provide independent reviews on a wide range of flooring system types.

The most important source of features listing can be augmented by the function analysis. The function analysis outlines what the product does, but not how well it performs particular functions.

The customer features of a sports surface when viewed across all sports surface categories would include:

- high friction (allow grip)
- low cost
- flat surface (allow tile interconnection/thermal expansion/contraction)
- durable
- simple to clean
- simple to maintain and repair
- simple to install and remove
- multipurpose/multi-sport
- sustainable
- colour variety
- reduce repetitive stress injury (attenuate HGRF and VGRF)
- moisture resistant
- fungus and mildew resistant
- no climate control required
- looks good and stays looking good.

The most critical features from the perspective of this project related to how well the surface functions perform from the perspective of player safety.

Once the analysis was complete for the current study, an assessment was made of the relative importance of each feature/benefit. Features were scored relative to each other from one to five points, the higher score indicating the features of importance as perceived by the user/customer for
the sports surface. The purpose of the analysis was to determine where particular emphasis should be placed during the design study.

In carrying out the rating process, facility staff at Netball South Australia’s ETSA Park were interviewed to allow the views and opinions of surface consumers to be captured in the features/benefits responses. The feature which was associated with the basic function for the particular market was ranked highest at five points. The scores allocated to other features reflected the importance that the respondents assigned to each.

When rating decisions for scores for the other features proved difficult to determine, a systematic paired comparison technique was used to develop a relative ranking of each feature. In this technique, each feature was considered relative to each other feature. The table used to record each successive decision is called the criteria scoring matrix.

<table>
<thead>
<tr>
<th>Features</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Friction (no slipping)</td>
<td>A = 13.23</td>
</tr>
<tr>
<td>Low cost</td>
<td>B = 12.21</td>
</tr>
<tr>
<td>Flat surface</td>
<td>C = 20.36</td>
</tr>
<tr>
<td>Durable (10 year warranty min)</td>
<td>D = 12.21</td>
</tr>
<tr>
<td>Simple to repair</td>
<td>E = 4.07</td>
</tr>
<tr>
<td>Simple to clean and maintain</td>
<td>F = 1.02</td>
</tr>
<tr>
<td>Simple to install and remove</td>
<td>G = 5.09</td>
</tr>
<tr>
<td>Multi-purpose/multi-sport</td>
<td>H = 23.41</td>
</tr>
<tr>
<td>Sustainable (over full lifecycle)</td>
<td>I = 9.16</td>
</tr>
<tr>
<td>Colour Variety</td>
<td>J = 3.05</td>
</tr>
<tr>
<td>Reduce repetitive stress injury</td>
<td>K = 28.6</td>
</tr>
<tr>
<td>Moisture resistant</td>
<td>L = 3.05</td>
</tr>
<tr>
<td>Fungus and mildew resistant</td>
<td>M = 1.02</td>
</tr>
<tr>
<td>No climate control required</td>
<td>N = 8.14</td>
</tr>
<tr>
<td>Looks good and stays that way</td>
<td>O = 15.27</td>
</tr>
</tbody>
</table>

**Figure 6.14** Paired comparison criteria scoring matrix

The ranking scores developed by the paired comparison criteria scoring matrix were then added to the customer feature/benefit analysis matrix. This matrix lists each competitor system under consideration and the target features and benefits which will be provided by the proposed new product. The surface systems considered were:

- timber sports surfaces
- prefabricated sheet sports surfaces
- pour-in-place sports surfaces
- modular plastic tile sports surfaces
proposed new modular plastic tile sports surface.

For each system, including the proposed new surface, a comparison was made against each feature as to how well it performed, where a score of five out of five is a perfect score (Kaufman 1992; Kaufman and Carter 1994). Each successive feature was evaluated, surface system by surface system and relative scores allocated against the five point scale. If no surface received a perfect score, this was taken as an indicator for potential for improvement. The feature ratings were multiplied by the individual feature scores for each surface type in turn to obtain a feature performance score. Once this process had been completed, the calculated figures were totalled to determine each product’s relative effectiveness (P). The surface with the highest score was considered to have the highest level of overall performance. As the approximate retail cost of each surface under investigation was known, the value received for the retail cost could then be determined by:

\[
\text{Effectiveness Cost Ratio (Customer Value)} = \frac{\text{Relative Effectiveness Score}}{\text{Retail Cost ($)}}
\]

Eq. 6.1

The highest effectiveness cost ratio score indicates which surface represents the best value. A product’s effectiveness cost ratio score indicates which product ‘should’ rate highly in the opinion of a person making a surface purchasing decision. In order to increase a surface’s value-for-money, the surface’s retail price can either be decreased, the surface’s relative effectiveness improved, or both.

Lowering the retail cost by virtue of lowering manufacturing costs is the traditional objective of techniques such as value management. However, increasing the performance of important features, such as ‘reduce repetitive stress injury’ by attenuating HGRF and VGRF or ‘flat surface’ by reducing the negative effects of thermal expansion and contraction, or making the surface suitable for ‘multipurpose/multi-sport’ applications, may be a more effective approach to increasing a surface’s value-for-money and therefore potential sales. The analysis of the data is described in Table 6.2.

Analysing the competitive strengths and weaknesses of each product is an important source of design opportunity. Noting why certain products have low individual feature/benefit scores and identifying why certain surfaces have high ratings. Areas where no existing product rates highly for a given feature, indicates a ‘hole in the market’ and therefore a design opportunity, as is the case in this study with ‘reduce repetitive stress injury’. The argument may be made that timber sports
surfaces already target this benefit, but this is achieved at the expense of cost, difficulty to repair, install, remove, colour variety, lack of capacity for multi-use, poor resistance to moisture and temperature variation.

Table 6.2  Customer benefits analysis

<table>
<thead>
<tr>
<th>CUSTOMER REQUIRED FEATURES/BENEFITS</th>
<th>COMPETITOR SURFACE SYSTEMS</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rating of features relative to each other</td>
<td>2.7</td>
<td>2.3</td>
<td>3.9</td>
<td>2.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Timber Sports Surface</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>Pre-fabricated Sheet Sports Surface</td>
<td>8.48</td>
<td>8.48</td>
<td>8.48</td>
<td>8.48</td>
<td>8.48</td>
<td></td>
</tr>
<tr>
<td>Multi-Use</td>
<td>4.0</td>
<td>5.0</td>
<td>5.0</td>
<td>3.0</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>Modular Plastic Tile Sports Surface</td>
<td>15.4</td>
<td>19.25</td>
<td>19.25</td>
<td>7.7</td>
<td>11.55</td>
<td></td>
</tr>
<tr>
<td>Proposed New Surface</td>
<td>11.55</td>
<td>6.93</td>
<td>6.93</td>
<td>6.93</td>
<td>6.93</td>
<td></td>
</tr>
</tbody>
</table>

| F  | Simple to clean and maintain | 0.2 | 3.0 | 4.0 | 0.77 | 3.85 |
|    |                              |     |     |     |     |     |
| G  | Simple to install and remove | 1.0 | 1.0 | 1.0 | 0.96 | 1.92 |
|    |                              |     |     |     |     |     |
| H  | Multi-purpose/multi-sport    | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |
|    |                              |     |     |     |     |     |
| I  | Sustainable (over full lifecycle) | 1.7 | 3.0 | 3.0 | 3.0 | 3.0 |
|    |                              |     |     |     |     |     |
| J  | Colour variety               | 0.6 | 1.0 | 1.0 | 0.58 | 1.74 |
|    |                              |     |     |     |     |     |
| K  | Reduce repetitive stress injury | 5.0 | 4.0 | 4.0 | 2.0 | 2.0 |
|    |                              |     |     |     |     |     |
| L  | Moisture resistant           | 0.6 | 1.0 | 1.0 | 0.58 | 1.16 |
|    |                              |     |     |     |     |     |
| M  | Fungus and mildew resistant  | 0.2 | 2.0 | 2.0 | 0.38 | 0.57 |
|    |                              |     |     |     |     |     |
| N  | No climate control required  | 1.5 | 1.0 | 1.0 | 1.54 | 6.15 |
|    |                              |     |     |     |     |     |
| O  | Looks good and stays looking good | 2.7 | 5.0 | 5.0 | 2.0 | 2.0 |
|    |                              |     |     |     |     |     |
| P  | RELATIVE EFFECTIVENESS TOTAL | 85.85 | 95.98 | 94.84 | 100.07 | 119.69 |
| Q  | APPROXIMATE COST/m2          | 5m2 | 120 | 100 | 100 | 80 | 90 |
| R  | EFFECTIVENESS COST RATIO (VALUE FOR MONEY) | 0.72 | 0.95 | 0.95 | 1.25 | 1.33 |

1/9
6.3.7 Sustainable design approaches and considerations

It is clear that we are currently living in an unsustainable manner and the need to address sustainability in all aspects of our daily lives is urgent. Everyone involved in the commercialisation of new products, buildings and services has an obligation to address the related environmental, social and ethical impacts of their activities. This presents commercial opportunities for innovative companies. Sustainable design considers environmental impacts at every stage in the life of a sports surface and includes the materials and energy consumed over its life cycle, and the wastes and emissions produced over its life cycle. Sustainable design seeks to address environmental issues at their source by locking in positive environmental attributes and locking out negative environmental features. To achieve these goals, a number of sustainable design approaches were employed as a source of idea generation (White, Stewart et al. 2008).

**Question conventional approaches to the problem.** Develop alternative approaches to achieving sports surface force reduction and question whether conventional force reduction approaches are the most appropriate to providing low injury risk sports surfaces to the community. Are current approaches the most environmentally benign techniques available to achieve force reduction and is it possible that the business model to provide a sports surface to the market can be converted from a retail business model to a service business model? A service model could be achieved by leasing sports surfaces rather than selling sports surfaces, and is there an appropriate business case which can be developed in order to justify this approach?

**Can the surface be made less complicated?** Simple, well-designed surface solutions can decrease material content, weight per m² and manufacturing process variety. Simplified designs also usually entail reduced material variation and therefore increase the recyclable potential of a surface. Simple, compact and freight effective surface designs can improve transport efficiency. Pallet loading optimisation should therefore be targeted.

**Make the surface multi-sport and multi-use.** This approach may seem at first to contradict the previous approach, but there can be considerable differences between aspects of complexity and usefulness. Exploiting a logical additional use for a surface may make a surface more multipurpose adaptable and flexible. Multi-use surfaces can reduce material and energy consumption and
increase convenience, but it is important that added usefulness does not detract from its primary sports safety focus.

**Reduce surface material variety and volume.** Where feasible, the surface should be created using the minimum amount of material and manufactured from as few material types as possible. This will encourage efficiencies in recycling at the surface’s end-of-life.

**Avoid the use of toxic materials and chemicals.** Commonly used sports surface materials, such as PVC, polystyrene and formaldehyde should, where possible, be avoided. These materials in many cases have non-toxic equivalents, such as polypropylene. However, it is important to make sure that the lifecycle and durability of replacement materials are fully considered.

**Reduce the weight and size of surface components.** The use of light-weight materials can reduce energy consumption and cost through more efficient freight movements. Similarly, weight reduction can reduce emissions for products that need to be transported as part of their manufacture or operation. Weight and size can often be reduced by simplifying designs and eliminating unnecessary components and features. However, care should be taken not to reduce surface durability in order to achieve weight reductions, as a surface which has reduced durability may need to be replaced more often over the life of a sports facility.

**Optimised manufacturing processes.** Determine which manufacturing processes are appropriate for the surface. Manufacturing processes are highly complex and vary greatly, and often embodied energy, embodied water and material waste can be concealed within complex manufacturing systems.

**Design surface packaging in parallel with the surface.** Lightweight packaging solutions which use sustainable, biodegradable, recycled or recyclable materials, can reduce carbon emissions and material waste. The new surface design proposal will therefore utilise full pallet loads of preassembled tile sheets, with each pallet holding approximately 100m$^2$ of surface.

**Design for surface upgradeability.** Develop surfaces that can be modified or customised, to keep abreast of changing user needs. Products that are designed to be modifiable in the absence of durability may fail before they are ready to be modified. The floating surface proposed can be
removed, the underlay modified to suit changing force attenuation needs which may be required by an alternative selection of sports and then the playing surface replaced if required.

**Create durable high quality sports surfaces.** Customers desire high quality sports surfaces that maintain an acceptable appearance and function well for a minimum of 15 years. Designed correctly, sports surfaces can transcend our disposable culture.

**Create energy and water efficient sports surfaces.** Surfaces which consume less energy are increasingly out-competing energy hungry alternatives. The predicted large increases in energy prices as non-renewable resources become scarcer and carbon taxation will demand a greater focus upon energy efficiency. In addition, water efficiency is becoming a key differentiator for products. There are therefore increasing opportunities for sports surfaces that promote more efficient use of energy and water.

**Design for life after death.** Most products, including sports surfaces, will not last forever. Surfaces should therefore be designed for ease of disassembly and material sorting for recycling, at their end-of-life.

**Modular approaches.** Modular sports surfaces are more easily recovered for recycling at the end of their life and are also more easily refurbished and repaired, therefore extending their life. Modular surfaces are, in addition, generally more efficient to manufacture and distribute, leading to reduced levels of embodied energy. Surfaces should not, however, be made more complex in order to achieve modularity. The application of additional fasteners and materials should be avoided in order to establish modularity, unless the fastening technology can be made integral with the design, as has been achieved with modular tile surface systems, where fastening features are included on injection moulded tile components.

**Use recycled, recyclable, renewable and biodegradable surface materials.** The new surface and its packaging will utilise recycled or easily recyclable polymers, such as co-polymer polypropylene, paper, cardboard and timber. Sourcing sustainable materials from distant locations can, however, occasionally prove more harmful than beneficial, and the overall lifecycle impacts should therefore be considered.

**Avoid using surface coatings and other material contaminants.** Painting a material, applying a surface coating or applying line-marking coatings, generally makes the constituent materials used
in the manufacture of the surface more difficult to recycle at the surface’s end-of-life, as the coating cannot be simply separated from the surface. As a consequence, many painted or coated surfaces are not recycled at end-of-life.

6.4 Phase 3: Final concept development, final prototype testing and pre-production

Phase 3 of the design process sought to explore a range of processes which enable creative thinking approaches in answer to the product definition and validation testing. Specifically, this phase addressed failure modes and effects analysis, morphological analysis and unit cost analysis.

6.4.1 Failure modes and effects analysis (FMEA)

Failure modes and effects analysis (FMEA) is a product research and development tool which enables potential design problems to be predicted during the early stages of the design process. FMEA provides a highly controlled approach to the analysis of the potential root causes of design failure, the assessment of the impacts of failure, and the effectiveness of potential strategies for failure circumvention.

The eventual output from the FMEA process is a variety of courses of action to evade, identify or decrease the impact of the possible modes of failure (Kmenta and Ishii 2004). FMEA is a fundamental tool in product design and development, and is normally recommended as a
component of an organisation’s quality management system. Its use encourages the product design team to consider:

- What aspects of a design could potentially fail?
- The level or severity of the failure?
- What features can be introduced to avoid the issue?

FMEA analyses what could go wrong with a sports surface during its various life-cycle phases, as a result of a design deficiency.

- FMEA is normally carried out in the early stages of the surface design process.
- FMEA presupposes that the product will be developed in accordance with the surface product definition.
- FMEA aims to reduce the organisation’s dependence on process controls and part inspection in order to satisfy any deficiencies which may exist in the surface’s design.
- FMEA considers what could go wrong with a modular plastic sports tile sports surface during its manufacture, installation service/use and end-of-life, as a result of non-compliance to the required product definition or the developed design. The information acquired while undertaking the FMEA process is gathered and presented in a tabulated format, as demonstrated in Table 6.3
Table 6.3  Sports surface failure modes and effects analysis

<table>
<thead>
<tr>
<th>1 System/component/function</th>
<th>2 Potential failure mode</th>
<th>3 Potential effects of failure</th>
<th>4 Severity</th>
<th>5 Critical</th>
<th>6 Potential root cause of failure</th>
<th>7 Occurrence</th>
<th>8 Current design controls</th>
<th>9 Detection</th>
<th>10 Risk priority number</th>
<th>11 Recommended actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tile-connector attenuation gap</td>
<td>Gap becomes blocked with dirt</td>
<td>Loss of tile movement and hence force attenuation potential</td>
<td>5</td>
<td>Safety issue. Increase of injury risk.</td>
<td>Inadequate cleaning. Maintenance procedures not being followed. Adjacent walls too large.</td>
<td>2</td>
<td>Detailed in cleaning and maintenance guide. Form allowing dirt to build up on adjacent tile/connector faces.</td>
<td>3</td>
<td>30</td>
<td>Use vacuum scrubber. Emphasise the importance of weekly cleaning schedule. Make adjacent walls on tile and connector broken, to minimise surface area where dirt can accumulate.</td>
</tr>
<tr>
<td>Tile-connector attenuation gap</td>
<td>Gap closing as a result of thermal expansion</td>
<td>Floor buckling</td>
<td>5</td>
<td>Safety issue</td>
<td>High temperatures (above 37 degrees centigrade)</td>
<td>2</td>
<td>Designed to operate over a 0 to 37 degree centigrade operating temperature range.</td>
<td>4</td>
<td>40</td>
<td>Warning, stating that the surface should not be played on in on court temperatures above 37 degrees centigrade of if there is any evidence of buckling.</td>
</tr>
<tr>
<td>Tile-connector inter-connection</td>
<td>Excessive ‘flash’ in the snap-locking region</td>
<td>‘Flash’ at the parting line is not acceptable. Flash will reduce the ‘intentional’ gap, which exists between the tile and connector edges when assembled. Tile and connector will not lock together during assembly</td>
<td>5</td>
<td>Quality issue</td>
<td>Higher than normal injection pressures in connector moulding.</td>
<td>2</td>
<td>Split-line weld.</td>
<td>3</td>
<td>30</td>
<td>Detail periodic flash inspection in moulding and assembly SOP.</td>
</tr>
<tr>
<td>1</td>
<td>System/ component/ function</td>
<td>2</td>
<td>Potential failure mode</td>
<td>3</td>
<td>Potential effects of failure</td>
<td>4</td>
<td>Severity</td>
<td>5</td>
<td>Critical</td>
<td>6</td>
</tr>
<tr>
<td>Excess plastic on playing surface support ribs of tile or connector.</td>
<td>Broken ejector pin</td>
<td>Excessive plastic in the underlay connection surface</td>
<td>5</td>
<td>Quality issue</td>
<td>Broken ejector pin.</td>
<td>1</td>
<td>Spare machined ejector pins.</td>
<td>2</td>
<td>10</td>
<td>Detail periodic rib inspection in moulding and assembly SOP.</td>
</tr>
<tr>
<td>Tile cupping</td>
<td>Wrong moulding profile and low packing pressure.</td>
<td>Surface will not be flat. Shallow dish effect over the surface.</td>
<td>5</td>
<td>Quality issue</td>
<td>Lower than acceptable packing pressure.</td>
<td>3</td>
<td>Tile part weight to be between 800 to 840 grams.</td>
<td>4</td>
<td>60</td>
<td>Check for correct program. With minimal delay, remove part from die. Quickly place part flat side up (ribbed side down) on a flat surface. Allow 10 parts to cool. Check cool part for flatness with a straight edge. 1mm maximum allowable gap.</td>
</tr>
<tr>
<td>Tile bowing</td>
<td>Wrong moulding profile and low packing pressure.</td>
<td>Surface will not be flat. Shallow bow effect over the surface.</td>
<td>5</td>
<td>Quality issue</td>
<td>Higher than acceptable packing pressure.</td>
<td>3</td>
<td>Tile part weight to be between 800 to 840 grams.</td>
<td>4</td>
<td>60</td>
<td>Check for correct program. Parts MUST be moulded flat and remain flat (a maximum gap of 1mm is allowable at any point on the flat surface, when a steel rule edge is placed on the face of the tile).</td>
</tr>
<tr>
<td>Correct colours for tile connector sheet sub-assembly combination</td>
<td>Wrong tile and connector colour combinations.</td>
<td>Inconsistent visual appearance.</td>
<td>3</td>
<td>Quality issue</td>
<td>Operator error.</td>
<td>1</td>
<td>First sheet in pallet stack is confirmed as correct colours.</td>
<td>2</td>
<td>6</td>
<td>Detail order inspection in moulding and assembly SOP.</td>
</tr>
<tr>
<td>Tile gate</td>
<td>Sharp ‘dag’ at tile gate.</td>
<td>Can hurt athlete if they come into contact with the ‘dag’.</td>
<td>4</td>
<td>Safety issue</td>
<td>Changed operating window.</td>
<td>3</td>
<td>First-off checked with last-off.</td>
<td>1</td>
<td>12</td>
<td>Detail periodic gate inspection in moulding and assembly SOP. Trim ‘dag’ flush and Smooth if required.</td>
</tr>
</tbody>
</table>
For the FMEA process, the following 11 step method was adopted:

1. **System/component/function**: The specific name or describing feature of the sports surface element or the issue under study is recorded.

2. **Potential failure modes**: The means by which FMEA step 1 could possibly fail while being used. All potential failure modes should be identified at this stage.

3. **Probable effects of failure**: For each possible failure mode, what are the probable ramifications? What effect will the failure have on the surface’s different stakeholders? What will the probable outcomes be, if the component or surface system fails, where an individual failure mode could potentially have more than one resulting effect.

4. **Severity rating**: Each failure result is judged for its probable importance, on a scale from 1 to 5, as indicated below.

<table>
<thead>
<tr>
<th>Severity rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The customer will not detect the failure.</td>
</tr>
<tr>
<td>2</td>
<td>The customer may notice the failure and be dissatisfied a little.</td>
</tr>
<tr>
<td>3</td>
<td>Possible moderate customer dissatisfaction, minor injury, inconvenience or delay.</td>
</tr>
<tr>
<td>4</td>
<td>Possible high levels of customer dissatisfaction, serious injury or major disruption.</td>
</tr>
<tr>
<td>5</td>
<td>Possible safety risk or legal problems, there is the potential for loss of life or result in major user displeasure.</td>
</tr>
</tbody>
</table>

5. **Critical**: The identification of theoretically critical surface failures which must be rectified (e.g. sales concerns, safety concerns).

6. **Possible root cause/mechanisms of failure**: Each failure mode will have an original cause. Therefore, it is important to identify the potential root causes of failure.

7. **Occurrence ranking**: Requires deliberation of the likelihood of the potential failure occurring on a 1 to 5 scale. This stage is critical to the process and each response categorised as very high or high must be immediately considered and rectified.

<table>
<thead>
<tr>
<th>Occurrence ranking</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Unlikely probability of occurrence.</td>
</tr>
<tr>
<td>2</td>
<td>Low probability of occurrence.</td>
</tr>
<tr>
<td>3</td>
<td>Moderate probability of occurrence.</td>
</tr>
<tr>
<td>4</td>
<td>High probability of occurrence.</td>
</tr>
<tr>
<td>5</td>
<td>Very high probability of occurrence.</td>
</tr>
</tbody>
</table>
8 **Current design controls**: Are there design controls in place which aim to diminish or eradicate the possible risk of failure? These controls could include prototyping, testing or market surveys.

9 **Detection rating**: This rating aims to establish how perceptible the potential fault will be. Again, recommended ratings would be on a scale from 1 to 5:

<table>
<thead>
<tr>
<th>Detection rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Almost certain to identify potential failure cause</td>
</tr>
<tr>
<td>2</td>
<td>Good chance of detecting potential failure cause</td>
</tr>
<tr>
<td>3</td>
<td>Not likely to detect potential failure cause.</td>
</tr>
<tr>
<td>4</td>
<td>Close to no probability of detecting potential failure cause.</td>
</tr>
<tr>
<td>5</td>
<td>No probability of detecting the potential failure cause.</td>
</tr>
</tbody>
</table>

10 **Risk Priority Number (RPN)**: Each potential failure mode necessitates the assignment of a ‘Risk Priority Number’, to allow the ranking of mitigating activities which need to be applied. The RPN is the product of the severity, incidence and detection ratings:

\[
RPN = \text{Severity rating} \times \text{Occurrence rating} \times \text{Detection rating}
\]

The RPN value gives an indicator of the design risk, the items with the highest RPN and severity ratings being given first concern.

11 **Recommended actions**: Actions to decrease the impact or probability are critical and these actions should be targeted and quantifiable. Focus should address the root causes of any potential failures and not only the symptoms of failure.

The recommended actions identified in section 11 were deployed in the subsequent manifestations of the product and process controls which were developed.

6.4.2 **Sports surface innovation**

At the core of any problem solving activity, there is the need to employ creative thinking approaches, in order to find alternative ways of developing explicit improvements. Innovation can be described as ‘the successful exploitation of creativity’. Taking this definition further, creativity can be applied to a new product or service, or even an entirely new business model, and exploitation suggests that the concept must be executable and ideally value creating. Lastly, success suggests that the innovation is desirable and is embraced by the target customer.
Innovation = Creativity + Successful Exploitation \hspace{1cm} \textbf{Eq. 6.2}

Where:

Creativity = a desirable sports surface or sports surface provision service concept which satisfies unmet needs of value to the customer and/or user.

Successful exploitation = a feasible sports surface commercial strategy which creates a sustainable competitive advantage for the concept, which can be offered to and embraced by the customer and/or user.

In order to successfully exploit the innovations flowing from the new sports surface, the surface product or service provided must commercially meet the various unmet needs of the user, with particular emphasis on community safety, the economic and environmental needs of the user, as identified in the conceptual vision for the project, in subsection 6.2.2.

\subsection*{6.4.3 Innovation through morphological analysis}

As creativity is a key component of innovation, enhanced creativity through the use of creative thinking techniques was employed. This exercise utilised morphological analysis as an idea generation technique to provide a structured approach to concept generation in the creative phase of the project in order to broaden the scope of potential solutions to the defined design problem and product definition (Jones 1981).

This creative thinking process was used to contribute to the generation of alternative design approaches for the creation of a force attenuating surface through the systematic analysis of form, configuration and functions that a modular tile surface may embody. Morphological charting is a visual technique for capturing the required product system’s functionality, and can be used to expose alternative conceptual embodiments and arrangements of a sports surface, in order to achieve appropriate levels of functionality.

For each identified surface function, a number of potential solutions, along with morphological mapping, enabled these solutions to be clearly expressed and delivered a structured approach for the consideration of unconventional solution combinations. In addition, this process also contributed to the early consideration of product architecture and structural systems through the creation and reflection of different groupings of sub-solutions.

**Product function solution ideation.** Functions that were required in order for the product to fulfil the highest order need, that is, ‘provide a low injury risk sports playing surface’, were categorised
into primary and secondary functions and listed. Ideally, the number of functions under consideration should be limited. Therefore, in this case, four primary functions and nine required secondary functions were identified for morphological analysis. Once each primary and secondary function was identified, a brainstorming approach was used to generate suggestions for potential solutions by which the functions might be realised. New conceptual approaches, as well as known solutions or components were listed and the concept solutions generated were expressed visually as well as textually.

**Charting functions and combinations.** A ‘morphological chart’ containing all potential sub-solutions was generated, representing the ‘solution space’ for the product and was composed of combinations of sub-solutions. In this case, Alexander Osborne’s ‘idea stimulation checklist’ was used as an idea generation tool (Osborn 1957; Jones 1981).

The developed ideas were interpreted and analysed in a mind-mapping format (Buzan and Buzan 1996) as shown in Figure 6.15, and the ideas presented in the yellow rectangles shown, were those initially selected for further development. The total number of combinations was very large, therefore those displayed, were limited to the most technically feasible, environmentally sustainable and commercially attractive options. User need issues identified during the peeves analysis were also considered during the morphological analysis. Figure 6.16 indicates the solution groupings, which were identified for further development.
Figure 6.15  Conceptual mind map
### Table 6.7  Potential concepts for development

<table>
<thead>
<tr>
<th>Low Injury risk sports playing surface morphological analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary functions</strong></td>
</tr>
<tr>
<td>1 Attenuate horizontal ground reaction forces</td>
</tr>
<tr>
<td>2 Attenuate vertical ground reaction forces</td>
</tr>
<tr>
<td>3 Allow tile interconnection</td>
</tr>
<tr>
<td>4 Allow grip</td>
</tr>
<tr>
<td>5 Allow horizontal tile movement</td>
</tr>
<tr>
<td>6 Allow gap expansion</td>
</tr>
<tr>
<td>7 Allow gap contraction</td>
</tr>
<tr>
<td>8 Allow horizontal force dampening</td>
</tr>
<tr>
<td>9 Allow vertical tile movement</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Secondary functions</strong></th>
<th><strong>Viable development options</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Attenuate horizontal ground reaction forces</td>
<td>Lower friction levels required as a result of lower braking forces through Horizontal Force Damping. Avoid tissue overload.</td>
</tr>
<tr>
<td>2 Attenuate vertical ground reaction forces</td>
<td>Intermittent application of different treatments which can immediately alter the coefficient of friction, for different sports.</td>
</tr>
<tr>
<td>3 Allow tile interconnection</td>
<td>Interchangeable textured tool inserts which change the frictional characteristics of the surface from one surface to the next.</td>
</tr>
<tr>
<td>4 Allow grip</td>
<td></td>
</tr>
<tr>
<td>5 Allow horizontal tile movement</td>
<td></td>
</tr>
<tr>
<td>6 Allow gap expansion</td>
<td></td>
</tr>
<tr>
<td>7 Allow gap contraction</td>
<td></td>
</tr>
<tr>
<td>8 Allow horizontal force dampening</td>
<td></td>
</tr>
<tr>
<td>9 Allow vertical tile movement</td>
<td></td>
</tr>
<tr>
<td>Secondary functions</td>
<td>Viable development options</td>
</tr>
<tr>
<td>----------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>10 Allow vertical force dampening</td>
<td>Use co-moulded TPE/PP/PU rib to eliminate need for underlay</td>
</tr>
<tr>
<td></td>
<td>Tile rib/underlay shaped to ‘bed-in’ to each other</td>
</tr>
<tr>
<td></td>
<td>Use co-moulded PP/TPE/PU foam tile to eliminate need for underlay</td>
</tr>
<tr>
<td></td>
<td>Entire tile and connector moulded from more compliant material</td>
</tr>
<tr>
<td>11 Allow tile movement</td>
<td>Use co-moulded spring elements between tile and connector to absorb dimensional changes</td>
</tr>
<tr>
<td></td>
<td>Multi-directional (0, 30, 45, 60 and/or 90 degree increment) ribs under tile to guide and promote tile sliding and movement</td>
</tr>
<tr>
<td></td>
<td>Tile/connector interlocking interface which promotes universal movement</td>
</tr>
<tr>
<td></td>
<td>Reduce friction between tile/connector and underlay to promote movement and hence ability to allow dampener compression</td>
</tr>
<tr>
<td>12 Allow thermal expansion and contraction</td>
<td>Use co-moulded spring/dampener elements between tile and connector to absorb dimensional changes</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>13 Allow horizontal and vertical colour change</td>
<td>Octagonal tile (close to uniform material flow lengths) with 4 surrounding concave square connectors, which promote 90 degree colour changes</td>
</tr>
<tr>
<td></td>
<td>Metric tile (0.5m), which can comply with in-game mapping for various sports</td>
</tr>
<tr>
<td></td>
<td>Concave/convex forms to indicate connecting/interfacing edges when assembling surface</td>
</tr>
<tr>
<td></td>
<td>Half and quarter moulded connector forms with connecting loop features (and no gap) to allow for full colour change. May be cut as a cost-effective alternative to moulding.</td>
</tr>
</tbody>
</table>

The development options identified in the morphological chart were grouped and potential solutions modelled in two and three dimensions as shown in Figure 6.16, to allow further exploration of each concept to assist the development of a number of mathematical models of the tile and connector.
### Table 6.8  Functional groupings and potential solution modelling approaches

<table>
<thead>
<tr>
<th>Functional groupings and potential solution modelling approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
</tr>
<tr>
<td>11</td>
</tr>
<tr>
<td>9</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
</tbody>
</table>

![Diagram](image_url)
### Functional groupings and potential solution modelling approaches

<table>
<thead>
<tr>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tile connector/tile snap-fit at 90 degrees to interface to promote lateral movement.</td>
<td><img src="image1.png" alt="Illustration" /></td>
</tr>
<tr>
<td>Tile/connector interface which promotes horizontal movement via hoop and loop sliding mechanism.</td>
<td><img src="image2.png" alt="Illustration" /></td>
</tr>
<tr>
<td>Low coefficient of friction at the tile underlay interface (i.e. coated underlay) to promote tile/underlay 'slipping'.</td>
<td><img src="image3.png" alt="Illustration" /></td>
</tr>
<tr>
<td>4 Allow grip</td>
<td><img src="image4.png" alt="Illustration" /></td>
</tr>
<tr>
<td>8 Allow horizontal force dampening</td>
<td><img src="image5.png" alt="Illustration" /></td>
</tr>
<tr>
<td>In-mould film added during the injection moulding process, which can customise the coefficient of friction to suit different categories of sport.</td>
<td><img src="image6.png" alt="Illustration" /></td>
</tr>
<tr>
<td>Lower friction levels achievable as a result of lower braking forces through horizontal force dampening.</td>
<td><img src="image7.png" alt="Illustration" /></td>
</tr>
</tbody>
</table>

8 Allow horizontal force dampening

Use co-moulded or insert-moulded spring/isolator elements between tile and connector (may be integral with the tile or connector). It will be more economical to co-mould this feature with the connector as opposed to the tile, as the connector tool will be smaller, significantly reducing tooling complexity and therefore costs.

Octagonal tile with 4 surrounding concave square shock attenuating connectors, which promote horizontal force reduction.

Isolator designs with 2mm height and low form factor. See chapter 7 for advanced isolator development.
<table>
<thead>
<tr>
<th>8</th>
<th>Allow horizontal force dampening</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Allow horizontal and vertical colour change</td>
</tr>
</tbody>
</table>

- Circular/dodecagonal tile with 6 surrounding triangular concave connectors, or octagonal tile with 4 surrounding square connectors, which promote 360 degree horizontal force reduction.
- Octagonal tile (close to uniform material flow lengths) with 4 surrounding concave square connectors, which promote 90 degree colour change.
- Metric tile (0.5m), which can comply with in-game mapping for various sports.
Figure 6.16 represents the final iterations of the tile and connector of this process and Figure 6.17 represents a 4m X 4m section of octagonal tile sports surface laid using the tile and connector surface format.

![Figure 6.16](image)

**Figure 6.16** Final iteration of octagonal tile and square connector

![Figure 6.17](image)

**Figure 6.17** Four meter X four meter section of sports surface laid utilising the octagonal tile and square connector shown in Figure 6.16

### 6.4.4 Unit cost analysis

Determining the cost of the proposed new surface is an important element of the product development process and an important aspect in being able to provide an affordable, low life-cycle cost and safe alternative to competing surfaces. Understanding the unit cost or the cost per square meter of the installed sports surface is critical to determining the commercial viability of the surface. Assessing the unit cost is an approach which is relevant to all stages of the product development method. At the beginning of a new product development project, it is essential to assess costs in order to determine a project’s feasibility. As the development of the conceptual method progresses, it should be possible to improve the accuracy of cost forecasts, but before full manufacture commences, along with the investment in expensive direct costs, such as injection moulding tooling, a clear and accurate understanding of the expected unit cost must be established. With an injection moulded tile surface, the extent to which the surface area can be covered per tile can have a significant impact on unit cost. Larger surfaces will have improved economies of scale...
through more economic production. In other words, the larger the tile area covered, the more efficient will be the cost to area covered.

**Factors considered in determining the new surface unit cost.** Surface unit cost can be defined as the surface manufacturing cost, divided by the area of surface produced. The time taken to apportion fixed costs must also be determined, which includes the amortisation period for injection moulding tooling, moulding fixtures and other elements of direct capital expenditure. Therefore, appreciating unit costs requires a detailed understanding of all variable and fixed costs which would be incurred in the manufacture of an injection moulded plastic tile sports surface, as detailed in Figure 6.18.

**Manufacturing fixed costs.** Manufacturing fixed costs are sustained regardless of the sport surface’s production volume and include the tile and connector injection moulding tools, cooling fixture procurement costs and any other costs directly related to the manufacture of the surface.

**Variable costs.** On the other hand, increasing the number of tile and connector units moulded in a production run and including injection moulding tool setup, injection moulding machine time, the assembly labour required to assemble the tile/connector sheet modules, polypropylene copolymer tile and connector material, flame and smoke retardant additives, ultraviolet radiation protection additives, colour additives, injection moulding machine cycle time, rubber underlay per unit area, packaging, freight and installation labour.

The production run-time will vary as a direct result of the floor area of surface being manufactured. Typically a netball surface will require approximately 800 square meters of playing surface, whereas an inline hockey stadium will require approximately 1800 square meters of playing surface. Therefore, the playing surface required for a sports facility is directly related to the individual sports which will be offered by the facility. A larger inline hockey surface will benefit from the efficiencies gained from the longer production runs required to manufacture a larger playing surface, and therefore will have a lower cost per unit area, in comparison to a much smaller netball surface.
Unit cost analysis is a useful approach to consider when balancing the effects of single cavity tooling, with more complex, expensive multi-cavity, inserted, over-moulded or co-moulding tooling. Combinations include low unit cost combined with high tool cost, versus complex expensive parts with corresponding lower tooling costs, but lower fixed costs. Moulding, tooling and assembly costs can be assessed through experience and through the acquisition of supplier quotations.

**Figure 6.18** Sports surface unit cost analysis structure.

**Table 6.9** Netball surface manufacturing cost analysis.

<table>
<thead>
<tr>
<th>Component</th>
<th>Purchased tile and connector moulded components ($/m²)</th>
<th>Surface installation labour/m² ($/m²)</th>
<th>Total unit variable cost ($/m²)</th>
<th>Tooling fixed cost ($)</th>
<th>Tooling life (moulding cycles)</th>
<th>Total unit fixed cost ($/m²)</th>
<th>Total unit cost ($/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tile (single cavity injection moulding tool)</td>
<td>4.19/unit (based on a production run of 2000 units)</td>
<td></td>
<td></td>
<td>95,000</td>
<td>1,000,000</td>
<td>0.19</td>
<td>25.59</td>
</tr>
<tr>
<td>Connector (double cavity injection moulding tool)</td>
<td>0.45/unit (based on a production run of 4000 units)</td>
<td></td>
<td></td>
<td>32,000</td>
<td>1,000,000</td>
<td>0.02</td>
<td>29.10</td>
</tr>
<tr>
<td>Total</td>
<td>24.24</td>
<td>1.14</td>
<td>25.38</td>
<td></td>
<td></td>
<td></td>
<td>25.59</td>
</tr>
<tr>
<td>Underlay/m²</td>
<td>3.23</td>
<td>0.28</td>
<td>3.51</td>
<td></td>
<td></td>
<td></td>
<td>3.51</td>
</tr>
<tr>
<td>Total direct cost/m²</td>
<td>27.47</td>
<td>1.42</td>
<td>28.89</td>
<td>127,000</td>
<td>0.21</td>
<td>29.10</td>
<td></td>
</tr>
</tbody>
</table>
A typical 800m$^2$ netball playing surface installation would require a total of 3744 tiles and 7488 connectors, therefore each tool built would require a level of quality that would allow it to run through 1,000,000 injection moulding cycles, or the equivalent of manufacturing 267 netball courts.

Herculan Australia, the potential distributor of the proposed new surface, estimate that an installed retail price target of less than $90/m$^2$ would be desirable for the new surface, regardless of the size of the surface area being installed. The surface manufacturing cost of $29.10/m^2$ represents a gross profit margin of 67.70%, therefore making the business model commercially attractive as gross profit margins of between 20% and 30% are typical in this industry. This Figure, however, excludes freight, as the distance and therefore cost would not be known until a sale is made.

### 6.5 Conclusion

The creative process followed in this chapter, incorporating the research findings from the proceeding chapters, has resulted in the design of a novel, commercially improved modular plastic tile sports surface system. This has been realised through the development of an innovative, sustainable, shock attenuating tile and connector geometry, used in conjunction with braking-force reducing dampening elements, which aim to reduce braking forces on the surface to acceptable levels, and thus reduce the risk of athlete injury. The decision was made to include the isolation feature on the connector component in preference to the tile moulding since the connector component will require a smaller injection tool than the tile component, which will entail the use of a smaller, more efficient injection moulding machine with lower clamping tonnage and a more cost effective lower machine rate. In addition, over-moulding or co-moulding the connector component, given that it is significantly smaller than tile component, would significantly reduce the complexity of the injection moulding tool required and therefore lower the tooling cost.

Floor expansion and the potential for tile buckling are also major issues for most modular plastic tile floor surface manufacturers, as a result of differential rates of linear thermal expansion between the polymer floor and subfloor material, which is normally concrete. Different coefficients of linear expansion between the floor and subfloor, will normally result in the polymer synthetic surface expanding more than the subfloor when court temperatures increase, generating internal compressive forces, which may result in the floor buckling or lifting up from the subfloor. This
problem is traditionally managed by the creation of expansion gaps at walls or other features which prevent the surface from expanding or contracting.

The potential for ‘lifting’ tile corners or edges through buckling can create a significant safety hazard for the athlete, as well as limiting the effective use of the surface for sport, due to the erratic behaviour of balls or pucks. The connector element developed through this design process links the octagonal tiles together, with each tile effectively being surrounded by four connectors, creating adjoining ‘sprung biased’ expansion features around each tile, which close and open as the tiles move under braking forces exerted by the athlete. This feature therefore has the additional benefit of being able to locally manage the dimensional changes experienced by the surface as a result of temperature changes in a sports facility.

The product development process therefore succeeded, by realising the research goal to seek improved environmentally sustainable over the life of the sports surface, and the potential for the surface to achieve reduced the rates of lower limb injury. The detail design of how force reduction may be achieved will be addressed in Chapter 7 and the methods developed to measure improved sports surface force reduction, will be addressed in Chapter 8.
Chapter 7  

Structural analysis and manufacturing of modular tile sports surface

Research objective E called for a process-based analysis of the new modular tile system, which requires the optimisation of each individual component, material and process in the playing surface’s value chain. The materials and processes considered in this regard therefore include all aspects needed to manufacture, install, maintain and ultimately dispose of the surface. This chapter aims to develop an approach where the societal need for the design of a safer sports surface and the development of a business case for an affordable sports surface are considered over the full lifecycle of the modular tile surface.

7.1 Modular tile and connector configuration and material selection

Polypropylene is a low cost commodity polymer which is extensively used as a playing surface material in the sports tile industry. Alternative materials were considered, but co-polymer polypropylene, given its broad range of physical properties, ease of processing and recycling, was ultimately selected.

In order to maximise manufacture and installation efficiency, an octagonal tile and square connector configuration utilising a large format fixed tile centre to tile centre position of 500mm were selected, which would allow the creation of a metric playing surface which could easily be assembled to create horizontal and vertical colour changes, in order to define the ‘in-play’ surface areas. A metric format modular tile also meets the metric needs of sports such as netball (30.5 metres long by 15 metres wide), basketball (28 metres long by 15 metres wide) and volleyball (18 metres long by 9 metres wide). Such a feature would have the potential to reduce game-line confusion while playing sport. The anticipated service temperature range for the surface was 0 to 37 degrees centigrade.

The injection moulding tools would be designed for construction and trialling using three different grades of polypropylene for evaluation purposes:

- unfilled co-polymer polypropylene (PP) with ultraviolet (UV) and flame retardant (FR) inhibitors
- 20% talc filled co-polymer PP with UV and FR inhibitors
- 40% talc filled co-polymer PP with UV and FR inhibitors.
High aspect ratio mineral fillers, such as talc, have been used as reinforcing agents in polypropylene for many years, primarily to increase stiffness (flexural modulus) and to provide dimensional stability (Wernett, Wiebking et al. 2004). The introduction of talc fillers into the tile surface is primarily to control excessive levels of component expansion and distortion which may be experienced with changes in temperature, and to increase the surface’s flexural modulus. It was anticipated that mould-fill analysis would demonstrate that the use of fillers in the polymer might
be unnecessary, as the use of additives should, wherever possible, be minimised to increase the recycling potential for the surface at end-of-life.

Parts moulded from these materials exhibit reduced thermal expansion rates and higher levels of dimensional stability, as the levels of filler increase. The dampener/spring element of the proposed connector design would be treated as a ‘tunable’ aspect of the connector tool and manufactured in a ‘metal safe’ condition.

7.2 Modular connector material selection for increased horizontal force reduction

As described in research objective A, loading and loading rates are major contributors to athletic injury because they are representative of the stress being absorbed by an athlete’s lower limbs. The aim therefore was to find a means by which loading could occur less abruptly and be spread over a longer period of time in order to reduce the risk of injury. A surface that encourages horizontal elastic deformation during contact from the horizontal anterior-posterior direction through an arc to the horizontal medial-lateral direction by means of horizontal deformation and displacement, offers the potential to reduce lower limb loading. In order to achieve this, the surface should maximise horizontal energy attenuation while at the same time provide satisfactory levels of energy return to avoid player fatigue.

The connector design is the most critical aspect of the new modular tile surface as this component, along with the unique octagonal tile and square connector configuration, combines to allow horizontal displacement in the surface in order to reduce horizontal braking forces.

Each connector in the surface configuration attaches to four separate tile components, which in turn attach to four separate connector components, as shown in Figure 7.1, collectively dampening the energy being transferred into and through the surface as an athlete decelerates or changes direction on the surface.

The isolator elements on each connector have the effect of separating the tiles and connectors, while also permitting a limited amount of displacement in the surface. This separation permits the tiles to move when a horizontal load is applied to the surface, and the isolators dampen the transmission of force and vibration horizontally through the surface. The isolator elements can potentially take a variety of forms, where the relative displacements between the interconnected tile
elements are controlled by strain in the elastic material as opposed to shear or friction, as is more commonly the case with commercially available modular tile surfaces.

![Proposed octagonal modular tile and square connector surface configuration](image)

7.2.1 **Surface isolator material selection**

Any element that can experience frequent deflection and then revert to its original form under the influence of a set force can be considered a spring. When developing a spring, the use of elastomeric polymer materials can offer processing cost and weight reductions, the ability to create compound forms and an overall reduction in the number of parts and manufacturing stages. This is an advantage in the design of the modular connector if an over-moulding approach to tile manufacture is adopted. A viscoelastic polymer (a material which is characterised by both viscous and elastic properties while undergoing deformation) can experience elastic deformation under stress and return to its original shape without experiencing permanent deformation. Viscoelastic polymers initially under consideration for an isolator design fell into several categories of material:

- polyurethane elastomers (e.g. Sorbothane, Viscolas)
- polyurethane foams (e.g. Poton, PPT)
- polyethylene foams (e.g. Plastazote, Pelite)
- polyvinyl chloride foams (e.g. Implus)
- ethylene vinyl acetate (e.g. EVA)
- synthetic rubber foams (e.g. Neoprene, Noene Ucolite)
- silicone rubber.
The requirement of the current study for the isolator to be over-mouldable onto a polypropylene injection moulded connector excluded most non-injection mouldable thermoset elastomeric polymers. Thermoplastic elastomers (TPEs) are a classification of copolymer or mix of polymer, which are composed of materials which exhibit both elastomeric and thermoplastic properties and can be manufactured by injection moulding. There are six categories of commercially available thermoplastic elastomer:

- styrene block co-polymer (S-TPEs)
- polyolefin blends (TPOs)
- polyolefin alloys (TPVs)
- thermoplastic urethanes (TPUs)
- thermoplastic co-polyester (COPEs)
- thermoplastic polyamides (PEBAs).

Thermoplastic elastomeric materials are characterised by having the ability to return to close to their original shape after being stretched, are injection mouldable and are not significantly affected by creep. Thermoplastic elastomers are commonly used in the manufacture of suspension bushes in automotive applications, as a result of their resistance to deformation in comparison to conventional rubber bushings.

Limitations on material selection were enforced due to the fact that the connector if manufactured from a TPE material, would be necessary to either return quickly to its original form, as is the case with the introduction of a sudden surface braking action; or to maintain a minimum compression in a deflected position over a period of time, as may be experienced with an isolator absorbing the gradual application of compressive forces through surface thermal expansion. For low strains and small periods of loading, surface recovery is normally quick and whole, while for high strains over long loading periods, recovery is gradual and some permanent distortion may potentially occur (Sorbothane 2013). In the second situation, the problem results from the material ‘creeping’ under load.

Material characteristics which should be considered when selecting a polymeric material for an isolator application, include its load-bearing properties, creep resistance and fatigue characteristics, as well as environmental considerations, such as moisture absorption and temperature tolerance.
The most efficient way to use plastic in an isolator capacity is to modify the design to incorporate spring-like response features which include consideration of:

- loading on the isolator
- form of the isolator
- isolator functional cycle
- operating temperature (0 to 37 degrees centigrade)
- life cycle operational requirements (10 to 15 years).

7.2.2 Tile and connector configuration for optimal part flatness

A flat surface is a fundamental requirement of all high performance sports surfaces. It is therefore critical to ensure that the injection moulded tiles and connectors remain flat as the components continue to cool after moulding. Part ‘cupping’ and ‘propelling’ forms of distortion commonly occur with injection moulded flat and square shapes, especially when semi-crystalline materials such as co-polymer polypropylene are injection moulded, as these materials exhibit high levels of shrinkage. These forms of distortion are due to three conditions – part differential shrinkage, differential cooling and uneven shrinkage.

Differential shrinkage occurs commonly with square objects which feature long diagonal material flow lengths from a centrally positioned tool-gate, into the corners of the square form which experience increased shrinking during the cooling phase of the injection moulding cycle (GE Plastics 1998). Shorter flow lengths from the gate to the midpoint on the side of a square form tend not to experience this issue. The effect can be reduced to a certain degree by the use of multiple gates and increased packing pressures, however cupping can still result once the square form has been thermally cycled a number of times during its use phase and stress relaxation in the material takes place. The octagonal shape of the proposed new modular tile design is a form which has more uniform flow lengths, and will therefore experience reduced levels of cupping distortion.

In order to avoid part differential cooling, the cooling rate of the playing surface wall at the end of the injection moulding cycle should ideally match the cooling rate of the part’s wall support ribs. If these two features are not matched, the rib material will ‘freeze’ before the tile wall material and this will cause the tile to ‘cup’. Alternatively, if the tile wall ‘freezes’ before the support ribs freeze,
the tile will ‘dome’. To achieve uniform cooling, the tool will be designed where one half or the tool operates at a different temperature to the other, in order to match the cooling requirements of the part design.

Uneven shrinkage relates in particular to ribbed parts, where, in order to avoid the detrimental visual effects of material ‘sinking’ (localised material shrinkage) on visible part faces, ribs typically are designed to be thinner than an abutting wall (GE Plastics 2000). ‘Cupping’ is due to the ribs cooling at a faster rate than the wall and the polymer material in the ribs ‘freezing-off’ before the thicker main wall, which will ultimately shrink more, as it has more available cooling time. Tile flatness should always take priority over sink marking on the tile surface, and part and tool design should endeavour to encourage the ribs to cool at the same rate as the tile surface wall. Uneven shrinkage is particularly a problem with long ribs, therefore the proposed ‘interrupted’ rib design should minimise this negative effect. These principles have been embodied in the rib and wall features described in Figure 7.2.

7.2.3 **Tile and connector rib connection boss configuration**

In the current study, hollow cylindrical bosses were positioned at the rib intersections, in order to reduce the material mass at the point of rib juncture and so minimise the potential detrimental effects of internal stress concentration and material sinking which, would develop as the part cools after injection moulding. The nominal dimensions for the bosses are detailed in Figure 7.2 and Figure 7.3. As is accepted with good moulding practice, the wall thickness immediately below the centre of the boss has been locally thinned in order to reduce the material mass in this region and reduce the risk of the part sinking (GE Plastics 2000).
7.2.4 Playing surface wall thickness

Wall thickness is a critical factor when attempting to design flat parts. Thin parts are more sensitive to ‘molecular orientation’ as they fill quickly and also cool quickly. Thin parts therefore have only a small amount of time during which they can be ‘adjusted’ during the holding-pressure phase of the injection moulding cycle (GE Plastics 1998). Parts with dissimilar wall thicknesses experience distortion because they will harden variably due to the variations in thickness.

This phenomenon can however be put to beneficial use in a tile design. A centrally-gated large, flat, octagonal shaped part with a warpage tendency due to the large number of support ribs on one side of the part, can be forced into a repeatedly flat shape by making the center section of the tile thicker. This allows the injection moulding machine operator to maintain the holding pressure for an extended period of time, inducing a reduced level of shrinkage in the center of the tile. Therefore a variable tile wall thickness would be desirable with its center being 3.0mm thick, stepping down to 2.25mm thick at its outer edge. The connector on the other hand, given its smaller size and reduced tendency to distort, will have will only have a 2.5mm wall thickness at its centre, stepping down to a 2.25mm wall thickness closer to its edge. Flatness will not be so critical with this part, as its size is considerably smaller than the tile.

7.2.5 Tile and connector rib, side wall and boss draft angles and radii

The rib configuration that was developed for the current project features an array of non-connected, radiating ribs, which have a nominal 1° of draft (taper) per side and are connected to smaller blind cylindrical bosses at each end. These bosses have a generous 5° internal draft and a 3° external draft in order to reduce the tendency for the bosses to ‘hang’ onto the moving side of the injection
moulding tool during part ejection. All other draft angles on the tile and connector are 1° per side.
Externally on the tile and connector a ‘split draft’ of 1° above and below the parting line is used, as illustrated in Figure 7.4.

![Figure 7.4 Tile and connector rib and side wall configuration](image)

A general fillet radius of 0.75mm was used at all internal corners except in between the ribs and where the ribs attach to the top of each boss, where a 1.0mm radius is used. The edges of the playing surface on the tile and connector have a 1.0mm external radius applied to all edges in order to reduce the risk of skin trauma if an athlete falls or slides over the modular tile surface.

### 7.2.6 Tile and connector injection moulding tool design considerations

There are three main factors which govern part shrinkage behaviour:

- injection moulding part cooling
- injection moulding part packing during tool fill
- material molecular orientation.

Uneven part cooling can result in differential shrinkage leading to tile distortion and warping. Uneven cooling can be produced by mould surface temperature variances during the part cooling process, causing the material to ‘freeze-off’, inducing ‘frozen-in’ stresses which are locked-in within the part. This issue can be reduced by ‘optimising’ the tool cooling circuit. This requires that the temperature variance of the tool coolant over the entire length of cooling circuit should be as uniform as possible, optimising the distance between the cooling channel and the wall of the tile cavity. In addition, the distance between the cooling channel and areas of differing part wall
thicknesses which require ‘controlled cooling’ will be optimisation through the use of mould-fill analysis. Wherever possible, the tile injection mould cavity temperature should be uniform.

The packing stage in the injection moulding cycle will have a substantial influence on tile shrinkage. The greater the holding pressure and the more extended the period of time that the holding pressure is effective, the lower the part shrinkage experienced. It is vital to use an adequately large gate, as the point in time when the tool gate freezes-off defines the conclusion of the tile packing phase (GE Plastics 1998). A part with a large projected area, as is the case with a 500mm X 500mm octagonal tile form, will require a gate of 3mm diameter or greater. The injection moulding tool will also require a hot manifold and ‘hot tip’ gate to increase the efficiency of the injection moulding process, as the part will therefore not need to have a sprue to be removed, reducing labour and material waste, therefore reducing the manufacturing cost and material waste.

Molecular orientation can cause differential shrinkage in material flow and cross flow directions within an injection mould part, which can impact the uniformity of moulded tile components considerably. Therefore, in addition to material choice, the method by which the part is gated will play a significant role in achieving uniform tile flatness.

7.2.7 **Injection moulding tool gate location and size**

The selection of the injection moulding tool gate location and gate size is particularly important when attempting to design flat injection moulded parts. Gate location and tile shape should each be optimised in order to attempt to provide as short flow length, uniform orientation and optimum pressure distribution at fill as possible. A large, centrally located ‘hot tip’ gate is desirable for both the tile and connector. A large gate opening into a thick 3mm section of the tile wall surface reduces the molecular orientation level of the part.

Small gates generate higher levels of shear, pressure loss and molecular orientation than larger gates. Small gates also reduce the effectiveness the tile packing stage as a result of pressure loss. The tile gate diameter should be a minimum of 60% of the thickness of the wall into which it opens, in order to facilitate the greatest achievable component processing window. If a gate size of at least 3.0mm diameter is targeted in the center of the new tile design, this will represent 100% of the wall thickness at that location and will produce optimal results.
7.2.8 Tile and connector injection moulding considerations

Tile and connector injection moulding tool operating temperatures. Tool temperature has a significant effect on tile distortion and shrinkage, as higher tool temperatures encourage increased crystallisation of semi-crystalline co-polymer polypropylene. In addition, relaxation time is longer, which results in a reduction in the orientation effects induced in the moulded tile. The resulting increase in injection cycle time however will result in increased part cost. Optimal tool operating temperatures will be determined through mould fill analysis and at subsequent tool trials.

Tile and connector injection moulding cycle-time. The time taken to fill the tile tool cavity has a direct effect on the level of molecular orientation in the tile, as the higher the material injection speed, the higher the levels of molecular orientation. In addition, part filling speed has an effect on the temperature distribution within the tool, as the moment that the tool cavity is completely filled, the material packing pressure begins to be effective. Therefore, controllable variables in the injection phase will play a significant part in regulating the tile’s warpage and shrinkage. It was anticipated that a target injection cycle time of approximately 60 seconds for the tile component and 30 seconds for the connector component would be achievable.

Injection moulding tool packing pressure. Tile moulding packing pressure is also a significant variable when attempting to regulate tile shrinkage. The manner in which an injection moulded part is packed, controls the concluding volumetric shrinkage in each region of the part. The more consistent the volumetric shrinkage over the entire component, the more close the moulded tile will be to the required form, with the minimal part edge distortion and higher levels of part flatness and uniformity.

Tile secondary distortion effects. After tile ejection and once the part has finished cooling, the tile can still experience undesirable distortion, particularly when large temperature changes take place during the surface’s use-phase of its life-cycle. There are a number of aspects which can momentarily or permanently resulting in dimensional changes as a result of post-crystallisation and thermal expansion. During the service life of the tile, thermal expansion will cause the part to expand. If there is no means of managing these dimensional changes, each tile will exert compressive stress on its neighboring tile via the joining connector, potentially causing the floor to buckle. If critical stress levels are reached in the tile, permanent distortion may ensue as a result of
creep under load. In addition, polypropylene can also exhibit post moulding shrinkage, particularly at higher temperatures, as a result of post crystallisation within the part. The part, tool processing strategies described in this chapter should however minimise distortion effects.

7.3 Structural analysis of modular tile and connector

7.3.1 Introduction

The aim of this section is to define the energy inputs, outputs and attenuation characteristics of the new modular plastic sport tile surface through calculation and finite element analysis (FEA) methods, incorporating inputs from measured ground reaction forces.

Many polymer materials exhibit viscoelastic characteristics. A viscoelastic material approach was employed, incorporating measured limits from tested sports surface samples.

HGRF and frequency data collated through testing were applied through calculation and FEA techniques and were then used to evaluate the energy flows in the proposed sports surface design. Sports surfaces have the goal of reducing potentially damaging forces from being returned to an athlete, while improving an athlete’s performance (Baroud, Nigg et al. 1999). During rapid changes in direction or while landing on a sports surface, forces are transmitted from the athlete into the sports floor. Energy is preserved in the surface as the floor deforms, with a component of this energy being dissipated as a result of the dampening characteristics of the materials which are used to construct the sports surface. The FEA method is an analytical technique commonly used for sports surface analysis, and has the advantage of being able to predict the energy flows in a sports surface, under any predetermined loading conditions.

All sports surfaces exhibit some aspect of mechanical dampening. As surface dampening increases, the potential for the surface to transmit energy decreases. Dynamic loading delivered by an athlete to a surface involves accelerations and large amplitude forces. The use of isolation will involve the application or hysteresis in force reduction via the compression and recovery from deformation of isolator elements.
7.3.2 Tile and connector mathematical model construction

A series of three-dimensional mathematical models of the modular plastic tile, isolator and connector were created, with each model’s x-axis (Rx) corresponding to the medial-lateral force vector, y-axis (Ry) representing the anterior-posterior force vector and z-axis (Rz) the vertical ground reaction force vector as shown in Figure 7.5. Existing commercially available modular tile systems use rubber underlays as a means of reducing VGRF and are capable of achieving VGRF reductions of:

- 3mm thick rubber underlay - 20% to 25% force reduction
  (which is outside the scope of the current EN 14904 force reduction standard)
- 5mm thick rubber underlay - 25% to 30% force reduction
  (EN14904 force reduction, category P1)
- 7mm thick rubber underlay - 30% to 35% force reduction
  (EN14904 force reduction, category P1)
- 10mm thick rubber underlay - 35% to 40% force reduction
  (EN14904 force reduction, category P2).

(Sport Court 2013)

For the purposes of each analysis undertaken, the bottom face of the rubber underlay was considered to be firmly attached to the concrete subfloor, as the rubber underlay is normally laid in a large sheet format and is therefore capable of resisting horizontal movement relative to the surface subfloor under its own weight. The resolution of energy magnitude is centred on the principle of mechanical energy conservation, where the maximum value of energy returned to the sports participant \( (E_{\text{returned}}) \) is quantified by the energy input to the surface \( (E_{\text{input}}) \) minus the energy attenuated by the surface \( (E_{\text{attenuated}}) \).

\[
E_{\text{returned}} = E_{\text{input}} - E_{\text{attenuated}}
\]  
Eq. 7.1

The finite element analysis outputs for complex stresses were obtained using von Mises equivalents for direct comparison with tensile yield stress, according to the strain energy theory of failure.

Each tile, isolator and connector model geometry must be capable of being meshed into a complete, finite element mesh. Reducing the number of elements used in each mesh model in order to improve meshing effectiveness has a number of significant effects. It must be possible to
generate a mesh which is capable of providing a solution to the data of interest, such as
displacements or stresses. In the case of each tile, isolator and connector analysis, the models
require simplification through de-featuring modifications, which were undertaken by removing
geometry features which were redundant to the integrity of the analysis, such as external fillets.

Another incentive for the adoption of a de-featuring process is to reduce the size and complexity of
the resultant mesh model, as mathematical models which include features that are unnecessary to
the integrity of the analysis will result in the calculation process being unnecessarily large, causing
the analysis to run slowly or even fail. Simpler part geometries result in simpler meshes and
reduced calculation times.

De-featuring model features which are necessary for the mathematical accuracy of the analysis
should be avoided, however. Successful model meshing depends on the integrity of the geometry
developed for meshing and the sophistication of the meshing tools present in the finite element
analysis software. Once the meshable but as yet unmeshed geometry was created during this
project, material properties, load inputs, supports, restraints and analysis type were defined.

7.3.3 Finite element model

The mathematical models of the tile, isolator and connector were divided into a number of finite
elements, through the process of model discretisation. During the discretisation process, the defined
loads and supports were also meshed and the discretised loads and supports applied to the
individual nodes of the finite element mesh. Guisasola et al. (2010) stated that the surface contact
area of an athlete’s footwear during foot-strike was estimated to be 3800mm² (Guisasola, James et
al. 2010) and biomechanical studies conducted by Steele and Milburn (1987) provided the loading conditions for each subsequent analysis.

Steele and Milburn concluded that a shod athlete with mass of 65kg, height 165 cm could apply loads of:

- anterior posterior force (Ry) = 2470N to 2700N
- vertical ground reaction force (Rz) = 2295N to 3530N.

(Steele and Milburn 1987)

This research found that athlete induced forces could result in a combined VGRF/HGRF resultant force of 6.0 times body weight, or 3.826kN (6BW x 65kg x 9.81). This resultant force equates to two equal force vectors of:

- anterior posterior force (Ry) = 4.243BW or 2.706kN
- vertical ground reaction force (Rz) = 4.243BW or 2.706kN.
Depending on the isolator configuration employed in the surface, the horizontal ground reaction force Ry is divided by the quantity of isolator elements that may be efficiently integrated into the design of each connector. Use of a large numbers of mesh elements permits improved approximations of displacements and stresses to be made, therefore the constraints imposed by the discretisation stage reduce as the mesh becomes more refined.

Displacements are the primary unknown in a structural finite element analysis, as calculated stresses are extrapolated from the displacement results to all of the model’s element nodes. If a node shares a relationship with more than one element, then the stress values from all sharing nodes are averaged and a single stress node value is derived for each node. An alternative approach to stress value determination is to calculate stress levels at each Gauss Point and then calculate the average of all points.

There are 16 Gauss points for a quadrilateral element and the stress is defined as an element value. Node values are more regularly used as they provide a ‘smoothed’ stress value. Elemental values however can provide valuable information on the accuracy of the stress results. If the elemental values derived from two neighbouring elements differ too greatly, this situation may indicate that the size of mesh elements used in this particular component location may be too large to adequately define a stress gradient and they should therefore be reduced. Elemental values can therefore be used to target meshing deficiencies without performing a convergence analysis on the model. If the elemental values of stress are several colours apart on the stress colour scale, then a more detailed mesh should be generated in that particular region of the model.

7.3.4 Analysis and interpretation of FEA results
The analysis of data resulting from a finite element analysis can be the most complex step in the analytical process. The analysis provides comprehensive results data, which can be accessed in a wide variety of data formats. Accurate results interpretation requires that the analysis assumptions, simplification and errors introduced are fully identified and acknowledged. The tile modelling and de-featuresing process itself introduces unavoidable ‘idealisation’ errors. Discretisation of the tile mathematical model during meshing introduces discretisation errors and the solving process introduces numerical errors. Of these three error types, only discretisation errors are specific to finite element analysis and therefore only discretisation errors can be managed using finite element
analysis techniques. The type of mesh elements created during discretisation is reliant on the type of model geometry which is being meshed and the finite element analysis type which is to be performed. The element types which were selected for use with the tile, isolator and connector geometries used in this study are tetrahedral solid elements for volumetric geometries.

In order to interpret the results of a structural finite element analysis adequately, analysis interpretation criteria should be established. While frequency and displacement criteria are relatively simple to establish, stress criteria can be less obvious. In order to establish stress criteria, the mechanisms of failure need to be established and the stress levels which best describe a particular mode of failure, fully described. In the forms of analysis used in the current study, three common failure criteria were used – maximum shear stress failure, maximum normal stress failure and von Mises stress failure.

**Maximum shear stress failure.** Maximum shear stress failure is based upon maximum shear stress theory, which predicts that failure will occur when the absolute maximum shear stress (τ_{max}) reaches half the yield stress. This failure criterion is used for ductile materials where the factor of safety (FOS_{a}) is described as:

\[
FOS_{a} = \frac{\sigma_{\text{limit}}}{(2\tau_{\text{max}})}
\]

Where \(\sigma_{\text{limit}}\) is the yield strength

\[
\text{Eq. 7.2}
\]

**Maximum normal stress failure.** Maximum normal stress failure accounts for three principal stresses, \(\sigma_{1}, \sigma_{2}\) and \(\sigma_{3}\). This criterion is used for brittle materials and assumes that the ultimate tensile strength of the material is the same in both compression and tension. This failure criterion predicts that failure will take place when \(\sigma_{1}\) exceeds ultimate tensile strength. The factor of safety (FOS_{b}) for this criterion is described as:

\[
FOS_{b} = \frac{\sigma_{\text{limit}}}{\sigma_{1}}
\]

Where \(\sigma_{\text{limit}}\) is the yield strength.

\[
\text{Eq. 7.3}
\]

**von Mises stress.** von Mises stress accounts for all six stress components of a 3D stress state and is a scalar stress measure. The maximum von Mises stress criterion is founded on the shear energy
theory, which states that a ductile material begins to yield where the von Mises stress becomes equivalent to the stress limit. The yield strength is normally used as the stress limit and the factor of safety (FOSc) is described as:

$$FOSc = \frac{\sigma_{\text{limit}}}{\sigma_{\text{vm}}}$$

Where $\sigma_{\text{limit}}$ is the yield strength. \hspace{1cm} \textbf{Eq. 7.4}
7.4 Linear surface analysis versus non-linear surface analysis

The natural world is inherently non-linear, therefore any linear form of analysis can only estimate the actual non-linear behaviour of the tile, isolator and connector components and assemblies. In many cases however, linear approaches can provide acceptably accurate results. In critical applications, however, linear assumptions may diverge too far from reality in order to be reliable.

Stiffness defines the fundamental difference between the two main types of non-linear and linear finite element analysis. Stiffness is the main aspect of a sports surface which will describe its behaviour under the application of a load delivered by an athlete. The main characteristics which influence the stiffness of a surface component are its form, material and the type of support that the surface component accepts. When a sports surface deforms under load, its stiffness characteristics can alter as a result of its form, material characteristics or its support characteristics being modified, or a combination of all three. If the change in stiffness is, however, only comparatively small, it can be assumed that form, support and material characteristics will not alter and therefore it may be acceptable to assume that a surface linear analysis will produce results of reasonable accuracy. This assumption of linearity has the potential to greatly abbreviate the analytical process where:

\[ k = \frac{F}{\delta} \]

where:

- \( F \) is the load vector
- \( k \) is the material stiffness
- \( \delta \) is the displacement vector

In the case of a linear analysis, one can assume that the surface’s stiffness will not change and the FEA equation will only need to be resolved once for a single set of loading conditions, removing the need to iteratively alter values as the surface deforms under load. These assumptions change radically, however, if a non-linear approach is assumed, as the surface’s stiffness is no longer considered to be constant and its stiffness must be continually modified through an iterative analytical process.

There can be different sources of surface non-linearity, making it sensible to categorise different types of non-linear behaviour based upon the source of non-linearity. As it is not always possible to
identify a single source of non-linearity, some forms of analysis may need to incorporate more than one form of non-linearity.

7.4.1 Surface geometry linearity and non-linearity

As described, non-linear behaviour becomes increasingly prevalent when the stiffness of a sports surface changes under load. If the resulting changes in stiffness are a result of the surface’s form becoming significantly altered, the non-linear behaviour exhibited in the modified surface can be described as ‘geometric non-linearity’. Geometric changes will often result if a surface experiences large changes in its form, normally perceptible to the human eye. The accepted convention for geometric non-linearity proposes, is that deformations in excess of 5% of an object’s major dimension in the direction of the applied force, will require the adoption of a non-linear approach.

A compressive horizontal load of 2.706kN over the width of a 92mm connector segment, results in a deformation of only 3.0mm or 3.3% deformation as shown later in this chapter, hence in this particular case a linear approach should deliver acceptably accurate results.

The less resilient isolator element placed within the tile to connector gap will however compress excessively, hence a non-linear approach would be appropriate in this case. Many finite element analysis applications including Solid Works Simulation Premium provide alternative approaches to geometric non-linearity, with the provision of ‘following’ and ‘non-following’ loading options. In the case of the tile connector, the loading condition will always be ‘following’, as the loading direction will always be in the same direction as the applied load, a result of the connector geometry being restrained by the subfloor and its interconnection with surrounding tiles. The loading direction will therefore not change as the isolator deforms under load.

7.4.2 Surface material linearity and non-linearity

If the stiffness of a sports surface alters as a result of its material properties changing while in use, the surface will exhibit material non-linearity. In the case of normal material linear behaviour, stress is assumed to be directly proportional to strain and the resulting deformation will be proportional to the change in loading experienced. This will result in a surface which experiences no permanent deformation once the applied load has been removed. If loading results in permanent deformation or where strains experienced by the surface are excessively large, then a non-linear material model approach should be adopted.
The integral isolator elements which were placed along the tile contacting edge of each connector could experience excessively large strains of up to 60% under dynamic deflection and therefore a non-linear approach would be appropriate. Integral passive dampening is normally based on the application of viscoelastic materials (VEM) technology, and this is a widely used structural passive dampening technology. The main effect of increased dampening in a sports floor structure is to reduce the energy which will be returned to an athlete, with corresponding decreases in stress, displacements, fatigue and sound. A passively isolated sport flooring system comprises a mass, surface structure, spring and dampener and responds to the application of force in a harmonic oscillating configuration. The mass and spring stiffness define the natural frequency of the isolation system, and the dampening element attenuates a proportion of the input energy, modifying the natural frequency of the sports surface and therefore protecting the athlete from the potentially damaging effects of the returned energy.

Two important facets of energy sports surface management are isolation and dampening. In order to protect an athlete from injurious interactions with a sports surface, the process must both isolate and dampen the energy flows within the sports surface system. Isolation prevents energy from entering a system, whereas dampening absorbs energy that has entered a system and then dissipates that energy by converting into another form. These two facets of energy management are used in conjunction with each other in a sports surface in order to achieve the desired levels of safety and performance. They are different from one another, but are used together to achieve the desired levels of performance and safety.

As a result of changing in-service material behaviours, the von Mises or Tresca finite element analytical techniques can be used to emulate these characteristics. This analysis model is used for materials which normally exhibit stress strain curves that plateau before reaching their ultimate tensile strength. This characteristic applies to most engineering polymers, such as polyurethanes.

**7.4.3 Surface restraint linearity and non-linearity**

If the surface element’s support conditions, including its contact areas, change during loading, a non-linear analysis will normally be required. Stresses normally develop at the juncture of contacting surfaces. The contact stress area of the dampening element of the tile connector will increase as loading increases and deformation increases, therefore the changing stiffness of the dampener contact zone will require a nonlinear approach.
7.5 Tile and connector support rib design linear static finite element analysis

The transference of material properties to a finite element analysis model is an important step in the modelling process in order to guarantee extrapolative accuracy. The stress and strain captured within a structure are linked to the material properties of the structure. For all the finite element simulations undertaken in this chapter, the material properties adopted for copolymer polypropylene are provided in Table 7.1.

Table 7.1 Material properties for copolymer polypropylene (Basell Polyolefins 2013)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>elastic modulus</td>
<td>8960000000</td>
<td>N/m(^2)</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.4103</td>
<td>N/A</td>
</tr>
<tr>
<td>shear modulus</td>
<td>315800000</td>
<td>N/m(^2)</td>
</tr>
<tr>
<td>density</td>
<td>890</td>
<td>kg/m(^3)</td>
</tr>
<tr>
<td>tensile strength</td>
<td>27600000</td>
<td>N/m(^2)</td>
</tr>
<tr>
<td>thermal conductivity</td>
<td>0.147</td>
<td>W/(m·K)</td>
</tr>
<tr>
<td>specific heat</td>
<td>1881</td>
<td>J/(kg·K)</td>
</tr>
<tr>
<td>yield strength</td>
<td>30</td>
<td>N/mm(^2) (MPa)</td>
</tr>
</tbody>
</table>

The material properties shown in Table 7.1 are those of a high flow impact copolymer with a modified molecular weight distribution. It is formulated for injection moulding applications which require good mould filling properties required for the large flat tile form, low warpage and good impact strength. The FEA outputs for complex stress were obtained as von Mises equivalents for direct comparison with the tensile yield stress, according to the strain energy theory of failure. Stresses and deflections for the compressive loads experienced by the tile and connector in this system can be considered linear for the small deflections encountered. The coding systems used for finite element analysis were a combination of Solid Works Simulation 2012 and MSC Nastran 2011. In each case, fixtures were kept to a minimum, as over restraining a finite element model can unnecessarily increase the stiffness of the model.

7.5.1 Static analysis of tile rib structures in horizontal compression

In order to calculate the maximum displacement expected during braking on a tile surface, a number of mathematical models were generated for alternative configurations of the tile rib support structure, which had a fixed restraint applied to one end of each model and a maximum 2706N compressive load uniformly distributed along the end face, opposing the supported face, as shown in Figures 7.6 and 7.7. This condition is representative of a worst case scenario where an athlete stops suddenly with two feet located on a single tile, decelerating from a speed of 3.85 m/sec.
Although this situation is improbable as two tiles would probably be required for an athlete to stop satisfactorily, it was considered as a ‘worst-case scenario’ in order to determine the suitability or otherwise for the adoption of linear or non-linear modes of analysis, through the calculation of the tile segment’s maximum deformation.

In this restraint case, the mathematical model does not have any rigid body modes, preventing it from moving without experiencing deformation. The definition of an appropriate load for the analysis involves many assumptions. Load distribution and magnitude are approximations and therefore significant idealisation errors can be made if actual measured values are not taken into account. In this case, the results of experimental data were applied. A fine 2.86mm second order element with a 0.14mm element size tolerance was used, as mesh density has a direct influence on the accuracy of the results obtained.

In Figure 7.6 the most severe stresses accompanying this rib design approach rise to around 17 MPa von Mises equivalent, or 57% of yield in this worst case loading condition.

![Figure 7.6](image_url)

**Figure 7.6** von Mises stress plot for a column configuration support structure, based on a competitor tile

In Figure 7.7, the most severe stresses in this design approach rise to around 30 MPa von Mises equivalent, or 100% of yield in this worst case loading condition. The peak deflection under this
load is about 3.0mm, and occurs at the end of the 92mm tile sample segment, representing 3.3% deformation in comparison to the model’s largest dimension.

![Diagram showing von Mises stress plot for the proposed new rib configuration support structure under horizontal loading.](image)

Figure 7.7 von Mises stress plot for the proposed new rib configuration support structure under horizontal loading

The accepted convention for geometric non-linearity proposes is that deformation in excess of 5% of an object’s largest dimension will require the adoption of a non-linear approach. For subsequent analyses which consider horizontal surface loading, the tile and connector components can
therefore be considered linear in compression, whereas the more compressible connector isolators will be considered non-linear in subsequent analyses.

Figure 7.8 Displacement plot for the proposed new rib configuration support structure under horizontal loading

7.5.2 Tile to connector linkage development and analysis

In accordance with research objective B, in order to reduce the potential for injury, the vertical and horizontal reaction forces applied to the modular tile surface by an athlete need to be reduced. This research has concluded that modular plastic tile surfaces which permit a limited amount of horizontal displacement via the tile connections have the potential to attenuate more braking force in comparison to a homogenous contact layer sports surface. A system whereby a modular plastic tile surface would be used to encourage a limited amount of horizontal displacement via the tile ties was therefore developed. This mechanism should also allow ease of tile attachment and disengagement for assembly and disassembly.

Each tile and connector developed for the current study therefore required a retaining clip system in order to hold the connector loops and tile hooks in firm engagement for surface assembly. Yet, each clip also had to be able to be pulled apart for disassembly. In addition, the tile and connector had to be able to move independently from each other, in order for the surface to be able to dissipate energy. In order to achieve energy dissipation, this aspect required the tile and connector to be able to slide towards and away from each other. The conventional clipping approach adopted
by all manufacturers of current modular plastic sports surfaces, is to utilise a connection ‘snap hook’ similar to the representations shown in Figure 7.9.

Analysis of the stiffness of competitor tile clip designs suggests that the cantilever design approach shown in Figures 7.9 and 7.10 would be overstressed when attempting to deform the 2mm required, in order providing a minimum of 2mm of full engagement. In addition, once the tile to connector gap closes as a result of tile displacement, clip engagement will also increase by the same amount, increasing the tile and connector interlock on the mating faces. With small engagements, tile or connector displacement will however potentially risk tile disengagement when an athlete brakes suddenly on the surface. As detailed in Table 6.7, the maximum acceptable gap size from a user’s perspective was determined to be 2mm.
Figure 7.10  Conventional retaining clip approach modelled without and with internal fillets
In order to reduce the stress concentrations visible in the internal corners of the existing design, 1mm fillets were added and a prescribed minimum displacement of 2mm was introduced. The resultant stresses concentrated in the internal corners at the bottom of the hook cantilever, however, were over three times greater than the material’s yield strength.

Alternative design approaches were therefore investigated with the goal of rotating the clipping action through 90 degrees as shown in Figure 7.11, which also allowed the flexibility of the loop to contribute to the snapping action. This approach allows the tile and connector to be displaced by each sliding towards and away from each other, without increasing or decreasing the clip engagement dimension.

The maximum allowable loop displacement in this configuration was however only 0.2 mm and there was a potential issue with loop stiffness being too high. Subsequent analysis indicated that the clip may be too stiff in the location where this feature passed through the mating wall on the connector.

In order to make the side-wall of the clip on the tile more flexible, further development was undertaken, as shown in Figure 7.12. The subsequent finite element analysis indicated that these hook designs would function satisfactorily. At 1.2mm deflection, the material begins to enter yield at the base of each cantilever and at 1mm of snapping deflection, the material is below yield. Altered material properties through the addition of mineral fillers may however increase stiffness.
and change the material modulus, resulting in the feature being overstressed, and should therefore be avoided.

![Initial design for flexible side-wall hooks engaging laterally on the loop to promote clipping and unclipping for ease of assembly and disassembly](image)

Figure 7.12

The revised loop and hook approach was further refined with the inclusion of negative ‘shelving’ on the underside of each hook, as this characteristic would allow the tuning and adjustment of the unclipping pull-out force. This aspect of fine tuning is best done at the tooling stage, however, by leaving clearance between the hook and loop. Then the ability is available to adjust the tooling in a ‘metal-safe’ tool tuning process.

As the connector and tile geometries are symmetrical, the analyse was performed with half the mathematical model present and the other half replaced through symmetry boundary conditions. In order to simulate the entire tile or connector, even though only a portion of the connector and tile geometries is present, symmetry boundary conditions were applied to the faces located in the plane of feature symmetry. Symmetry boundary conditions however only permit in-plane displacements and in this case, symmetry was used as a restraint condition.

In this final version of the tile to connector clipping system, the tile hook can be deflected by 1.2mm per side. Under these conditions the maximum von Mises equivalent stress in the cantilever is 32.5 MPa or just over 100% of the 30 MPa von Mises equivalent yield strength. In reality, deflection will be shared between the hook and the loop; therefore this level high of displacement will not be experienced by the hook cantilever. The loop analysis shown in Figure 7.13 shows the levels of stress expected under the application of a 1N clipping force, bringing the interconnection process well within acceptable stress levels.
7.5.3 Effects of mineral filler additive materials on part stiffness during clipping assembly and disassembly

Mineral filled copolymer polypropylene blends which are used primarily to increase part dimensional stability and flatness have considerably higher stiffness properties than unfilled grades of copolymer polypropylene, by a factor of 2 to 3. This means that for the same deflection of the same hook cantilever, the stress will rise by a similar factor. This would not present a design issue with this design feature if the material yield stress rose by the same factor, but unfortunately yield stress remains almost constant. In respect to the retaining clip design, the snapping distance should be reduced in inverse proportion to the part’s stiffness. Two times the stiffness will require a 50% reduction in the clipping overlap. This not only maintains the assembly stress at the same level, but it also maintains the pull-out disassembly force at the same level. This approach however will require highly accurate injection moulding tool details to be maintained in this area of the tile tool, over the life of the injection moulding tool.

7.5.4 Tile and connector loading

In this case, the focus of the analysis was the loading on the surface while in static equilibrium, where the relative positions of surface elements do not vary over time, and where in this condition the surface will be considered at rest. According to Newton’s first law, the net force and net moment on every element of the sports surface will be zero. From this constraint, quantities for stress can be therefore be developed. Once a meshable but yet to be meshed model had been developed, the material properties, loading and restraint parameters and the type of analysis to be
undertaken, were defined. The model was analysed with a distributed pressure loading of 3.5 MPa, as shown in Figure 7.14.

![Connector underside deformation contours for uniform loading](image)

**Figure 7.14** Connector underside deformation contours for uniform loading

A number of displacement and stress analyses were performed utilising meshes with different finite element sizes in order to ascertain the part’s sensitivity to discretisation intensity. The part was supported and loaded as shown in Figure 7.14. As the supporting substrate was concrete, the assumption was made that the support medium was rigid and that a distributed compressive load of 3.5 MPa was uniformly distributed over the playing surface, opposite to the supported face. The model was therefore fully supported by the sub-floor, did not exhibit rigid body motions and could not move without experiencing deformation. A common error made in many forms of FEA is to over constrain the mathematical model resulting in an overly stiff floor structure, which can lead to underestimation of stresses and displacements.

The uniform loading condition resulted in the most severe stresses. The stresses rose to around 20 MPa von Mises equivalent, or 60% of yield. The peak deflection under this load was about 0.3mm, and it occurred in the spans at the base of the loops at the apexes of the connector. This was reduced by deepening the web in this immediate area.

Figure 7.15 shows the von Mises stress from the deck side and underside. As can be seen, the ribs sustain more stress than the deck surface.
7.5.5 Surface spot impact loading

The multi-sport use intended for the surface required it be able to withstand many different types of loading, including being struck with sports equipment, including inline hockey-stick elbows. Several additional load cases were therefore applied to the surface, such as spot loads of 10mm diameter in order to simulate the impact effects of the surface being struck in this manner. The classical method of calculating impact stresses is to equate the strain energy to the work done at the impact site. A vertical ‘unit’ load of 1 MPa over a 10mm diameter circular area was therefore applied to three different locations. Figure 7.16 shows a typical deformation crater on the top of the tile structure.
The crater was graphically divided into elemental areas and the average deformation for each obtained numerically. The work done by the applied load was therefore estimated by integrating the pressure * volume with respect to deformation, assuming a linear response where the work done by the applied unit load = ½ x Pmax x volume displaced. For each load location, the corresponding maximum von Mises stress was extracted from the analysis. Figure 7.17 shows the underside view of the three impact cases explored.

![Figure 7.17](image)

The energy absorbed in the ‘unit’ load was then scaled so that the stress would peak at the nominal yield stress (30 MPa). For a linear system, this is achieved by multiplying the energy by the square of the stress ratio.

Where:

\[
\text{Energy absorbed to cause yield} = (\text{Energy absorbed in unit load}) \times (\text{Yield Stress/Stress from unit load})^2
\]

Eq. 7.6
Table 7.2  Spot load analysis for new tile and connector design

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>1552</td>
<td>1305</td>
<td>1364</td>
<td>microns</td>
</tr>
<tr>
<td>Volume</td>
<td>1.56</td>
<td>1.31</td>
<td>1.36</td>
<td>mm^3</td>
</tr>
<tr>
<td>Energy</td>
<td>776.2E-6</td>
<td>652.7E-6</td>
<td>682.0E-6</td>
<td>Joules</td>
</tr>
<tr>
<td>von Mises Stress Peak</td>
<td>1.6</td>
<td>1.95</td>
<td>2.2</td>
<td>MPa</td>
</tr>
<tr>
<td>Allowable Stress</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>MPa</td>
</tr>
<tr>
<td>Maximum Energy</td>
<td>272.9E-3</td>
<td>154.5E-3</td>
<td>126.8E-3</td>
<td>Joules</td>
</tr>
</tbody>
</table>

A competitor tile was modelled and analysed in precisely the same way with the equivalent results as shown in Figure 7.18. While the competitor’s tile is generally more flexible and deforms more under the unit load, the stress levels are also significantly higher. When the absorbed energy is scaled to achieve yield, the energy absorbed is well below the data developed with the new tile and connector rib designs.

![Analysis of a competitor arch rib tile](image)

Figure 7.18  Analysis of a competitor arch rib tile

Table 7.3  Spot load analysis for competitor arch rib tile

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>4409</td>
<td>7055</td>
<td>10873</td>
<td>microns</td>
</tr>
<tr>
<td>Volume</td>
<td>4.41</td>
<td>7.06</td>
<td>10.87</td>
<td>mm^3</td>
</tr>
<tr>
<td>Energy</td>
<td>0.0022</td>
<td>0.0035</td>
<td>0.0035</td>
<td>joules</td>
</tr>
<tr>
<td>von Mises stress peak</td>
<td>5.5</td>
<td>9.0</td>
<td>7.0</td>
<td>MPa</td>
</tr>
<tr>
<td>Allowable stress</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>MPa</td>
</tr>
<tr>
<td>Maximum energy</td>
<td>65.6E-3</td>
<td>39.2E-3</td>
<td>99.9E-3</td>
<td>joules</td>
</tr>
</tbody>
</table>
7.5.6 Tile and connector support rib design linear static finite element analysis outcomes and recommendations

The new design as currently modelled, is capable of withstanding a general static pressure loading of 3.5 MPa when assembled directly onto a concrete subfloor, which is a worst case scenario. The impact resistance is also superior to at least one market-leading commercially available tile, as shown in Figure 7.18.

The revised design of the tile to connector clipping mechanism can also satisfactorily accomplish tile to connector independent displacement, where the connector is able to slide towards and away from any adjoining tile. The tile and connector must be able to move independently of each other, in order for energy dissipation to occur and this new approach has the advantage of being independent of the variable engagement distances which would be experienced with the current accepted methods.

Finally, the use of material fillers was avoided, as fillers would negatively affect stiffness and load induced stresses. The use of fillers, which can be regarded to be material contaminants, would also reduce the effectiveness of surface material recovery for recycling.

7.6 Sports surface isolator analysis

The primary goal of increased horizontal ground reaction force dampening in a sports surface as described in research objective A is to reduce the amount of braking energy which is returned to an athlete while playing sport on the surface. There are two important aspects of energy management in respect to the dynamic loading of a sports surface – energy isolation and energy dampening. In order to protect an athlete from injurious interactions with a sports surface, the energy transfer process must both isolate and dampen the energy flows within the structure. Isolation prevents energy from entering the system, whereas dampening absorbs energy that has entered the structure and dissipates it. These two forms of energy management are different from each other, but can be used together in order to achieve the desired levels of performance and safety.

7.6.1 Surface isolation

The dynamic energy flows involved in shock and vibration isolation are related. However, differences in isolator behaviour exist due to the transient properties of shock and the steady-state properties of vibration. The purpose of sports surface isolation is to control the negative effects of shock in order to allow their more undesirable aspects to be controlled within safe limits, reducing the risk of injury. If an athlete is the source of shock, the purpose of isolation is to reduce the levels
of energy transmitted from the athlete into to a sports surface structure. In addition, if the athlete requiring isolation is the recipient of unwanted shock, the purpose of isolation is to reduce the energy which is returned from the sports surface structure back to the athlete. A sports surface isolator is a robust structural element, which has the potential to decouple an athlete from the potentially injurious levels of energy returned from a sports surface, immediately following some form of physical interaction with the sports surface. Natural frequency and damping are the basic properties of an isolator, which determine the transmissibility of a structural system designed to provide shock isolation.

7.6.2 Surface dampening

When an athlete starts, stops, turns or lands on a sports surface, unless the surface incorporates some aspect of dampening, the surface will deform and return to its original shape, releasing at an uncontrolled level the energy that it initially absorbed. The surface will continue to oscillate at its natural frequency until all of the energy originally transferred into the surface has been exhausted.

With some categories of isolator, the natural frequency and damping characteristics are combined within a single component, as is the case with viscoelastic materials. The purpose of damping in an isolator is to decrease or dissipate the energy present in a structure as quickly as possible. Damping can have the effect of reducing vibration amplitudes of an object in a state of resonance. Resonance occurs when the natural frequency of an isolator matches the frequency of the object’s input vibration. An optimised isolator design would aim to exhibit as little damping as possible in its isolation region and as much dampening as possible at the isolator's natural frequency, to reduce the potential for vibration amplification at resonance.

Viscoelastic materials are characterised by both viscous and elastic properties while undergoing deformation. Elastic implies that there is perfect energy conversion, in that all energy stored during surface loading is returned once the load has been removed. Therefore, elastic materials exhibit an in-phase stress-strain relationship. Purely viscous behaviour, on the other hand, implies that the material does not recover any of the energy stored during loading once the load has been removed.
Therefore, with these materials, the phase angle between stress and strain is $\frac{\pi}{2}$ radians and all energy is lost through ‘pure damping’.

Viscoelastic materials exhibit behaviours which exist between these elastic and viscous limits. The rate at which the viscoelastic material dissipates energy through shear determines the effectiveness of the damping material. The phase shift between stress and strain is a measure of the material’s damping performance. The moduli of a typical viscoelastic material are described by the following equations:

\begin{align*}
E^* &= E' + iE'' = E'(1 + i\eta) \quad \text{Eq. 7.7} \\
G^* &= G' + iG'' = G'(1 + i\eta) \quad \text{Eq. 7.8}
\end{align*}

Where ‘*’ denotes a complex quantity and E and G represent the elastic modulus and the shear modulus. Therefore the moduli of a viscoelastic material has a component described as the loss modulus, which is representative of the material’s viscous behaviour, and another described as the storage modulus, representative of the elastic behaviour of the viscoelastic material. The loss modulus is equal to the ratio of the loss modulus to the storage modulus.

In order to model mass and stiffness proportional dampening, the most common approach is to calculate viscous or Rayleigh damping, an approach commonly used in non-linear dynamic finite element analysis (Wilson 2004). This approach assumes that the damping matrix is proportional to the mass [M] and stiffness matrices [K], where:

\[ [C] = \alpha [M] + \beta [K] \quad \text{Eq. 7.9} \]

It is important to note that if $[C] = \alpha [M]$ (with $\beta = 0$), the higher modes of the surface structure will be assigned very little damping. While if $[C] = \beta [K]$ (with $\alpha = 0$), the higher modes will be heavily damped. Therefore, by assigning appropriate values to alpha and beta, the effects of the higher modes can be filtered or retained. For finite element analysis, an iterative, incremental approach to a numerical solution is normal, where different values for alpha and beta are trailed and observed as the solution changes. This iterative approach shows that alpha (alpha = 0.05 is the default) is the easier parameter to manipulate.
7.6.3 Surface shock isolation

Shock is a vector quantity with both magnitude and direction, involving sudden acceleration or deceleration and the application of an opposing force can have the effect of reducing the transmission of shock. The application of an opposing force can be achieved with the use of a resilient isolator material, which when exposed to shock will deflect at the natural frequency of the isolating system. If the natural frequency of the isolating system is lower than the disturbing frequency caused by the athlete braking on the surface, the applied load forces the isolator into a state of dynamic deflection. Once the athlete’s braking force has been removed from the surface, the isolator begins to recover from deflection at the isolator’s natural frequency but at a much lower rate than the initial disturbing frequency. The greater the ratio of the disturbing frequency to the natural frequency of the isolator, the higher the resultant efficiency of the surface’s isolation system.

An isolator material must have the ability to return to its original form, once the force has been removed. Regardless of the isolator’s form, elastomeric isolators can experience fatigue failure as a result of cyclic loading. Fatigue failure begins gradually in the visible outer layers of the isolator and progressively propagates throughout the isolator, resulting in a gradual loss of material stiffness. As with the design of most polymeric forms, stress concentrations should be avoided through the use of internal radii.

The disturbing frequency of an athlete braking on a sports surface has been measured in previous research conducted in the area. Tests directed by Steele and Milburn (1987) determined that the time to reach peak horizontal braking on concrete, bitumen and rubber sports surfaces recorded the athlete disturbing frequency at approximately 16.7 hertz. As this disturbing frequency is low, a horizontal ground reaction force reducing isolator will therefore require an even lower natural frequency.

The primary aim of shock isolation in a sports surface is to prevent force from being transferred into a sports surface, which may then be returned back to the athlete. Shock is a momentary condition, where an impulse of energy is transmitted into a surface over a relatively short period of time. Energy is then released from the isolator at the natural frequency of the shock isolation system over a longer period of time. Energy is stored in the isolator as a consequence of the isolator deforming and the efficiency of a shock isolator is measured by the quantity of force transmitted.
through the isolator and its corresponding deformation. The two aspects of shock isolation which should be considered are:

- Shock characterised by forces applied to a sports surface by an athlete, where an isolator system reduces the severity of shock experienced by the surface.
- Shock characterised by motion in a surface, where the shock isolator reduces the amplitude and increases the duration of the energy returned to the athlete from the sports surface.

In a conventional vertical ground reaction force reducing area elastic sports surface system, the maximum force that can be transferred into the surface is dependent on the resultant vertical deformation of the surface. The smaller the deflection of the surface, the higher the impact force will be. In conventional sports surfaces, the potential for horizontal deformation however is minimal. Shock loads have complex wave forms, where the most important characteristics of shock are amplitude, duration and wave shape. In the case of an athlete impacting vertically on a sports surface, previous tests have shown that the wave form generated is a half-sine shock pulse.

All physical systems exhibit some aspect of mechanical dampening. Dampening reduces the amount of amplification at the system’s natural frequency and as dampening increases, the potential to transmit energy decreases (Johnson 1995). Structural dampening which is also known as hysteresis, is expressed as internal friction which is generated within a material, where the hysteresis of a particular material is its capacity to attenuate energy while recovering from deformation. The tan delta or dampening coefficient is a value which determines a material’s dampening effectiveness. The greater the tan delta value, the higher the surface’s dampening effectiveness and a high level of dampening in a polymer has the effect of lowering the impulse peak of an impact. The proposed new sports surface will incorporate a hysteresis approach to the absorption of horizontally induced shock via the compression of elastomeric isolator elements, resulting in a lower rate of loading and a more gradual deceleration of an athlete’s the limbs when
jumping, landing, turning starting and stopping on a sports surface, which will provide better protection from injury to the athlete.

Passive dampening can be described by two main classifications – inherent dampening and designed-in dampening. All current modular plastic tile sports surfaces already exhibit the characteristics of inherent horizontal dampening, as a result of the frictional forces which exist between the polypropylene tile’s ribbing or column support structure and the rubber underlay.

Material dampening in the connection loop system and the resultant small amounts of independent movement which are possible within the tile assembly, as was demonstrated in previous research conducted also contributes to passive dampening and force reduction (Bagley 1992; Walker and Subic 2010). Designed-in dampening, on the other hand, refers to passive dampening that is deliberately implemented within a sports surface structure, with the purpose of reducing the quantity of energy being returned to an athlete from a sports surface. This form of designed-in dampening supplements and enhances the inherent dampening of the system and can increase the effectiveness of passive dampening substantially. In order to achieve high levels of dampening, structural dynamics requires the manipulation of material properties, analysis and predictive methods for the evaluation of a passive dampening system.

7.6.4 Viscoelastic materials

Many polymers exhibit viscoelastic characteristics. Viscoelastic materials (VEMs) are commonly applied in passive dampening situations in commercial area elastic vertical ground reaction force reducing sports surface applications. VEMs are elastomeric polymers which readily convert mechanical energy into heat energy when they become deformed (Aklonis and MacKnight 1983). Critical to the design of passive dampening, is the evaluation of a material’s storage modulus and its mechanical loss factor. A material’s shear modulus determines how much energy can be absorbed by the material and the loss factor determines how much energy can be dissipated. Both of these characteristics are frequency and temperature dependent and of these two aspects, temperature has the greatest influence on a material’s dampening characteristics (Johnson 1995).

In order to be able to accurately design passive dampening within a sports surface utilising viscoelastic materials, accurate material property data must be known. As dampening performance is both frequency and temperature dependent, data addressing both of these aspects must be known. The relationship linking temperature and frequency in all combinations is called characterisation.
A functional relationship between frequency and temperature must be established in order to determine the storage modulus and the mechanical loss factor at any combination of frequency and temperature. Many material suppliers present this form of viscoelastic material data, in the form of a material nomogram or an international plot.
7.6.5 Passively dampened surface design

Designed-in dampening systems utilising high-loss materials can achieve highly predictable levels of energy dissipation. Such systems aim to absorb substantial amounts of strain energy and then dissipate this energy through an appropriate dissipation approach. The passive dampening approach intended for use with the proposed new modular plastic sports tile surface is a form of discrete joint/interface isolator. This approach requires a joint test or modal strain energy primary design method. Modal strain analysis aims to determine the natural frequencies and modal shapes of an
object experiencing free vibration. Finite element analysis is commonly used in order to undertake this form of analysis (Nashif, Jones et al. 1985).

This style of discrete joint isolator is very efficient and relatively simple to implement. Isolated connectors are regularly utilised in truss style structures and are used where multiple components of a structure can become displaced in respect to each other as the result of loading, as is the case when a modular plastic tile sports surface experiences displacement due to the application of an athlete’s braking forces.

In the case of the proposed new modular plastic sports surface, joint/interface embedded dampening elements were applied in a series configuration and the isolator embedding process occurred during connector manufacture through either over-moulding or secondary adhesion, depending on the material characteristics of the final isolator material selected. Due to the creep constraints of VEMs, high static loads were avoided and alternative static loading pathways through the structure were employed. The physical design of the surface isolator is an integral aspect of the proposed new sports surface and in order to achieve adequate levels of athlete protection, two conditions must be achieved: Substantial levels of strain energy must be directed towards the dampening element and the energy attenuated by the dampening element must be adequately dissipated.

The first condition specified was the main focus of the isolator design developed during the current study. The surface design required detailed consideration of the structural properties and configuration of the tile/connector system, the positioning and form of dampening elements within the tile/connector system, mode shapes, material stiffness, and material thickness. Secondly, attenuating energy through dampening is characterised by a suitable loss factor that matches the designed surface stiffness.

The main considerations in dampener material selection in the current study, therefore, were:

- high dampening coefficient
- extensive temperature range
- extended fatigue life.

7.6.6 Surface loading analysis
It is vital that the nature of the surface loading problem is fully understood. Passive dampening solutions for complex structures are normally developed using finite element analysis (FEA) (Johnson 1995). Methods for FEA of dampened structures can be defined as either mode-based or response-based. The latter approach utilises the bottom-line dynamic response to guide the design process, whereas mode-based approaches use a substitute metric.

The most common mode based approach is modal strain energy and complex eigenvalue analysis (Johnson and Kienholz 1982). For each of these analytical approaches, the dampening element is represented in the finite element model as an embedded element. The iterative design approach for a viscoelastic material, passive dampened sports surface system is therefore conducted as follows:

**Design approach problem definition**

- Determine specifications, requirements and design constraints.
- Specify surface interaction dynamics that result in high responses.

**Develop initial isolator design configurations**

- Develop isolator element/connector concepts.
- Undertake analysis using reduced order modelling.
- Adjust design variables to select optimal dampening characteristics.
- Undertake response prediction analysis.

**Develop final isolator design configurations**

- Develop detailed finite element model of dampened surface structure.
- Adjust design variables to select optimal dampening characteristics.
- Perform modal strain energy response analysis using selected VEM properties.
- Determine if all specifications and constraints have been met.

(Johnson 1995)

**Design approach problem definition.** In order to reliably predict the horizontal ground reaction force loading on the proposed new sports surface during competitive play, previous studies conducted into the magnitude and rate of the loading forces generated on landing in netball were investigated. Studies conducted by Steele and Milburn (1987) and Steele and Lafortune (1989),
concluded that in the sport of netball, peak VGRF mean measurements of a forefoot strike and heel strike, are typically 5.70 times body weight and 5.25 times body weight, respectively.

Peak HGRF mean measurements of a forefoot strike and heal strike typically are 2.00 times body weight and 3.30 times body weight respectively, with a total resultant force of 5.90 times body weight and 6.00 times body weight respectively (Steele and Lafortune 1989). These measurements relate directly to the type of netball manoeuvre being analysed and can be as high as VGRF mean 5.25 times body weight and HGRF mean 4.61 times body weight respectively. Time to peak horizontal braking shock force values of 30.0 msec are typical for most of the tests undertaken (Steele and Milburn 1989), which equate to an excitation frequency of 16.7 Hertz.

Body weight tends to vary slightly depending on position played in the sport of netball, with defence players having an average weight of 66.6 ± 7.5kg, shooters having an average weight of 66.3 ± 7.8kg and centre court players having an average weight of 59.2 ± 2.7kg (Bale and Hunt, 1986. Assuming a shod athlete with mass of 65kg, height 165 cm (Steele and Lafortune 1989), the
expected forces applied to a sports surface by the athlete would result in a combined VGRF/HGRF resultants force of 6.0 times body weight, representing a force of $= 6 \times 65 \times 9.81 = 3.826 \text{kN}$.

This equates to two equal force vectors acting at 45 degrees to the sports surface of:

\[
\begin{align*}
R_y &= 4.243BW \text{ or } 2.706\text{kN} \\
R_z &= 4.243BW \text{ or } 2.706\text{kN}
\end{align*}
\]

The mechanical properties of a playing surface should be attuned to the types of physical movement being conducted on the surface and the loads being exerted on the surface; otherwise there will be an increase in the injury risk to an athlete. The aim of the current research was to design a surface which can attenuate combined vertical and horizontal ground reaction forces extrapolated from the EN 14904 standard for point elastic force reduction in the P1 range of classifications. The research target for netball was force reduction levels of $HGRFR \ 20\% \ \text{to} \ 30\%$ and $VGRFR \ 20\% \ \text{to} \ 30\%$.

\[
VGRFR \ \text{and} \ HGRFR = 100 - \frac{F_{\text{sportsurf}}}{F_{\text{concrete}}} \times 100
\]

Where:

\begin{itemize}
\item $VGRFR = \text{Vertical ground reaction force reduction of the system expressed in percentage terms} \ (%)$.
\item $HGRFR = \text{Horizontal ground reaction force reduction of the system expressed in percentage terms} \ (%)$.
\item $F_{\text{sportsurf}} = \text{Maximum impact force generated on the sports surface being tested} \ (\text{N})$.
\item $F_{\text{concrete}} = \text{Maximum impact force generated on concrete} \ (\text{N})$.
\end{itemize}

\textbf{Development of initial HGRF isolator design configurations.} The purpose of this stage of the design process was to develop various iterative dampening element/connector concepts and then undertake an analysis of each isolator concept, utilising appropriate analytical methods.

Form factor, compression and isolator displacement or isolator bulge, are important factors in determining an optimal isolator design for a HGRF surface attenuator. Polyurethane elastomer isolators do not return all energy after compression, and the quantity of energy retained through hysteresis loss is converted into heat energy. If the frequency of compression is low, as is the case with an athlete impacting a sports surface, normally a low spring rate material will absorb higher levels of shock.
Polyurethane elastomeric materials consist of elastic response and viscous response components. The elastic response component stores energy and then returns the energy, whereas the viscous hysteretic response component absorbs energy and converts it into heat. Materials with high resilience have higher elastic to viscous ratios. Low elastic to viscous ratio polyurethanes retain energy and convert more input energy into heat than high ratio materials. Importantly, polyurethane elastomers do not dissipate heat quickly as a result of the polymeric material’s low thermal conductivity. Therefore, if cyclic loading is applied to the surface, heat generation should be avoided by minimising strain or isolator deflection per cycle, maximising the compression modulus of the material, increasing the form factor or minimising the stress or load per unit area.

In this low frequency sports surface shock scenario, heat generation will not be a concern as it is unlikely that the same connector and isolator will be deflected repeatedly over a short period of time, therefore:

- Isolator deflection per cycle may be high.
- The compression modulus may be low, making the isolator easily compressible.
- The form factor may be low (less than 1.0), implying a low spring rate and an increased tendency to deform under load.

A polyurethane elastomeric material was required for the isolator elements, therefore Sorbothane was chosen as this is a well-proven and commercially accessible material available in a variety of durometers, as shown in Figure 7.19. As a core aim of this research was to construct and test prototype surfaces, it is critically important that commercial quantities of sample materials can be sourced for testing purposes. Following best practice approaches, a number of isolator forms were developed during the current study, and the form factors for the isolator shapes calculated. Form factor is a mathematical expression which is used to quantify the ability of an elastomeric material to deform under the application of force (Sorbothane 2013). An elastomeric isolator with a high form factor implies that it has a reduced ability to deform and an isolator with a low form factor implies a softer material form with an increased ability to deform. Inherent in isolators with a low form factor is low spring rate and the capacity for the isolator to have a low natural frequency. Initial
isolator designs were evaluated by considering each isolator’s performance in respect to form factor, static deflection, system natural frequency, transmissibility and precent isolation.

**Form factor.** The form factor is calculated from the ratio of the average contacting surface area (one side), divided by the object’s perimeter area. Commonly used dampener forms are described mathematically by:

Dampener shape factor (SF) = \frac{\text{Loaded Area}}{\text{Unloaded Area}} \quad \text{Eq. 7.11}

Rectangular prism dampener (SF) = \frac{\text{Length} \times \text{Width}}{2 \times \text{Thickness} \times (\text{Length}+\text{Width})} \quad \text{Eq. 7.12}

Square prism dampener (SF) = \frac{\text{Length}}{4 \times \text{Thickness}} \quad \text{Eq. 7.13}

Disk dampener (SF) = \frac{\text{Diameter}}{4 \times \text{Thickness}} \quad \text{Eq. 7.14}

Toroidal dampener (SF) = \frac{\text{Outside Diameter}}{4 \times \text{Thickness}} - \frac{\text{Inside Diameter}}{4 \times \text{Thickness}} \quad \text{Eq. 7.15}

(Sorbothane 2013)

**Static deflection.** Static deflection ($\delta_{ST}$) is the deflection of the isolator under the static or deadweight load of an athlete or an isolator pre-loaded during tile and connector assembly. Values for compressive stress can be extracted from Figure 7.19 (compressive stress vs durometer).

![Figure 7.19](image)

**Figure 7.19** Compressive stress vs durometer (Sorbothane 2013)

Compressive modulus = \frac{\text{Compressive Stress (Cs)}}{\text{Assumed Percentage Deflection}/100} \quad \text{Eq. 7.16}
Corrected compressive modulus = (compressive modulus) x [1 + 2 x SF^2] \quad \text{Eq. 7.17}

Static deflection ($\delta_{ST}$) = \frac{\text{Load per Dampener x Thickness}}{\text{Corrected Compressive Modulus x Loaded Area}} \quad \text{Eq. 7.18}

Percent deflection ($\% \delta$) = \frac{\delta_{ST}}{\text{Thickness}} \times 100 \quad \text{Eq. 7.19}

**System natural frequency.** According to Newton’s first law of motion, system natural frequency, also known as resonant frequency ($f_n$) is the specific frequency at which an object will naturally vibrate if disturbed by an external force and allowed to come to rest without further influences. In its simplest form, a single degree of freedom system, natural frequency is a function of mass and stiffness. Every sports surface will have numerous natural frequencies, as each element present in a surface structure will have a different natural frequency. In the case of horizontal shock dampening, we are primarily concerned with the horizontal stiffness of the surface structure. Values for dynamic shear modulus ($G_{dyn}$) can be extracted from Figure 7.20 (frequency vs shear modulus).

![Figure 7.20](frequency_vs_shear_modulus.png)

**Figure 7.20** Frequency vs shear modulus (Sorbothane 2013)

Dynamic Young’s modulus ($E_{dyn}$) = Dynamic shear modulus ($G_{dyn}$) x 3 \quad \text{Eq. 7.20}

Dynamic spring rate ($K_{dyn}$) = \frac{E_{dyn} x (1+2 x SF^2) x \text{Loaded Area}}{\text{Thickness}} \quad \text{Eq. 7.21}

System natural frequency ($f_n$) = \sqrt{\frac{K_{dyn} \times \text{gravity} / \text{Load per Dampener}}{2\pi}} \quad \text{Eq. 7.22}
**Transmissibility.** Transmissibility (T) is a dimensionless unit which expresses the ratio of response amplitude of a surface in steady state forced vibration to an input excitation amplitude. It can be measured as motion, force, velocity or acceleration. Values for tan delta can be extracted from Figure 21 (frequency vs tan delta). Tan delta, also known as the dampening coefficient is also a dimensionless unit which describes the ‘out of phase’ time relationship between a shock and the transmission of force. The phase shift is known as tan delta and the higher the tan delta, the more surface dampening occurs. A high dampening coefficient will attenuate more energy and reduce the transmissibility of the system.

![Figure 7.21 Frequency vs tan delta (Sorbothane 2013)](image)

**Equations:**

- Frequency ratio \( (r) = \frac{\text{Excitation Frequency (f_{exc})}}{f_n} \) \hspace{1cm} Eq. 7.23
- Dynamic shear ratio \( (\text{Gr}_{\text{dyn}}) = \frac{G_{\text{dyn}} \text{ @ } f_n}{G_{\text{dyn}} \text{ @ } f_{\text{exc}}} \) \hspace{1cm} Eq. 7.24
- Transmissibility \( (T) = \frac{1+(\text{Tan Delta})^2}{\sqrt{(1-r^2 \times \text{Gr}_{\text{dyn}})^2 + (\text{Tan Delta})^2}} \) \hspace{1cm} Eq. 7.25
- Percent isolation = \( (1 - T) \times 100 \) \hspace{1cm} Eq. 7.26
- Transmissibility at resonance \( (Q) = \frac{1+(\text{Tan Delta @ f_{exc}})^2}{(\text{Tan Delta @ f_{exc}})^2} \) \hspace{1cm} Eq. 7.27
A number of iterative horizontal isolator forms were developed based on Santoprene Durometer 70 and the key performance determinants of form factor, natural frequency, tan delta, transmissibility and percent isolation were calculated.
<table>
<thead>
<tr>
<th>Table 7.4</th>
<th>Loading per isolator during peak braking on one (IL1) and two (IL2) tiles or connectors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Static deflection in mm ($\delta_{s}$)</td>
</tr>
<tr>
<td>Square Isolator, 10mm x 10mm x 2mm, Durometer 70, Form Factor 1.25</td>
<td></td>
</tr>
<tr>
<td>Load per isolator- 169.1N (16 IL1 and 8 IL2 )</td>
<td>1.78</td>
</tr>
<tr>
<td>Load per isolator- 84.6N (32 IL1 and 16 IL2)</td>
<td>1.52</td>
</tr>
<tr>
<td>Load per isolator- 42.3N (64 IL1 and 32IL2)</td>
<td>0.51</td>
</tr>
<tr>
<td>Load per isolator- 21.1N (128 IL1 and 64 IL2)</td>
<td>0.25</td>
</tr>
<tr>
<td>Square Isolator, 5mm x 5mm x 2mm, Durometer 70, Form Factor 0.62</td>
<td></td>
</tr>
<tr>
<td>Load per isolator- 169.1N (16 IL1 and 8 IL2 )</td>
<td>15.75</td>
</tr>
<tr>
<td>Load per isolator- 84.6N (32 IL1 and 16 IL2)</td>
<td>7.87</td>
</tr>
<tr>
<td>Load per isolator- 42.3N (64 IL1 and 32IL2)</td>
<td>3.81</td>
</tr>
<tr>
<td>Load per isolator- 21.1N (128 IL1 and 64 IL2)</td>
<td>2.03</td>
</tr>
<tr>
<td>Rectangular Isolator, 5mm x 10mm x 2mm, Durometer 70, Form Factor 0.83</td>
<td></td>
</tr>
<tr>
<td>Load per isolator- 169.1N (16 IL1 and 8 IL2 )</td>
<td>5.84</td>
</tr>
<tr>
<td>Load per isolator- 84.6N (32 IL1 and 16 IL2)</td>
<td>3.04</td>
</tr>
<tr>
<td>Load per isolator- 42.3N (64 IL1 and 32IL2)</td>
<td>1.52</td>
</tr>
<tr>
<td>Load per isolator- 21.1N (128 IL1 and 64 IL2)</td>
<td>0.76</td>
</tr>
<tr>
<td>Rectangular Isolator, 3mm x 10mm x 2mm, Durometer 70, Form Factor 0.57</td>
<td></td>
</tr>
<tr>
<td>Load per isolator- 169.1N (16 IL1 and 8 IL2 )</td>
<td>27.18</td>
</tr>
<tr>
<td>Load per isolator- 84.6N (32 IL1 and 16 IL2)</td>
<td>13.72</td>
</tr>
<tr>
<td>Load per isolator- 42.3N (64 IL1 and 32IL2)</td>
<td>6.86</td>
</tr>
<tr>
<td>Load per isolator- 21.1N (128 IL1 and 64 IL2)</td>
<td>3.30</td>
</tr>
<tr>
<td>Disk Isolator, 10mm OD x 2mm, Durometer 70, Form Factor 1.25</td>
<td></td>
</tr>
<tr>
<td>Load per isolator- 169.1N (16 IL1 and 8 IL2 )</td>
<td>4.32</td>
</tr>
<tr>
<td>Load per isolator- 84.6N (32 IL1 and 16 IL2)</td>
<td>2.03</td>
</tr>
<tr>
<td>Load per isolator- 42.3N (64 IL1 and 32IL2)</td>
<td>1.01</td>
</tr>
<tr>
<td>Load per isolator- 21.1N (128 IL1 and 64 IL2)</td>
<td>0.51</td>
</tr>
<tr>
<td>Disk Isolator, 5mm OD x 2mm, Durometer 70, Form Factor 0.62</td>
<td></td>
</tr>
<tr>
<td>Load per isolator- 169.1N (16 IL1 and 8 IL2 )</td>
<td>38.86</td>
</tr>
<tr>
<td>Load per isolator- 84.6N (32 IL1 and 16 IL2)</td>
<td>19.30</td>
</tr>
<tr>
<td>Load per isolator- 42.3N (64 IL1 and 32IL2)</td>
<td>9.65</td>
</tr>
<tr>
<td>Load per isolator- 21.1N (128 IL1 and 64 IL2)</td>
<td>4.83</td>
</tr>
<tr>
<td>Torus Isolator, 10mm OD 3mm x 2mm, Durometer 70, Form Factor 0.87</td>
<td></td>
</tr>
<tr>
<td>Load per isolator- 169.1N (16 IL1 and 8 IL2 )</td>
<td>7.62</td>
</tr>
<tr>
<td>Load per isolator- 84.6N (32 IL1 and 16 IL2)</td>
<td>3.81</td>
</tr>
<tr>
<td>Load per isolator- 42.3N (64 IL1 and 32IL2)</td>
<td>1.78</td>
</tr>
<tr>
<td>Load per isolator- 21.1N (128 IL1 and 64 IL2)</td>
<td>1.01</td>
</tr>
<tr>
<td>Torus Isolator, 8mm OD 3mm x 2mm, Durometer 70, Form Factor 0.62</td>
<td></td>
</tr>
<tr>
<td>Load per isolator- 169.1N (16 IL1 and 8 IL2 )</td>
<td>13.71</td>
</tr>
<tr>
<td>Load per isolator- 84.6N (32 IL1 and 16 IL2)</td>
<td>6.86</td>
</tr>
<tr>
<td>Load per isolator- 42.3N (64 IL1 and 32IL2)</td>
<td>3.30</td>
</tr>
<tr>
<td>Load per isolator- 21.1N (128 IL1 and 64 IL2)</td>
<td>1.78</td>
</tr>
</tbody>
</table>
The loading per isolator indicates the number of isolators required on each connector edge, for each of the initial isolator designs developed, where IL1 indicates the loading per isolator with an athlete landing on a single tile/connector at 2.706kN total load, and IL2 indicates the loading per isolator with an athlete landing on two tiles/connectors at 1.353kN total load (Table 7.4). The developed data correlates closely with the material supplier data shown in Figures 7.19 to 7.20, and the early iterations of isolator design indicated that multiple isolators would be required on each connector edge, lowering the force per isolator. Each isolator was designed to have a low shape factor in order to bring isolator dampening performance within acceptable levels inside the available isolator edge envelope. A major constraint on the ultimate isolator design was the 205mm x 10mm x 2 mm connector edge profiles available.

**Analysis of results.** As a low isolator form factor can contribute to low spring rate and therefore the capacity for the isolator to have a low natural frequency, the developed data confirms that forms where the isolator projected area in the direction of the applied force is low, results in lower system natural frequency. Isolators which exhibit higher delta tan figures provide higher dampening effects and lower transmissibility. As transmissibility is the ratio of the output response in relation to the input vibration, where T>1, there is a likely frequency increase and the maximum increase arises when the forcing frequency ($f_f$) and natural frequency ($f_n$) of the structure correspond, as can be seen in the developed data. In the loading cases where the tan delta is low, the transmissibility also lowers, to the point where percent isolation values become negative and vibration amplification results. Future versions of the isolator developed during the current study will aim to lower the loading per isolator by increasing the number of isolators per connector side.

### 7.6.7 Development of final HGRF isolator design configurations

Surface shock is a sudden transient acceleration caused by an athlete landing, starting, stopping or turning on a surface and will be composed of both vertical and horizontal components. In this case, the horizontal kinetic energy was considered in the design of the isolator:

\[
\text{Kinetic energy (KE)} = \frac{1}{2}mV^2
\]

**Eq. 7.28**

A 65kg netball player can sprint to receive a pass at an average speed of 3.85 m/sec. The game-rule structure of netball allows a player to take 1.5 steps while holding the ball, therefore forcing them to brake suddenly on the netball surface once they have received a pass. The kinetic energy of the netball player can therefore be expressed as:
Total kinetic energy (KE) = \( \frac{1}{2} \times 65 \times 3.85^2 = 481.73 \) J

By considering dynamic deflection, the spring rate for the isolator form can be derived from:

\[ K = \frac{\text{Load per Isolator}}{\delta_{st}} \quad \text{Eq. 7.29} \]

Spring energy is expressed as:

\[ \text{Spring energy (SE)} = \frac{1}{2}k\delta_{st} \quad \text{Eq. 7.30} \]

Equate spring energy to kinetic energy, where:

\[ \text{Spring energy per isolator (SE)} = \text{kinetic energy per isolator (KE)}: \quad \text{Eq. 7.31} \]

\[ \text{Kinetic energy (KE)} = \frac{1}{2}k\delta^2 \quad \text{Eq. 7.32} \]

Dynamic deflection is therefore derived from:

\[ \delta_{dyn} = \sqrt{\frac{2 \times \text{KE per Isolator}}{k}} \quad \text{Eq. 7.33} \]

Dynamic % deflection is therefore derived from:

\[ \delta_{dyn} \% = \frac{\delta_{dyn}}{t} \times 100 \quad \text{Eq. 7.34} \]

Given the 2mm gap thickness limit of the dampener height, a number of isolator forms were developed and their dampening effectiveness evaluated. As discussed earlier, the forces applied to a surface can equate to two equal force vectors acting at 45 degrees to the sports surface of: \( R_y = 4.243BW \) or 2.706kN and \( R_z = 4.243BW \) or 2.706kN. Assuming that within the constraints of the anticipated connector design that there would be multiple isolators per connector side, the loading and kinetic energy conditions per isolator would be as shown in Table 7.5.
Table 7.5 Loading and kinetic energy conditions per isolator during peak braking, on single and double loaded tiles/connectors

<table>
<thead>
<tr>
<th>Isolator number per connector side</th>
<th>Loading per isolator landing on a single tile/connector, at 2.706kN total load</th>
<th>Loading per isolator landing on two tiles/connectors, at 1.353kN total load</th>
<th>Kinetic energy per isolator landing on a single tile/connector, at 481.73J KE</th>
<th>Kinetic energy per isolator landing on two tiles/connectors, at 240.86J KE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2706.00</td>
<td>1353.00</td>
<td>461.73</td>
<td>240.86</td>
</tr>
<tr>
<td>2</td>
<td>1353.00</td>
<td>676.50</td>
<td>240.87</td>
<td>120.43</td>
</tr>
<tr>
<td>4</td>
<td>676.50</td>
<td>338.25</td>
<td>120.43</td>
<td>60.22</td>
</tr>
<tr>
<td>6</td>
<td>451.00</td>
<td>225.50</td>
<td>80.29</td>
<td>40.14</td>
</tr>
<tr>
<td>8</td>
<td>338.25</td>
<td>169.13</td>
<td>60.22</td>
<td>30.11</td>
</tr>
<tr>
<td>10</td>
<td>270.60</td>
<td>135.30</td>
<td>48.17</td>
<td>24.09</td>
</tr>
<tr>
<td>12</td>
<td>225.50</td>
<td>112.75</td>
<td>40.14</td>
<td>20.07</td>
</tr>
<tr>
<td>14</td>
<td>193.29</td>
<td>96.64</td>
<td>34.41</td>
<td>17.20</td>
</tr>
<tr>
<td>16</td>
<td>169.13</td>
<td>84.56</td>
<td>30.11</td>
<td>15.05</td>
</tr>
<tr>
<td>18</td>
<td>150.33</td>
<td>75.17</td>
<td>26.76</td>
<td>13.38</td>
</tr>
<tr>
<td>20</td>
<td>135.30</td>
<td>67.65</td>
<td>24.09</td>
<td>12.04</td>
</tr>
<tr>
<td>22</td>
<td>123.00</td>
<td>61.50</td>
<td>21.90</td>
<td>10.95</td>
</tr>
<tr>
<td>24</td>
<td>112.75</td>
<td>56.38</td>
<td>20.07</td>
<td>10.04</td>
</tr>
<tr>
<td>26</td>
<td>104.08</td>
<td>52.04</td>
<td>18.53</td>
<td>9.26</td>
</tr>
<tr>
<td>28</td>
<td>96.64</td>
<td>48.32</td>
<td>17.20</td>
<td>8.60</td>
</tr>
<tr>
<td>30</td>
<td>90.20</td>
<td>45.10</td>
<td>16.08</td>
<td>8.03</td>
</tr>
<tr>
<td>32</td>
<td>84.56</td>
<td>42.28</td>
<td>15.05</td>
<td>7.53</td>
</tr>
<tr>
<td>34</td>
<td>79.59</td>
<td>39.79</td>
<td>14.17</td>
<td>7.08</td>
</tr>
<tr>
<td>36</td>
<td>75.17</td>
<td>37.58</td>
<td>13.38</td>
<td>6.69</td>
</tr>
<tr>
<td>38</td>
<td>71.21</td>
<td>35.61</td>
<td>12.68</td>
<td>6.34</td>
</tr>
<tr>
<td>40</td>
<td>67.65</td>
<td>33.83</td>
<td>12.04</td>
<td>6.02</td>
</tr>
<tr>
<td>42</td>
<td>64.43</td>
<td>32.21</td>
<td>11.47</td>
<td>5.73</td>
</tr>
<tr>
<td>44</td>
<td>61.50</td>
<td>30.75</td>
<td>10.95</td>
<td>5.47</td>
</tr>
<tr>
<td>46</td>
<td>58.83</td>
<td>29.41</td>
<td>10.47</td>
<td>5.24</td>
</tr>
<tr>
<td>48</td>
<td>56.38</td>
<td>28.19</td>
<td>10.04</td>
<td>5.02</td>
</tr>
<tr>
<td>50</td>
<td>54.12</td>
<td>27.06</td>
<td>9.63</td>
<td>4.82</td>
</tr>
<tr>
<td>52</td>
<td>52.04</td>
<td>26.02</td>
<td>9.26</td>
<td>4.63</td>
</tr>
<tr>
<td>54</td>
<td>50.11</td>
<td>25.06</td>
<td>8.92</td>
<td>4.46</td>
</tr>
</tbody>
</table>

The final isolator design procedure entailed:

- Defining the loading characteristics applied, requiring isolation. Load and kinetic energy are divided by the number of isolators that may be efficiently integrated into the design of the connector, considering tool cost, manufacturing efficiency, surface assembly, recyclability and other design constraints relevant to the connector.

- Developing an appropriate isolator design to create a system a natural frequency lower than the sports surface’s excitation frequency. The natural frequency of the dampened system should ideally be 33% lower than the surface excitation frequency. The isolator loading should not be oversized, as this will have the effect of increasing the natural frequency and reducing the dampening potential of the isolator.
A number of different isolator forms were developed and evaluated, in order to create an isolator form which was compatible with the design characteristics of the tile and connector. In this way an isolator with as little dampening as possible in its isolation region and as much dampening as possible at the isolator’s natural frequency reduces the risk of vibration amplification at resonant frequency. The damping ratio for the isolator material is dependent on the excitation frequency. The damping ratio ($\zeta$) is equal to tan delta. Therefore, where the excitation frequency is 16.7 Hertz (frequency $= 1/(2*\text{exposure time})$), the dampening ratios for durometer 30, 50 and 70 grade materials would be 0.66, 0.60 and 0.56 respectively. The durometer scale represents values between 0 and 100, with higher values indicating a more resilient form of polyurethane elastomer.

<table>
<thead>
<tr>
<th>Property</th>
<th>Durometer grade</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>hardness</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>dynamic elastic modulus at 5 Hertz</td>
<td>620,528</td>
<td>723,949</td>
</tr>
<tr>
<td>dynamic elastic modulus at 15 Hertz</td>
<td>930,792</td>
<td>1,034,213</td>
</tr>
<tr>
<td>dynamic elastic modulus at 30 Hertz</td>
<td>1,282,424</td>
<td>1,447,899</td>
</tr>
<tr>
<td>dynamic elastic modulus at 50 Hertz</td>
<td>1,696,110</td>
<td>1,861,584</td>
</tr>
<tr>
<td>tan delta at 5 Hertz</td>
<td>0.30</td>
<td>0.56</td>
</tr>
<tr>
<td>tan delta at 15 Hertz</td>
<td>0.38</td>
<td>0.58</td>
</tr>
<tr>
<td>tan delta at 30 Hertz</td>
<td>0.45</td>
<td>0.57</td>
</tr>
<tr>
<td>tan delta at 50 Hertz</td>
<td>0.35</td>
<td>0.50</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>shear modulus</td>
<td>862200000</td>
<td>862200000</td>
</tr>
<tr>
<td>mass density</td>
<td>1372</td>
<td>1364</td>
</tr>
<tr>
<td>tensile strength</td>
<td>574,954</td>
<td>845,366</td>
</tr>
<tr>
<td>thermal conductivity</td>
<td>0.370</td>
<td>0.2618</td>
</tr>
<tr>
<td>specific heat</td>
<td>1900</td>
<td>1900</td>
</tr>
<tr>
<td>compressive yield strength</td>
<td>0.300</td>
<td>0.610</td>
</tr>
</tbody>
</table>

Four additional isolator forms were developed and evaluated in order to create an isolation form which was more compatible with the design characteristics determined by tile and connector functionality. In this way an isolator with as little dampening as possible in its isolation region and as much dampening as possible at the isolator’s natural frequency was created, in order to reduce the risk of vibration amplification at resonant frequency.
Table 7.7  Square isolator design evaluations with durometer 50 and 70 grade material

<table>
<thead>
<tr>
<th>Load/Isolator</th>
<th>Static deflection in mm ($\delta_{st}$)</th>
<th>Percent deflection (%)</th>
<th>System natural frequency (Hz)</th>
<th>Tan delta</th>
<th>Transmissibility (T)</th>
<th>Percent isolation (%)</th>
<th>Spring rate (k)</th>
<th>KE</th>
<th>Dyn δ</th>
<th>% δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>169.1N-50</td>
<td>57.15</td>
<td>2851</td>
<td>3.60</td>
<td>0.46</td>
<td>0.10</td>
<td>89.70</td>
<td>2.95</td>
<td>30.1</td>
<td>4.52</td>
<td>225.87</td>
</tr>
<tr>
<td>112.8N-50</td>
<td>38.10</td>
<td>1900</td>
<td>4.41</td>
<td>0.52</td>
<td>0.15</td>
<td>85.08</td>
<td>2.95</td>
<td>20.1</td>
<td>3.69</td>
<td>184.57</td>
</tr>
<tr>
<td>96.64N-50</td>
<td>32.77</td>
<td>1628</td>
<td>4.76</td>
<td>0.55</td>
<td>0.17</td>
<td>82.79</td>
<td>2.95</td>
<td>17.2</td>
<td>3.41</td>
<td>170.74</td>
</tr>
<tr>
<td>75.17N-50</td>
<td>25.40</td>
<td>1266</td>
<td>5.40</td>
<td>0.58</td>
<td>0.22</td>
<td>77.95</td>
<td>2.95</td>
<td>13.4</td>
<td>3.01</td>
<td>150.70</td>
</tr>
<tr>
<td>56.38N-50</td>
<td>19.05</td>
<td>949</td>
<td>6.23</td>
<td>0.58</td>
<td>0.30</td>
<td>70.24</td>
<td>2.95</td>
<td>10.0</td>
<td>2.60</td>
<td>130.19</td>
</tr>
<tr>
<td>39.79N-50</td>
<td>13.46</td>
<td>671</td>
<td>7.42</td>
<td>0.58</td>
<td>0.43</td>
<td>56.71</td>
<td>2.95</td>
<td>7.08</td>
<td>2.19</td>
<td>109.54</td>
</tr>
</tbody>
</table>
| 30.75N-50    | 10.41                                   | 518                    | 8.44                          | 0.59      | 0.58                | 42.10                 | 2.95              | 5.47 | 1.93   | 96.29 
| 25.06N-50    | 8.38                                    | 418                    | 9.45                          | 0.59      | 0.75                | 24.71                 | 2.95              | 4.46 | 1.74   | 86.94 |
| 25.06N-70    | 4.32                                    | 216                    | 10.21                         | 0.50      | 0.87                | 13.21                 | 5.80              | 4.46 | 1.24   | 62.00 |

Table 7.8  Disk isolator design evaluations with durometer 50 and 70 grade material

<table>
<thead>
<tr>
<th>Load/Isolator</th>
<th>Static deflection in mm ($\delta_{st}$)</th>
<th>Percent deflection (%)</th>
<th>System Natural Frequenc (Hz)</th>
<th>Tan Delta</th>
<th>Transmissibility (T)</th>
<th>Percent Isolation (%)</th>
<th>Spring Rate (k)</th>
<th>KE</th>
<th>Dyn δ</th>
<th>% δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>169.1N-50</td>
<td>72.90</td>
<td>3631</td>
<td>3.19</td>
<td>0.42</td>
<td>0.08</td>
<td>91.72</td>
<td>2.32</td>
<td>30.1</td>
<td>5.09</td>
<td>254.70</td>
</tr>
<tr>
<td>112.8N-50</td>
<td>48.51</td>
<td>2419</td>
<td>3.90</td>
<td>0.48</td>
<td>0.12</td>
<td>88.05</td>
<td>2.32</td>
<td>20.1</td>
<td>4.16</td>
<td>208.13</td>
</tr>
<tr>
<td>96.64N-50</td>
<td>41.66</td>
<td>2073</td>
<td>4.22</td>
<td>0.51</td>
<td>0.14</td>
<td>86.23</td>
<td>2.32</td>
<td>17.2</td>
<td>3.85</td>
<td>192.53</td>
</tr>
<tr>
<td>75.17N-50</td>
<td>32.26</td>
<td>1612</td>
<td>4.78</td>
<td>0.56</td>
<td>0.17</td>
<td>82.63</td>
<td>2.32</td>
<td>13.4</td>
<td>3.40</td>
<td>169.94</td>
</tr>
<tr>
<td>56.38N-50</td>
<td>24.13</td>
<td>1209</td>
<td>5.52</td>
<td>0.58</td>
<td>0.23</td>
<td>76.87</td>
<td>2.32</td>
<td>10.0</td>
<td>2.94</td>
<td>146.81</td>
</tr>
<tr>
<td>39.79N-50</td>
<td>17.02</td>
<td>854</td>
<td>6.57</td>
<td>0.58</td>
<td>0.33</td>
<td>66.70</td>
<td>2.32</td>
<td>7.08</td>
<td>2.47</td>
<td>123.52</td>
</tr>
<tr>
<td>30.75N-50</td>
<td>13.21</td>
<td>659</td>
<td>7.48</td>
<td>0.58</td>
<td>0.44</td>
<td>55.89</td>
<td>2.32</td>
<td>5.47</td>
<td>2.17</td>
<td>108.58</td>
</tr>
<tr>
<td>25.06N-50</td>
<td>10.67</td>
<td>533</td>
<td>8.37</td>
<td>0.59</td>
<td>0.57</td>
<td>43.11</td>
<td>2.32</td>
<td>4.46</td>
<td>1.96</td>
<td>98.04</td>
</tr>
<tr>
<td>25.06N-70</td>
<td>5.33</td>
<td>275</td>
<td>9.05</td>
<td>0.48</td>
<td>0.64</td>
<td>36.43</td>
<td>4.70</td>
<td>4.46</td>
<td>1.38</td>
<td>68.88</td>
</tr>
</tbody>
</table>

Table 7.9  Torus Isolator design evaluations with durometer 50 and 70 grade material
**Table 7.10** Rectangular isolator design evaluations with durometer 50 and 70 grade material

<table>
<thead>
<tr>
<th>Load/Isolator</th>
<th>Static Deflection in mm ($\delta_{sa}$)</th>
<th>Precent Deflection (%)</th>
<th>System Natural Frequeuncy (Hz)</th>
<th>Tan Delt a</th>
<th>Trans-missibility (T)</th>
<th>Precent Isolation (%)</th>
<th>Spring Rate (k)</th>
<th>KE</th>
<th>Dyn δ</th>
<th>% δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load/Isolator- 169.1N-50</td>
<td>129.79</td>
<td>6473</td>
<td>2.39</td>
<td>0.35</td>
<td>0.05</td>
<td>95.07</td>
<td>1.30</td>
<td>30.1</td>
<td>6.80</td>
<td>340.25</td>
</tr>
<tr>
<td>Load/Isolator- 112.8N-50</td>
<td>86.61</td>
<td>4313</td>
<td>2.92</td>
<td>0.40</td>
<td>0.07</td>
<td>92.91</td>
<td>1.30</td>
<td>20.1</td>
<td>5.56</td>
<td>278.04</td>
</tr>
<tr>
<td>Load/Isolator- 96.64N-50</td>
<td>74.17</td>
<td>3696</td>
<td>3.16</td>
<td>0.42</td>
<td>0.08</td>
<td>91.85</td>
<td>1.30</td>
<td>17.2</td>
<td>5.14</td>
<td>257.20</td>
</tr>
<tr>
<td>Load/Isolator- 75.17N-50</td>
<td>57.66</td>
<td>2874</td>
<td>3.58</td>
<td>0.45</td>
<td>0.10</td>
<td>89.78</td>
<td>1.30</td>
<td>13.4</td>
<td>4.54</td>
<td>227.02</td>
</tr>
<tr>
<td>Load/Isolator- 56.38N-50</td>
<td>43.18</td>
<td>2155</td>
<td>4.14</td>
<td>0.50</td>
<td>0.31</td>
<td>86.71</td>
<td>1.30</td>
<td>10.0</td>
<td>3.92</td>
<td>196.12</td>
</tr>
<tr>
<td>Load/Isolator- 39.79N-50</td>
<td>30.48</td>
<td>1522</td>
<td>4.92</td>
<td>0.57</td>
<td>0.18</td>
<td>81.67</td>
<td>1.30</td>
<td>7.08</td>
<td>3.30</td>
<td>165.02</td>
</tr>
<tr>
<td>Load/Isolator- 30.75N-50</td>
<td>23.62</td>
<td>1175</td>
<td>5.60</td>
<td>0.58</td>
<td>0.24</td>
<td>76.19</td>
<td>1.30</td>
<td>5.47</td>
<td>2.90</td>
<td>145.05</td>
</tr>
<tr>
<td>Load/Isolator- 25.06N-50</td>
<td>18.80</td>
<td>944</td>
<td>6.29</td>
<td>0.58</td>
<td>0.30</td>
<td>69.67</td>
<td>1.30</td>
<td>4.46</td>
<td>2.62</td>
<td>130.97</td>
</tr>
<tr>
<td>Load/Isolator- 25.06N-70</td>
<td>9.65</td>
<td>487</td>
<td>6.79</td>
<td>0.44</td>
<td>0.32</td>
<td>68.13</td>
<td>2.60</td>
<td>4.46</td>
<td>1.85</td>
<td>92.61</td>
</tr>
</tbody>
</table>

**Analysis of results.** Given the 10mm x 206mm x 2 mm available connector to tile edge gap profile and excluding the 4 x 17.5mm connection loop locations on each connector edge, there is enough space available for 54 square isolators including a 1mm bulge expansion gap between each isolator loaded at 25.06N per isolator, or 44 rectangular isolators with a 1mm deformation or bulge expansion gap, between each isolator loaded at 30.75N per isolator. Although the higher packing density of the square isolator shown in Table 7.7, results in a lower effective loading per isolator, the lower form factor of the rectangular isolator shown in Table 7.10, results in similar levels of precent dynamic deflection at 86.94% and 90.22% respectively. The rectangle therefore by virtue of its lower form factor proved to be the more efficient means of attenuating energy.
It was important in the experimental flooring system that each isolator was free to deform or bulge, free from interference from adjacent isolators. Contact with a neighbouring isolator would likely limit the isolator’s dampening effectiveness, as its ability to deform freely would be restricted. A displacement analysis was performed as shown in Figure 7.22, to determine the minimum permissible isolator spacing utilising the more efficient rectangular isolator in order to determine the maximum packing density achievable. The analysis indicated that along the long edge of each rectangular isolator, deformation was limited to 0.15mm per side, and therefore at a gap of 1mm, the isolators would not come into contact with each other, resulting in unhindered deformation.

![Figure 7.22 Isolator deformation at 25.06N loading](image)

The large permanent gap remaining after deformation therefore provided the opportunity to reduce the gap to 0.5 mm leaving a 0.2mm clearance gap after deformation and providing the opportunity to increase the isolator packing density to 54 rectangular isolators per side, each attenuating a maximum force of 25.06N. While these results were promising, the rectangular isolator analysis was taken further by varying the isolator form factor.

**Table 7.11** Rectangular Isolator design evaluations with alternative form factors with durometer 70 grade material
## Analysis of results

Material supplier data stated that for an isolator with a form factor of less than 1.2 and percentage dynamic deflections less than 40%, the expected fatigue life would be in excess of one million cycles and for dynamic deflections between 40% and 60%, the expected fatigue life would be in excess of 1,000 cycles (Sorbothane 2013). Dynamic isolator deflection therefore should ideally not exceed 60%, as the risk of shortening the isolator’s fatigue life will increase.

It was therefore reasonable to expect that an isolator with a maximum dynamic deflection of 63.85% (rectangular isolator, 2.00mm x 10mm x 2mm thick, form factor 0.42) would be acceptable in this worst-case scenario. In reality, loading seldom would reach this level as the horizontal braking loads would generally be lower or they would be distributed over the entire playing surface and not repeated to any great extent on one connection point. Furthermore, given the ease of tile and connector replacement within the design, the surface could be easily refurbished in high traffic areas (for example in the goal area), in order to maintain the surface’s HGRFR performance level.

The greater the ratio of the disturbing frequency to the natural frequency of the isolator, the higher the resultant efficiency of the isolator system. As natural frequency decreases, percentage dynamic deflection increases. With a maximum percentage dynamic deflection of 60% (or 63.85% in this case), the expected minimum natural frequency would be 9.80 Hertz. In this context, other important aspects of the design include the tan delta equating to 0.49 and the percentage isolation equalling 21.71%. As transmissibility is the ratio of the output response in relation to the input...
vibration, a transmissibility value of 0.78 was acceptably lower than the point of amplification, where T\(>1\).

7.7 Conclusion

In consideration of research objective A, a means where surface loading could occur less suddenly and where loading could be dispersed over a longer time period in order to reduce the severity of shock and therefore the risk of injury, was explored. A solution was developed through a combination of iterative calculation and finite element simulation with the solution encouraging horizontal elastic deformation during athlete to surface contact, as a result of horizontal deformation and displacement.

In addition, to reduce the potential for injury as described in research objective B, the horizontal reaction forces applied to the modular tile surface by an athlete were reduced by a means of surface displacement. A novel tile surface linkage system which permits a limited amount of horizontal tile displacement via the tile connections in order to attenuate braking forces was developed. The new configuration of the modular plastic tile surface encourages a limited amount of horizontal displacement via the tile connections. In addition the means of attachment now easily permits tile attachment and disengagement for surface assembly and disassembly purposes.

The tile and connector are able to move independently of each other allowing the surface to dissipate energy. The connector to tile interface is the most critical aspect of the new modular tile surface as this feature, along with its unique octagonal tile and square connector configuration, combine to allow horizontal displacement in the surface, and therefore reduce horizontal braking forces.

The tile and connector retaining clip system which holds the connector loops and tile hooks in engagement for surface assembly also permits them to be easily pulled apart for disassembly at the surface’s end-of-life. This will substantially increase the opportunities for the surface to be recovered, resold or recycled at the end of its use, in alignment with research objective E. A process-based analysis of the new modular tile system as described in research objective E was conducted, and resulted in an manufacturing optimised version of each element in the playing surface’s value chain. The materials, processes and design features considered have included all of the detailed aspects required to manufacture, install, maintain and ultimately dispose of the surface.
This considered approach has resulted in the development of a sports surface where the societal needs for the design of a safer sports surface and the business case for an affordable sports surface have been considered over the full lifecycle of the surface.

Simulations of the modular tile sports surface under different surface configuration scenarios have predicted the potential for a significant reduction in peak braking forces. These assumptions are further explored in Chapter 8 where exploratory, assessment and validation testing are discussed.
Chapter 8

Exploratory design, assessment and validation

8.1 Introduction

During any new product development process, it is essential to differentiate between the different categories of evaluation introduced at different stages of the product development process. The current study contributes to our general understanding of the intent of each test and encourages reflection on the ways in which the results from tests can be recorded and inform the developing design of the sports floor. Alternative test methods shown in Figure 8.1 have different purposes, methods and categories of test modelling.

<table>
<thead>
<tr>
<th>Phase 0- Continuous commercial product opportunity generation process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1- Problem definition, research and product definition development</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Product development phases</td>
</tr>
<tr>
<td>A. Exploratory testing</td>
</tr>
<tr>
<td>B. Assessment testing</td>
</tr>
<tr>
<td>C. Validation testing</td>
</tr>
<tr>
<td>D. Comparison testing</td>
</tr>
<tr>
<td>Test categories</td>
</tr>
</tbody>
</table>

Figure 8.1 Test types and occurrence in relation to the product development process

8.2 Surface exploratory testing

Once there is a clear understanding of the needs of the surface’s primary users, in this case the safety and performance of athletes playing netball, exploratory tests can be undertaken early in the product development process, when the problem definition is being articulated and early prospective solutions to the problem are being deliberated. The main aim of exploratory testing within the context of this research, is to analyse the potential of early conceptual ideas and to address fundamental questions about whether modular tile surfaces have the potential to attenuate potentially damaging horizontal ground reaction forces.
This style of initial analysis is possibly the most important type of evaluation testing. If any assumptions were incorrect, then problems would have been unavoidable later in the new surface development project.

In order to investigate the potential for modular tile sports surfaces to attenuate braking forces, a number of exploratory tests were undertaken. Research conducted by Walker and Subic (2010) revealed that homogenous sports surfaces, such as hardwood timber, prefabricated pour-in-place or
prefabricated sheet surfaces, could only attenuate very small amounts of braking force energy (Walker and Subic 2010).

Surfaces constructed from modular tile elements however, have the potential to dissipate more braking force. In addition, they also have the potential to increase the time to reach peak HGRF. This may be due to the fact that an interconnected modular tile sports surface allows a limited amount of horizontal displacement via the tile connections. The ability for the surface elements to move laterally, unlike homogenous surfaces, may reduce the forces experienced by an athlete’s lower extremities while braking and may therefore reduce potentially injurious stress to the athlete’s musculoskeletal system.

8.2.1 Exploratory test method

In order to better simulate an athlete’s interaction with a sports surface, an apparatus was developed and constructed, which could strike a floor repeatedly with a 20kg weight and at a predetermined impact angle. The decision to utilise a 20kg weight was influenced by the current internationally accepted force reduction test requirements of EN 14904. The 20kg mass, and 55mm vertical drop height of the impact device were therefore based on the design of the Berlin Artificial Athlete, but the device was adapted to provide a range of angular impacts. Fine angular adjustment was achieved through the use of a threaded rod to accurately raise or lower the rear of the impact hammer, and thus change the impact angle of the apparatus. The centre of mass of the impact hammer was designed to pass through the angular adjustment pivot point. The apparatus was supported directly off the sub-floor and not the surface being investigated. A pin release mechanism would cause the impact hammer to fall a vertical height of 55mm when activated (the vertical height was adjusted, in relation to the impact angle that was being investigated), and the hammer head would then strike the anchored sports surface which was sitting above the Kistler force platform.
The impact test apparatus shown in Figure 8.2 mimics the principles of the Berlin Artificial Athlete, as the BAA is the internationally accepted force reduction test apparatus used for the measurement of force reduction. The BAA, however, can only be regarded as providing a generic indication of the mechanical behaviour of the athlete or the surface (Young and Fleming 2007). The exploratory, inclined impact test apparatus (EIITA) simulates an athlete’s interaction with a sports surface much more closely than the BAA in this instance. The device can be used to measure combined horizontal and vertical forces, which are more typical of an athlete’s loading on a sports surface. During the exploratory study, impact variables were recorded using a Kistler force plate positioned below the sports surfaces tested.

The EIITA provided enhanced biomechanical fidelity and a fuller understanding of athlete/surface interaction on sports surfaces compared to the current BAA, which lacks a biomechanically valid horizontal force measurement component, as evidenced in the EN 14904 (EN14904 2006) standard. The data developed by the EIITA indicated the potential for such an apparatus to be used as a tool to assess the dynamic horizontal stiffness of sports surfaces. Developing and using a mechanical test device to replicate the horizontal dynamic stress that an athlete can apply to a surface allows an increased understanding of surface behaviour in response to an athlete braking on a surface, as well as indicating the extent to which a surface may deliver braking force reduction.
The EIITA allowed the measurement of maximum horizontal and vertical force reduction and the energy dissipation achievable when an athlete starts, stops, turns or lands on a surface.

The behaviour of the surface when an athlete brakes is not evaluated by current test devices, but should be considered since the viscous and elastic properties of the surface are significant in terms of its durability and athletic performance (Guisasola, James et al. 2010). Furthermore, the non-linear stress-strain behaviour of sports surfaces requires the use of a device which has the ability to vary the angle of the impaction force to something other than perpendicular (Walker and Subic 2010).

The magnitude and direction of the ground reaction forces were collected using a standard piezoelectric force plate (Kistler force platform) with a sampling frequency of 600 Hertz. For clinical analysis, ground reaction forces were resolved into two vector components orthogonal to each other along a two-dimensional system. The components were described: Rz, vertical (up-down) component; and Ry, an anterior-posterior (forward-backward) component. A number of rubber coated spherical impact heads were tested using the EIITA, and the most effective for generating HGRF was found to be an athletic footwear impact head as shown in Figure 8.2.

The apparatus was initially calibrated and impact data recorded with no surface present. Subsequent tests were performed on different sports surfaces using the exploratory test apparatus, and data recorded to evaluate the vertical and horizontal impact attenuation capability of different surfaces. Impact data for each surface type was recorded and mean peak VGRF, mean peak HGRV and mean time to peak HGRV data were recorded, as shown in Table 8.1.

The performance of two structurally diverse synthetic sports flooring systems was then evaluated using a force platform in conjunction with the test apparatus. The aim of the test was primarily to quantify the HGRF attenuation performance characteristics of a sports flooring system consisting of interconnected tiles. Interconnecting tiles allow a limited amount of horizontal displacement via the tile connections, in contrast to a shock absorbent, homogenous vinyl sports flooring system which permits no horizontal movement.

### 8.2.2 Discussion of results

In the tests conducted, the modular tiled surface dissipated more braking force energy, as evidenced by the reduction in peak HGRF (294N) in comparison to the homogenous surface (522N). In the case of the modular tile sports surface, this represents a 45% reduction in the braking forces. In
addition there was a 10% increase in the time to reach peak HGRF. These observed behaviours may have been due to the fact that an interconnected modular tile sports surface permits a limited amount of horizontal displacement via tile connections. This ability to displace horizontally, unlike most other homogenous surfaces, may reduce the forces experienced by the lower extremity while
braking and may reduce potentially injurious stress levels on the musculoskeletal system (see Figure 8.6).

**Table 8.1** Summary of the magnitude and rate of loading for vertical and horizontal forces generated by the exploratory incline impact test apparatus (Walker and Subic 2010).

<table>
<thead>
<tr>
<th>Condition</th>
<th>Peak VGRF (N)</th>
<th>Percentage reduction from A. (%)</th>
<th>Peak HGRF (N)</th>
<th>Percentage reduction from A. (%)</th>
<th>Time to peak HGRF (MSEC)</th>
<th>Percentage increase from A. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>force plate (no sports surface).</td>
<td>825</td>
<td></td>
<td>533</td>
<td></td>
<td>35.2</td>
<td></td>
</tr>
<tr>
<td>vinyl sports surface.</td>
<td>742</td>
<td>10</td>
<td>522</td>
<td>2</td>
<td>34.3</td>
<td>-3</td>
</tr>
<tr>
<td>modular tile sports surface.</td>
<td>633</td>
<td>23</td>
<td>294</td>
<td>45</td>
<td>38.9</td>
<td>10</td>
</tr>
</tbody>
</table>

Note: All values represented are mean values.

**Figure 8.3** Inclined impact test apparatus with spherical and athletic footwear impact heads.

**Figure 8.4** Constructional features of a 10mm thick injection moulded polypropylene modular square tile sports surface, with 6mm thick SBR crumbed rubber shock-pad underlay.
8.2.3 Conclusion

A Berlin Artificial Athlete dynamic testing device was adapted for use at an adjustable angle to the surface being tested to more closely replicate an athlete’s combined stress interaction with a sports surface. This apparatus could therefore be used to increase understanding of the behaviour of sports surfaces under athlete impact and the energy dissipation characteristics that an athlete may experience. Calibration experiments indicated that the horizontal component of the peak impact force found no significant differences in the repeatability of the recorded data.

The modular tile sports surface recorded a significant reduction in peak braking forces accompanied by an increase in the time to peak braking force. This behaviour may be due to the fact that an interconnected modular tile sports surface allows a limited amount of horizontal displacement via the tile connections, and may therefore be able to reduce the forces experienced by the lower limbs of an athlete during braking, thereby reducing stress on the musculoskeletal system.
8.3 Surface assessment testing

While exploratory tests were undertaken to investigate the ways in which different surface types exhibited mechanical behaviours that could result in horizontal force reduction, assessment testing conducted later in the development process, aimed to identify design details which could enhance force reduction. Assessment testing ensures that design expectations remain valid and that the increased detail and design options are correct and appropriate for evaluating the early levels of surface performance. Assessment tests confirm (or note weaknesses in) the direction of design development. Once assessment tests produce positive results, more detailed lines of inquiry can then be initiated.

Assessment testing normally requires prototypes of greater complexity than may have been used in the exploratory tests. Analytical models manufactured from laser cut 9mm thick medium density fibreboard (MDF), with a density of 0.5 g/cm$^3$ and 3D printed acrylonitrile butadiene styrene (ABS) prototypes with a density of 1.04 g/cm$^3$ were developed for assessment testing in the current study. The solid MDF connector weighed 243 grams and the 3D printed ABS connector weighed 254 grams, making the two connector versions reasonably comparable when considering test mass and inertia. The tile and connector geometry was 3D modelled with sufficient detail to allow the manufacture of a series of prototypes of varying complexity, which could be tested in combination with different dampening materials. This allowed the horizontal stiffness characteristics of the evolving sports surface design to be evaluated.
8.3.1 Assessment test method

The horizontal stiffness of a sports surface relates to its rigidity and the extent to which a surface can resist deformation in response to a braking force (Baumgart 2000). The stiffness of the surface $k$, is the measure of resistance offered by an elastic sports surface to deformation. The horizontal
stiffness of the tile surface in a particular direction or single degree of freedom is therefore defined as:

\[ k = \frac{F}{\delta} \]

where:

\( F \) = the force applied to the surface by an athlete starting, stopping or changing direction.

\( \delta \) = the tile horizontal displacement produced in the surface by the applied force. \textbf{Eq. 8.1}

Surface displacement under horizontal loading was measured under the two loading configurations described in Figure 8.7. Configuration 8.7a shows the tile-connector interface with the connector moving directly between two tiles, and configuration 8.7b describes the tile-connector interface with the connector moving directly onto a tile. Configuration 8.7a is representative of an athlete braking on the surface in a ‘down-court’ direction and configuration 8.7b is representative of an athlete braking at a ‘cross-court’ angle of 45 degrees to configuration 8.7a. A fixture surrounding the tile prototype test specimens restricted the movement of the tile components during testing.

Horizontal loads were then applied to the connector in the directions indicated in Figure 8.7 and the displacements measured for different types of isolator material, quantity and configuration. Ideally, the stiffness of the surface is uniform between configurations 8.7a & b, in order to maintain the response predictability of the surface as an athlete brakes on the surface.

Two dampener materials were initially tested – \textit{htyrel thermoplastic elastomer} and \textit{sorbothane polyurethane elastomer}. The connector/tile interface was tested by incorporating isolators 3mm x 10mm x 205mm in size, equally spaced in 2, 3, 4 and 5 isolator configurations per connector side. A load of 98.1N was applied using a Salter Brecknell Super Samson 10kg x 50g spring gauge, drawing the connector onto the mating tile forms. The connector/tile gap displacement was then measured at location ‘D’ in each test configuration.
Figure 8.7  Surface assessment tests with prototypes in configuration a) the tile-connector interface with the connector moving directly between two
tiles, and test configuration b) the tile-connector interface with the connector moving directly onto a tile.

The assessment test was then repeated with 3D printed tiles and connector components as shown in Figure 8.8, in order to determine whether the loop interconnection method developed would provide the anticipated independent movement characteristics required for the two configurations tested. When tested, the 3D printed parts, incorporating identical isolator materials, produced the same displacement and stiffness values when identical combinations of isolator were used. This comparison test is significant, as a combination of FDM and 3D printed components could then be used in the subsequent validation tests, overcoming the prohibitive costs which would be incurred by 3D printing the large numbers of tiles and connecters required for validation testing.

![Figure 8.8](image)

**Figure 8.8** Surface assessment tests with 3D printed ABS prototypes showing top view and ribbed bottom view

The Sorbothane Engineering Design Guide (2013) states that the percentage static deflection of the isolator material under continuous load without impact, should not exceed 20%. For dynamic deflections less than 40%, the expected fatigue life should be considered to be in excess of one million cycles (Sorbothane 2013). In order to measure the horizontal surface stiffness in a static
application, as described in this assessment test method, a maximum static deflection of 20% was therefore adopted.

### Table 8.2 Measurement of isolator stiffness in tile-connector configurations a) and b)

<table>
<thead>
<tr>
<th>Sorbothane isolator material durometer 50 with form factor 1.59 (3mm x 10mm x 205mm)</th>
<th>Configuration a)</th>
<th>Configuration b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (kg)</td>
<td>6.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Load (N)</td>
<td>58.86</td>
<td>49.05</td>
</tr>
<tr>
<td>Displacement (mm)</td>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>Deflection (%)</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Stiffness (GPa)</td>
<td>0.98</td>
<td>0.82</td>
</tr>
</tbody>
</table>

### 8.3.2 Discussion of results

A testing approach was developed by which the efficiency of the tile to connector loop interconnection method could be assessed. In addition, it was possible to determine the surface’s horizontal directional stiffness, influenced by whether an athlete brakes on the surface, in a down-court direction or in a cross-court angle of 45 degrees to the down court direction. The octagonal tile and square connector configuration produces geometric symmetry in 45 degree increments over a 360 degree sweep of the surface, therefore testing the surface at 0 degree (down-court) and 45 degree (cross-court) increments would cover the maximum and minimum values expected. Testing in these angular directions would therefore determine if the horizontal stiffness values changed significantly, as a result of the tile and connector geometries.

The interconnection tests indicated that there were no significant difference in stiffness values between the 3D printed parts which included the interconnection loops and the FDM components without interconnection loops. Therefore a combination of FDM and 3D printed components would be acceptable for use in the validation tests, without the results being compromised.

When horizontal loads were applied to the connector in either of the two selected directions (down-court or at an angle of 45 degrees cross-court) and the displacements of the tiles and connectors were measured using the same isolator materials and isolator forms, the horizontal stiffness values were almost 20% higher when braking down court than when the braking was in a cross-court direction. Ideally, the stiffness of the surface would be uniform in both directions in order to maintain the surface’s response predictability. However, although this difference in surface directional stiffness was not ideal, surface validation tests would aim to validate surface stiffness
variability under dynamic loading conditions as opposed to the static loading conditions simulated in the surface assessment tests.

8.4 Surface validation tests

Validation tests are normally conducted towards the end of the new product development process, and are used to confirm that the surface design objectives have been satisfied. Validation tests aim to assess real surface functionality and horizontal force attenuation performance, as would be anticipated in a production version of the surface. It is likely that validation tests are the first opportunity to appraise all of the individual elements of the surface as they operate together.

The prototype surface tested should therefore be as representative as possible of the final product and simulate the features of the intended production process and materials used. Formal surface evaluation, which may be required for certification, safety or legislative purposes, potentially can also be included in a validation testing process. In comparison to assessment testing, however, there is greater emphasis on experimental rigour, testing uniformity and in service conditions during surface validation tests.

The EIITA used in the exploratory tests lacked a high degree of experimental rigour, however, as it was possible for the impact data to be influenced by the coefficients of friction between the test device and the surface being tested, due to the nature of the impact head used and the textural characteristics of the surface being tested. Therefore, a new form of test device was required for validation testing.

8.4.1 Validation test method

The mechanical behaviour of sports surfaces is commonly assessed using the Clegg Impact Hammer and the Berlin Artificial Athlete. The Clegg Impact Hammer is commonly used to measure the surface hardness of sports pitches, horse racing courses and playground surfaces. The device consists of the following main components:

- cylindrical impact hammer of 0.5 kg or 2.25 kg in mass and 50 mm in diameter
- accelerometer.

The impact hammer is dropped directly onto the surface being tested from a height of 550 mm or 40 mm. Surface hardness is therefore described by the peak deceleration of the impact hammer after it strikes the surface and the higher the reading, the harder the surface.
The Berlin Artificial Athlete test has been in use for many years as the preferred method for measurement of the force reduction property of sports surfaces. The device comprises of the following key mechanisms:

- falling 20.0 kg impact hammer
- spring, of spring rate 2 MN
- force quantifying device, having a capacity of 10 kN and, in combination with its associated instrumentation, the ability to quantify forces with an accuracy of 0.1%
- circular test foot, through which the impact is applied to the floor under test, having a diameter of 70 mm and a bottom surface with a radius of 500 mm.

In execution of the test, the impact hammer is permitted to drop from a height of 55mm onto the spring and the force delivered to the surface is documented. The quantity by which the peak value of the force is lower than the peak value measured when the test is performed on a concrete substrate is determined. The load cell is connected to a charge amplifier, signal processor and signal conditioner. The peak impact force is measured and force reduction is then communicated as a percentage force reduction, in comparison to concrete (Walker and Subic 2010).

The Berlin Artificial Athlete is, however, time consuming to use and highly specialised, which limits the frequency with which it is used to test sports surfaces. In Australia, its use is highly infrequent. To address this issue, the researcher developed a highly portable impact test apparatus drawing on aspects of both the Clegg and BAA devices.

A number of motivations exist for the measurement of the mechanical behaviour of sports surfaces. These include providing an understanding of ball-surface interaction, player surface interaction and player safety. In Australia, there is no statutory requirement for sports surfaces to be tested. In North America and Europe, however, it is common to evaluate the mechanical behaviour of sports surfaces using devices that benchmark surface behaviour (American Society for Testing and Materials 2000). Testing under this framework is dominated by impact devices such as the Clegg Impact Device and the BAA (Young and Fleming 2007).

These two devices provide objective measures of vertical surface hardness and the mechanical behaviour of the surface being tested. While the Clegg Impact Device is relatively lightweight and portable, the BAA is cumbersome and awkward and the 20kg impact hammer makes transportation
and setup of this equipment arduous. Owing to these impediments, data collection on court playing surfaces with this device is seldom performed.

Young and Fleming (2007), along with Walker and Subic (2010), considered it important that new testing methodologies be developed to allow multiple surface parameters to be quantified from single determinations. This device would be time and resource efficient, easy to use and portable. In addition, it could be used in conjunction with intelligent decision support systems for sports surface management. In order to address these issues, a test apparatus was developed as a surface assessment tool for the evaluation of sports surfaces, in order to increase the efficiency of surface testing.

8.4.2 Inclined impact test apparatus for validation of results

A validation inclined impact test apparatus (VIITA), as identified in research objective C, was developed by the researcher with the assistance of the Industrial Design Program workshop facilities at the University of South Australia. The device was used to provide objective measurement of the horizontal force reduction potential of the developing sport surface.

The developed device mimics the performance of the BAA with the additional capacity to provide perpendicular or angular surface impacts. The 20kg mass, and 55mm vertical drop height of the VIITA as with the EIITA, were based on the design of the Berlin Artificial Athlete, but it was adapted for both vertical and angular impacts. In addition, the spring and head specifications were directly based on the parameters used with the Berlin Artificial Athlete. The device is resource efficient due to the integration of non-specialised mobile communication devices, and detailed usability evaluation indicates that the device is more ergonomic than its predecessors. The device is also portable and can be used in conjunction with an intelligent graphical user interface (GUI) decision support Smartphone application for sports surface management. The reliability of the apparatus was successfully confirmed through repeatability and surface comparison trials.
During operation, the test foot is placed on the sports surface and the apparatus is held perpendicular to the surface using the integrated accelerometers within the mobile device to ensure accurate perpendicularity. The global positioning system embedded within the sports surface management application records the position of the VIITA on the sports surface while the measurement is being made. This allows accurate force reduction measurements to be repeated at the same location to determine whether the performance of the surface in a particular location alters over time, for example in high traffic areas under a netball goal. The release trigger disengages the impact hammer causing the hammer to freely fall 55mm onto the device spring.

Accelerometers within the test foot record the impact and send this information back to the mobile device. The measured data is then recorded and displayed in the mobile sports surface management application. In the standard user mode, testing locations are prescribed and force reduction values recorded for each position indicated in the application. Mean values for each test location are calculated automatically within the sports surface management software. The data can be viewed in the form of a numerical scale which is aligned to qualitative surface descriptors or calculated by an algorithm which compares the recorded impact data in relation to a calibrated impact performed on a concrete surface. Actual mean force reduction values are stored in the mobile device and can also be viewed on a PC version of the software when data are downloaded to the PC.
The VIITA testing protocol is intentionally aligned to the Berlin Artificial Athlete EN 14808: 2006, the internationally accepted test standard for sport surface force reduction testing. This being the case, the VIITA features, a 20kg free-falling hammer, a 55mm minimum vertical drop height, a
spiral foot spring (69mm dia., 2000N/mm, 3x coils), a steel base plate (500mm radius face, 1mm edge radius, >10mm thickness) and a test foot mass of 3kg (DIN18032-II 2001).

In respect to the EN standard, force reduction evaluates the capability of a sports surface to diminish the maximum impact force in comparison to an impact on a non-resilient surface such as concrete. This property is an gauge of the level of ‘comfort’ that may be delivered by the sport surface to an athlete and this property is the strongest biomechanical basis of all properties in the EN 14904 standard. Force reduction is represented as a percentage of the impact force generated on concrete and the ensuing equation is used to determine a sport surface’s force reduction:

\[
FR = 100 - \frac{F_{\text{sportsurf}}}{F_{\text{concrete}}} \times 100
\]

Where:

- \( FR \) = Force reduction of the system expressed in percentage terms (%).
- \( F_{\text{sportsurf}} \) = Maximum impact force generated on the sports surface (N).
- \( F_{\text{concrete}} \) = Maximum impact force produced on a concrete surface (N).

\textbf{Eq. 8.2}

VIITA enhancements which go beyond the capabilities of the Berlin Artificial Athlete include an impact hammer that can strike the sports surface at an angle of 90 degrees or 45 degrees in response to the type of VGRF or VGRF+HGRF impact data required. The VIITA features a mobile device interface with graphical interface, utilising Smartphone GPS, accelerometer and wireless features to set-up and record impact data. These features provide ease of use for a variety of tests and test environments.
The use of electronics in the VIITA is vital to create a test device that can be directly aligned with desired test standards and also have high levels of data accuracy. The VIITA records the impact via a load cell mounted in the VIITA test foot, which then sends an electronic signal to the PCB in the VIITA head-unit, from where it is then sent wirelessly to the synchronised mobile device.

Accelerometers within the mobile device enable the operator to determine whether the unit is oriented at 90 degrees or at 45 degrees to the sports surface. Similarly, the in-built GPS feature in the mobile device can be used in conjunction with Google Earth or a similar GPS mapping tool.
application to accurately place the unit within a given test environment or identify the test location position on a sports surface.

When recording inclined impact test data as shown in Figure 8.12, a test foot adapter featuring an array of eight equally spaced interconnection pins can be used in conjunction with the VIITA to connect with a mating array of interface holes in the surface being tested. The interface hole array allows the VIITA to reliably transfer forces into the surface being tested, preventing the VIITA from slipping on the surface.

![VIITA mounted in inclined test frame](image)

In addition, the 45 degree angular separation of each hole in the array will allow a VIITA with a matched test foot adapter to impact the surface at various combinations of ‘down-court’ (parallel to the sides of the court) and ‘across-court’ (diagonal) angles around a 360 degree sweep of the sports surface. In the case of the test foot adapter eight position interface hole array shown in this instance, the VIITA would be able to measure the combined vertical and horizontal reaction force reductions in 45 degree increments.

This ability to achieve angular adjustment ‘across’ and ‘down’ the court surface was considered an important aspect to be included in the validation tests. It was assumed from the data obtained
During assessment testing that impact data acquired when measuring the combined horizontal and vertical force reduction in the validation tests, would generate non-uniform horizontal force reduction measurements due to the irregular tile and connector geometries.

Based on the outcomes from the assessment tests which explored various connector/isolator configurations, a series of tile, half tile, quarter tile, connector, half connector and quarter connector prototypes were manufactured. These prototype surface combinations allowed the construction of two styles of tile/connector validation test configuration, one with a tile in a central position within the test rig and the other with a connector in a central position within the test rig. These test rig variants explored potential differences in the resultant displacements from tile impacts directed between connectors and directly onto connectors as shown in Figure 8.13a, and differences in resultant displacements from a connector impact directed substantially between tiles and directly onto tiles as shown in Figure 8.13b.

![Figure 8.13](image)

**Figure 8.13** Geometric differences in displacements achieved on a surface composed predominantly from square and octagonal elements

Figure 8.13a describes the surface configuration test for ‘tile’ focussed impacts, while Figure 8.11b indicates the surface configuration test for ‘connector’ focussed impacts. Tiles and connectors have been shown in different colours in Figure 8.13 for increased clarity.

The product definition criteria for the developed design of the VIITA included:

- The testing procedure should closely align with the EN 14808 testing procedure.
- The product should be highly portable.
- The testing should produce results of medium to high accuracy.
The testing procedure should provide an easy to interpret user interface, featuring graphical feedback and control features.

- Testing should be simple to conduct in a variety of test scenarios and environments.
- The test device should be simple to prime and release from a usability and ergonomic perspective.
- A single person should be able to perform the test.
- The testing procedures should be adaptable in order to perform VGRF only testing and combined VGRF and HGRF testing.

The design of the test apparatus was heavily influenced by current standards and in particular the Berlin Artificial Athlete EN 14808: 2006. Key features included device portability and user interaction in relation to usability, along with ergonomic considerations within the handle design, hammer release trigger mechanism, the operator hammer priming to its release position and all aspects of device portability. The raising, latching and release of the hammer could be achieved with the use of either one or two hands, depending on the strength of the operator and the handle area of the hammer included a cut-away gripping section, making possible a used friendly ‘power-grip’ or ‘dead-lift’ action.

To ensure reliable contact between the VIITA and the sports surface being tested, the hole configuration in the surface and pin configuration on the test foot adaptor shown in Figure 8.14 allows the VIITA to consistently convey impact forces onto the sports surface in 45 degree increments, throughout a full 360 degree sweep of a surface.

![Test foot adaptor with 2000N/mm VIITA spring and tile connector, which reliably links the VIITA with the modular synthetic tiled sports surface](image)

For the purposes of increased experimental accuracy during validation testing, the tests were conducted under laboratory conditions at the Human Performance Laboratories of the University of
South Australia, School of Health Sciences, utilising a Kistler Force Platform. The magnitude and direction of the resulting ground reaction forces were collected using a standard piezoelectric Kistler force plate, with a sampling frequency of 600 Hertz. The impact foot which is angled to the sports surface at 45 degrees allows the VIITD to strike the surface at this angle, removing the potential variances in friction, as was experienced with the original test device. Once struck, the energy imparted to the impact foot was delivered directly into the surface onto which the impact foot was attached.
8.4.3 VIITA laboratory testing

A series of controlled laboratory experiments using the VIITA were undertaken at the Human Performance Laboratories in the School of Health Sciences at the University of South Australia’s City East Campus.

For each test, sports surface samples were placed within a 1000mm X 1000mm surface displacement containment frame, which restricted all horizontal movement to the area within the frame. The containment frame was anchored to the laboratory floor surrounding a Kistler Force Platform and the surface materials to be tested were located on top of the force platform, with all impacts being performed directly above the force platform. In addition, each surface configuration tested incorporated an identical rubber shock-pad underlay positioned under the playing surface, as is typically used in such sports flooring applications.

Prototype tiles and connectors manufactured to allow the assembly of two different configurations of the proposed new tile and connector surface design were installed within the displacement containment frame. The surface was prototyped in individual tile and connector components, using a combination of fused deposition modelling (FDM) and laser cutting processes.

Fused deposition modelling (FDM) is an additive manufacturing technology which is frequently used in rapid prototyping applications and was considered suitable for this application. In this case, an acrylonitrile butadiene styrene (ABS) filament was heated until it liquefied, after which it was extruded in layers from a nozzle. The nozzle was moved in both horizontal and vertical directions under the regulation of a numerically controlled device, which was directed by a three dimensional mathematical model of the tile and connector design.

The FDM 3D printer used in this case was a Stratasys uPrint. Although the final intended surface material would be co-polymer polypropylene, the ABS material used in the prototype surface simulation adequately replicated the physical interconnection characteristics of the tile to connector interlock which was developed, as shown in Figure 8.15. Isolator elements which simulate the desired material dampening characteristics were added to each connector used in each test, in order to produce a ‘biased gap’ between each tile and connector.
In order to construct the two configurations of the tile surface shown in Figures 8.13a and 8.13b, the following laser cut MDF prototype tile and prototype connector models were created:

- four full tiles (one with a test foot adaptor hole array)
- four half tiles
- four quarter tiles
- four full connectors (one with a test foot adaptor hole array)
- four half connectors
- four quarter connectors
- one full homogenous timber surface 1000mm X 1000mm surface (with a test foot adaptor hole array).

These experiments allowed surface tests to be conducted in a controlled environment and provided reference data for the new modular tile surface in a number of different test configurations. Six test scenarios were simulated in total as shown in Table 8.3.

**Table 8.3  Surface test scenarios**

<table>
<thead>
<tr>
<th>Test Configuration</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>45 degree inclined impact validation test onto a uniform homogenous sports surface being impacted directly down-court (parallel to the sides of the court).</td>
</tr>
<tr>
<td>B</td>
<td>45 degree inclined impact validation test with a centrally positioned tile being impacted directly down-court (parallel to the sides of the court).</td>
</tr>
<tr>
<td>C</td>
<td>45 degree inclined impact validation test with a centrally positioned tile being impacted at 45 degrees across-court (diagonally across the court).</td>
</tr>
<tr>
<td>D</td>
<td>45 degree inclined impact validation test with a peripherally positioned tile being impacted at 45 degrees across-court (diagonally across the court).</td>
</tr>
<tr>
<td>E</td>
<td>45 degree inclined impact validation test with a centrally positioned connector being impacted directly down-court (parallel to the sides of the court).</td>
</tr>
<tr>
<td>F</td>
<td>45 degree inclined impact validation test with a centrally positioned connector being impacted at 45 degrees across-court (diagonally across the court).</td>
</tr>
</tbody>
</table>
Figure 8.16 shows the test foot adapter with an array of interconnection pins being lowered into its mating array of interface holes on a 1000mm X 1000mm X 9mm homogenous test floor. In this test configuration, the impact foot is oriented in the ‘down-court’ direction of the surface. The homogenous surface cannot move within the displacement containment frame, as would be the case with this style of surface being normally securely anchored to the sports surface subfloor.

As it was expected that very little HGRF attenuation would be detected in a homogenous surface, as described in the exploratory tests conducted by Walker and Subic (2010), the results obtained from each of the following test configurations were compared against configuration A. Ten impacts were recorded on the test surface in this configuration and mean values were determined.

The test data recorded was consistent and repeatable, therefore 10 impacts per surface configuration was regarded as being sufficient.

**Figure 8.16 Validation Test A- 45 degree inclined impact test centrally positioned on a homogenous hardwood timber court surface**

In Figure 8.17, the impact foot is oriented in the ‘down-court’ direction of the surface. The impacted tile was displaced directly towards an adjoining tile. However, the connectors oriented 45 degrees either side of the tile were opposing this displacement, and were displaced into their adjoining tiles. In each case, the isolator elements at each tile and connector contact point
attenuated a portion of the HGRF impact energy. Ten impacts were undertaken with the test surface in this configuration and mean values determined.

Figure 8.17 Validation Test B - 45 degree inclined impact test with a centrally positioned tile being impacted directly down-court

Figure 8.18 shows the impact foot oriented at 45 degrees to the ‘down-court’ direction of the surface (into the corner of the test rig). The impacted tile was displaced directly into the adjoining connector, and this connector in turn displaced onto its adjoining tile. In addition, the connectors immediately to each side of the impacted tile were forced away from the tile as a result of the impacted tile displacement interacting with the concave and convex mating faces on the respective tiles and connectors. In each case, the isolator elements at each tile and connector contact point
attenuated a proportion of the HGRF impact energy. Ten impacts were applied to the test surface in this configuration and the mean values determined.

Figure 8.18 Validation Test C- 45 degree inclined impact test with a centrally positioned tile being impacted at 45 degrees across-court

In Figure 8.19, the impact foot is oriented at 45 degrees to the ‘down-court’ direction of the surface (into the corner of the test rig), where the impacted tile is not in the centre of the test rig, but is located in the furthest corner. The impacted tile was displaced directly into the central connector and this connector in turn was displaced into its adjoining tile. In addition, the connectors immediately to each side of each displaced tile were forced away from the displaced tile as a result of the tile displacement interaction with the concave and convex mating faces of the respective contacting tiles and connectors.

This test is similar to test configuration C but there is the opportunity for the compounding effect of more tile and connector displacements to be taken into account, as the impact is taking place in the farthest corner of the test rig. In each case, the isolator elements at each tile and connector contact...
point attenuated a proportion of the HGRF impact energy. Ten impacts were applied with the test surface in this configuration and mean values determined.

In Figure 8.20, the impact foot is oriented in the ‘down-court’ direction of the surface, where the impacted connector is displaced towards and directly between the adjoining tiles. This displacement was designed to separate the adjoining tiles but this was prevented by the connector’s attachment loops, causing the connector’s isolator elements to deform under load. These tiles in turn were displaced into their adjoining connectors and so forth. In each case, the isolator elements at each tile and connector contact point attenuated a proportion of the total HGRF impact energy,
until the isolator elements had attenuated all of the HGRF resulting from the impact. Ten impacts were applied to the test surface in this configuration and mean values determined.

In Figure 8.21, the impact foot is oriented at 45 degrees to the ‘down-court’ direction of the surface (into the corner of the test rig), where the impacted connector is displaced directly into the adjoining tile and this tile in turn was displaced into its adjoining ‘quarter connector’, as this connector is in contact with the displacement containment frame. In addition, the connectors immediately to each side of the impacted connector were forced away from the impacted connector as a result of its displacement interacting with the concave faces on these tiles. In each case, the isolator elements at each tile and connector contact point attenuated a proportion of the HGRF.
impact energy. Ten impacts on the test surface in this configuration were performed, and mean values determined.

![Diagram showing inclined central tile impact diagonally across court](image)

**Figure 8.21** Validation Test F- 45 degree inclined impact test with a centrally positioned connector being impacted at 45 degrees across-court

### 8.4.4 Results and discussion

A typical force-time history for the vertical ground reaction force (Fz), the horizontal anterior-posterior force (Fy) and the horizontal medial-lateral force (Fx) generated by the VIITA in validation tests B to E is shown in Figure 8.22.

![Graph showing force-time history](image)

**Figure 8.22** Typical force-time history for the vertical ground reaction force (Fz), the horizontal anterior-posterior force (Fy) and the horizontal medial-lateral
force (Fx) generated by the VIITA. The VIITA can be considered a simplified but repeatable simulation of athlete/surface interaction.
Mean force-time data from the impacts for each test scenario configuration evaluated are illustrated in Table 8.4. In these data, zero was defined as the point at which the hammer contacted the test foot on the apparatus. Irrelevant data were removed, such as when the device begins to move towards the surface or when the device continues to bounce after the impact.

Table 8.4 Summary of the mean magnitude and rates of loading for horizontal forces generated by the VIITA in surface test scenarios A to F

<table>
<thead>
<tr>
<th>Surface test scenario configuration</th>
<th>Mean peak HGRF (N)</th>
<th>Percentage force reduction from A. (%)</th>
<th>Mean time to reach peak HGRF (MSEC)</th>
<th>Percentage time difference from A. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>homogenous sports surface. (Test A configuration).</td>
<td>2112</td>
<td></td>
<td>0.027</td>
<td></td>
</tr>
<tr>
<td>new modular plastic tile sports surface. (Test B configuration).</td>
<td>560</td>
<td>73.5</td>
<td>0.021</td>
<td>-0.22</td>
</tr>
<tr>
<td>new modular plastic tile sports surface. (Test C configuration).</td>
<td>495</td>
<td>76.6</td>
<td>0.021</td>
<td>-0.22</td>
</tr>
<tr>
<td>new modular plastic tile sports surface. (Test D configuration).</td>
<td>485</td>
<td>77.0</td>
<td>0.024</td>
<td>-0.11</td>
</tr>
<tr>
<td>new modular plastic tile sports surface. (Test E configuration).</td>
<td>562</td>
<td>73.3</td>
<td>0.022</td>
<td>-0.19</td>
</tr>
<tr>
<td>new modular plastic tile sports surface. (Test F configuration).</td>
<td>497</td>
<td>76.5</td>
<td>0.025</td>
<td>-0.07</td>
</tr>
<tr>
<td>mean across all new modular plastic tile sports surface scenarios</td>
<td>520</td>
<td>75.4</td>
<td>0.023</td>
<td>-0.15</td>
</tr>
</tbody>
</table>

In the laboratory study, mean values were produced for the peak horizontal ground reaction force and the time to reach peak horizontal ground reaction force. The mean data were then analysed with descriptive statistics, including mean, minimum, maximum and interquartile range, in order to assess the data central tendency, and explore the range of data recorded across each of the test configurations.
In each tile and connector surface scenario tested (B, C, D, E and F), the modular tile approach (recording a mean across all new modular plastic tile sports surface scenarios of 520N) was found to attenuate more braking force than the homogenous surface (recording a mean of 2112N), as demonstrated by the mean peak HGRF recorded across all testing scenarios. Results for the modular tile sports surface represented a 75% reduction in peak braking force. However, there appears to be a 15% reduction in the time to reach peak HGRF, which was unexpected, as the period of the impact was expected to increase. Rate of loading is an important variable for
evaluating sports surfaces for athlete injury (Dixon, Batt et al. 1999), and is not currently measured by the BAA.

Closer inspection of the data indicated that the reason for the reduction in the time to reach peak HGRF could be as a result of vibration in the test apparatus. As the recorded zero for the impact was defined as the point where loading constantly remained above zero (the point at which the hammer contacts the test foot on the apparatus), vibration caused by the falling hammer during the first 0.017 milliseconds of the impact (1 to 10, 600ths of a second) making the cause of vibration difficult to isolate. After this point, the loading rates of both impacts illustrated in Figure 8.23 continue to increase. The hammer release mechanism is currently assumed to be the cause of the vibration and vibration reduction will be addressed in future versions of the VIITA.

The irregularity observed in the loading region of the impact curve evidenced in scenario B in comparison to scenario A, may be due to individual tile and connector movements as the tiles and connectors release, lock and release as they displace from their unloaded positions during loading. This behaviour is not evidenced in configuration A where there is no displacement in the surface.

In scenarios A and B, the impact peak in both cases occurred at almost the same point (point 17 in scenario A and point 16 in scenario B), followed by a steep recovery in scenario A and a more gradual recovery in scenario B.
These validation tests agree with the earlier exploratory tests and reconfirms that a modular tile surface has the potential to dissipate more horizontal energy than a homogenous surface. Again, this is may be due to the interconnected modular tile sports surface allowing a limited amount of horizontal displacement via the tile linkages. In addition, this beneficial characteristic may be greatly enhanced with the introduction of horizontal isolation into the surface as the percentage force reduction in the exploratory tests increased from 45% in the exploratory tests to 75% in the validation tests. These data were however derived from different test devices, the EIITA and the VIITA respectively. These behaviours will now be discussed in more detail in respect to each scenario explored.

In validation test A, which featured a 45 degree inclined impact test centrally positioned on a homogenous hardwood timber court surface, the test agreed with the previous exploratory tests. These indicated that a homogenous sports surface experiences little or no horizontal deformation and therefore little or no horizontal ground reaction force reduction when impacted at an angle.

In validation test B, a 45 degree inclined impact test, a centrally positioned tile was struck using an impact foot oriented in the ‘down-court’ direction of the floating surface. The impacted tile was displaced directly towards an adjoining tile, meaning that the load was being dissipated by two connectors oriented at 45° to the direction of the impact. This scenario exhibited the second lowest force reduction, recorded as 73.5%.

In validation test C, also a 45 degree inclined impact test, a centrally positioned tile was struck at 45 degrees across-court and displaced directly into the adjoining connector. This connector was then displaced into its adjoining tile. The load was therefore dissipated directly into a single connector. This scenario had the second highest force reduction at 76.6%.

In validation test D, again a 45 degree inclined impact test, a peripherally positioned tile was struck at 45 degrees across-court. The impacted tile was not, however, located in the centre of the test rig, but in the furthest corner. In this case, the impacted tile was displaced directly into the central connector and this connector in turn was displaced into its adjoining tile. This test is similar to
configuration C but there is the opportunity for a compound effect with more tile and connector displacements taking place due to the position of the tile for the test impact.

In each case, the isolator elements at each tile and connector contact point attenuated a proportion of the HGRF impact energy. This scenario demonstrated the highest level of force reduction of all configurations tested at 77.0%. This is however only slightly greater than configuration C which recorded a 76.6% force reduction. The result implies that the vast majority of the energy is dissipated by the immediately juxtaposed connectors, rather than through any anticipated compounding effect from a wider floor matrix.

Validation test E, a 45 degree inclined impact test, included a centrally positioned connector being impacted directly down-court. The impacted connector was displaced towards and directly between the adjoining tiles. This displacement attempted to separate the adjoining tiles, but separation was prevented by the connectors’ attachment loops, causing the connector’s isolator elements to deform under load. This scenario exhibited the lowest force reduction recorded at 73.3%.

The configuration was similar to that of test B, in that the impact force in each case is being directed between two floor tile elements. In test B, the load was directed into two connectors oriented at 45° to the direction of the impact, while in test E, the load was being directed into two tiles. The force reduction data should therefore be similar, which was the case at 73.6% and 73.3% respectively.

In validation test F, which featured a 45 degree inclined impact test with a centrally positioned connector being impacted at 45 degrees across-court, the connector was displaced directly into the adjoining tile. This tile in turn displaced its adjoining ‘quarter connector’, as this connector was in contact with the displacement containment frame. This scenario exhibited the third highest force reduction recorded at 76.5%. This configuration is similar to test C, in that the impact force in each case was directed onto an adjoining floor element. The force reduction data measured should therefore be similar, which is the case at 76.6% and 76.5% respectively.

For prototyping convenience, all of the configurations tested replicate loading being applied centrally to each tile and each connector. In reality, an athlete’s foot will also land across the join of two tiles or a tile and a connector. It is not anticipated that this will have a significant effect on the
system’s HGRF reduction efficiency, as the isolator elements in the abutting tiles and connectors will still undergo elastic deformation, resulting in dampened tile displacement.

8.4.5 Conclusions

As discussed in subsection 8.3.1, the stiffness of the surface should ideally be uniform in any horizontal direction in order to maintain the surface’s HGRF braking response predictability, as an athlete will break at different down court and across court angles while playing sports on a surface. During validation tests where surface stiffness variability was evaluated under dynamic loading and horizontal loads were applied to the surface in configuration scenarios B, C, D, E and F, the horizontal force reductions were found to be acceptably uniform in all of the down-court and across-court angles tested (73.3% minimum force reduction and 77.6% maximum force reduction). Therefore, the surface’s response should be acceptably uniform and therefore predictable. This assertion will however be explored in future planned research.

Previous research has concluded that load and loading rates are major contributors to athlete injury, increasing the stress being absorbed by an athlete’s lower limbs and therefore increasing an athlete’s susceptibility to stress fractures, knee and ankle joint injuries. In the realisation of research objective A, the validation tests have therefore clearly demonstrated that it is possible for a conceptually new modular plastic sports surface to reduce loading. The anticipated increase in loading period was not observed, however, although this outcome may be due to deficiencies in the design of the VIITA’s hammer release mechanism.

The loading rate over the period that loading was applied during testing was reduced, however, and the risk of overloading injury would therefore also be reduced. The developed modular plastic tile surface encourages elastic deformation in the isolator elements resulting in dampened tile displacement, through a process of horizontal deformation and displacement. Therefore, a surface design which has the potential to reduce athlete loading while braking on a sports surface has been realised.

Previous research undertaken has concluded that in order to reduce the potential for injury, both vertical and horizontal ground reaction forces require attenuation. In the realisation of research objective B, modular plastic tile sports surfaces have been shown to dissipate more braking forces than homogenous surfaces. Modular plastic tile surfaces which have the ability to permit a limited amount of horizontal displacement via the tile linkages have the potential to attenuate more braking
force than a homogenous sports surface. The validation tests have demonstrated through the increased levels of force reduction attained that the developed tile interconnection linkages which allow ease of tile attachment and disengagement, also encourages a limited amount of horizontal displacement.

Horizontal ground reaction force reduction measurement has been ignored in the development of the new European Standard for Sports Hall Floors (EN14904 2006) which utilises the Artificial Berlin Athlete as the definitive test for shock absorption. Previous research has argued that a test mechanism should be developed which takes into account the non-linear horizontal and vertical behaviours of different surface types and also that an athlete-surface impact device should be developed. Therefore, in the realisation of research objective C, this research has informed the development of a new sports surface test device based upon the Berlin Artificial Athlete, which can strike a sports surface with a known mass at a known angle and can measure the resultant horizontal forces and vertical forces.

The VIITA was developed and deployed as a means of assessing the mechanical behaviours of court sports surfaces and the apparatus successfully used to measure the horizontal braking force reduction behaviours of a modular tile sports surface in comparison to a homogenous sports surface. The two key parameters for this research, peak horizontal ground reaction force and time to reach peak horizontal ground reaction force, were measured consistently, emphasising the repeatability of the apparatus. The portability and the ease of use mean that the VIITA provides a means to evaluate surfaces more thoroughly and efficiently than pre-existing test devices. The apparatus has the potential to be easily implemented within decision-making methodologies for surface selection, management and as a research tool, to increase the understanding of surface behaviour in future research.

Testing with the modular tile sports surface under different surface configuration scenarios recorded a significant reduction in peak braking forces which validated the assumptions made in the development of the modular plastic tile surface. The conclusion to the validation test series is therefore that in terms of being able to displace horizontally and attenuate the braking forces applied by an athlete, the developed sports surface can reduce the forces being returned to an athlete at much higher levels than common homogenous sports surfaces. This characteristic offers
the potential for surface specifiers to reduce potentially injurious stresses on an athlete’s musculoskeletal system.
Chapter 9

Conclusions and recommendations for future research

9.1 Original contributions

9.1.1 Background

Conventional homogenous point elastic and area elastic sports surfaces only reduce vertical ground reaction forces due to their structure. The attenuating behaviour reduces the energy being returned to the athlete, thus protecting them from injury. This property satisfactory protects an athlete if they are not travelling over the surface and are only landing on the surface from a static jump. Playing sports and other forms of physical activity, however, normally require an athlete to travel over a sports surface at speed and perform various manoeuvres at speed.

The need to dissipate vertical, as well as horizontal forces. Research indicates that the magnitude and repetitive nature of the high braking forces experienced while playing sport contribute to the incidence of lower limb injury. There is also evidence that the horizontal ground reaction forces experienced by an athlete during braking, twisting or turning can be even higher than the vertical ground reaction forces experienced. Any sports surface which does not adequately decouple the athlete from the surface on which they are playing through shock attenuation can cause injury.

In the research reported in this thesis, it was discovered that modular tiled surfaces have the potential to dissipate more braking force energy than uniform, homogenous sports surfaces, such as timber, synthetic pour-in-place and synthetic sheet sports surfaces. It was concluded that this behavior could be due to the fact that an interconnected modular tile sports surface can allow a limited amount of horizontal displacement via the tile linkages. The ability of the sports surface to displace horizontally, just as a conventional sprung surface displaces vertically, may reduce the forces experienced by the lower extremity while braking, and reduce potentially injurious stress to the musculoskeletal system.

This property satisfies the need for a conceptually new, horizontal energy absorbing modular sports surface, which aims to reduce injury from sport and other forms of physical activity. The surface incorporates a horizontal hysteresis approach to the absorption of horizontally induced shock via
the compression of elastomeric elements, resulting in lower rates of loading when jumping, landing, turning, starting and stopping, which will provide better protection from injury to an athlete.

**The sustainability of the sports surface life cycle.** The construction of any sports surface, including its installation, maintenance and disposal, is currently not very sustainable in terms of the waste of resources. While most components that make up sports floors are potentially recyclable or reusable, only a small percentage of waste surface products currently are handled in these ways, and land-based disposal is by far the most common form of disposal for sports flooring in Australia. National concerns about recycling, disposal capacity, the relatively short operational life expectancy of sports flooring, combined with a floor structure’s bulk have contributed to the search for alternative means of recycling or disposal. Increased recycling and reuse would reduce waste and recover valuable resources while significantly reducing their environmental impact. The research for this thesis therefore investigated the potential to reduce the environmental footprint of a sports surface, defined in terms of the local, regional and global environmental impacts to which it contributes over its life, while improving horizontal force attenuation.

The aim of the current research study was therefore to advance our understanding of the mechanical behaviour of court sport surfaces through laboratory experiments, by developing new testing devices and a means whereby the results of these tests can be evaluated. The purpose of sports surface force reduction was to reduce the negative effects of athlete induced shock in order to allow the undesirable aspects of returned energy to be reduced to safe limits, therefore lowering the risk of injury. Test devices therefore were used to inform the development of a new generation of sustainable shock attenuating sports surfaces to better meet the needs of athletes’ sports associations and surface specifiers by reducing the injury rates of athletes travelling over a sports surface, improving athletic performance and environmental performance simultaneously.

To achieve these outcomes, five research objectives were established (see subsection 1.3) and successfully pursued. The outcomes aligned with these research objectives include:
9.1.2 Research objective A

A means by which loading could occur less suddenly, in order to reduce the loading rate and therefore the risk of overloading injury. This may be achieved by maximising horizontal energy attenuation in order to reduce the risk of injury while at the same time provide satisfactory energy return to avoid player fatigue.

Load and loading rates on sports surfaces are major contributors to athletic injury because they influence the stress being absorbed by an athlete’s lower limbs. The current research identified a means by which loading would be less severe. This would reduce the loading rate and therefore the risk of overload injury. The results of the current study demonstrated that a modular tile sports surface which encourages elastic deformation during athlete contact in the horizontal anterior-posterior direction and the horizontal medial-lateral direction through a process of horizontal displacement, would result in reduced lower limb loading when compared with homogenous playing surfaces.

A1 The new prototype modular tile sports surface which features horizontal isolation was developed and successfully attenuated high levels of horizontal force, recording a mean increase of 75.4% force reduction in comparison to a conventional homogenous sports surface which cannot deform to any significant extent in the horizontal plane.

A2 Although this surface design did not extend the anticipated duration of the loading period under laboratory conditions, and the time to reach peak impact increased slightly (with a mean increase of 0.15% compared to a conventional homogenous sports surface), the loading rate over this period was still significantly lower. The surface would therefore reduce the risk of overloading and repetitive stress injury.

This research is therefore original, as currently no sports surface commercially exists which specifically targets horizontal force reduction in addition to vertical force reduction.

9.1.3 Research objective B

A flooring system to attenuate both vertical and horizontal ground reaction forces. A high performance modular plastic tile surface which would permit limited multi-directional lateral surface displacement and would allow ease of tile attachment and disengagement.
Research into sports surface behaviour indicated that in order to reduce the potential for injury, the attenuation of both vertical and horizontal ground reaction forces would be required. This research demonstrated that all sports surfaces that incorporate elastic structures under the playing surface will reduce vertically applied forces.

Modular plastic tile sports surfaces which normally incorporate elastic underlays under the playing surface also reduce vertical ground reaction forces but have the added characteristic of being able to potentially attenuate horizontal ground reaction forces, a behaviour which is not demonstrated by homogenous playing surfaces. This feature was achieved in this research by the surface being specifically configured to allow a limited amount of horizontal displacement via the tile linkages.

B1 The new surface’s connector components and linkages were uniquely configured in such a way that they could promote unimpeded multi-directional horizontal movement, by allowing the interlocking connector loops and tile hooks to slide towards and away from each other, as the surface components undergo displacement while being impacted. The surface assessment tests indicated that there was a 20% increase in horizontal surface stiffness while braking in a down-court direction in comparison to braking in a cross-court direction.

The validation tests subsequently conducted explored this phenomenon further by simulating combined horizontal and vertical impacts utilising a Berlin Artificial Athlete methodology and found no significant differences in percentage force reduction over the various surface impact scenarios explored, ranging from 73.3 percentage horizontal force reduction in test configuration ‘E’ (a 45 degree inclined impact on a centrally positioned connector impacted in a down-court direction), through to 77.0 percentage horizontal force reduction in test configuration ‘D’ (a 45 degree inclined impact on a peripherally positioned tile impacted in a cross-court direction).

The surface assessment tests and the surface validation tests therefore clearly demonstrate that the new tile and connector interconnection mechanism encourages a limited amount of horizontal displacement in various down court and cross court directions.

B2 In addition, surface assessment testing and surface validation testing has shown that the displacement optimised modular plastic tile surface which encourages a limited amount of horizontal displacement, also allows ease of tile attachment and disengagement to assist with the surface’s assembly and disassembly.
This research is therefore original, as currently no commercial sports surface exists which specifically encourages unimpeded multi-directional horizontal tile displacement.

9.1.4 Research objective C

The development of a new sports surface test device based upon the Berlin Artificial Athlete, which can strike a sports surface with a known mass at a known angle and to therefore measure the resultant horizontal and vertical forces.

Previous research argued that a test mechanism should be developed which could apply stress to a surface in order to take into account the non-linear vertical and horizontal material stiffness properties of different surface types. The current research, therefore, informed the development of two new sports surface test devices based upon the Berlin Artificial Athlete. The devices are able to strike a sports surface with a known mass at a known angle and to therefore measure the resultant horizontal forces and vertical forces. Both of these test devices are capable of measuring forces, which can be interpreted as horizontal force reduction and vertical force reduction.

C1 The Exploratory Inclined Impact Test Apparatus (EIITA). The EIITA was used initially to investigate the potential for modular tile sports surfaces to attenuate braking forces and to determine the extent of these forces. The apparatus successfully measured the horizontal braking force reduction of a modular tile sports surface in comparison to a homogenous sports surface. The two key parameters for this research, peak horizontal ground reaction force and time to reach peak horizontal ground reaction force, were measured consistently emphasising the repeatability of the apparatus.

The EIITA confirmed that a homogenous sports surface, such as hardwood timber, prefabricated pour-in-place or prefabricated sheet, can only attenuate very small amounts of braking force energy. Surfaces constructed from discrete tile and connector elements have the potential to dissipate more braking force. It was hypothesised that this behaviour might be due to the fact that an interconnected modular tile sports surface can allow a limited amount of horizontal displacement via the tile linkages. The ability of the tile and connector elements to move independently and laterally, unlike homogenous surfaces, may reduce the forces experienced by an athlete’s lower extremities while braking.

C2 The Validation Inclined Impact Test Apparatus (VIITA). The VIITA was deployed as a means of assessing the mechanical behaviour of the new modular tile sports surface. This apparatus is also capable of measuring peak vertical ground reaction forces and time to reach peak vertical
ground reaction forces. Nevertheless, vertical ground reaction forces were deliberately excluded from the analysis, as vertical ground reaction force reduction is a well-known and readily accepted behaviour of all existing modular plastic tile surfaces.

Horizontal ground reaction force reduction, however, has been a neglected property in force reduction test standards and testing procedures. The portability and ease of use of the apparatus provides a means to evaluate surfaces more thoroughly and efficiently than currently existing test devices. The apparatus can therefore be easily implemented as part of decision-making methods of surface selection, management and as a research tool, to increase the understanding of surface behaviour in future research.

C3 VIITA was adapted for use at a 90 degree angle and a 45 degree angle to the surface being tested, in order to mimic the existing Artificial Berlin Athlete test apparatus and also to more closely replicate an athlete’s combined stress interaction with a sports surface, respectively. Testing the VIITA with the new modular tile sports surface under different configuration scenarios recorded a significant reduction in peak braking forces in comparison to a homogenous surface as described in research objective A.

This research is therefore original, as currently no test device can record impacts at both 90 degrees and 45 degrees to the surface being tested, mimicking an Artificial Berlin Athlete test apparatus, in order to more closely replicate an athlete’s combined stress interaction with a sports surface.

9.1.5 Research objective D

A means whereby results obtained from vertical and horizontal force reduction measurements can be categorised in relation to existing test categories.

As horizontal force reduction testing has been neglected by all other test standards, a means was required to meaningfully categorise the results which would be obtained from VIITA-derived vertical and horizontal force reduction measurements, in relation to existing test categories. To this end, combined horizontal ground reaction force reduction and vertical ground reaction force reduction classifications based on the EN 14904 standard were developed, where the horizontal axis represented HGRF and the vertical axis represented VGRF. Given the relative similarity in horizontal and vertical ground reaction forces measured (Steele and Milburn 1987), it would be reasonable to expect the horizontal and vertical force reduction components to be treated in a
similar manner for classification purposes. The results obtained from the optimised horizontal isolation system incorporated into the new tile surface design exceeded expectations and recorded
horizontal force reduction performance values which would sit in the high horizontal force reduction regions of the P1 H3V and P2 H2V categories, as shown in Figure 9.1.

Utilising rubber underlays of different thicknesses (3mm, 5mm, 7mm and 10mm) and based on the vertical force reduction data published by Sport Court (2013), the new modular tile surface should be capable of achieving combined horizontal ground reaction force reduction and vertical ground reaction force reduction classifications of:

- 3mm rubber underlay – HGRF 70% to 75% and VGRF 20% - 25% as shown in ‘A’ in Figure 9.1 (outside EN14904)
- 5mm rubber underlay – HGRF 70% to 75% and VGRF 25% - 30% as shown in ‘B’ in Figure 9.1 (P1 H3V)
- 7mm rubber underlay – HGRF 70% to 75% and VGRF 30% - 35% as shown in ‘C’ in Figure 9.1 (P1 H3V)
- 10mm rubber underlay – HGRF 70% to 75% and VGRF 35% - 40% as shown in ‘D’ in Figure 9.1 (P2 H2V).

(Sport Court 2013)

This research is therefore original, as currently no test standard exists which can meaningfully categorise results obtained from vertical and horizontal force reduction measurement in relation to existing test EN 14904 test categories. The new test standard also has the capability of articulating the horizontal force reduction potential resulting from the conceptually new surface, which specifically targets horizontal force reduction and vertical force reduction.

9.1.6 Research objective E

An approach where the societal need and business case for sustainable approaches will be considered through lifecycle thinking methods and data collection processes suitable for the evaluation of a streamlined life-cycle assessment model.

The current research demonstrated that sports surface specifiers require objective, consistent and comprehensive data detailing the environmental impacts and waste implications of their surface selection decisions in order to better manage the environmental impacts of the facilities that they design. To this end, a life-cycle thinking approach was investigated for the specification of sports surfaces, which included a process-based analysis looking at each individual material and process in the playing surface value chain.

The materials and processes to be considered, including every aspect of the manufacture, installation, maintenance and, ultimately, the disposal of a variety of indoor sports surfaces. This research saw the development of an informed approach where the societal needs and the business case for a sustainable system were considered through lifecycle thinking methods and data collection processes suitable for the evaluation of a streamlined life-cycle assessment model.

- The outcomes of this approach clearly demonstrated that when installed and used in the South Australian context, the use phase of a hardwood timber sports surface which requires electrical powered HVAC management, has a significant impact in comparison to the use phases of the other surface types assessed.
In addition, the impacts resulting from the human toxicity impact category generated during the end-of-life phase of the pour-in-place synthetic sports surface were unexpected.

In order to improve the performance of the new modular tile surface, the following sustainable design strategies are recommended:

- Source alternative materials and reduce material inputs through more eco-efficient designs. This would include closed-loop extended product responsibility (EPR) business models, which attempt to recover the material used in older installations for reuse in new sports surfaces. A unique benefit of a floating prefabricated tile synthetic sports surface is the capacity for it to be disassembled and re-used or totally recycled. This is not currently feasible with any of the other systems investigated.

- Wherever possible, more environmentally efficient materials should be sourced to replace those materials which are non-renewable, toxic or require energy intensive processes. In addition, design principals, such as dematerialisation, should be employed in order to reduce material inputs and waste as much as possible.

- Exploit the surface’s potential for product life extension. Ruggedising the surface in order to make it more durable to increase its average life from 10 to 15 years would further increase its environmental performance in comparison to other types of surface. The durability of the materials should, where possible, support more than one life cycle. Surface coatings or films which protect the polypropylene tile playing surface should be investigated for their cost feasibility and environmental sustainability.

9.2 **Recommendations for future research**

Moving beyond the current study, and in-line with objective F, further research should take the form of a sports surface comparison test, focusing on steps 1) and 2) of the injury prevention research sequence as described by van Mechelen, Hlobil el al. (1992) in Figure 2.3 and again in Figure 9.2. A future trial will aim to develop a more complete understanding of injury causation in netball through the implementation of a surface related injury minimisation strategy by addressing the multi-factorial nature of the extrinsic risk factors associated with netball injuries, with a particular focus on horizontal ground reaction force reduction.

Testing may be performed at the end of the design process to compare a sports surface against some alternative. Comparison testing should include the capturing of both performance and preference data for each solution. The comparison test will be used to establish a preference,
determine superiority or understand the advantages, disadvantages and injury characteristics of alternative surface types.

A. Exploratory Testing (EIITA)

B. Assessment Testing (AST)

C. Validation Testing (VIITA)

D. Comparison Testing

Figure 9.2 Sports surface test types including surface comparison testing

This research objective however cannot be realised at this point in time, as significant financial investment is required to manufacture indoor and outdoor versions of the new surface designed during the preparation of this thesis. To allow the new surface to be manufactured and installed, this stage of the further research will initially require funding to cover the cost of injection moulding tooling manufacture, surface manufacture and installation at Netball SA’s ETSA Park.

1) Establish the extent and characterisation of the injury occurrence. (Surface comparison test)

2) Establish the aetiology, mechanisms and risk factors of sports injury. (Surface comparison test)

3) Introduce preventative measures through the development of injury prevention programs. (Manufacture and installation of new indoor/outdoor surfaces)

4) Assess effectiveness of injury prevention programs by repeating step 1). (Trial now including new prototype surfaces)

Figure 9.3 Four step sequence for injury prevention research incorporating the proposed surface related injury prevention measures

The survey instrument utilised will be an online document, accessible via Netball South Australia’s website. Information gathered by the injury survey was divided into the following six major data categories:
In South Australia, there are over 26,000 players directly linked to clubs and associations affiliated with Netball South Australia. The survey sample will centre on players and facilities at Netball South Australia’s ETSA Park, which has four shock absorbent indoor netball courts and can cater for up to 3,200 spectators. There are also 26 bituminised, flood-lit outdoor netball courts, featuring
a variety of surface treatments. On a typical match day, over 3000 netball players use the facility (Netball SA 2013).

The survey will include players from both junior and senior groups. Age eligibility for the junior category is between 12 and 15 years. The senior category is 16 years and above. The junior competition consists of four different grades (A-D) of up to four subdivisions (1-4). In the senior category, there are seven different grades (A-G) of up to six subdivisions (1-6).

The study will take into consideration more sports surface types than have been considered in previous studies and included each surface’s detailed structural, material and performance characteristics. Each surface included in the survey will undergo testing and evaluation, and the following characteristics recorded:

- surface category (indoor- sheet synthetic, prefabricated synthetic tile, pour-in-place synthetic, hardwood and wood composition. outdoor- concrete, rubber combination, bitumen and acrylic combination surfaces)
- surface condition (poor, average, good or excellent)
- surface age (years)
- coefficient of friction (EN 13036-4)
- vertical force reduction (EN 14808)
- horizontal force reduction (modified EN 14808)
- vertical deformation (EN 14809)
- thermal performance (surface temperature and court air temperature above ambient temperature, 1 metre above the playing surface in the centre of the netball court).

In addition, other aspects, such as the athletes’ perceptions of comfort, glare and the impact of climatic conditions will be recorded.
**Netball Injury Reporting Form**

<table>
<thead>
<tr>
<th>General Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Netball type being played at the time of injury:</td>
</tr>
<tr>
<td>□ 7 aside outdoor netball</td>
</tr>
<tr>
<td>□ 7 aside indoor netball</td>
</tr>
<tr>
<td>□ 8 aside indoor mixed netball</td>
</tr>
<tr>
<td>Name of person injured:</td>
</tr>
<tr>
<td>Date of injury:</td>
</tr>
<tr>
<td>Physical characteristics:</td>
</tr>
<tr>
<td>□ Age:</td>
</tr>
<tr>
<td>□ Gender:</td>
</tr>
<tr>
<td>□ Weight:</td>
</tr>
<tr>
<td>□ Height:</td>
</tr>
<tr>
<td>Level of activity at the time of injury:</td>
</tr>
<tr>
<td>□ Social School</td>
</tr>
<tr>
<td>□ Primary School</td>
</tr>
<tr>
<td>□ Secondary School</td>
</tr>
<tr>
<td>□ Club</td>
</tr>
<tr>
<td>How would you describe your level of fitness:</td>
</tr>
<tr>
<td>□ Not very fit</td>
</tr>
<tr>
<td>□ Average level of fitness</td>
</tr>
<tr>
<td>□ Good level of fitness</td>
</tr>
<tr>
<td>□ Very fit</td>
</tr>
<tr>
<td>How would you describe your level of flexibility:</td>
</tr>
<tr>
<td>□ Not very flexible</td>
</tr>
<tr>
<td>□ Average level of flexibility</td>
</tr>
<tr>
<td>□ Good level of flexibility</td>
</tr>
<tr>
<td>□ Very flexible</td>
</tr>
<tr>
<td>Level of activity at the time of injury:</td>
</tr>
<tr>
<td>□ 1st</td>
</tr>
<tr>
<td>□ 2nd</td>
</tr>
<tr>
<td>□ 3rd</td>
</tr>
<tr>
<td>□ 4th</td>
</tr>
<tr>
<td>Playing position at the time of injury:</td>
</tr>
<tr>
<td>□ GS</td>
</tr>
<tr>
<td>□ GA</td>
</tr>
<tr>
<td>□ WA</td>
</tr>
<tr>
<td>□ C</td>
</tr>
<tr>
<td>□ WD</td>
</tr>
<tr>
<td>□ GD</td>
</tr>
<tr>
<td>□ GK</td>
</tr>
<tr>
<td>Name of netball centre where injury occurred:</td>
</tr>
<tr>
<td>Name in number letter/identifier of court where injury occurred:</td>
</tr>
<tr>
<td>□ Timber</td>
</tr>
<tr>
<td>□ Synthetic Sheet</td>
</tr>
<tr>
<td>□ Synthetic pour-in-place</td>
</tr>
<tr>
<td>□ Modular Tile</td>
</tr>
<tr>
<td>□ Parquet</td>
</tr>
<tr>
<td>□ Composition block</td>
</tr>
<tr>
<td>□ Bitumen</td>
</tr>
<tr>
<td>□ Bitumen/Rubber</td>
</tr>
<tr>
<td>□ Bitumen/Acrylic</td>
</tr>
<tr>
<td>□ Modular Tile</td>
</tr>
<tr>
<td>□ Outdoor Concrete</td>
</tr>
<tr>
<td>□ Outdoor Rubber</td>
</tr>
<tr>
<td>□ Outdoor Concrete/Acrylic</td>
</tr>
<tr>
<td>□ Outdoor Grass</td>
</tr>
<tr>
<td>□ Clay</td>
</tr>
<tr>
<td>□ Uncomfortable</td>
</tr>
<tr>
<td>□ Poor grip</td>
</tr>
<tr>
<td>□ OK</td>
</tr>
<tr>
<td>□ Quite comfortable</td>
</tr>
<tr>
<td>□ Quite good grip</td>
</tr>
<tr>
<td>□ Very comfortable</td>
</tr>
<tr>
<td>□ Very good grip</td>
</tr>
<tr>
<td>Surface playing comfort experienced:</td>
</tr>
<tr>
<td>□ Level of grip provided by surface:</td>
</tr>
<tr>
<td>□ Uncomfortable</td>
</tr>
<tr>
<td>□ Poor grip</td>
</tr>
<tr>
<td>□ OK</td>
</tr>
<tr>
<td>□ Quite comfortable</td>
</tr>
<tr>
<td>□ Quite good grip</td>
</tr>
<tr>
<td>□ Very comfortable</td>
</tr>
<tr>
<td>□ Very good grip</td>
</tr>
<tr>
<td>□ Level of comfort provided by shoe:</td>
</tr>
<tr>
<td>□ Uncomfortable</td>
</tr>
<tr>
<td>□ Poor support</td>
</tr>
<tr>
<td>□ Poor grip</td>
</tr>
<tr>
<td>□ OK</td>
</tr>
<tr>
<td>□ Quite good support</td>
</tr>
<tr>
<td>□ Quite good grip</td>
</tr>
<tr>
<td>□ Very good support</td>
</tr>
<tr>
<td>□ Very good grip</td>
</tr>
<tr>
<td>□ Level of support provided by shoe:</td>
</tr>
<tr>
<td>□ Uncomfortable</td>
</tr>
<tr>
<td>□ Poor support</td>
</tr>
<tr>
<td>□ Poor grip</td>
</tr>
<tr>
<td>□ OK</td>
</tr>
<tr>
<td>□ Quite good support</td>
</tr>
<tr>
<td>□ Quite good grip</td>
</tr>
<tr>
<td>□ Very good support</td>
</tr>
<tr>
<td>□ Very good grip</td>
</tr>
<tr>
<td>□ When did you buy this pair of shoes:</td>
</tr>
<tr>
<td>□ 3 months ago</td>
</tr>
<tr>
<td>□ 6 months ago</td>
</tr>
<tr>
<td>□ 1 year ago</td>
</tr>
<tr>
<td>□ More than 1 year ago</td>
</tr>
<tr>
<td>□ Weather conditions when injury occurred:</td>
</tr>
<tr>
<td>□ Dry</td>
</tr>
<tr>
<td>□ Damp</td>
</tr>
<tr>
<td>□ Light rain</td>
</tr>
<tr>
<td>□ Heavy rain</td>
</tr>
<tr>
<td>□ Cold</td>
</tr>
<tr>
<td>□ Cool</td>
</tr>
<tr>
<td>□ Warm</td>
</tr>
<tr>
<td>□ Hot</td>
</tr>
<tr>
<td>□ 0-10 degrees C</td>
</tr>
<tr>
<td>□ 11-20 degrees C</td>
</tr>
<tr>
<td>□ 21-30 degrees C</td>
</tr>
<tr>
<td>□ 31-40 degrees C</td>
</tr>
</tbody>
</table>

Figure 9.4 Online netball injury reporting form A
Changes in surface friction characteristics have been shown to affect the degree of foot fixation on playing surfaces, which can increase the stresses transmitted to the structures of the knee. Shoe/surface combinations which result in high torque pose the greatest risk to an athlete in terms
of injury. The optimum shoe/surface combinations therefore are most important at the point where the shoe releases from the surface, when an applied torque reaches unsafe levels.

The ideal level of friction between the shoe and the surface is where sufficient traction is provided to enable an athlete to accelerate and decelerate without accidentally slipping, while at the same time allowing movements, such as twisting and turning, with minimal stress being placed on the lower limb.

Footwear is considered very important to the performance of all netball players, and previous studies have reported that 40% of injured players had some problems with their shoes (Hopper 1986). The study will take into account netball shoe tread patterns, traction, comfort, support, insulation from surface heat, brand and model, footwear age and the athletes’ perception of the level of support provided and the contribution that their footwear made to the reported injury.

Injury data will be collected over three playing seasons (three years), with information being progressively compiled and processed at the end of each playing season. Each month of the survey, all coaches will be contacted by email to ensure that all new injuries and injury exposure data is recorded. Injury risk associated with each floor type will be recorded by each coach on a monthly basis. Exposure data will be calculated by recording the number of games and training sessions, multiplied by the duration of each session, multiplied by the number of players participating in each session. Injury incidence will be calculated as the number of injuries reported per 1000 player hours of exposure on each surface type included in the survey.

The health, safety and comfort of athletes must be a prime consideration when selecting a surface. The interaction between the athlete, shoe and surface all combine with the particular sport being played on that surface to determine the type and seriousness of an injury. It is not, however, realistic to assume that the level of fitness of an athlete can be altered or that the type, age or condition of the footwear used can be controlled. There does exist an opportunity, on the other hand, to select an appropriate surface on which to train and compete. Selecting an appropriate surface will not eliminate sports injury, but it could reduce the incidence of injury by better managing extrinsic risk factors.

Insufficient attenuation of recurrent forces generated during netball manoeuvres can result in repetitive stress injuries. In addition, the high frictional forces generated following abrupt landings can subject the ligaments of the lower extremities to undue stress and increase the potential for ligament damage. These risks can be reduced by the selection of an appropriate surface in accordance with the demands of a particular sport. The main surface variables that influence injury risk include: force reduction, stiffness, friction, heat absorption and transfer, surface colour,
contrast and reflectivity, and can all be controlled to a large degree through surface design and material selection.

It is anticipated that the outcomes of this research will provide a greater understanding of the associated injury risks. Through a better understanding of injury mechanisms, protective strategies can be developed, including safer playing surfaces. This outcome may ultimately have the effect of increasing sports participation while at the same time reducing injury rates.
References


Dickson, P. R., & Ginter, J. L. (1987), Market segmentation, product differentiation, and marketing strategy. *Journal of Marketing*, 51(2), 1-10.


Dupré, S. (2005), Talk the walk: Advancing sustainable lifestyles through marketing and communications, United Nations Environmental Programme (UNEP), Retrieved from http://www.talkthewalk.net/.


EN14904. (2006), Surfaces for sports areas: Indoor surfaces for multi-sports use, Comité Européen de Normalisation.


International Rugby Board. (2011), Artificial rugby performance specification, Dublin: IRB.


Kmenta, S., & Ishii, K. (2004), Scenario-based failure modes and effects analysis using expected cost. *Journal of Mechanical Design*, 126(6),


Lees, A. (1981), Methods of impact absorption when landing from a jump. Engineering in Medicine, 10(4), 207-211.


Marieb, E. (2008), Essentials of Human Anatomy and Physiology (8th ed.).


Nigg, B. M. (1990), The validity and relevance of tests used for the assessment of sports surfaces, *Validite et applicabilite des tests d'evaluation des sols sportifs, Medicine & Science in Sports & Exercise*, 22(1), 131-139.


Sports Injury Prevention Task Force (2013), Final report May 2013. Sport and Recreation Victoria, Department of Transport, Planning and Local Infrastructure


Steele, J. R. (1987), Netball the Australian way: are we inviting the potential for injury. Court action (Brisbane, Aust.), 1(4), 28-33.

Steele, J. R. (1987), The relationship of selected body proportionality measures and lower extremity characteristics to the mechanics of landing in netball. Non-technical report, part B. Wollongong, N.S.W.


321


