Smart Football Footwear for Advanced Performance Analysis and Training Purposes

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

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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 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.

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Nomenclature

I  Current
V  Voltage
R  Resistance
Z  Resistivity
σ  Conductivity
G  Conductance
F  Force
η  Viscosity/Electrical viscosity
Ω  Ohm
℧  Mho
$  Dollar
C  Capacitance
A  Surface area
σ  Standard deviation (statistics) or Stress (Mechanics)
N  Newton
D  Dimension
ε₀  Permittivity of free space
ε  Strain
εᵣ  Relative permittivity of the dielectric material
d  Distance between the plates (capacitance)
Hz  Hertz
Kg  Kilograms
H (t)  Heaviside function
\( \hat{E} \)  Laplace transform
R  Gradient
tan \( \delta \)  Loss tangent
\( \omega \)  Angular frequency
d  Delta (change)
K  Stiffness
x  Displacement
MDF  Medium Density Fiber Board
R_{rer}  Resistance of reference resistor
Vin  Input Voltage
RGB  Colour model
**Publications Resulting from Thesis**


Patents Resulting from Thesis


3. 2016: China - patent application number 2014800388513

4. 2016:USA - patent application number 14/903663

5. 2016:India - patent application number 201637001684

6. 2016:Australia - patent application number 2014252763

7. 2016:Europe - patent application number 14822446.2

8. 2016:Japan - patent application number –TBA
1. Introduction

1.1 Abstract

Overview and Aims

Kicking performance in soccer is a major skill that can strongly influence the success of a team. Existing methods for performance and activity monitoring of the foot to ball impact phase during different types of the kicking have their limitations. They usually gather insufficient information to study the biomechanical characteristic and patterns due to high speed of the kicking action and unavailable commercialized techniques. Based on the literature, the fundamental performance criteria when kicking a ball are kicking accuracy and the characteristics of the foot to ball impact phase. Previous methods used high speed video imaging technology, motion analysis systems and simulation and computer simulation.

The study aims to identify and characterise a suitable piezoresistive, conductive polymer that can be used as a pressure sensor for measuring impact forces in an electrical format during the kicking action. The polymer will be developed into a high resolution pressure grid which will convert raw pressure data from the foot to ball impact phase into advanced kicking parameters that will contribute to a better understanding of kicking performance. The advanced parameters studied here are the movement of the centre of pressure (COPx, COPy), COP velocity (v), normal force (FN), friction force (FF), impact duration time and peak forces location. The main goal product of the study is a smart football footwear for advanced kicking performance analysis and training purposes.

Methods and Development

In order to select the best piezoresistive material, material characterization tests were conducted for model function selection and electrical viscosity constant (see below: Figure 1.1 Flowchart of research conducted). Material characterization experiments all employed a methodology where electrical properties were measured in response to differing mechanical properties. These included known, widely used tests such as: Creep, Stress Relaxation and Strain Rate Dependency as well as a new electrical methodology developed
here: Electrical Creep and the discovery of two new electrical parameters: electrical viscosity constant $\eta$ and conductive stiffness.

Next, the coefficients of determination during peak impact forces with calibration functions were measured. For each specimen, the experiment included 5 force slamming levels sets using a Kistler Force Plate. Each set had 10 comparatively equal forces level slamming. In total: about 50-60 slamming per material. All experiments were carried out at room temperature.

The next phase included the development, calibration and validation of the sensor array system including its prime prototypes sensors (smart mat, smart insole 1 & 2) and the smart footwear. In order to accomplish the smallest dimensioning and weight boundary conditions of the sensory system, and to achieve best portability conditions, a minimum size and weight of a powerful, low cost microcontroller board was chosen. In addition, a similar-sized electronic printed circuit board carrying all extra electronics components was designed and mounted on top of the microcontroller.

The instrumentation, consisting of piezoresistive material used as a novel pressure array and a programmable microcontroller, measured the magnitude of the kick force and centre of pressure (COP) with respect to a soccer boot coordinate system.

The movement of the COP and the force vector diagram of curve kicks, colour-coded with progressing time, were displayed on a 4D model of a soccer boot in AutoCAD. The magnitude of the kick force and the movement of the COP during the impact phase between the soccer ball and the foot were determined by developing a novel low-cost pressure sensing system.

**Results**

Initial experiments set out to investigate whether an off-the-shelf conductive polyurethane (RmatFb) has piezoresistive properties and can be used as a pressure sensor. The compression velocity dependency experiment of force against conductance for strain rates of 1 mm/sec and 5 mm/sec showed different slopes for different compression rates. The experimental stress relaxation results, force vs. time graph, reflected a negative decreasing slope of the curve over 600 seconds.
Next, a second specimen’s electro-mechanical properties were tested (Rmat1 x 5 layers) with mechanical forces plotted against time for non-linear model function selection. The mechanical properties of the specimen follow a logarithmic law function with $\eta = 5.473$ (mechanical viscosity). The electrical properties of the specimen were found to follow the power law function with $\eta = 0.192$ (electrical viscosity). The mechanical strain rate dependency and stiffness of Rmat1x5 were found to be $\eta = 4.95$ for logarithmic function and $\eta = 0.0847$ for power function both at deflection of 0.0003-0.0004m.

The next experiment determined the electrical viscosity model functions and the constant of electrical viscosity for 10 conductive polymer specimens. $\eta$ ranged between 0.003-0.351 or 0.3%-35.1% and all specimens were found to follow a power law function. Electrical viscosity is a characteristic that represents the decrease of electrical change over time under constant mechanical load.

Subsequently, peak impact forces were measured for the same above mentioned 10 specimens and their calibration functions found. The electro mechanical peak impact forces coefficients of determination ($r^2$) ranged between 0.989 and 0.803. The most suitable specimen was found to be Rmat1 with a coefficient of determination of 0.989 and electrical viscosity constant (a new electrical property of conductive polymers identified during our experiments) of 18.6%.

After the material characterisation experiments were completed, a unique sensor array system technique was developed and patented. Three prototypes were then created, using the Rmat1 specimen, to test the functionality and feasibility of using the system for different pressure mapping applications (1. Smart Mat; 2. Smart Insole 1; and 3. Smart Insole 2).

Based on the abovementioned prototypes, the smart kicking boot was developed (using the sensor array system technique). A feasibility prototype of the boot was successfully designed and tested with a visual feedback mechanism to display the location and magnitude of pressure applied to a multi-node cells area, made of 16 pressure sensors. The results of the pressure-conductivity calibration analysis showed that the two best $r^2$ values were node1 $r^2 = 0.988235$; node2 $r^2 = 0.976236$ (range 0.9333 - 0.9882). For system validation, the calculated system forces against the Kistler force plate data was $FK; n = 58$ with residual standard deviation $\sigma_R = 125.6$ N ($r^2 = 0.91252$). $\sigma_R$ is force dependent ($\sigma_R=$...
0.0437 FK + 70.4), i.e. between 7.5% and 9% of FK at the range of 1-2kN. COP could not be validated due to a system limitation of the Kistler force plate in calculation of impact forces.

The path of the COP between the boot and the ball for two curved kicks was then plotted. Results showed the movement pattern and the location of the COP and exhibited a similar curve for both kicks; (i) the COP moving backwards towards the ankle, as the ball slides and rolls simultaneously in the same direction, and force gradually increases until reaching peak force (approximately 1100N), and (ii) the COP moving away from the ankle towards the toe, as the ball continues rolling as in the first phase while sliding in the opposite direction gradually decreasing in force. Additional advanced parameters against time of one kick were then calculated (COPx, COPy, COP velocity, normal force and friction force) and used to generate a colour coded 4D vector diagram. The 4D vector diagram illustrated force projected on a soccer boot model of one kick over 12ms.

Discussion and Conclusions

Following our review of the available literature, pizoresistive sensors were identified as our preferred type for further investigation. After identification of a potential material (RmatFb), the off the shelf conductive polyurethane foam was electromechanically tested for application into a smart sensing system. Our preliminary experiment showed that off-the-shelf conductive polyurethane foam can be used as piezoresistive pressure sensors.

Next, we tested a second specimen (Rmat1x5 layers) to verify our results, determine the mechanical and electrical function model selection and investigate the mechanical and electrical conductive stiffness dependency on different strain rates. Results showed that mechanical viscosity in Rmat1x5 follows a logarithmic law function whereas its electrical viscosity follows a power law function so only the power function viscosities were compared and showed a higher electrical viscosity value. The specimen was found to be more electrically viscous than mechanically. This new parameter, conductive stiffness, may become a gold standard benchmark for material characterisation in the future. Further, this experiment confirms that conductive polymers have viscoelastic properties, an important part of material characterisation for final product development.

Following this, we set out to study the electrical viscosity constant of 10 specimens of conductive polymers. Whereas mechanical viscosity is a parameter that has been previously
described in the professional literature (Fuss, 2012), electrical viscosity is a new parameter described here. The electrical viscosity constant is an attribute that characterises electrical change over an identified time under a mechanical load. Results showed that all specimens’ electrical viscosity constant was found to fit a power function, supporting previous findings for Rmat1x5. Based on electrical viscosity characteristics, Rmat2a was found to be the most suitable specimen for further development.

Subsequently, the electro mechanical peak impact forces coefficients of determination and calibration functions were determined for the same 10 specimens. Rmat1 – vinyl was found to be the most suitable material for peak impact forces measurements showing the highest repeatability and an electrical peak resistance that remained within the unsaturated part of the plotted slope at a high force. Although Rmat1 did not show the lowest electrical viscosity constant in the previous experiment, we chose to continue development with this material based on the coupling between impact force magnitude and contact time in impacts.

This experiment marked the end of our material characterisation phase and initiated the development point of the novel multi-point sensor array system. Rmat1 was used for the development stage.

Once we developed the sensor array system and algorithms for pressure data, we designed three prototypes to trial the methodology. We succeeded in testing the system through all different types of prototypes with differing feedback signals and proved the concept’s functionality. The final sensory system aimed to measure pressure distribution between the foot and ball and to calculate advanced parameters. The core parameters that were investigated were the impact forces magnitude and location on the system and the COP displacement during the foot to ball impact phase. The COP was tested for curve kicks and the COP data were displayed on a 4D colour-coded vector diagram model of a soccer boot. The COP data was constructed from four phases of the foot to ball impact. This data reveals new information about foot to ball dynamic parameters during a curved kick measured in this study for the first time and have not been previously described in the literature.

A unique low cost instrumented system for soccer kicking in soccer was successfully incorporated into a soccer boot, calibrated, validated and tested during a full kicking
motion. The smart soccer boot is useful for counting the number of kicks, assessing the magnitude of the kick force and displaying the COP. The sensor has high resolution, is thin and flexible, wearable and light weight. The results assist to illustrate the movement of the COP during the short impact phase between the foot and the ball.

In conclusion, this research extends our knowledge of important soccer kicking parameters such as kicking force magnitude, and location and movement of the COP. The study makes several noteworthy contributions and adds to a growing body of literature on the characterisation of conductive polymers and measurement of advanced parameters during the foot to ball impact phase of kicking in soccer. These parameters can be measured and displayed using the novel low-cost sensing platform that was designed and developed at RMIT to study kicking performance.

1.2 Objective and Research Questions

The main objective of this research is to develop a new platform of pressure sensing measurement system with one specific end product, smart football footwear for advanced kicking performance analysis and training purposes.

In order to achieve this, the following principal research questions were formulated:

**Sensor**

1. How can we identify and select a suitable sensor for measuring pressure during kicking and how can we measure the properties of pressure sensitive piezoresistive materials?

2. What material is ideal for sensor development - in order to measure pressure in an electrical format – taking into account suitability and cost? Based on the measurable properties, how do we select the right material for measuring impact forces?

3. How can the sensing material be calibrated and what is the peak impact forces relationship between pressure and measured electrical data?
Development of prototypes and the Smart football footwear

1. What is the most efficient way of measuring pressure data with a high resolution pressure grid?
2. What advanced kicking parameters can be delivered from raw pressure data?
3. How can these advanced parameters be converted into a biofeedback signal?
4. Which advanced parameters can be correlated to the accuracy of the kick?
5. How can a standard test method be developed in order to assess advanced kicking parameters?

It is hypothesised that the following advanced parameters will be generated by this study (independent of whether they are useful or not): position of the centre of pressure (COPx, COPy), COP velocity (v), friction force (FF), normal force (FN), coefficient of friction (COF), kick force, impact time, velocity at maximum force. Whether or not this hypothesis will be confirmed depends on the experimental data.

1.3 Scope
The scope of this research includes:

- Basic understanding of foot to ball impact phase in soccer
- Pressure sensors and their applications
- Peak impact forces- resistance characterization of different conductive materials
- Conceptual development of a sensor array system and prototypes
- Calibration and validation of sensor array system
- Development of smart football footwear with advanced parameters

1.4 Contribution
The contribution of this research to the field includes:

Novelty

- Development of a novel device: the smart soccer boot which directly measures foot-to-ball impact forces and derived advanced parameters
- Novel use of a piezoresistive material for impact forces measurements
- Development of a novel material characterisation methodology: Electrical Creep
• Discovery of two new electrical parameters:
  i. Electrical Viscosity Constant.
  ii. Conductive Stiffness.
• Patents filed- refer to list above.

A) Contribution to current knowledge gap:

• The magnitude of the kick force and the movement of the centre of pressure (COP) during the impact phase between the soccer ball and the foot have been described here for the first time.
• Although the effect of viscosity on electrical sensors is known (Partsch et al., 2006), it has been measured here through a new electrical creep methodology and two new electrical parameters (Electrical Viscosity Constant, Conductive Stiffness).

B) Breadth and depth:

  Breadth:
  • Material characterization of different conductive polymers usage of different methods for assessing the mechanical and electrical viscoelastic parameters of piezoresistive sensors.
  • Development of a novel array pressure sensing system.
  • Development of a novel device: the smart soccer boot which directly measures foot-to-ball impact forces and derived advanced parameters.

  Depth:
  • Calibration (mechanical force to electrical conductivity) of different piezoresistive materials.
  • Measurement of the magnitude of the kick force and the movement of the centre of pressure.
  • Measurement and characterization of viscosity through a new electrical creep methodology and two new electrical parameters.
1.5 Achievements

Prizes

• RMIT Student Innovation Award (2015).
• RMIT University Award for Research Excellence - Team Award for the SportzEdge Team (2014).
• Recipient of RMIT PhD Scholarship (2013-15).

Publications and patents

• 10 peer-reviewed journal papers-refer to list above.
• 1 patent- refer to list above; filed as a PCT patent, and national applications in AUS, EUR, USA, CHN, IND, JAP

Funding

• Insoles project PhD student stipend. Funded by: Wound Management Innovation CRC from (2014 to 2017), $100,000.
• Venous Leg Ulcer Compression (smart bandage project) - based on Sensor Array System (current thesis). Funded by: Wound Management Innovation CRC from (2014 to 2017), $635,000.
• Burn wound project, monitoring the pressure of burn wound for therapeutical purposes, $125,000.
• Rizmik Insole-converts pressure to sound, thereby encouraging physical activity as well as musical performance - based on Sensor Array System (current thesis). Funded by: Rizmik Pty Ltd (2013 to 2016), $62,500 Rizmik Pty Ltd.
• Total funding: $1,557,500.
1.6 Research flow chart

Material Identification and Characterisation

- Tactile sensors and array pressure sensors techniques

Research Development and Prototypes Characterisation

- Electro-mechanical feasibility study - single conductive foam material
- Electro-mechanical characteristic study - electrical viscosity multi material tests
- Peak forces-resistance multi-material tests
- Developing a new array pressure sensing system and related applications
- Prototypes: Smart mat; Smart insole 1 & 2
- Smart soccer footwear for kicking analysis performance including calibration & validation
- Pilot experiment of the Curve kick- 4D visualization of COP

Literature Review

- Kicking measurement techniques and industry performance enhancement patents and applications

Conductive polymer composites and viscoelastic material
2. Review of the Current Literature

2.1 Overview
This chapter aims to give a comprehensive overview of the existing body of knowledge relating to the research problem. Firstly, we will discuss the kicking phases in soccer, breaking down the main kicking action into components that influence the quality of the kick including measurement and improvement techniques from an industry perspective. Next, the review will cover different off-the-shelf sensors focusing on tactile and array pressure sensors. Then, conductive polymer materials and their main industrial usage will be summarised and lastly, viscoelasticity including mechanical model selection criteria for viscoelastic materials.

2.2 Kicking
Soccer is the most watched, played and profit generating sport in the world (Hennig, 2011) and Australian rules (AR) football is one of the most popular sport in Australia (Smith et al., 2009). The ultimate purpose of a team during a match is to score goals and the better the quality of the kicks of a team, the better the chances to score goals (Finnoff et al., 2002).

Kicking is the defining action of Soccer (Lees et al., 2010) and it is a dominant skill in all football codes (FC) such as AR football, Rugby codes, American football and Gaelic football (Ball, 2012). Recent literature reports that 80.6% of the total number of goals scored during the South Africa FIFA world cup were kicked from the foot (Njororai, 2013).

Figure 2-1: Kicking movement in soccer (image from Buer, 1990)
Soccer and other football codes involve different types of kicking styles used for different types of purposes during a game. The instep kick in soccer is the most powerful kick in the game (Finnoff et al., 2002) and it is most commonly used by athletes during a match (Ali et
The punt kick on the other hand is an important kick in football codes which is used for passing the ball to a teammate, defence or kicking away and kicking goals (Ball, 2012). Inaccurate kicks in soccer caused by error in the direction of the applied force generated at the foot, and the second is because the misplacement of the force (Kellis and Katis, 2007).

A Quick Guide to the Kicking Action
The kicking action is described such a “Whip- like” movement of the lower limb when the foot is the last segment in the open kinematic chain which generates the highest magnitude of speed and it categorized by segmental and joint rotations in several plans (Kellis and Katis, 2007). Components involved in the instep kick can be defined by:

The Approach to the Ball
Kicking a stationary ball involves an angled pre run phase to the ball before the kick. The angled approach allows more rigid and accurate foot to ball contact with the ball and also contributes significantly to the quality of the kick. The angle approach is more typical in free kicks in Soccer, Rugby, American football and Australian football. Also, for passing long distance balls and ball heightening into the opposition field in corner kicks in Soccer (Ben-Sira and Ayalon, 2007). Usually the athlete has a favourite preferred approach angle however; previous research (Kellis and Katis, 2007) found that 45 degrees of approach results in maximum launching velocity of the ball. This preferred angle most likely is the resulting angle of the trade-off phenomenon between the accuracy and the velocity when kicking a ball. The approach phase to the ball usually starts few strides before the balls location, subsequently the athlete make a curved approach path to the ball (Lees et al., 2010). Recent research of kicking in soccer evaluated that the maximum impact force could be greater than 2800N when attempting to kick a ball at maximum speed rate (Lees et al., 2010).

The Support Leg and Pelvis
It is reasonable to assume that the support leg influences the trajectory and magnitude of the kick (Ben-Sira and Ayalon, 2007) and in fact, the support leg placement brake the mechanical energy generated by upper body movement. This energy built up during the approach phase to the ball to enhance the balls’ velocity. Previous study (Ben-Sira and Ayalon, 2007) showed that ground reaction forces of the support foot, in addition to
reduced velocity of the hip, consequence in speed reduction during this phase. This slowing down in speed may link to stabilizing the kicking action, to enable more muscle forces to be generated or to influence the kicking limb action. To the best of knowledge of the author there are no clear evidence yet regarding ground reactions forces with respect to the quality of the kick apart from braking mechanical energy of the body. This topic requires further investigation (Ben-Sira and Ayalon, 2007) since it is important to the kick characteristics (Lees et al., 2010).

**The Kicking Leg**

The kicking leg action can be defined as proximal to distal movement which initiates from the most proximal or close segment of the lower limb to the distal or further segment of the lower limb. This sequence expresses by an initial swing of the pelvis followed by the hip movement and finally the shank movement (Ben-Sira and Ayalon, 2007, Lees et al., 2010). As mentioned above, the kicking technique can be described as “Whip-like” movement of the lower limb when the foot is the last segment in the open kinematic chain which generates the highest magnitude of speed. The basic kinematics of the kicking leg have previously reviewed extensively (Lees et al., 2010, Lees and Nolan, 1998, Kellis and Katis, 2007). Through the backswing phase the striking leg shifts backwards and the knee flexes. The backswing action ends only after the knee flexes and the hip extends, then the pelvis rotates around the supporting leg which results in forward movement of the thigh of the kicking leg and the knee maintains to flex. The hip begins to flex and the ankle is adducted and plantar flexed until foot to ball impact phase. During this phase the ankle is plantar flexed and adducted and as the hip is externally rotated, adducted and flexed (Kellis and Katis, 2007).

**The Upper Body**

The upper body also contributes to the performance of the kick. The non kicking side arm is concurrently elevated upward and extended horizontally. The shoulders rotate and move out of phase with the rotation of the pelvis. This consequence in twisting set up phase, before kicking, and untwisting phase during performing the kick (Lees et al., 2010). During the kick the upper body leans backward towards the support to allow a wider range in movement of the hip joint in addition to medial trunk twist.
The Importance of Kick Accuracy

There are different parts to the kicking action and even though it is normal to think that the quality of a kick is merely dependent on the speed of the ball when leaving the foot, it is not entirely the case and accuracy should also be taken in account as a major factor. To the best of the author’s knowledge, relatively high number of studies (Lees et al., 2010, Scurr and Hall, 2009, Nunome et al., 2006, Young and Rath, 2011) in the field deal mostly with this parameter (Kicking velocity) and neglect the final destination or the precision of the ball. It is important that the quality of the kick in different football codes and soccer takes into account the accuracy of the kick when assessing the quality of the kick.

Kicking accuracy (KA) refers to the precision of a kick towards a specific target (Ali et al., 2007) and it can improve the chances to score a goal, pass to a teammate and additional actions in the sport. The position or point of contact during the foot to ball phase when kicking a ball is a source of accuracy or inaccuracy of the kick (Kellis and Katis, 2007).

There are a reasonable number of studies on the biomechanics during a kick (Lees et al., 2010, Kellis and Katis, 2007, Ball, 2008). There is now more information about the foot to ball phase the effect of footwear on foot–ball impact (Lees et al., 2010) however not much researches available with regard the foot to ball impact phase and accuracy of the kick which is a predominant technical skill factor. Hence there is a need to further investigate this subject to reveal unknown advanced parameters which may contribute to the quality of the kick during the foot to ball phase.

Foot to Ball Impact Phase

The location of impact between the boot and the ball in addition to leg velocity determines the accuracy of a kick toward its desired destination (Cameron and Adams, 2003). This phase can be described mechanically as collusion between two bodies, the foot and the ball using different part of the foot with respect to the technique of the kick. The main kicking methods in soccer are full instep kick (most powerful), side instep kick, side kick and toe kick. In recent years, curve kicks are also becoming increasingly popular and require a high skill performance to spin and bend the trajectory of the ball (Asai et al., 2002).

Foot to ball impact location is an essential parameter when calculating the values for the ball to foot speed ratio. As the foot is in a plantar- flexed position before impact with the
ball, the toes of the foot reach a greater speed than the centre of mass of the foot, which attains a greater speed than the ankle joint (Lees et al., 2010).

**How Is Kick Accuracy Currently Measured and Improved?**

The attempt to measure and improve the kicking skill through different patented instrumentations and footwear started in the late 70’s with a kicking shoe to improve the accuracy and distance of a kick (Lawsen, 1978) and is still continuing today (Hatzilias 2009, Goldstein et al. 1997). At the same time, there is a limited number of scientific studies regarding the quality of the kick from the KV and KA perspective (Lees et al, 2010., Van den et al. 2014, Finnoff et al. 2002, Young and Rath, 2011).

To the best of our knowledge, limited scientific studies have been undertaken so far with regard to accuracy measurements of kicking a ball (Kellis and Katis, 2007, Finnoff et al., 2002). Hennig tested the differences between barefoot and shod kicking by placing a Pedar (Novel Inc.), pressure array measuring insole on the upper of two different shoes (Hennig, 2011). The study concluded that pressure in homogeneity between the shoe and the ball decreases the precision of the kick and therefore soccer shoe designers can enhance the kicking accuracy skill by constructing a suitable shoe upper for the athletes. Asai used computer simulation methods to review the fundamental characteristics of a curve ball kick through the foot to ball impact phase using high speed cameras (Asai et al., 2002).

Studies exploring the overall kick bio mechanical behavior often using high speed imaging technology (Lees et al., 2010, Flanagan, 2009). This method was found to be imprecise for studding the foot to ball impact phase which related to the accuracy due to limited time of this action (Lees et al., 2010).

Another way to assess the accuracy of a kick is by using data during a match such as the number of goals per game or the ability to strike a target during a match. This method does not reflect the results in real time (Finnoff et al., 2002).

A different method (Finnoff et al., 2002) to measure the kicking accuracy for Soccer players utilized a plywood bull’s eye target covered with Carbon paper and the author concluded that this apparatus can be used as a training tool for improving the skill of players. In the author’s opinion this suggestion is impractical since the method involves longer manually data processing.
2.3 The Industry Perspective

Nike Total 90

The Nike Total 90 is a brand of Nike sportswear, in particular shoes which started in 2000-2011. The main objective was to design boots to improve the strike zone during the kicking action and to enhance touch and control of the ball. The Total 90 Laser series includes soccer shoe specifically designed to enhance accuracy by even pressure using shape correcting foam inside the shoe and flat shot shield on top at ball contact area for a full instep kick (Nike Total 90, 2011).

![Figure 2-2: Nike Total 90](image from http://www.boccisport.com)

Adidas- F50 series

The Adidas F 50 released in late 2011. It features a ‘mi-Coach match analysis technology’ which reflects biofeedback on the running performance of the athlete. The boot was marketed as a "football boot with a brain" Mi-Coach is a three part system including a stride sensor, a heart monitor and a receiver. The boot tracks and uploads performance data including speed, maximum speed, number of sprints, distance, distance at high intensity levels and time. (Adidas F50, 2013).
Nike (Conceptual project) - Training smart soccer shoes with visual biofeedback

Conceptual project - March 2013. The objective behind this smart shoe (Figure 2-3) is to assist the athlete to enhance passing and shooting accuracy performance by providing instant visual bio feedback which ultimately develops the muscle memory with regard to foot to ball location action. The feedback reflects the location of foot to ball impact by using static electricity located on the upper layer of the shoe. (Nike train smart soccer shoe, 2013).

Existing Patents

Name: Kicking shoe (Lawson, 1978)

The purpose of the “kicking shoe” (Figure 2-4) is to improve the accuracy and distance of a kick by keeping the toes in an upward position. In this way the force transmitted to the ball through the metatarsal bones of the foot and not the toes.
Name: Kicking aid for a shoe (Hannah, 2002)

The apparatus (Figure 2-5) objectives are to enhance the power and accuracy when kicking a ball by improving the characteristic of the shoe. It includes a sleeve added to the foot which provides stronger and larger surface area to the upper sole of the foot to enable a player better power and accuracy during foot to ball phase.

Name: Footwear for gripping and kicking a ball (Konstantinos, 2009)

The patent (Figure 2-6) objectives are to enhance the power and accuracy when kicking a ball and for dribble by improving the grip of the upper surface of the shoe. The enhanced shoe upper including resiliently deformable protrusions extending from an outer surface of the shoe upper and positioned for better contact with a ball.
2.4 Sensors

Broadly speaking, a sensor’s purpose is to detect events or changes in its environment, and provide a corresponding output.

In industry, the most commonly used sensory techniques are capacitive, piezoresistive, piezoelectric, inductive, optoelectric and strain gauges methods (Table 2.1), as follows:

i. Capacitive sensors:
   Consists of two conductive plates with a dielectric material sandwiched between them. Where the capacitance expresses through:
   \[ C = \frac{A\varepsilon\varepsilon_0}{d}. \]  
   (2.1)
   Where C - capacitance, A – surface area of plates, ε0 - permittivity of free space, εr - relative permittivity of the dielectric material, d - distance between the plates.
   • Advantages: good frequency response, high spatial resolution, and have a large dynamic range.
   • Disadvantage: subject to noise and require relatively complex electronics to filter out this noise.

ii. Piezoresistive sensors:
   The Piezoresistive effect refers to a change in electrical resistance with tension or compression in a pressure sensitive element typically a form of a conductive rubber, elastomer, or ink. Where the resistance can be expressed though Ohm’s law, where V - voltage, I - current and R - electric resistance of the material.
   • Advantages: require less, they are less susceptible to noise and therefore work well in mesh configurations as there is no cross talk or field interactions.
• Disadvantages: hysteresis and therefore have a lower frequency response when compared to capacitive tactile sensors.

iii. Piezoelectric tactile sensors:
The piezoelectric effect refers to the change in the voltage potential of a crystal element when it deformed and the magnitude of the voltage is directly proportional to the applied force, pressure or strain.
• Advantages: good high-frequency response, consequently ideal choice for measuring vibrations.
• Disadvantages: limited to measuring dynamic forces and not capable to measure static forces due to their large internal and the developed electric charge decays with a time constant.

iv. Inductive sensors:
The inductive measurement technique refers to the change in magnetic field which is sensed in a secondary sense coil.
• Advantages: very high dynamic range and an often rugged construction,
• Disadvantages: bulky which leads to a very low spatial resolution when arrayed. Lower repeatability as coils, do not always return to the same position between readings, requires more complex electronics than normal resistive tactile sensors as the alternating signal amplitude must be demodulated.

v. Optoelectric sensors:
Optoelectric technique based on electronic devices that source, detect and control light.
• Advantage: High spatial resolution, and immune to common lower frequency electromagnetic interference (common issue).
• Disadvantage: Size and rigidness; Camera-based tactile sensors require considerable processing power but give a wide ranging frequency response.

vi. Strain gauges:
The principle of the strain gauge is that a piezoresistive sensor is attached to a required sensing surface of an object using an appropriate adhesive. Any deformation in the surface of the object simultaneously causes the sensor’s
electrical resistance to change. The change in resistance-strain correlation is known by the quantity gauge factor.

- Advantages: small size and low cost.
- Disadvantages: Limited operating temperature range, limited fatigue life, low electric output signal.

<table>
<thead>
<tr>
<th>Transduction technique</th>
<th>Modulated parameter</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitive</td>
<td>Change in capacitance</td>
<td>Excellent sensitivity, Good spatial resolution, Large dynamic range</td>
<td>Stray capacitance, Noise susceptible, Complexity of measurement electronics</td>
</tr>
<tr>
<td>Piezoresistive</td>
<td>Changed in resistance</td>
<td>High spatial resolution, High scanning rate in mesh, Structured sensors</td>
<td>Lower repeatability, Hysteresis</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>Strain (stress) polarization</td>
<td>High frequency response, High sensitivity</td>
<td>Higher power consumption, Dynamic sensing only</td>
</tr>
<tr>
<td>Inductive LVDT</td>
<td>Change in magnetic coupling</td>
<td>Linear output, Uni-directional measurement, High dynamic range</td>
<td>Moving parts, Low spatial resolution, Bulky</td>
</tr>
<tr>
<td>Optoelectric</td>
<td>Light intensity/spectrum change</td>
<td>Good sensing range, Good reliability, High repeatability, Immunity from EMI</td>
<td>Poor reliability, More suitable for force/torque measurement applications, Bulky in size, Non-conformable</td>
</tr>
<tr>
<td>Strain gauges</td>
<td>Change in resistance</td>
<td>Sensing range, Sensitivity, Low cost, Established product</td>
<td>Calibration, Susceptible to temperature changes, Susceptible to humidity, Design complexity, EMI induced errors, Non-linearity, Hysteresis</td>
</tr>
<tr>
<td>Multi-component sensors</td>
<td>Coupling of multiple intrinsic parameters</td>
<td>Ability to overcome certain limitations via combination of intrinsic parameters</td>
<td>Discrete assembly, Higher assembly costs</td>
</tr>
</tbody>
</table>

Table 2-1: Sensory techniques – summary (Table adapted from: Tiwana et al., 2012)

Tactile sensors
Tactile sensors are transducers that acquire data through an environmental physical interaction or direct physical contact such as: temperature, vibration, force, pressure and piezoresistivity. The involvement of these techniques in different industrial and commercial applications is currently elevated compared to the past three decades (Tiwana et al., 2012). Tactile-based approaches are usually an ideal choice in scenarios where the measured output is not easily visible. Although the use of tactile sensors is a major strategy in different areas, the relatively high costs is a key reason of why this technology has not fully embedded in many industry and consumer manufactured goods (Tiwana et al., 2012). This
technology can be used to overcome key challenges in different industries such as robotics, biomedical, sports aerospace automobiles industry and more. There are different types of techniques to implement these sensors and they all have their own advantages and disadvantages.

**Important specifications of pressure sensors**

When selecting the most suitable pressure sensor for research or practical applications, it is important to consider common key factors, including:

- **Hysteresis**: The difference between the loading and unloading output signal responses when pressure is applied onto the surface of the sensor. Typically measured at 50% pressure load.

- **Linearity**: The plotted curve between the sensor output data and the actual pressure applied to sensor indicates of the level of linearity. Higher linearity is usually preferred and reflects the complexity of the signal processing circuitry.
• **Pressure range**: Is a key specification for a pressure sensor selection. As different applications require different pressure ranges, the upper and lower pressure limits that the sensor can withstand need to be recognized by the user.

• **Sensing surface area of the sensor**: The dimensions and position of the sensor are important criteria to estimate the pressure peak value.

• **Operating Frequency**: Sufficient sampling frequency rate is also critical for sensor data measurement and need to be decided carefully for different pressure applications such as impact or gait analysis.

• **Creep**: Creep is the deformation of material under static stress. Low creep sensors are one of the main requirements especially in foot pressure measurement. Usually pressure sensors possess viscoelasticity (elastic and viscous) properties and creep test is a key experiment to determine the level of the viscosity (section 2.6 for more information).

Use of tactile sensors composed of an individual sensing point has been extensively explored. The advantages, limitations, and potential applications of such sensors are believed by many researchers to have reached a point of maturity. A multi-point, array-formation sensor is an important direction to research in next generation technology.

**Array Pressure Sensors**

Current measurement technologies are now focusing on new multi-node sensory techniques with algorithms for more complex measurements applications (Tiwana et al., 2012). Multiplexed pressure sensors have a significant advantage and potential for measuring contact pressure distribution and can be applied in many different disciplines. One of the main known limitations of the multinode sensory technique is its unstable output readings caused by a constant drift.
Industry review

From an industry perspective there are several pressure array sensors that are capable of measuring and recording real-time pressure distribution and magnitude over a surface.

Some of current commercialized systems are:

i. **Tactilus** ([http://www.sensorprod.com/tactilus.php](http://www.sensorprod.com/tactilus.php)): The array system is based on Piezoresistive technology, and can measure up to pressure range of 0.007-14.1 kg/cm$^2$. The system can reach a maximum of 16,384 unique sensing points resolution (128 x 128) with up to 1000Hz sampling rate frequency, conditioned for only for some configurations with fewer sensing points, and Accuracy of +/-10%.

ii. **Rs scan** ([www.rsscan.com](http://www.rsscan.com)): The sensor technology is resistive based with pressure measurement range of 1-127N/cm$^2$. The array includes 4096 sensor nodes (64 x 64) with up to 500Hz sampling rate frequency.

iii. **Tekscan** ([www.tekscan.com](http://www.tekscan.com)): The sensor technology is resistive based with pressure measurement range of 345-862kPa. The maximum array resolution is 256 and can reach up to 750Hz sampling rate frequency with wireless mode alternative (wireless-max of 100Hz sampling rate frequency).
iv. **Pedar system** ([http://www.novel.de/novelcontent/pedar](http://www.novel.de/novelcontent/pedar)): The sensor technology is not mentioned. Pressure measurement range of 30-1200kPa with resolution of 85-99 sensors. The system can reach up to 20,000 sensors/second (for 256 sensors-78.1Hz sampling rate frequency).

v. **Piezoresistive Array Sensors**: The use of piezoresistive sensing mechanism technology in array sensors systems is becoming increasingly demanded. Conductive polymer composites are often used as the sensitive element of flexible force or pressure sensor because of their flexibility and good electro-mechanical correlation. Although pressure array sensing systems seem to be a next generation technique and a few options are already available in the market, their relatively high costs prevent them from being commonly used in different everyday life applications. Off shelf, pizoresistive conductive polymers coupled with a novel design may offer a low-cost solution. In an attempt to identify the ideal materials to be used in the context of this study to build a sensor, we explored several conductive, pizoresistive polymers.

### 2.5 Conductive Polymer Composites

Piezoresistive sensors are commonly composed of conductive polymer composites. One of the advantages of nanotechnology studies is the ability to design a novel nano material with an inherent correlation between mechanical and electrical properties (Li et al., 2008). Conductive polymers are materials capable of conducting electricity due to their altering of single and double carbon-carbon bonds along the polymeric chains (Xia et al., 2010). They are highly useful as transducer devices, in special sensing applications, and in different areas such chemical gas sensors, biosensors actuators and smart fabrics (Brady et al., 2005).

Conductive polymers, also known as carbon nanotubes (CNT’s) or polymer nanocomposites, have gained a lot of interest since their discovery in 1991 (Obitayo and Liu, 2012) mainly because of their upper level electrical and mechanical properties. The characteristics of carbon nanotubes allow them to be used in different future technological applications similar to piezoresistive sensors or strain gauges (Wang et al., 2012). The electro-mechanical relation in conductive polymers is known to be directly affected by the carbon black...
concentration level in the composite (Luheng et al., 2009). Studies show that carbon black concentration has great effects on the relation between uniaxial pressure and the electrical resistance of a composite (Luheng et al., 2009). There is a high interest in further investigating the properties of nanotube materials from their physical and mechanical direction (Li et al., 2008).

Polymeric foam (Polyurethane) is commonly used in weight saving applications and is well studied mostly from a mechanical and thermal perspective. However, less attention has been given to its electrical properties which can offer different sensing or damage monitoring applications (Baltopoulos, 2012). Carbon nanotube filled silicon rubbers are classified as viscoelastic materials. The piezoresistivity of this material is time dependent and the stress-strain curve is different to elastic materials (Wang et al., 2011, Wang et al., 2012).

![Image](image.png)

Figure 2-10: High density closed cell conductive polyurethane foam structure

2.6 Viscoelasticity

Viscoelastic materials such as polymers are complex and possess both elastic energy-conservation and viscous non-energy conservative components. They are classified as non-linear materials as their mechanical properties are intrinsically dependent on strain and the strain rate. Material modeling assists in calculation and evaluation of mechanical behavior. When modeling such materials, different parameters such as viscosity and loss tangent have to be considered and quantified (Fuss, 2012).
Material Characterization

Main properties in viscoelastic materials:

A. Instantaneous elasticity
B. Creep under constant stress
C. Stress relaxation under constant strain
D. Instantaneous recovery
E. Delayed recovery
F. Permanent set

Figure 2-11: Viscoelastic material phenomena (image from Findley et al., 1989)

Testing Methods

Viscoelastic material characterization is based on stress relaxation or creep experiments which are basically similar tests (Fuss, 2012). Stress relaxation reflects the mitigation of stress over time when the material is subjected to a constant strain (Figure 2-12). Creep tests (Figures 2-13a, 2-13b) reflect the tendency of the strain of material to deform over time as a result of constant load. And the stiffness or the Young’s modulus of such materials is usually described by the stress strain curve. The dependency on the strain rate can be described such that at high strain rates the stiffness is higher (Fuss, 2012).
Constitutive Equations and Stress Relaxation Function of Non Linear Viscoelastic Models

This section introduces mathematical basis of constitutive equations of non-linear models from power and logarithmic law types as a result from stress relaxation (Fuss, 2012).

The equation for stress relaxation results from applying a constant strain $\varepsilon_0$ to the model through a Heaviside function $H(t)$:

$$ \varepsilon = \varepsilon_0 H(t) \quad (2.2) $$

The Laplace transform of which is:

$$ \hat{\varepsilon} = \frac{\varepsilon_0}{s} \quad (2.3) $$

Power law model (Fuss, 2012):

The power law model is characterised by a power decay of stress $\sigma$ with time $t$:

$$ \frac{\sigma}{\varepsilon_0} = R \ t^{-\eta} \quad (2.4) $$
Stress $\sigma$ is normalised to the constant strain $\varepsilon_0$ applied by the Heaviside function $H(t)$ of Eqn. 2.2.

Taking Laplace transform of Eqn. 2.4 yields:

$$\hat{\sigma} = \varepsilon_0 R \frac{\Gamma(-\eta + 1)}{s^{-\eta + 1}}$$

Where $\Gamma$ denotes the Gamma function.

By substituting Eqn. 2.3 into Eqn. 2.5, we obtain the constitutive equation of the power law of non-linear visco-elasticity:

$$\hat{\sigma} = s^\eta \hat{\varepsilon} \ R \Gamma(1 - \eta)$$

Eqn. 2.6 reveals the intrinsic properties of the power law model (Fuss, 2008):

(a) $0 \leq \eta < 1$, as the Gamma function in Eqn. 2.6 approaches infinity when $\eta$ approaches 1, and

(b) the stress $\sigma$ is the $\eta^{th}$ (fractional) derivative of the strain $\varepsilon$, times the constant $R \Gamma(1 - \eta)$.

Logarithmic law model (Fuss, 2012):

The logarithmic law model is characterised by a logarithmic decay of stress $\sigma$ with time $t$:

$$\frac{\sigma}{\varepsilon_0} = R - \eta \log(t)$$

Where “log” denotes the natural logarithm. Stress $\sigma$ is normalised to the constant strain $\varepsilon_0$ applied by the Heaviside function $H(t)$ of Eqn. 2.2.

Taking Laplace transform of Eqn. 2.7 yields:

$$\hat{\sigma} = \varepsilon_0 R - \varepsilon_0 \eta \left( -\frac{\gamma}{s} - \log \frac{s}{s} \right)$$

Where $\gamma$ denotes the Euler-Mascheroni constant (0.577215665...).

By substituting Eq. 2.3 into Eq. 2.8, we obtain the constitutive equation of the logarithmic law of non-linear visco-elasticity:
\[
\hat{\sigma} = \hat{\varepsilon} \ R + \hat{\varepsilon} \ \eta (\gamma + \log \ s)
\] (2.9)

**Model Selection Process**

To characterise non-linear materials such as polymers, the proper model selection has to be determined by quantifying the viscoelastic parameter viscosity constant- \( \eta \).

**Data plotting**

(Figure 2-14) Stress relaxation or creep data experiments data have to be plotted in three different coordinate systems: linear, single logarithmic and double logarithmic with three fit functions: exponential, power and logarithmic.

![Graphs showing linear, single log, and double log data plots](image)

*Figure 2-14: Stress relaxations of power and logarithmic models, as well as of Maxwell*

If single or double-logarithmic curves do not linearise the stress relaxation data, but rather show an s-shaped curve asymptoting to maximal and minimal values, then the function is exponential and a linear model would be selected, provided that perfectly linear materials exist in reality.

Writing Eqn. 2.7 of the power model in logarithmic form:

\[
\log \frac{\sigma}{\varepsilon_0} = \log R - \eta \log(t)
\] (2.10)
Shows that a linear fit to $\log(\sigma/\varepsilon_0)$ as a function $\log(t)$ is defined by the gradient $\eta$.

Eqn. 2.10 of the power model is similar to Eqn. 2.7 of the logarithmic model. In the logarithmic model, a linear fit to $\sigma/\varepsilon_0$ as a function $\log(t)$ is defined by the gradient $R$. This analysis allows for the quantification of $\eta$.

**Logarithmic or power models**

The decision between logarithmic and power law models is based on fitting logarithmic and power functions to the data segment (stress relaxation or creep) at long timeframes (Figure 2-14). A logarithmic and power fit provides a clue for model selection by mere inspection, and the coefficient of correlation ($r$) or determination ($r^2$) supports decision making. The viscosity parameter is directly obtained from the gradient of the appropriate linear fit function. As it can be seen from the graph below (Figure 2-15) at shorter times the data points are located below the power fit but above the logarithmic fit. This clearly indicates the material behaves according to a logarithmic law model as the fit curve to any data segment can never intersect any other part of the stress relaxation curve (if obtained from consecutive ramp and constant strain) due to asymptotic behaviour. The logarithmic fit (Yellow curve) is still not suitable as the slope and intercept are expected to change slightly at very long timeframes.

![Figure 2-15: Power (Yellow) and logarithmic (Blue) fit functions fitted to experiment data (Red) (image from Fuss, 2012)](image-url)
Loss tangent (Fuss, 2014)

The energy loss in viscoelastic materials is caused by inner frictions which depends on the viscosity parameter \( \eta \). The loss tangent (\( \tan \delta \)) is the ratio of loss to storage modulus (Eqn. 2.11), therefore the strain rate independent elasticity parameter \( E \) is also expected to influence the loss tangent. Consequently, the loss tangent is influenced by the viscosity parameter \( \eta \), the strain rate independent elasticity parameter \( E \) and the strain frequency \( f \) and is derived and evaluated in non-linear (power and logarithmic) viscoelastic model (Fuss, 2014).

The loss tangent, \( \tan \delta \), is defined as the tangent of the phase angle \( \delta \), which, in turn, is the ratio of loss modulus \( E'' \) to storage modulus \( E' \).

\[
\tan \delta = \frac{E''}{E'} 
\]  
(2.11)

Where:

\[
E' = \frac{\sigma_0}{\varepsilon_0} \cos \delta
\]  
(2.12)

\[
E'' = \frac{\sigma_0}{\varepsilon_0} \sin \delta
\]  
(2.13)

And \( \sigma_0 \) and \( \varepsilon_0 \) are the peak amplitudes of stress \( \sigma \) and strain \( \varepsilon \), respectively (Figure 4-16).

The complex modulus \( E^* \) is defined as

\[
E^* = \frac{\sigma_0}{\varepsilon_0} e^{i \delta} = \frac{\sigma_0}{\varepsilon_0} (\cos \delta + i \sin \delta) = E' + i E'' = |E^*| e^{i \delta}
\]  
(2.14)

where \( i = \sqrt{-1} \), and \( |E^*| \) is the dynamic modulus, the magnitude of \( E^* \), i.e. the resultant of loss modulus \( E'' \) and storage modulus \( E' \)

\[
|E'| = \frac{\sigma_0}{\varepsilon_0}
\]  
(2.15)
The loss tangent, $\tan \delta$, is usually determined by subjecting a material or structure to sinusoidal strain $\varepsilon$:

$$\varepsilon = \varepsilon_0 \sin \left( 2\pi f \ t \right)$$  \hspace{1cm} (2.16)

Where $f$ is the cyclic frequency (angular frequency $\omega = 2\pi f$). The resulting reaction stress $\sigma$ is equally sinusoidal, but out of phase with respect to the strain by the phase angle $\delta$:

$$\sigma = \sigma_0 \sin \left( 2\pi f \ t + \delta \right)$$  \hspace{1cm} (2.17)

A positive phase angle $\delta$ causes the stress peak to occur earlier than the strain peak (Figure 2-16), resulting in the typical hysteresis effect of visco-elastic materials when plotting stress against strain (Figure 2-17). The area of the hysteresis loop corresponds to the energy dissipated into the material as thermal energy.

---

**Figure 2-16:** Sinusoidal strain curve (blue) imposed on a visco-elastic material and resulting stress curve (pink); $\sigma_0$: stress amplitude, maximal stress; $\varepsilon_0$: strain amplitude, maximal strain; $\delta$: phase shift (image from Fuss, 2014)
Post analysis power and logarithmic models (Fuss, 2014)

Relationship between loss tangent and viscosity

Power law model: $\tan \delta$ and $\delta$ depend on $\eta$ only; $0 \leq \eta < 1$.

Logarithmic law model: $\tan \delta$ and $\delta$ depend on $E$, $\eta$, and $f$; but at the same $f$, larger $E/\eta$ have larger $\tan \delta$ and $\delta$.

Relationship between frequency and viscosity constant

Power law model: $\eta$ has no relationship with $f$ in $\tan \delta$ (as $f$ does not influence $\tan \delta$), whereas for $\sigma_0$, $\eta$ appears in the gamma function, and is the exponent of $f$, i.e. $f^\eta$.

Logarithmic law model: the viscosity constant appears as a standalone $\eta$, and as the product of $\eta$ and $\log 2\pi f$.

Transient and steady state parts

Power law model: transient part: Maclaurin series; steady state part: sine function with $\eta \pi/2$ phase shift (resulting in sine and cosine functions after applying addition rules).

Logarithmic law model: transient part: cosine and sine integrals; steady state part: sine and cosine functions.
Negative storage modulus if $\tan \delta > \pi/2$

Power law model: $\tan \delta < \pi/2$.

Logarithmic law model: $\tan \delta$ can be $> \pi/2$ at small $E/\eta$ (high viscosity) and small frequencies (large cycle periods with small strain rates).

Problem to be solved (Fuss, 2012):

By definition, stress relaxation and creep experiments are modelled by applying a Heaviside (unit step) function to the constant strain or stress, correspondently (Creep and stress relaxation, testing methods section). However, in practice, testing machines have limitations of the cross head that prevent them from replicating a step change (unit step). Instead, an initial ramp strain followed by a constant strain occurs (Figure 2-18 left) which causes the stress to initially overshoot and then asymptotically reach the Heaviside strain conditions (Figure 2-18 right). It is important to note that this overshoot can make logarithmic law materials appear like power law material (Fuss 2012). A solution for this issue can be found in “model selection” section.

![Figure 2-18: Actual test machines conditions during stress relaxation (Left) ramp strain followed by constant strain. Delta t = time period of the ramp segment, (right) the overshoot in stress and power fit model curve (images from Fuss, 2012)](image-url)


2.7 Summary
The kicking skill is the predominant expertise required in different football code sports, including soccer. The foot-to-ball impact phase of this action is a key component of the accuracy of the kick and reveals important information on advanced kicking parameters (e.g. COP). Several patents and industry instrumentations have been developed to improve this skill as well as a number of scientific studies such as those using high-speed recording and simulation techniques. Overwhelmingly, the main limitations to measuring this phase of the kick are the short impact time and the lack of tools with appropriate capabilities.

A potential method that can be employed to measure these parameters are pressure sensory techniques. The most commonly used sensory techniques are capacitive, piezoresistive, piezoelectric, inductive, optoelectric and strain gauges methods. Generally, these sensory techniques are limited to a single point capability which can limit information. Pressure array sensors allow for multiple point investigation, mostly used in gait analysis applications, but are highly costly and limited in their availability.

This is where the current research comes in – the development and use of a novel, low-cost multi-node array sensory platform, customised to a soccer footwear application. This provides the researcher with an opportunity to explore additional parameters regarding the foot to ball impact phase during kicking for performance analysis of the kicking action.

The final application described in this thesis will be based on pizoresistive, conductive polymers which are becoming more commonly used for different sensory applications. These materials have advantageous characteristics such as; thin, flexible and low cost. The viscoelasticity properties of these materials are another important parameter that will be explored during this project.

3.1 Overview
The study provides information about the behaviour of viscoelastic materials by presenting the mechanical characteristics of an off-the-shelf conductive Polyurethane foam (RmatFb) from a direct current (DC) approach. Two types of viscoelastic material characterization experiments were conducted on the specimen to present the compression velocity dependency of the foam’s stiffness and stress relaxation.

Objective
To investigate whether an off-the-shelf conductive polyurethane (RmatFb-first sample) has piezoresistive properties and can be used as a pressure sensor.

3.2 Experimental Set-Up
Two experiments were carried out to observe and compare mechanical and electrical characteristics of RmatFb (40 x 40 mm) (Figure 3-1):

1. Compression velocity dependency on stiffness.
2. Stress relaxation.

For the initial compression velocity dependency experiment, 2 tests were conducted using the Instron machine set to 1mm/second and 5mm/second strain rates. For the stress relaxation experiment, constant deformation was set by the Instron machine for 600 seconds. Both electrical and mechanical data were collected for both studies. All experiments were carried out at room temperature.

Apparatus
For stress relaxation and compression velocity tests, a compression machine- Instron, force transducer-(9317B, Kistler, Winterthur, Switzerland- Figure 3-2a, Figure 3-2b), electronic circuit board (Figure 3-3), data loggers - Logomatic v2 Serial and MC device SD Card and analog to digital with a four channel USB DAQ module (USB-2404-10, Measurement Computing, Norton MA, USA; minimum data sampling frequency 1.8 kHz) and recorded with TracerDAQ Pro (Measurement Computing, Norton MA, USA). The tested material used in
this experiment was 40mm (W) x 40mm (L) x 6mm (H), high density closed cell foam (RmatFb, Figure 3-1) and the data were sampled at 2kHz. The specimen was placed between 2 conductive copper aluminium plates (Electrodes) and 2 MDF (Medium Density Fibber Board) during the experiments (Figure 3-2).

Figure 3-1: x10 Magnified, 40mm x 40mm x 6mm High density closed

Figure 3-2: (a) Test set up; (b) Test set up illustration
**Mechanical Compression Measurement**

For measuring stress relaxation and velocity dependency of stiffness experiments the foam was placed on top of a force transducer to enable time data matching between the two data acquisition tools (refer equipment and accessories section).

All load forces, displacements and compression velocities of compression machine set by a computer and the stiffness of the specimen computed later on using:

\[
(3.1) k = \frac{dF}{dx}
\]

Where \( k \) = Stiffness, \( F \) = force and \( x \) = Displacement, \( d \) = change/delta.

**Electrical Conductance Measurement**
For observing the DC electrical conductance of the conductive foam, the specimen placed between 2 parallel copper plates used as Electrodes, F+ and F-. 2 MDF (Medium Density Fibber Board) plates used as an electrical isolations material. The Electronics circuit design for this study used power source of 3.24V, voltage measuring device or data acquisition device and standard reference resistor 1KΩ. The data logger sampling frequency preset in advanced by steady 3.3V applied across two ends of the circuit using as main power source of the circuit. The DC measurement method was initially to connect the voltage measuring device (Data logger) between the top and bottom copper electrodes of the conductive foam (or in parallel) for measuring the change in potential difference across specimen during compressions.

Electrical conductance across the foam was then calculated using the formula:

\[(3.2) \quad G = \frac{1}{r}\]

Where G- Foam conductance, Reference resistor, r- Foam resistance.

All experiments were conducted at room temperature. In addition, capacitance test conducted on the specimen using 2- probe configuration and a multimeter for measuring the capacitance of the conductive PU material.

### 3.3 Results

#### Compression Velocity Dependency

Data from mechanical and electrical experiments were normalized and the force vs. conductance data plotted for 1mm/sec and 5mm/sec strain rates. The top (red) linear curve for both figures 3-5 and 3-6 represents the loading phase and the bottom (purple) non-linear curve represents the unloading phase. Figure 3-5 present a constant positive linear slope (red) starting from approximately 100N to 400N and conductance range of approximately 0 to 1.2mΩ. Similarly, figure 3-6 present a constant positive linear slope (red) starting from approximately 100N to 500N and conductance range of approximately 0 to 1mΩ. In both graphs, the difference between the loading and unloading curves shows the hysteresis phenomenon in the specimen.
Figure 3-5: Force vs. Conductance at 1mm/sec compression rate

Figure 3-6: Force vs. Conductance at 5mm/sec compression rate

**Stress Relaxation**

Figure 3-7 represents the mechanical force versus time stress relaxation results recorded for 600 seconds, \( t_0 \) to \( t_{\text{end}} \) and reflects a negative decreasing slope of the curve starting at \( t_1 \) with an initial peak value in force of 355.5N to \( t_{\text{end}} \) value of 274.5N after 10 minutes, with a change in force of 81N.

Figures 3-8 and 3-9 represent two ways of showing electrical behaviour stress relaxation results, also, from \( t_0 \) to \( t_{\text{end}} \) over 10 minutes. Figure 3-8 shows resistance against time and
reflects a negative decreasing slope of the curve. Starting at \( t_1 \) with an initial peak value of 799.64\( \Omega \) to an end value of 436.18\( \Omega \) after 10 minutes (\( t_{\text{end}} \)), a change of 363\( \Omega \) was calculated. Figure 3-9 shows conductance against time and reflects a positive decreasing slope of the curve. Starting at \( t_1 \) with an initial peak value conductance of 1.241E-03\( \Omega \) to an end value of 2.293E-03\( \Omega \) after 10 minutes (\( t_{\text{end}} \)) indicating that over time, under a constant displacement, mitigation in the cell walls’ components of the specimen occurs constantly. A change of -1.052E0-3\( \Omega \) in conductance was calculated.

![Figure 3-7: Force vs. time stress relaxation test](image1)

![Figure 3-8: Resistance vs. time stress relaxation test](image2)
3.4 Discussion and Conclusions

Our experiment shows that the off-shelf conductive polyurethane foam (RmatFb) can be used as a piezoresistive pressure sensor.

Compression Velocity Dependency

In figures 3-5 and 3-6, a constant positive linear slope (red) is observed in both graphs showing that as the force increased the conductance increased simultaneously during loading phase (red curves), as the force was released or unloaded the conductance decreased (purple curves). At both velocities, the difference between the loading and unloading curves shows the hysteresis phenomenon in the specimen. If there was no hysteresis in this specimen, the loading and unloading would be identical.

The 5mm/s gradient loading is steeper than the 1mm/s showing that when the compression velocity was faster the force was higher and the conductance lower. This behaviour reflects the electro-mechanical viscoelastic phenomena of strain rate dependency of stiffness or conductance of the specimen. Importantly, the loading graphs show a linear relationship with mechanical force increasing as conductance increased and as the force was unloaded, conductance decreased. These findings clearly prove the piezoresistivity phenomenon in this specimen and open many avenues for exploration of these materials in the field.

Stress Relaxation

The experimental stress relaxation results, force vs. time graph (Fig 3-7), reflects a negative decreasing slope of the curve. Starting at t₁ with an initial peak value in force of 355.5N to tend value of 274.5N after 10 minutes, with a change in force of 81N.
Indicating that over time, under a constant displacement, mitigation in the cell walls components of the specimen occurs constantly making the electrical resistance drop asymptotically over time. This electrical phenomena can be linked to the mechanical stress relaxation characteristic of viscoelastic materials.

The experimental stress relaxation results resistance versus time graph (Figure 3-8) reflects a negative decreasing slope of the curve. Starting at $t_1$ with an initial peak value of $799.64\Omega$ to an end value of $436.18\Omega$ after 10 minutes ($t_{end}$), a change of $363\Omega$ was calculated. Indicating that over time, under constant displacement, mitigation in the electrical components of the specimen occurred.

The experimental stress relaxation results, conductance versus time graph reflects a positive decreasing slope (Figure 3-9) of the curve. Starting at $t_1$ with an initial peak value conductance of $1.241E-03\ \text{S}$ to an end value of $2.293E-03\ \text{S}$ after 10 minutes ($t_{end}$) indicating that over time, under a constant displacement, mitigation in the cell walls’ components of the specimen occurs constantly. A change of $-1.052E-03\ \text{S}$ in conductance was calculated.

The RmatFb specimen was selected for preliminary testing as it was the first conductive material identified and readily available to researchers at a low cost. For the initial compression velocity dependency experiment, the Instron machine was set to 1mm/second and 5mm/second strain rates. The 5mm/sec experimental compression rate was chosen for set-up as it is a medium speed (the maximum machine setting is 8.3mm/sec) and due to the low thickness of the specimen. The speed was then reduced by a factor of 5 (to 1mm/sec) to also test the material at a lower speed.

### 3.5 Summary

Following our review of the available literature, pizoresistive sensors were identified as our preferred type for further investigation. After identification of a potential material (RmatFb), the off the shelf conductive polyurethane foam was electromechanically tested for application into a smart sensing system.

The compression rate dependency tests show different gradients for different loading rates, with creep and stress relaxation tests exhibiting mitigation in the stresses and strains in the
material. This proves the viscoelasticity properties in RmatFb. Viscoelasticity, known to be a disadvantage in pressure sensors as it causes hysteresis, is important to identify and characterise for both mechanical and electrical considerations in development. Findings also clearly prove the piezoresistivity phenomenon in this specimen showing that off the shelf conductive polyurethane foam can be used as a piezoresistive pressure sensor. Next, we identified a second conductive polyurethane foam (Rmat1x5) in order to verify these preliminary results and further characterise piezoresistive polymers.
4. Electro-Mechanical Characteristic Study, Discovery of a New Parameter - Conductive Stiffness

4.1 Overview

Mechanical viscosity is a property which is determined through stress relaxation or creep experiments and carried out by recording mechanical data for long periods and fitting power or logarithmic functions to the last segment of time (Fuss, 2012). The study is a continuation of the previous chapter and includes two experiments. The first determines whether the specimen can be modelled using non linear, logarithmic or power law and the second explores the dependency of electrical and mechanical viscosity on different strain rates of a single (Rmat1) 5 layers material (note: chapter 5 explores the electrical viscosity constant in depth).

The mechanical and electrical experiments carried out in this study:

1. Stress relaxation
2. Strain rate dependency
3. Mechanical stiffness (and consequent discovery of conductive stiffness)

Objectives

1. To determine the mechanical and electrical model functions of a single polymer specimen and to establish whether these function models can be linked.

2. To investigate the mechanical stiffness and electrical conductive stiffness dependency on different strain rates.

4.2 Experimental Set-Up: Stress Relaxation and Strain Rate Dependency

Apparatus

A standard stress relaxation experiment was conducted on a five layered single specimen (Rmat1 x 5 layered) to determine and compare the non linear electrical and mechanical viscosity model selection characteristic. A standard strain rate dependency experiment was conducted on a five layered single specimen (Rmat1 x 5 layered) to determine and compare
the mechanical and electrical Young’s modulus and stiffness for strain rate dependency at 3 different strain rates. All experiments were carried out at room temperature.

**Specimen**

(Figure 4-1) The tested specimen used in this experiment was 40mm (W) x 40mm (L) x 6.4mm (H) high Rmat1 x 5 layered.

**Equipment**

For both tests a 50kN Instron compression machine, electronic circuit board, specimen placed between 2 conductive aluminium plates (40mm x 40mm electrodes) sandwiched between 2 pieces of paper to isolate the electric circuit (Figure 4-2), development board (ATmega328P, Atmel, San Jose, CA, United States of America) including data logger 5V power source and reference resistor.
Experimental Procedure

Stress Relaxation

To examine the mechanical viscosity function, the specimen was placed onto an Instron device set to constant deformation of -2.588mm for 600 seconds. Mechanical forces data was collected during the experiment at a 100Hz sample frequency rate. Forces were then plotted against time for mechanical material characterizations.

To observe the electrical viscosity function, the drop voltages and mechanical stress relaxation across the specimen were recorded simultaneously. The specimen was connected to a 5V power source and in series to a 91KΩ reference resistor. The data logger was connected in parallel to the reference resistor and sampled at 100Hz for 600 seconds. The specimen’s electrical resistance was then calculated and plotted against time for electrical characterization.

Strain Rate Dependency

To study the mechanical modulus dependency on strain rates, the specimen was placed onto the Instron machine and set with different compression strain rates of 3mm/s, 0.3mm/s and 0.03mm/s. Mechanical force and displacement data was recorded continuously during the test and repeated 3 times and results were averaged.

To observe the electrical modulus dependency on strain rates, the drop voltages and mechanical strain rate test across the specimen were recorded simultaneously.

Mechanical and Conductive Stiffness

Using the strain rate dependency data for three different velocities, the stiffness k was calculated using the following formula:

\[ k = \frac{dF}{dX} \]  

(4.1)

Where the \(dF\) is the differential force in and \(dx\) is the differential deflection.

Following this, conductive stiffness KG was then computed using the following formula:
\[ kG = \frac{dG}{dX} \]  

(4.2)

Where the \( dG \) is the differential conductance and \( dx \) is the differential deflection.

### 4.3 Results

**Mechanical Stress Relaxation**

Mechanical forces were plotted against time for non linear model function selection (Figure 4-3). Using fit function analysis, logarithmic and power curves were plotted on single and double logarithmic coordinate systems and the coefficients of determination were compared. An initial overshoot that reaches up to 225N appears at the first segment of the graph during the first second followed by asymptotic relaxation of the force from 100 N over time.

![Figure 4-3: Mechanical stress relaxation fit function analysis power and logarithmic; blue and yellow curves, respectively; Overshoot phenomenon indicated](image-url)
Mechanical fit function analysis:

Logarithmic (yellow) and power (blue) fit function curves applied from 3s-100s and R squared was calculated and compared.

The power function from 20s-100s: \( Y = \text{pow}(X,-0.07465243182) \times 97.79807419 \)

Power \( \eta \): 0.07465243182

\( r^2 = 0.995842 \)

The actual logarithmic function from 3s-100s: \( Y = -5.473250701 \times \ln(X) + 94.48723855 \)

Logarithmic \( \eta \): 5.473250701

\( r^2 = 0.998488 \)

\( r^2 \) logarithmic >\( r^2 \) power, meaning that the specimen follows mechanically the logarithmic law function with viscosity constant \( \eta \) of 5.473.

Electrical Stress Relaxation

(Figure 4-4) The electrical resistance of the specimen was calculated and plotted against time for electrical function selection. Using fit function analysis, logarithmic and power curves were plotted on single and double logarithmic coordinate systems and the coefficients of determination were compared to choose the correct coordinate system.

![Figure 4-4: Electrical stress relaxation data plotted on double logarithmic coordinate system](image-url)
Electrical stress relaxation fit function analysis:

Logarithmic (Yellow) and power (Blue) fit function curves applied from 3s-100s, and the specimen appears to be electrically power law material.

The actual power function calculated was from 10s-100s: \( Y = \text{pow}(X,-0.192919328) \times 52252.97143 \)

Actual power \( \eta = 0.192919328 \)

\( r^2 = 0.997 \)

The actual logarithmic function calculated was from 10s-100s: Equation \( Y = -8244.860899 \times \ln(X) + 70512.29332 \)

Logarithmic \( \eta \): 8244.86

\( r^2 = 0.991 \)

R squared power > R squared logarithmic, meaning that the specimen follows Electrically the power law function with viscosity constant \( \eta \) of 0.192.

**Comparison: Mechanical and Electrical Viscosity Constant (\( \eta \))**

The electrical and mechanical Log \( \eta \) and the electrical and mechanical power \( \eta \) values were then compared against each other:

Logarithmic \( \eta \) comparison:

- Electrical Logarithmic \( \eta \): 52252.971
- Mechanical Logarithmic \( \eta \): 5.473

Power \( \eta \) comparison:

- Electrical power \( \eta \): 0.192
- Mechanical power \( \eta \): 0.0746

The mechanical and electrical viscosities fit functions follow different model functions, log and power, and therefore cannot be compared. To allow comparison between the two
viscosity constants (η), only the power functions values were considered as they can be expressed as a percentage (as power η between 0 and 1 or 0% - 100%).

Thus, for power model function, the viscosity constants were: mechanical η - 7.5% and electrical η - 19.3%.

**Mechanical Strain Rate Dependency and Stiffness**

Mechanical forces were plotted against time and the calculated stiffness was plotted against deflection for all three strain rates 3mm/s, 0.3mm/s and 0.03mm/s (Figures 4-5a, 4-5b).

The viscosity constants η for logarithmic and power models were calculated according to the method of Fuss (2012), shown in figures 5.14 and 5.19 of Fuss’ publication.

The logarithmic and power η for 50-100N forces calculated:

Logarithmic η = 4.95 at deflection 0.0003-0.0004

Power η = 0.0847 at deflection 0.0003-0.0004

**Electrical Strain Rate Dependency and Conductive Stiffness**

The electrical conductance was plotted against deflection and the calculated conductive stiffness was plotted against deflection for all three strain rates 3mm/s, 0.3mm/s and 0.03mm/s, in different colours (black, blue and red respectively) (Figures 4-6a, 4-6b).
Calculation of the conductive stiffness

The stiffness $K$ is calculated from:

$$K = \frac{dF}{dx}$$ (4.3)

Where the $dF$ is the differential force in and $dx$ is the differential deflection.

The Modulus $E$ is calculated from:

$$E = \frac{d\sigma}{d\epsilon}$$ (4.4)

Where the $d\sigma$ is the differential stress and $d\epsilon$ is the differential strain.

And the conductive stiffness can be calculated from:

Conductive stiffness = $\frac{dG}{dx}$

Where $dG$ is the differential conductance.

4.4 Discussion and Conclusions

Once we ascertained that off the shelf conductive polyurethane foam can be used as a piezoresistive pressure sensor, we tested Rmat1x5 in order to verify our results and
determine the mechanical and electrical function model selection for the specimen (piezoresistive polymer). Specimen Rmat1x5 was selected for testing as it was the second piezoresistive material identified and was readily available to the group. Five layers of the specimen were used to increase the thickness of the material therefore allowing for testing with the Instron machine.

**Mechanical and Electrical Stress Relaxation**

Overshoot: This graph characteristic is explained by Fuss (2012) saying that, in practice, testing machines have limitations to produce a Heaviside function (unit strain) to represent the instantaneous change in strain. Instead, an initial ramp strain followed by a constant strain occurs causes the stress to initially overshoot and then asymptotically reach the Heaviside strain conditions.

Based on the stress relaxation experiments, the results show that mechanical viscosity model function in Rmat1x5 follows a non-linear logarithmic law whereas its electrical viscosity follows a non-linear power law. Therefore, these two models follow different functions and cannot be linked. In figure 4-3 (mechanical stress relaxation results) there is an initial overshoot, reaching up to 225N, appearing at the first segment of the graph during the first second followed by asymptotic relaxation of the force from 100N overtime. This characteristic is explained by Fuss (2012) saying that, in practice, testing machines have limitations to produce a Heaviside function (unit strain) to represent the instantaneous change in strain. Instead, an initial ramp strain followed by a constant strain occurs causes the stress to initially overshoot and then asymptotically reach the Heaviside strain conditions.

For the electrical results (Figure 4-4), we see a similar initial slight overshoot appearing in the first segment of the loading plot followed by a drop of the resistance through ramp loading and subsequently resistance shots back upwards, and finally approaches fit function asymptotically. Again, this overshoot can be attributed to a viscoelastic ramp effect which occurs due to testing machine limitations (literature review section). Results found for mechanical viscosity function is in line with other studies reported in the literature (Fuss, 2012) while the electrical viscosity findings are new. The mechanical and electrical viscosities fit functions presented different model functions, log and power, and therefore could not be compared. To allow comparison between the two viscosity constants ($\eta$), only
the power functions values were considered as they can be expressed as a percentage (as power \( \eta \) between 0 and 1 or 0% - 100%). Results showed that the specimen is more electrically viscous than mechanically. These electrical findings make it easier to determine the value of the materials’ viscosity by fitting a tangent gradient to the power curve in a double logarithmic coordinate system. Determining a conductive polymer’s electrical viscosity is a simpler and costs less in contrast to mechanical viscosity tests. This a new parameter that may become a gold standard benchmark for material characterisation in the future.

**Mechanical and Electrical Strain Rate Dependency**

For the strain rate dependency experiments (verification of results described in the previous chapter), the Instron machine was set to 3, 0.3 and 0.03 mm/sec. The 3mm/sec experimental compression rate was chosen for set-up as it is a medium speed with the speeds then being reduced by a factor of 10 to also test the material at lower speeds. The behaviour of all strain rate curves (Figure 4-5a) was comparatively alike: for similar deflections the force is higher for larger strain rates. The general behaviour of all three red curves is similar, they start to rise roughly at 2.5mm deflection followed by a sharp increasing and then begin to decline slightly at roughly 0.0005m. These data can be observed more clearly from the gradient of the stress strain curve (Figure 4-5b) where the green curve for all three strain speeds increases sharply until it reaches a peak value of stiffness and subsequently asymptotically declines. It can be concluded that the Young’s modulus is not only strain rate dependent but also a strain dependent material property.

From the conductance curves (Figure4-5a) it can be seen that for similar deflections the conductance is higher at smaller strain rates. The general behaviour of all three conductance curves is similar: they start to rise at low deflection, 0.0001m followed by a roughly constant gradient of the curves. The conductive stiffness is the first deflection derivative of the conductance, a new discovery made here which hasn’t been described before in the literature. The behaviour of all strain rate curves is comparatively alike: they start to increase at a low deflection of about 0.0001m, reach a sort of peak at 0.0005m and ripple inconstantly upwards. It can be concluded that the conductive stiffness is not only strain rate dependent but also strain dependent.
The compression rate dependency tests show different gradients for different loading rates. It can be concluded that the conductive stiffness is not only strain rate dependent but also strain dependent. At higher compression rates, both the mechanical and conductive stiffness of the specimen were lower. These results verify that conductive polymers have viscoelastic properties, an important part of material characterisation.

4.5 Summary
In the previous experiment, we determined that conductive polyurethane foam can be used as a piezoresistive pressure sensor. Here, we tested a second specimen (Rmat1x5) to verify our results, determine the mechanical and electrical function model selection and investigate the mechanical and electrical conductive stiffness dependency on different strain rates. Results show that mechanical viscosity in Rmat1x5 follows a logarithmic law function whereas its electrical viscosity follows a power law function so only the power function viscosities were compared and showed a higher electrical viscosity value. Results showed that the specimen is more electrically viscous than mechanically. This new parameter, conductive stiffness, may become a gold standard benchmark for material characterisation in the future. Further, this experiment confirms that conductive polymers have viscoelastic properties, an important part of material characterisation for final product development.

After concluding that off the shelf conductive polyurethane foam can be used as a piezoresistive pressure sensor, we collected specimens of other conductive polymers and conducted characterising experiments to determine which is most suitable for further development.
5. Electro-Mechanical Characteristic Study, Discovery of Electrical Viscosity and Development of a Method for Quantification of the Electrical Viscosity Constant

5.1 Overview
During this study, ten different piezoresistive polymers were investigated. After showing that mechanical and electrical viscoelastic model functions cannot be linked, this study was used to introduce a new method, based on mechanical creep experiments, to determine a new hypothesised characteristic called electrical viscosity parameter. Electrical viscosity constant is a characteristic that represents the decrease of electrical changeover time under constant mechanical load. This new method was introduced to assist in the classification of the materials in order to choose the most suitable specimen for further development. In addition, each specimen was tested to determine whether its viscoelasticity function can be modelled using non linear, logarithmic or power law.

Objectives
1. To categorized 10 conductive polymers by their electrical viscosity constant - \( \eta \).
2. To determine the electrical viscoelastic model function of multiple specimens.

5.2 Experimental Set-Up: Electrical-Viscosity Constant Determination Study

Apparatus
For each specimen, five creep experiments of 600 seconds were conducted using different loads, 49N, 98N and 147N to compare and determine electrical viscosity model functions and constants. All experiments were carried out at room temperature.

Specimen
Ten materials were tested in this experiment, as follows:

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Description</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>RmatFa</td>
<td>Soft open cell foam</td>
<td>40 X40 X 6mm</td>
</tr>
<tr>
<td>RmatFb</td>
<td>Hard closed cell foam</td>
<td>40 X40 X 6mm</td>
</tr>
<tr>
<td>#</td>
<td>Material</td>
<td>Type</td>
</tr>
<tr>
<td>---</td>
<td>------------</td>
<td>------------------</td>
</tr>
<tr>
<td>3</td>
<td>Rmat1</td>
<td>Vinyl</td>
</tr>
<tr>
<td>4</td>
<td>Rmat2a</td>
<td>Velostat</td>
</tr>
<tr>
<td>5</td>
<td>Rmat2a x 8</td>
<td>Velostat x 8 layered</td>
</tr>
<tr>
<td>6</td>
<td>Rmat2b</td>
<td>Thick Velostat</td>
</tr>
<tr>
<td>7</td>
<td>Rmat3a</td>
<td>Rubber type A- thin</td>
</tr>
<tr>
<td>8</td>
<td>Rmat3b</td>
<td>Rubber type B- thick</td>
</tr>
<tr>
<td>9</td>
<td>Rmat4</td>
<td>New rubber</td>
</tr>
<tr>
<td>10</td>
<td>Rmat5</td>
<td>New Vinyl</td>
</tr>
</tbody>
</table>

Table 5-1: All specimens

**Equipment**

Using a standard creep test protocol using electronic circuit (same as Figure 3-3) with different reference resistors for different specimens, 98N, 49N and 147N loads, 2 conductive aluminium plates (40mm x 40mm electrodes), 2 MDF (Medium Density Fibber) boards used to isolate the electric circuit, development board (ATmega328P, Atmel, San Jose, CA, United States of America) including data logger 5 volts power source and reference resistor, the data sampled at 90Hz – 100Hz for 600 seconds during each experiment.

**Experimental Procedure**

**Electrical Creep Test**

In order to calculate the change in electrical resistance, each material was placed between two 40mm x 40mm parallel aluminum plates used as top and bottom electrodes and sandwiched between one 40mm x 40mm MDF (Medium Density Fibber Board) plate (Figure 5-1), to isolate the electric circuit from external electric charge or interference.
The data logger sampling frequency was preset in advanced by the development board to 100Hz and steady 5V applied to the circuit. The electric voltage was measured by connecting the data logger device between top and bottom electrodes of each specimen and recording continuous change in potential difference across the specimen.

A constant load was applied for 600 seconds during each experiment (repeated five times) and with a minimum interval of 20 minutes between tests.

**Methods of Analysis**

**Calculating Specimens Resistance and Conductance**

The Electrical peak resistance and conductance across each specimen calculated using voltage divider formula:

\[
V_{-Rref} = \frac{Vin \times Rref}{R_{-specimen} + Rref}
\]

(5.1)

Or:

\[
R_{-specimen} = \frac{Vin \times Rref}{V_{-Rref}} - Rref
\]

(5.2)

The electrical peak conductance formula:

\[
G_{-specimen} = \frac{1}{R_{-specimen}}
\]

(5.3)

**Choosing an Electric Viscoelastic Model Function: Power or Logarithmic**

The calculated resistance data for each experiment were plotted against time firstly for model selection (power or logarithmic) and subsequently for viscosity constant determination (Figure 5-2).
Using fit function analysis, logarithmic and power curves were plotted on a double logarithmic coordinate system and the coefficient of determination \( r^2 \) compared at the linear segments (Fuss, 2012).

Conclusion from the graph: Power \( r^2 \) > logarithmic \( r^2 \) = Power law function material because log function does not fit perfectly at small times and the data deviates.

**Electrical Viscosity Constant - \( \eta \)**

For determining electrical viscosity constant, the gradient of the power function on a double log coordinate system has to be determined for large times (Fuss, 2012).
From Figure 5-3, the viscosity constant $\eta$ for Rmat1 was measured at: 19.4%.

Calculated from:

$$R = 23649.22^* t^{-0.194}$$
$$G = 4.22e-5^* t^{0.194}$$

$$\log R = \log 23649.22 - 0.194^* \log t$$
$$\log G = \log 23649.22 + 0.194^* \log t$$

Thus: $\eta =$ gradient of creep on a double log coordinates system is 0.194 or 19.4%.

### 5.3 Results

The following table lists the selected electrical viscoelastic model functions and the constant of electrical viscosity constant for 10 conductive polymer specimens.
5.4 Discussion and Conclusions

Once we ascertained that off the shelf conductive polyurethane foam (RmatFb) and 5 layered (Rmat1 x 5) can be used as a piezoresistive pressure sensors, we set out to study the electrical viscosity constant of 10 specimens of conductive polymers as described above. We succeeded in identifying and sourcing 10 different polymers from 4 countries (India, USA, New-Zealand, Australia) with varying characteristics such as: thick, thin, soft and hard materials.

After showing that mechanical and electrical model functions cannot be linked, this study was used to introduce a new method, based on mechanical creep experiments, to determine a new hypothesised characteristic called the Electrical viscosity constant ($\eta$). The Electrical viscosity constant is an attribute that characterises electrical change over an identified time under a mechanical load. Electrical viscosity constant ranges between $0 \leq \eta < 1$ and can therefore be expressed as a percentage where 100% represents maximum viscosity and 0% represents an inviscid material. Specimens were tested at a load of 5 and 10kgs. If reliable electrical readings could not be determined at 5kgs, the specimen was then also tested at 10 and 15kgs. The material with the lowest electrical viscosity constant and most repeatable data was Rmat2a = 0.064 (electrical viscosity constant of all materials ranged between 0.003-0.351). Although Rmat5 and Rmat2b also showed low electrical
viscosity constant values, they both had unstable (noisy) readings with a relatively large range of the constant.

The method of measuring the electrical viscosity constant introduced in this chapter offers a relatively simple alternative to conventional compression machine tests for stress relaxation and speed tests. Where these tests are traditionally complex and use sophisticated machinery for material characterisation, the same result can be achieved by a simple creep test with a weight.

In contrast to the mechanical viscosity of polymers which follows a logarithmic function model (Fuss, 2012), all specimens electrical viscosity constant was found to fit a power function. This supports our previous findings for Rmat1x5.

The Rmat2a specimen has a thickness of approximately 0.1mm, which is significantly thinner than all other materials tested (average thickness approximately 1.5mm). For this reason, another specimen was added - Rmat2a x 8 using 8 stacked layers of the Rmat2a velostat. Eight layers were chosen to increase the material thickness to 0.8mm and near the specimen thickness to that of the other materials. At this stage, the most suitable specimen for further development based on the electrical viscosity constant value is Rmat2a.

5.5 Summary

Previously, we conducted testing on two specimens and determined that off the shelf conductive polyurethane foam can be used as a piezoresistive pressure sensor. Here, we set out to study the electrical viscosity constant of 10 specimens of conductive polymers. The electrical viscosity constant, a new parameter discovered here, is an attribute that characterises electrical change over an identified time under a mechanical load.

Results showed that all specimens’ electrical viscosity constant was found to fit a power function, supporting previous findings for Rmat1x5. Based on electrical viscosity characteristics, Rmat2a was found to be the most suitable specimen for further development.

The next experiment measures impact forces in the same 10 specimens in order to gain further information on the most suitable material for further development. These experiments determine the mechanical and electrical peak impact data mimicking the foot
to ball impact phase during kicking.
6. Electro Mechanical Peak Impact Forces of Multiple Materials

6.1 Overview
The electro mechanic peak impact forces study aimed to determine the coefficient of
determination ($r^2$) between mechanical peak impact forces and peak electrical impact
resistances of 10 piezoresistive polymer specimens during ball slamming. Additionally, the
study aims to develop resistance-force calibration functions for different conductive
polymer materials. The study mimics the foot to ball impact phase during kicking by
slamming a stiff ball onto the specimens and simultaneously record the mechanical forces
and electrical drop voltages data. The investigation assists in the characterization of
different piezoresistive materials in order to choose the most suitable specimen for the
smart football footwear final application.

Objectives
1. To determine the electro mechanical peak impact forces coefficient of determination
   of ten piezoelectric specimens.
2. To establish calibration functions for each specimen.
3. To select the best specimen for further development.

6.2 Experimental Set-up
For each specimen, the experiment included 5 force slamming levels sets (range: 100N-
1700N, increasing by approximately 300N between each level). Each set had 10
comparatively equal forces level slamming (within a 300N range). In total, about 50 to 60
ball slamming per material. All experiments were carried out at room temperature.

Specimen
The tested piezoresistive materials used in this experiment the same as in previous chapter
(Table 5-1):

Equipment
Each specimen was placed on a force plate (Bioware 5kHz sampling frequency rate) and connected to an electronic circuit that included a 5 Volts power source and a reference resistor, analogue to digital converter module (USB-2404-10 Measurement Computing, 24 bits resolution) with data logger software (5kHz, TracerDAQ Pro software, Measurement Computing, Norton MA, USA). The slamming tests were conducted using a 85mm diameter stiff ball (image 6.1). Each set ran for 10 seconds with 5 minutes intervals between each set.

![Figure 6-1: Test set-up](image)

**Electrical Slamming Test**

For observing the peak DC drop voltages or peak resistance of the conductive materials during slamming, each material was placed between 2 conductive aluminium electrodes, F+ and F- connected in series to a 5 volts power source with a standard reference resistor. The data logger was connected in parallel to measure the change in voltage between the electrodes, F+ and F-, and to calculate the electrical resistance of the material during slamming.

**Mechanical Slamming Test**

At the same time as the electrical data recording, the mechanical impact forces were recorded by the force plate in each slamming set by the data logger which was connected to the force plate. Subsequently, the peak impact forces were compared to the peak resistances.
6.3 Methods Of Analysis

After the electrical data were recorded, they were needed to go through the voltage divider formula (3.4) to calculate other electrical peak parameter such voltage, resistance and conductance. The mechanical peak impact forces data were then also extracted to be determining the coefficient of determination \( (r^2) \) and calibration functions between the two.

**Calculating Electrical Peak Impact Parameters**

The Electrical peak resistance and conductance across each specimen was calculated using voltage divider formula:

\[
V_{\text{peak}} = \frac{Vin \times \text{Ref}}{R_{\text{specimen}} + \text{Ref}}
\]  
(6.1)

Or:

\[
R_{\text{peak}} = \frac{Vin \times \text{Ref}}{V_{\text{Ref}}} - \text{Ref}
\]  
(6.2)

The electrical peak conductance formula:

\[
G_{\text{peak}} = \frac{1}{R_{\text{specimen}}}
\]  
(6.3)

(Figure 6-2) The peak drop voltages determination was conducted manually by plotting the calculated peak voltages versus time and 10 peak voltage values were noted. Then, the voltages were converted to resistance and compared against compatible peak impact forces, from the subsequent mechanical slamming data.
Figure 6-2: Peak electric voltage values during slamming - example of 1 specimen, 1 set (Rmat1)

Mechanical Slamming Data Processing

The peak impact forces (Figure 6-3) determination was done manually by plotting the recorded forces versus time and 10 peak impact forces values were noted. The data was then placed into a table to be compared and plotted against compatible peak resistances, to determine coefficient of determination and find the right calibration function (Figure 6-4).
Figure 6-3: Peak impact forces values during slamming - example of 1 specimen, 1 set (Rmat1)

Coefficient of Determination ($r^2$) and Calibration Functions Determination
(Figure 6-4) To conclude the coefficient of determination and calibration function of the specimens the full peak impact force data was plotted against compatible peak resistance data and fit function analysis conducted (logarithmic, power and exponential).
Figure 6-4: Mechanical vs electrical slamming data, coefficient of determination and calibration function (power fit curve) - example of 1 specimen, 5 sets (Rmat1)

Exponential fit function: \( r^2 = 0.932813 \)
Logarithmic fit function: \( r^2 = 0.910276 \)
Power fit function: \( r^2 = 0.989304 \) - Higher
With calibration function: \( \text{pow}(X,-1.128871428) \times 15139683.28 \)
6.4 Results

The following table lists the coefficient of determination \((r^2)\) and calibration functions of all specimens tested:

<table>
<thead>
<tr>
<th>Specimen</th>
<th>(r^2)</th>
<th>Calibration function</th>
</tr>
</thead>
<tbody>
<tr>
<td>RmatFa - soft foam</td>
<td>0.936</td>
<td>(Y = \text{pow}(X,-1.029939049) \times 85326.80322)</td>
</tr>
<tr>
<td>RmatFb - hard foam</td>
<td>0.920</td>
<td>(Y = \text{pow}(X,-1.189743889) \times 49738120.52)</td>
</tr>
<tr>
<td>Rmat1 - vinyl</td>
<td>0.989</td>
<td>(Y = \text{pow}(X,-1.128871428) \times 15139683.28)</td>
</tr>
<tr>
<td>Rmat2a – velostat</td>
<td>0.984</td>
<td>(Y = \text{pow}(X,-2.007422514) \times 3975.902789)</td>
</tr>
<tr>
<td>Rmat2a x 8 - velostat x 8 layered</td>
<td>0.803</td>
<td>(Y = \exp(-3.900436375E-006 \times X) \times 1662.538507)</td>
</tr>
<tr>
<td>Rmat2b - thick velostat</td>
<td>0.983</td>
<td>(Y = \exp(-1.917527094E-005 \times X) \times 2305.067604)</td>
</tr>
<tr>
<td>Rmat3a - thin rubber</td>
<td>0.962</td>
<td>(Y = \text{pow}(X,-0.8753497347) \times 7349766.924)</td>
</tr>
<tr>
<td>Rmat3b- thick rubber</td>
<td>0.94</td>
<td>(Y = \text{pow}(X,-0.5940852939) \times 51457.81179)</td>
</tr>
<tr>
<td>Rmat4 - New rubber</td>
<td>0.906</td>
<td>(Y = \text{pow}(X,-1.188707326) \times 25764896.68)</td>
</tr>
<tr>
<td>Rmat5 - new vinyl</td>
<td>0.878</td>
<td>(Y = \text{pow}(X,-1.117742935) \times 690008584.7)</td>
</tr>
</tbody>
</table>

Table 6-1: Peak impact force, \(r^2\) (fit function) and calibration functions (all specimens)

6.5 Discussion and Conclusion

Of the 10 specimens tested, our findings suggest that Rmat1 – vinyl is the most accurate for peak impact forces measurements with a relatively high \(r^2\) (0.989). On the other hand, Rmat2a x 8 - Velostat was found to be the least accurate among all specimens with the lowest \(r^2\) (0.803).

Rmat1 was selected for use in the development stage as it showed:

1. The highest repeatability (with a \(r^2\) value of 0.989 for over about 60 repeated slamming experiments).
2. The mechanical peak impact forces are approximately 99% dependent on the electrical peak data \((r^2=0.989)\).
3. Electrical peak resistance that remained within the unsaturated part of the plotted force-resistance curve (1473Ω) at a high force (1702N).

Rmat2ax8 showed the lowest coefficient of determination value \( r^2 = 0.803 \) and a relatively low electrical viscosity constant (0.074) in the previous experiment (electrical viscosity constant of all materials ranged between 0.003-0.351). For impact, there is a relationship between duration and peak - the higher the force, the shorter the duration. Therefore, when impact forces are applied to conductive polymers, viscosity is not pronounced and doesn’t have a distinct effect when measuring electrical data. Although Rmat1 did not show the lowest electrical viscosity constant in the previous experiment, we chose to continue development with this material based on the force-time coupling during impacts. In a Hookean spring, the higher the impact force, the shorter is the contact time at impact. Depending on the shape and the non-linearity of an object, the contact time can decrease or increase as the impact force increases or even remain constant. This coupling effect of force and contact time avoids the variable visco-elastic decrease of the impact force as a function of the contact time. The more viscous a material, the smaller is the impact force when dropped from the same height. If a force is applied to an object other than be impact, the coupling effect does not apply any more, as an object can be loaded with a lower and higher force over shorter and longer periods. If a visco-elastic material is subjected to a constant strain but at different stain rates (shorter and longer contact times), then the resulting force is the smaller, the slower the strain rate is. In impacts however, the strain is linked to the strain rate such that a constant strain never results in different forces.

Interestingly, Rmat2b (single layer of velostat) showed a higher coefficient of determination \( r^2=0.983 \) than Rmat2ax8 (8 layers of velostat) \( r^2=0.803 \). This finding may be explained by the surface to surface contact of 8 layers of velostat causing a higher variation between mechanical force and electrical resistance.

Forces up to 1700N (range: 100-1700N) were used for slamming experiments for mimicking the foot to ball impact phase during the kicking action. A maximum force of 1700N was set as it was observed, through trial and error, that some materials could still withstand this force. Additionally, the literature shows that a full instep kick can generate more than 2800N (Lees et al., 2010) and it was hypothesised, that a force of 1700N would be sufficient for this stage of research and development. Materials that electrically saturated at forces...
lower than 1000N were not considered favourable for material selection. This is because of the high force nature of the kicking action.

The peak impact force studies were done using a high performance data logger (high sampling frequency rate, ADC 24bit resolution) to gain accurate and specific information about the specimens studied. In the final prototype, the data logger will be embedded in a micro-controller and its performance quality will have to be weighed against important characteristics such as small size, low cost and portability.

It seems that an advantage of measuring only peak electrical values is that they are not affected by electrical displacement (hysteresis) which is a result of the loading and unloading phases. Therefore, peak impact force measurements may reflect more repeatability than non-peak impact forces results during loading and unloading phases.

Ten calibration functions were successfully obtained for each specimen, some followed a power and others an exponential function. These functions allow us to calculate peak impact forces using the measured electrical resistance of the material. This relationship allows conductive polymers to be used as pressure sensors.

6.6 Summary
We identified and sourced 10 different polymers with varying characteristics such as: thick, thin, soft and hard materials. These specimens were initially characterised (Chapter 5) by their electrical viscosity constant and electrical function models. In this experiment, the electro mechanical peak impact forces coefficients of determination and calibration functions were determined for each specimen. Rmat1 vinyl was found to be the most suitable material for peak impact forces measurements showing the highest repeatability and an electrical peak resistance that remained within the unsaturated part of the plotted slope at a high force. Although Rmat1 did not show the lowest electrical viscosity constant in the previous experiment, we chose to continue development with this material based only on its favourable characteristics during peak impact forces.

The experiment marks the end of our material characterisation phase and begins the development point of the novel multi-point sensor array system. Rmat1 was used for the development stage.
7. **Prototype Development and Proof of Underlying Research Concept**

7.1 **Overview**

This section sets out to prove the feasibility of the sensor array system research principle (patent pending, Appendix 1). The technical principle of the sensor array consists of piezoresistive material pressure mapping via microcontroller, biofeedback output data, algorithms for converting raw pressure data to advance pressure parameters and potentially to audio/visual biofeedback signals.

Based on the sensor array system platform, three prototypes were developed to test the functionality and practicality of the concept.

The prototypes:

1. Smart mat.
2. Smart insole 1.
3. Smart insole 2.

**Objectives**

To test the sensor development principle through different prototypes, feedback mechanisms and advanced parameters (algorithms).

7.2 **Methods– Common to all Prototypes**

- All prototypes used the Rmat1 piezoresistive material.

- All prototypes used a similar programmable micro-controller chip (Atmel, San Jose, CA, United States of America) and data was logged at 10bits ADC.

- All prototypes used internal multiplexer of the microcontroller to shift between digital and analog input and output.

- In principle, the system always measured data from each of cell individually. Each cell’s pressure threshold can be determined in advance so that only those cells activated (pressed) will be utilized.
In order to overcome “neighboring resistance effect”, which may influence the measured resistance of a single cell, each digital signal had to be electrically isolated. To do that, the internal multiplexer which is embedded in the microcontroller set all other output signals to an inactive mode except one in a sequence.

**Common operating principle:** when force is applied onto the insole sensor grid, the electric resistance of the cells declines and, following Ohm’s Law, the electric voltage drops.

### 7.3 First Prototype - Smart Mat

**Overview**

The smart mat was the first prototype developed to test feasibility for the sensor development. The system includes a visual feedback mechanism to display the location and magnitude of pressure (in volts) applied to the surface of a mat (Figure 7-1a). The sensing area was made from conductive vinyl material that was used as sensor array grid.

![Smart mat prototype](image)

**Figure 7-1:** Smart mat prototype; (a) sensing area, (b) Full system

**Objectives**

1. To determine whether each node in the system can provide a discrete data reading and whether all cells can function simultaneously.
2. To display pressure magnitudes (voltage).
3. To display pressure location coordinates on the grid.

**Set-up**

(Figure 7-1) The principle of operation includes a programmable micro-controller chip (ATmega328P, Atmel, San Jose, CA, United States of America) connected to 16 segregated cell grid, made of separated conductive material (Rmat1, overall system size: 58mm x 75mm).
58mm, individual cells: 14mm x 14mm). The programmable integrated circuit generates 5/0 Volts electrical signals by the blue electrodes (Figure 7-2) and the red electrode read the drop voltage in each cell. Data then was processed and displayed on LCD screen.

**Methods**

Force was applied onto the system either through pressing a single cell (single node) or through rolling a stiff ball over a random cluster of cells (multi node). Data is transferred to the microcontroller for processing which finally displays the activated cells location (X and Y orientation) and the magnitude of the pressure in volts (Eqn. 7.2).

![Figure 7-2: Smart mat technical principle](image-url)
The connections in the system are 4 blue digital output electrodes, X0 - X3, connected vertically to the mat and the programmable integrated circuit to generate 0 or 5 V at their time. 4 red Analog inputs electrodes, Y0 - Y3 connected horizontally to the mat and the microcontroller to read data from 4 reference resistors, 22 KΩ, connected in series to each output signal (Figure 7-3a).

The programmable chip operates in the following order:

1. Digital (blue) output X0 generates 5v and all other digital outputs X1, X2, X3 deactivated through the internal programmable multiplexer or on floating mode.

2. Analogue (red) inputs Y0 - Y3 run from top to bottom and read the drop voltages from 4 reference resistors.

3. Digital output X1 generates 5v and all other digital outputs X0, X2, X3 deactivated through the internal programmable multiplexer or on floating mode.

4. Analogue inputs Y0 - Y3 run from top to bottom and read the drop voltages from 4 reference resistors.

5. Digital output X2 generates 5v and all other digital outputs X0, X1, X3 deactivated through the internal programmable multiplexer or on floating mode.
6. Analogue inputs Y0 - Y3 run from top to bottom and read the drop voltages from 4 reference resistors.

7. Digital output X3 generates 5v and all other digital outputs X0, X1, X2 deactivated through the internal programmable multiplexer or on floating mode.

8. Analogue inputs Y0 - Y3 run from top to bottom and read the drop voltages from 4 reference resistors.

This covers 16 readings from 16 cells.

**Data Processing and Feedback**

All measured drop voltages data from 16 cells were processed through a programmable chip to display only pressure magnitudes above a certain level. The output (blue) electrodes generate voltage magnitudes of 0 or 1023 ASCII character encoding (10 bit Analog to digital converter resolution) equivalent to 0 and 5 Volts (Eqn. 7.2). The input (red) electrodes measure the drop voltage of the references resistor which can be calculated using voltage divider equation below and reflect different pressures in electric format.

\[
V_{-Ref} = \frac{Vin \times R_{ref}}{R_{cell} + R_{ref}}
\]  

(7.1)

Or ASCII character encoding:

\[
ASCII_{-Ref} = \frac{124 \times V_{Ref}}{Vin}
\]

(7.2)

**7.4 Second Prototype- Smart Insole 1**

**Overview**

After proving the functionality of the system, the next prototype used specific algorithms to measure an advanced parameter during gait (Figure 7-4). The smart insole prototype aimed to calculate the polar angle (360 degrees) of the centre of pressure (COP) and wirelessly transmit a real-time audio biofeedback to the user.
Objectives

To reflect the polar COP angle during gait through audible wireless feedback

Set-up

The principle of operation of the prototype is illustrated in Figure 7-5. A programmable micro-controller chip (ATmega328P, Atmel, San Jose, CA, United States of America) is connected to 2x2 cells sensors grid, made of Vinyl conductive material (Rmat1, individual cells: 10mm x 10mm). The programmable integrated circuit generates 5/0V electrical signals through the blue output electrodes and the red input electrodes read the drop voltages from 2 reference resistors. Data is then processed in the microcontroller using mathematical equations (IP algorithms) and returns wireless audio feedback to the user.

Methods

All four cells in the system were measured individually and in sequence and the data transferred to the microcontroller for further processing analysis using special algorithm (Please refer – sensor development, Advanced pressure parameters and algorithms section) and finally a real time RF audio pitch signal (433MHz RF transceiver module, WenShing, Taiwan) transmitted (HC-05 Wireless Bluetooth Transceiver Module) to a smart phone (Nexus s, Google Samsung, Seoul, South Korea). During gait, the pitch of the audio signal changed according to the displacement of the COP with respect to the centre of the insole.
The connections in the system are 2 digital (blue) output electrodes, X0, X1 (displayed in blue Figure 7-5), connected to the programmable integrated circuit to generate 0 or 5 V at their time. 2 analogue (red) inputs electrodes, Y0, Y1 (displayed in red Figure 7-5), connected to the microcontroller to read data from 2 reference resistors, 22KΩ, connected in series to each output signal.

The programmable chip is programmed to operate in the following order:

1. Digital (blue) output X0 generates 5V and X1 is deactivated through the internal programmable multiplexer or on floating mode.
2. Analogue (red) inputs Y0, Y1 read from top to bottom and read the drop voltages from 4 reference resistors.
3. Digital output X1 generates 5V and X0 is deactivated through the internal programmable multiplexer or on floating mode.
4. Analogue inputs Y0, Y1 run from top to bottom and read the drop voltages from 2 reference resistors.

This covers 4 readings from 4 cells.

**Data processing and feedback**

All measured drop voltages data from 4 cells were processed through a code (C programming language) to display only pressure magnitudes above a certain level. The
threshold level for each cell determines the minimum drop voltage or pressure point of a cell single which will reflect audio pith feedback. The blue output electrodes generate voltage magnitudes of 0 to 1023 character encoding (10bit analogue to digital converter resolution), equivalent to 0 and 5V. The red input electrode measures the drop voltage of the references resistor which can be calculated using voltage divider:

\[ V_{\text{ref}} = \frac{V_{\text{in}} \times R_{\text{ref}}}{R_{\text{cell}} + R_{\text{ref}}} \]  

(7.3)

or ASCII character encoding:

\[ \text{ASCII } R_{\text{ref}} = \frac{1024 \times V_{\text{ref}}}{V_{\text{in}}} \]  

(7.4)

### Centre of pressure analysis

If pressure is distributed unevenly over a surface, then the COP is defined as the intersection of at least two lines about which the moments generated by forces (per unit area, distributed over an area) on either side of each line are balanced. The accurate determination of the instantaneous COP requires evenly distributed sensors over the measurement area with a high resolution.

Cop is described from Eqn. 7.5 and Eqn. 7.6

\[ \text{COP}_x = \sum_{i=1}^{n} \frac{x_i p_i}{n} \]  

(7.5)

And:

\[ \text{COP}_y = \sum_{i=1}^{n} \frac{y_i p_i}{n} \]  

(7.6)
Where COPx and COPy are the coordinates of the COP; xi and yi are the distances of the i-th sensor from the origin of the sensor matrix coordinate system; pi is the pressure on the i-th sensor, and n is the total number of sensors.

\[ \theta = \text{ATAN2} \frac{COPy}{COPx} \]  
(7.7)

And:

\[ R = \sqrt{COPx^2 + COPy^2} \]  
(7.8)

Where theta is the polar angle of the COP, ATAN2 is the 2nd inverse tangent function (returning the polar angle in any of the 4 quadrants), and R is the distance between the COP and the origin of the coordinate system and \( \theta \) is the angle (Figure 7-6).

7.5 Third prototype- Smart insole 2

Overview

This prototype (Figure 7-7) is a second gait biofeedback system application based sensor array grid. It aimed to give visual biofeedback of the pressure distribution and centre of pressure over an insole during walking.
Objectives

1. To reflect the gait pressure distribution mapping by real time RGB visual biofeedback.

2. To reflect real-time displacement of the COP during gait.

Figure 7-7: Smart insole 2 prototype (from left to right); (a) electrodes and conductive material layers, (b) 3 layers insole, (c) logic board

As in the first prototype, the idea of using a visual biofeedback system during walk is that the user can watch at real time or record his/her gait analysis patterns.

Set-up

The principle of operation includes a development board with a programmable chip (ATmega328P, Atmel, San Jose, CA, United States of America) connected to 5 x 15 (75) cells sensors grid (Rmat1, insole size: UK7.5, men) and integrated with a graphics design software (Processing v.2). The programmable chip is programmed to generate 5/0V electrical signals through the blue output electrodes and the red input electrodes read the drop voltage in each cell from reference resistors. The data is then been processed through algorithms and presented on a computer screen.

Methods

All cells in the system were measured individually and in sequence and the data transferred to the microcontroller for further processing analysis using special algorithms (RGB colour model, interpolation function and centre of pressure) to present a real time visual feedback about the location of pressure (in RGB colour format) and the centre of pressure of the user.
The connections in the system are 15 blue digital output electrodes (X0-X14) which connected to the programmable chip to generate 0 or 5 volts. 5 red analog inputs electrodes, Y0-Y4 connected from top to bottom to the microcontroller to read data from 5 reference resistors, 22KΩ, connected in series to each output signal.

The programmable chip is programmed to operate in the following order:

1. Digital (blue) output X0 generates 5v and all other signals (X1 - X14) are deactivated through the internal programmable multiplexer or on floating mode.
2. Analogue (red) inputs Y0-Y4 read the drop voltages from 5 reference resistors.
3. Digital output X1 generates 5v and all other signals (X0, X2-X14) are deactivated through the internal programmable multiplexer.
4. Analogue inputs Y0-Y4 read the drop voltages from 5 reference resistors.

The sequence repeats overall 15 times to complete full reading cycle of the entire insole surface.

**Data processing and feedback**
All measured drop voltages data, 75 cells resolution, were processed through programming code (C language) and delivered to the visual Processing software to be displayed on the screen using RGB and interpolation functions to display pressure distribution and the centre of pressure.
To display only pressure magnitudes above a certain level a threshold level for each cell determined with a minimum drop voltages. The blue output electrodes generates voltage magnitudes of 0 or 1023 ASCII character encoding (10 bit Analog to digital converter resolution), equivalent to 0 and 5V. The red input electrodes measure the drop voltage of the references resistor which can be calculated using voltage divider (from Eqn. 7.8 and Eqn. 7.9):

\[ V_{\text{Ref}} = \frac{Vin \times R_{\text{ref}}}{R_{\text{cell}} + R_{\text{ref}}} \]  

(7.8)

Or ASCII character encoding:

\[ \text{ASCII}_{\text{Ref}} = \frac{1024 \times V_{\text{Ref}}}{Vin} \]  

(7.9)

**Time interpolation**

The nature of the system is to read the data in a series manner during a single cycle (5x15 cells) and then displays each data cell separately. To improve this presentation (for large number of cells), time interpolation function was embedded to the code. In essence, with the function, the system displays data of full cycle array (5x15) instead of displaying each reading individually. Therefore, the function was aimed to include all cells reading in the display and to give a “smoother” result.

\[ \text{Time int}[k] = \frac{\text{sensorValue}[\text{sensorNumber} - k] + \text{previousSensorValue}[k]}{\text{sensorNumber}} \]  

(7.10)

**Bilinear interpolation**

The function used aimed to be used for as spatial interpolation between the nodes of the array in order to give smoother transition from one cell to another. The values at the corners of the area is know from the sensors been represented by f(0,0), f(0,1), f(1,0) and f(1,1) and the formula used to calculate the unit square interpolation was:

\[ f(x, y) = f(0,0) \cdot (1-x) \cdot (1-y) + f(1,0) \cdot x \cdot (1-y) + f(0,1) \cdot (1-x) \cdot y + (f1,1) \cdot x \cdot y \]  

(7.11)
RGB colour model

The circular RGB colour model function (Figure 7-11) used for representation of the force distribution over the insole gives a better colour representation over linear function (Figure 7-10).

\[
pow(\sin(X), 0.7) \times 255 \tag{7.12}
\]

Increasing the exponent of 0.7 up to 1 (Eqn. 7.12), reduces the width of C and Y (Figure 7-10). When the exponent of 0.7, orange is defined as RGB 255, 200, 0 instead of 255, 128, 0 and the data x (Eqn. 7.13) from each pressure cell was correlated to \( M (0 \rightarrow 1) \) by:

\[
M = \pi \frac{x - \min}{\max - \min} \tag{7.13}
\]

And \( M \) was converted to RGB:

Heaviside version (\( H = \) Heaviside function)

Red:

\[
R = 255 \left\{ \sin \left( \left( M - \frac{\pi}{2} \right) H \left( \frac{\pi}{2} - M \right) \right) \right\}^{0.7} \tag{7.14}
\]

Green:

\[
G = 255 (\sin M)^{0.7} \tag{7.15}
\]

Blue:

\[
B = 255 \left\{ \sin \left( \left( \frac{\pi}{2} - M \right) H \left( \frac{\pi}{2} - M \right) \right) \right\}^{0.7} \tag{7.16}
\]
Figure 7-10: Circular RGB colour range

Figure 7-11: Circular RGB colour range
Centre of pressure analysis

The centre of pressure was defined using Cartesian coordinate system. The data from x and y, full cycle, averaged and the centre of pressure was calculated through the code (Eqn. 7.17 and Eqn. 7.18):

\[
COP_x = \sum_{i=1}^{n} \frac{x_i P_i}{n}
\]

(7.17)

and:

\[
COP_y = \sum_{i=1}^{n} \frac{y_i P_i}{n}
\]

(7.18)
7.6 Discussion and Conclusions

The sensor array system provides a method for converting raw pressure data to advanced pressure data and potentially converting it to auditory and visual biofeedback signals. The three prototypes developed here have proven the feasibility of using the system for different pressure mapping applications.

Prototype One – Smart Mat

The smart mat application successful presented the location and magnitude of applied pressure on a LCD screen under two scenarios: (i) a single node; and, (ii) multi node test. The LCD display provided real-time numeric/visual feedback to the user of both the pressure location and magnitude. The prototype successfully showed discrete data readings from each individual node as well as simultaneous readings from clusters of cells. It is important to note that the system was not tested for impact forces at this stage due to the limited sampling frequency rate of the micro controller.

Prototype Two - Smart Insole 1

This application successfully used the Rmat1 material to allow calculation of the polar COP with respect to the centre of the insole and wirelessly transmit a real-time audio feedback
to the user. This application received a $90,000 (AUS) patent license partnering with private industry to develop the RIZMIK Insole – which converts pressure to sound, thereby encouraging physical activity as well as musical performance.

**Prototype Three - Smart Insole 2**

This application successfully used the Rmat1 material to real-time displacement of the COP during gait using RGB visual biofeedback. This application received $1.5M (AUS) funding from the Wound Management Innovation Cooperative Research Centre (WMI-CRC), Australia for projects on smart insoles and bandages for the management of diabetic and venous ulcers. This CRC-university collaboration has a dedicated full-time team doing ongoing research for 3 years to develop this product for commercial use.

**Limitations**

A major limitation of these prototypes came from the relatively low sampling rate frequency of the microcontroller (up to about 700Hz) which is not sufficient to measure impact forces during kicking (6-16 msec). A minimum required sampling rate frequency of 2000Hz is necessary for final product development. In addition, a smaller and lighter microcontroller would also be advantageous to allow for easier portability and wearability of the final product.

**7.7 Summary**

Once we developed the sensor array system and algorithms for pressure data, we designed three prototypes to trial the methodology. We succeeded in testing the system through different types of prototypes with differing feedback signals and proved the concept’s functionality. The second prototype concept received a patent license partnering with private industry to develop the RIZMIK Insole – which converts pressure to sound, thereby encouraging physical activity as well as musical performance. After completion of the prototype development phase proving the functionality of the initial principle, we continued on to build and test the smart football footwear.
8. Smart Kicking Footwear: System Development and Validation, Pilot Test

8.1 Overview
This chapter explains the design, development and testing of the final instrument. The aim of the sensory system was to measure pressure distribution between the foot and ball and to calculate advanced parameters. The core parameters that were investigated were the impact forces magnitude and location on the system and the centre of pressure (COP) displacement during the foot to ball impact phase.

This was carried out in three main stages:

1. Design and development of the smart football footwear
2. Calibration and validation of system (forces and COP)
3. Pilot: kicking experiment

Objectives
1. To develop, calibrate and validate a low cost instrumented system for soccer footwear to be incorporated into a soccer boot.
2. To incorporate the system into a soccer boot and trial it’s durability during a full kicking motion.
3. To investigate advanced parameters: (i) force distribution and, (ii) movement of the COP during a full kicking motion.

8.2 Methods
Design and Development
The dimensions of the sensor surface area were set at 83 X 83mm and manufactured from 16 cells of the Rmat1 material (20x20 mm per cell size with 1mm space between each cell) (Figure 8-1). The orientation of the sensor coordinate systems in relation to the boot is shown in Figure 8-2c.
Figure 8-1: 16 cells of the system with their respective cell number

<table>
<thead>
<tr>
<th>x (m)</th>
<th>y (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04</td>
<td>-0.04</td>
</tr>
<tr>
<td>0.02</td>
<td>-0.02</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-0.02</td>
<td>0</td>
</tr>
<tr>
<td>-0.04</td>
<td>-0.04</td>
</tr>
</tbody>
</table>

Figure 8-2a shows 16 cells in a grid formation connected through front and rear flexible aluminium electrodes to a microcontroller. The TEENSY 3.1 microcontroller was used in the system (32 bit ARM Cortex-M4 72 MHz CPU, PJRC, Oregon, USA). In addition, a similar-sized electronic printed circuit board carrying all extra electronics components was selected and mounted on top of the microcontroller (Figure 8-2b). The basic operating electronic design principle is that the programmable chip generates a 3.3/0V electrical signal through the top electrodes and reads data through the rear electrodes. The Arduino platform (Arduino v1.0.6 IDE, Teensyduino 1.22) was used to program the microcontroller to read and generate electrical signals to and from each node (via C language).

The Cartesian coordinate system of the instrumented footwear is: x-axis pointing from the centre to the right side of the right foot, y-axis pointing from the centre of the foot to the toes and z-axis pointing vertically into the centre of the array (Figure 8-2c). Therefore, when pressure is applied onto the sensing grid, the electric resistance of the nodes declines and
data are recorded for further analysis of the pressure magnitude, location and movement of COP during impact.

![Figure 8-2: Experimental set-up](image)

**Figure 8-2: Experimental set-up:** (a) electronics and array sensor system (16 cells); (b) system electronic design; (c) Cartesian coordinate system in relation to the boot

**System Forces: Calibration**

To calibrate the system, both impact forces (from the Kistler force plate) and electrical conductivity data (generated from the system) were correlated. In order to calibrate impact forces applied to the system, four different force levels were applied (at approximately: 500, 1000, 1500, 2000N) by x10 slamming a 85mm diameter stiff ball on all possible quarters of the system (9 quarters, Figures 8-3, 8-4, 8-5, 8-6) using a MDI wooden square (40 x 40mm). Each set included 10 slams conducted within a relatively similar force level, resulting in a total of 40 peak impact data points applied onto each possible quarter of the system (N=360). Nine pressure-conductivity curves for nine quarters of the array were plotted based on the recorded forces and surface areas (40x40mm), and based on the conductivity which was calculated from the measured drop voltage and a single cell dimension (20x20x1.3mm).

The ball was slammed onto a MDI wooden square with the exact dimensions of the quarter to ensure the force distribution over only 4 cells. The data collected from 9 quarters of the system was then extrapolated back to each of the 16 individual cells by averaging the common pressure-conductivity linear functions for each cell. The individual calibration function for each cell in the system was then calculated by the specific cell’s related quarters linear functions, and then averaging the origin intercept and gradient values.
From there 16 conductivity-pressure calibration functions, for each individual cell, were extracted (Table 8-2). To calibrate the impact forces applied to the system, the peak pressure-conductivity correlation was determined using a Kistler force plate (type 9260AA6, Kistler, Winterthur, Switzerland) at 10 kHz sampling frequency to record the vertical forces. A programmable microcontroller (Teensyduino 1.22) with 2-2.5 kHz sampling frequency rate recorded the drop voltage of all 16 cells during impact tests.

Figure 8-3: All 4 possible diagonal quarters of the system

Figure 8-4: 4 cross quarters of the system
System Forces: Validation

To validate the system, measured electrical conductivity data was used in the 16 extrapolated calibration functions and results were compared to measured impact forces from the Kistler force plate. Increasing forces were applied (at approximately: 500-2000N. Actual range ) by x10 slamming a 85mm diameter stiff ball directly onto 5 quarters of the system (x4 crosses and x1 centre) and one random slam. Each set included 10 slams conducted increasing in force level, resulting in a total of 10 peak impact data points applied onto each quarter of the system (N=60). The forces were measured using a Kistler force plate (type 9260AA6, Kistler, Winterthur, Switzerland) at 10 kHz sampling frequency to record the vertical forces. A programmable microcontroller (Teensyduino 1.22) with 2-2.5kHz sampling frequency rate recorded the drop voltage of all 16 cells during impact tests. The measured and calculated peak impact forces were then compared to determine the standard deviation on average and the coefficient of determination.
Centre of Pressure: Validation

Once the system forces were calibrated and validated, the system’s COP could be calculated based on the orientation of the 16 cells and their forces magnitude using the Moment of Equilibrium. The system was then placed exactly on the centre of the force plate to match both coordinate systems. Two force magnitudes were applied (approximately: 1500 and 2000N) by x20 slamming a 85mm diameter stiff ball on all possible quarters of the system on 9 quarters d1-d4 and c1-c5. Each set included 20 slams, resulting in a total of 20 peak impact data points applied onto each quarter of the system (N=180). The COP was extracted from the Kistler force plate (type 9260AA6, Kistler, Winterthur, Switzerland) at 10 kHz sampling frequency. From the system, the COP was calculated using a programmable microcontroller (Teensyduino 1.22) with 2-2.5 kHz sampling frequency rate.

To validate the calculated location of the COP, measured electrical conductivity data was used in the 16 extrapolated calibration functions and results were compared to measured impact forces from the Kistler force plate. The measured and calculated COP were then compared to determine the system’s accuracy.

Kicking Experiment

In the final part of the experiment, the sensory system was tested inside a leather indoor-soccer boot (FILA men’s indoor soccer/ Futsal boot) to trial it’s durability during a full kicking motion. The system was sandwiched between two socks on the instep of the foot (in the foot to ball impact area) and connected via an extension USB cable to a laptop for recording data. Inner curve kicks were performed by a skilled soccer player (high-level amateur) and were analyzed and processed for 4D visualization. The kicks were carried out using a standard soccer ball (no.5) in a controlled, indoor environment (sports engineering laboratory). The kicker was instructed to approach the ball at a 450 angle with a 2 meter ‘run-up’ distance and perform a medium-force curve kick towards a foam wall (5 meters away).
Figure 8-7: Experimental set-up; (a) system inside a protective box; (b) experimental setup - placement of system on foot

4D Vector diagram calculations
Advanced parameters were calculated during a full kicking motion (force distribution and, movement of the COP). The 4D visualisation diagram displays 12 ms (foot to ball impact) of time (the 4th dimension) through a colour coded scale (rainbow scale: red to violet). As the calculated kick force corresponds to the normal force at the boot, the friction forces required for a 3D force vector diagram were estimated in the following way:

1. A force vector diagram displays the forces acting on system 2 (on the ball in kicking), applied by system 1 (soccer boot), directly on system 1 (in contrast to a standard free-body diagram where forces acting on system 2 are displayed on system 2) this convention allows displaying the force vectors outside system 1 instead of penetrating its surface and thereby becoming invisible;

2. The direction of the kinetic friction force on system 1 is the same as the direction of velocity vector of the moving COP on system 1 (i.e. if the boot (system 1) moves forward with respect to the ball (system 2), then the COP moves backward on the boot, the friction force on the boot points backwards, and the friction force on the ball points forwards [to be displayed on the boot]);

3. The kinetic friction coefficient (COF) of polymers and leather undergoes force- and velocity-weakening at high forces and velocities (Fuss, 2012);

4. The COF at zero velocity (static) and small forces was set to a) 100%, b) at peak velocities and small forces to 50%, c) at peak impact forces and small velocities to 50%, decreasing linearly with the decadic logarithm of velocity and force, and d) to
the product of the equivalent percentages at any force and velocity (e.g. 25% at peak velocity and force);

5. The average static friction coefficient at small forces between leather and a range of FIFA Soccer World Cup and UEFA Euro-Cup balls since 1960 is 0.54 (Fuss, unpublished data 2016);

6. If the direction of the COP reverses (and so does the direction of the friction force), then the COF is not necessarily static, but can very well be sub-static (COF smaller than the static COF, and even instantaneously zero when reversing the direction of the COP).

The data sets of normal force, displacement and velocity of the COP against time were fit with a 5th–order polynomial function. The 4D force vector diagram, with the time colour-coded as 4th dimension, was imported into AutoCAD with a script file and visualised directly on the boot, using the vector diagram method of Fuss and Niegl (Fuss and Nigel, 2008).

8.3 Results

Apparatus Design and Development

A feasibility prototype was successfully designed with a visual feedback mechanism to display the location and magnitude of pressure applied to a multi-node cells area, made of 16 pressure sensors.

System Forces: Calibration

The results of the pressure-conductivity individual cell calibration analysis are shown for all possible quarters of the multi-node area for each single cell (Tables 8-1, 8-2).

<table>
<thead>
<tr>
<th>Quarter</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>d1</td>
<td>$D1 = 4425154670 \times X - 280179.0398$</td>
</tr>
<tr>
<td>d2</td>
<td>$D2 = 5570491199 \times X - 79427.39423$</td>
</tr>
<tr>
<td>d3</td>
<td>$D3 = 3853571504 \times X - 63253.36981$</td>
</tr>
<tr>
<td>d4</td>
<td>$D4 = 4704045439 \times X + 110269.3488$</td>
</tr>
<tr>
<td>c1</td>
<td>$C1 = 3813590979 \times X - 70109.70234$</td>
</tr>
<tr>
<td>c2</td>
<td>$C2 = 4798425350 \times X + 55101.32517$</td>
</tr>
<tr>
<td>c3</td>
<td>$C3 = 6048817252 \times X + 6443.727581$</td>
</tr>
</tbody>
</table>
Table 8-1: All 9 possible quarters (d1-d4, c1-c5) pressure-conductivity linear calibration functions

<table>
<thead>
<tr>
<th>Cell number</th>
<th>Conductivity-pressure calibration function</th>
</tr>
</thead>
<tbody>
<tr>
<td>cell 1</td>
<td>( f_{cell\ 1} = 4425154670 \times x - 280179.0398 )</td>
</tr>
<tr>
<td>cell 2</td>
<td>( f_{cell\ 2} = 4564600054.5 \times x - 84954.8455 )</td>
</tr>
<tr>
<td>cell 3</td>
<td>( f_{cell\ 3} = 5214918893 \times x - 49074.3256 )</td>
</tr>
<tr>
<td>cell 4</td>
<td>( f_{cell\ 4} = 5570491199 \times x - 79427.39423 )</td>
</tr>
<tr>
<td>cell 5</td>
<td>( f_{cell\ 5} = 4119372824.5 \times x - 175144.3711 )</td>
</tr>
<tr>
<td>cell 6</td>
<td>( f_{cell\ 6} = 4354195584.5 \times x - 117365.2437 )</td>
</tr>
<tr>
<td>cell 7</td>
<td>( f_{cell\ 7} = 5199336285 \times x - 48038.97481 )</td>
</tr>
<tr>
<td>cell 8</td>
<td>( f_{cell\ 8} = 5809654225.5 \times x - 36491.83332 )</td>
</tr>
<tr>
<td>cell 9</td>
<td>( f_{cell\ 9} = 3833581241.5 \times x - 66681.53608 )</td>
</tr>
<tr>
<td>cell 10</td>
<td>( f_{cell\ 10} = 4196069483.75 \times x - 44678.18067 )</td>
</tr>
<tr>
<td>cell 11</td>
<td>( f_{cell\ 11} = 4967494535.75 \times x + 17840.85646 )</td>
</tr>
<tr>
<td>cell 12</td>
<td>( f_{cell\ 12} = 5376431345.5 \times x + 58356.53819 )</td>
</tr>
<tr>
<td>cell 13</td>
<td>( f_{cell\ 13} = 3853571504 \times x - 63253.36981 )</td>
</tr>
<tr>
<td>cell 14</td>
<td>( f_{cell\ 14} = 4325998427 \times x - 4076.02232 )</td>
</tr>
<tr>
<td>cell 15</td>
<td>( f_{cell\ 15} = 4751235394.5 \times x + 82685.33699 )</td>
</tr>
<tr>
<td>cell 16</td>
<td>( f_{cell\ 16} = 4704045439 \times x + 110269.3488 )</td>
</tr>
</tbody>
</table>

Table 8-2: All 16 cells calibration functions extrapolated from 9 quarters

All 9 quarters (d1-d4, c1-c5) measured force (kistler force plate) against calculated force (system) were plotted: The highest \( r^2 \) values was quarter c1 \( r^2 = 0.988 \); all quarters ranged between 0.9333 - 0.9882 (\( r^2 \) max = 0.9882, \( r^2 \) min =0.933, \( \sigma \) min = 58.536N, \( \sigma \) max = 124.558N). Figures 8-8, 8-9, 8-10, 8-11, 8-12 and 8-13 show pressure against conductivity calibration tests, for all 9 possible quarters of the array for approximately 1.5MPa.
Figure 8-8: Quarters d1 and d2 calibration results (a) d1: $r^2 = 0.972$, $\sigma = 73.831$N; (b) d2: $r^2 = 0.964$, $\sigma = 87.703$N

Figure 8-9: Quarters d3 and d4 calibration results (a) d3: $r^2 = 0.941$, $\sigma = 106.534$N; (b) d4: $r^2 = 0.98016$, $\sigma = 72.328$N
Figure 8-10: Quarters C1 and C2 calibration results
(a) C1: \( r^2 = 0.988, \sigma = 58.536 \) N
(b) C2: \( r^2 = 0.976, \sigma = 68.896 \) N

Figure 8-11: Quarters C3 and C4 calibration results
(a) C3: \( r^2 = 0.951528, \sigma = 108.855 \) N
(b) C4: \( r^2 = 0.933349, \sigma = 124.558 \) N
System Forces: Validation

Figure 8-14 shows the calculated system forces (range: 368-2146N) against the Kistler force plate data (range: 368-2146N) (FK; n = 58) with residual standard deviation $\sigma_R = 125.6$ N ($r^2 = 0.91252$). $\sigma_R$ is force dependent ($\sigma_R = 0.0437 \times FK + 70.4$), i.e. between 7.5% and 9% of FK at the range of 1-2kN.
Figure 8-14: Validation results: calculated system forces against measured Kistler force plate forces

Centre of Pressure: Validation

COP – force plate data

Figure 8-15 shows the COP locations from the force plate at peak impact forces including two readings before and after each peak force, in x and y direction for all 9 quarters of the sensor array system for tests at 1500N and 2000N. Further analysis was conducted on this data to try and find further patterns in the data (Figure 8-16). Data of all 9 quarters $r^2$Kistler data alignment with linear fit functions ranged between 0.004-0.871.
Figure 8-15: Kistler force plate: Cop bubble plot impact tests data for all 9 possible quarters (d1-d4,c1-c5) forces 1500 and 2000N
The COP data could not be validated due to incorrect calculations of the COP during impact forces of the Kistler force plate (see discussion):

COP – system data

Figure 8-17 shows the same impacts peak results for sensor system for 1500N and 2000N in different colours (black-1500N; red-2000N). Figure 8-18 shows the same results defining cluster margins and showing standard deviation.
Figure 8-17: Sensor array system COP for 1500N (black) and 2000N (red) impact tests of 9 possible quarters.

Figure 8-18: Calculated system COP – all data points, 9 quarters: Red-average; ellipse is 1 standard deviation and the thin circle defines a cluster for each quarter.
The force plate COP data was then superimposed with the sensor COP data (Figure 8-19).

**Figure 8-19:** Superimposed average COP data from kistler force plate (red) and sensor array system (green) of 9 quarters for 1500N and 2000N tests

**Kicking Experiment and 4D Visualisation Vector Diagram**

An example of results from 2 curved kicks (at approximately 1100N and 12ms), COPx against COPy data is shown below (Figure 8-20) in relation to the x and y coordinate system displayed in Figure 8-21.
Figure 8-20: Path curve of the centre of pressure (COPx against COPy; the size of the bubbles correspond to the magnitude of the force; kick 1 in red, and kick 2 in green)

Figure 8-21: The soccer boot coordinate system orientation

Figure 8-22 shows results of advanced parameters against time of one kick (COPx, COPy, COP velocity, coefficient of friction (COF), normal force (FN) and friction force (FF)).
8.4 Discussion and Conclusion

Design and Development

After completion of the prototype development phase proving the functionality of the initial principle, we continued on to build the wearable sensing system. The final dimensions of
the sensor surface area were determined by taking several considerations into account such as: (i) size, (ii) practicality, and (iii) ball impact surface area. The later was determined by slamming a standard soccer ball onto a surface and measuring the ball imprint area (chalk) at magnitudes up to 2000N. After determining the overall size of the system, the division of nodes needed to be decided. The nature of the system is such that the higher the number of cells included in the system (resolution), the lower the sampling rate frequency (due to the load of the CPU in the microcontroller) and the higher the COP location accuracy. Initially, a resolution of 4 cells (2 x 2, 40 x 40mm per cell) was tested but found to be inaccurate in determining the COP. For this reason, the final construct of the system was determined at 16 cells which provided.

In previous prototypes, the ARDUINO microcontroller was used. The two main limitations of this microcontroller were its large size and low sampling rate frequency that did not allow for measuring the fast foot to ball impact phase. In order to accomplish the smallest dimensioning and weight boundary conditions of the sensory system, and to achieve best portability conditions, a minimum size (35 x 18mm) and weight (5g) of a powerful, low cost microcontroller board was chosen (TEENSY 3.1, 32 bit ARM Cortex-M4 72MHz CPU, PJRC, Oregon, USA). Most importantly, the TEENSY has for a higher sampling rate frequency (up to 2,500Hz per 16 cells) and allowed a major shortcoming to be overcome.

During the electronic design of the sensing platform, a space of 1mm was left between each cell to prevent electric neighboring cross talk noise that can be caused from bending of the material or physical connections of the nodes. Since the nature of the sensory system was to read each cell individually, the main code was designed to give delay intervals of 50µs between each node to assure the system’s electrical stability through the full array pressure readings.

**System Forces: Calibration**

Initially, we attempted to calibrate each of the 16 nodes individually however results reflected inaccuracies due to the practical difficulty of activating a single cell with a small surface area (20 x 20mm) with high forces. For this reason, the system was divided into 9 possible quarters (40 x 40mm). The data collected from 9 quarters of the system was then extrapolated back to each of the 16 individual cells by averaging the common pressure-conductivity linear functions for each cell. The coefficients of determination ($r^2$) of all
pressure-conductivity calibration curves were higher than 0.9 ($r^2_{\text{max}} = 0.9882$, $r^2_{\text{min}} = 0.9333$) and maximum standard deviation of 124.558N showing that the system is sufficiently accurate and functioning at forces up to 2000N.

**System Forces: Validation**
The system calibration functions were derived through use of a Kistler force plate (current gold standard force sensor plate), validation was carried out using measured data of a direct impact between the ball and the system (to ensure more realistic conditions). The results showed a measured $r^2 = 0.9125$ with a gradient of 0.944 reflecting that the system is accurate and repeatable for impact tests. The residual standard deviation of 7.5- 9% of the actual force is considered unexpectedly accurate given the low costs of the material for a range of forces (368 up to 2146N). Given that the calculation of the COP is dependent on force (pressure) results, validated here, we now moved on to calibrating and validating the COP of the system during impact forces.

**Centre of Pressure Validation**
After the system forces were calibrated and validated, the system’s COP could be calculated based on the orientation of the 16 cells and their forces magnitude using the Moment of Equilibrium. The system’s COP points distinctly fall within their quarter showing no overlap between data in different quarters. These calculated numbers were then compared to the measured COP data extracted from the force plate. However, the later step proved unsuccessful as the COP data, at a short impact duration (approximately 10msec, average), could not be accurately generated by the force plate and showed a scattered spread. Figure 8.10 shows that linear fit functions were generated for all quarters with variable results ($0.004 < r^2 < 0.871$) and may show a possible pattern in the scattered results. It was not possible to validate the COP against the force plate, as the Kistler force plate could not be benchmarked against the pressure sensing platform. The reason for this is that the force plate was not able to measure the COP accurately, and about half of all COPs were located outside the cells of the sensing platform (Fig 8.9, Fig 8.13). A reason for this may be a possible sideward force when slamming the ball against the wooden block (placed on a specific quarter of the system). Although the ball was slammed directly from above, shear forces are still possible.
Even though it was not possible to validate the COP against the Kistler force plate, it can be visually confirmed in figure 8.13 that the system COP points (green) fell approximately at the centre of each quarter. From this viewpoint, the sensing platform greatly exceeded the accuracy of the force plate. Although the Kistler force plate is the current gold standard force sensor plate, our system can be considered more accurate in this case. What can be concluded from the data is that the system's calculated COP for 1500N and 2000N slamming tests always landed within the correct quarter of cells. This finding, combined with system forces validation and calibration data was sufficient for us to move to the next phase of testing the system in a full kicking motion.

**Kicking Experiment and 4D Visualisation Vector Diagram**

From the results, the pattern seen for the movement of the COP can be divided into two parts; (i) the COP moving backwards towards the ankle, as the ball slides and rolls simultaneously in the same direction, and force gradually increases until reaching peak force (approximately 1100N), and (ii) the COP moving away from the ankle towards the toe, as the ball continues rolling as in the first phase while sliding in the opposite direction gradually decreasing in force. The later phase was unexpected because as the ball rolls towards the ankle, the COP moves away from the ankle.

This may be explained by the following four phases observed here for the first time and revealing new information on the dynamics and kinematic parameters of a curved kick:

(i) **Phase 1: Dynamic phase of the COP** where the foot scoops the ball from the ground and the ball is rolling and sliding in the same direction, at the same time towards the ankle to generate spin. Figure 8-24a shows different COP points during the sliding and rolling of the ball. The overall net COP direction points to the ankle and occurs for approximately the first 5.5ms of impact (Figure 8-22). The forces vector diagram is shown in Figure 8-24b and the resultant force vector applied by the boot to the ball is seen in Figure 8-24c.
Figure 8-24: Phase 1 of the foot to ball contact (a) COP points - AS/BS/CS=COP Shoe (at three points A, B, C on the shoe) AB/BB =COP ball (at two points A, B on the shoe), NET - net direction of the COP; (b) Forces and velocity vector diagram V_s-net velocity from t

(ii) Phase 2: Rolling phase of the COP: ball still rolling backward on shoe, but the backward sliding of phase 1 reverses to forward sliding, such that the sliding motion is instantaneously zero and so is the friction force (Figures 8-25a, 8-25b, 8-25c).
(iii) Phase 3: Static phase of the COP when the net COP movement is zero. The ball continues rolling towards the ankle (Figure 8-26a). This is the point between changing the direction of the net COP movement direction where the force reaches its maximum. The forces vector diagram is shown in Figure 8-26b and the resultant force vector applied by the boot to the ball is seen in Figure 8-26c.
(iv) Phase 4: Second dynamic phase of the COP, as the limb moves towards maximum extension, the ball simultaneously slides in one direction (away from the ankle) while spinning in the opposite direction (towards the ankle, as in the previous two phases) (Figures 8-27a). This phase occurs from approximately time 5.5 to 12ms of impact. The forces vector diagram is shown in Figure 8-27b and the resultant force vector applied by the boot to the ball is seen in Figure 8-27c.
Results shown in the 4D vector diagram (Figure 8-23) were extracted from the resultant force (Fr) vectors between the shoe and the ball (Figures 8-24c, 8-25c, 8-26c and 8-27c).

Figure 8-22 shows that the COP is located on the inner side of the instep contact area. The movement pattern and the location of the COP (COPx and COPy) exhibited a similar curve for both kicks, starting with moving backward first, and reversing its direction at the peak forces of about 1100N during the 12ms impact phase. Interestingly, the results also show that the COP moves in y-direction within only a very small range of 10mm in each direction.

Subsequently, additional foot to ball advanced parameters (Figure 8-22) were calculated and used to generate the colour coded vector diagram (Figure 8-23). The 4D force vector diagram illustrates multiple results in a single, visual illustration. The forces vectors displayed in the 4D image are pointing out of the boot and not into the boot. This was essential for better visualisation of the forces vectors diagram between the boot to the ball. This data reveals new information about foot to ball dynamics measured in this study for
the first time as there are no other literature sources available on these parameters, to the
best of the author’s knowledge.

A curved kick technique was chosen to trial the system because it was expected to be more
complicated in terms of mapping COP displacement and therefore provide more evident
results. During a curve kick, in order to generate spin of the ball, the ball is scooped by the
foot towards the ankle and then expelled into the air.

It is important to note some of the limitations of this study that could be improved in
related future research. Although the sampling rate frequency of the system was sufficient
for observing the movement of the COP, it could be improved in future studies to give
smoother more refine data.

Given that the nature of the experiment requires system durability at high forces, the
system hardware could benefit from higher rigidity of the electronic components. Although
the investigators acknowledge that more kicks, by different participants at different skill
levels are needed, the kicks analysed showed a clear repeatability of some parameters
which may indicate a high level of the skill of the subject.

In conclusion, the system was successfully incorporated into a soccer boot and remained
functional through all phases of a full kicking motion. The results assist to illustrate the
movement of the COP during the short impact phase between the foot and the ball.
8.5 Summary

In summary, a low cost instrumented system for soccer footwear was successfully incorporated into a soccer boot, calibrated, validated and tested during a full kicking motion. The magnitude of the kick force and the movement of the COP during the impact phase between the soccer ball and the foot were determined. This system was calibrated by a Kistler force plate and then validated for a range of forces. The COP was tested for curve kicks and the COP data were displayed on a 4D colour-coded vector diagram model of a soccer boot. The COP data was constructed from four phases of the foot to ball impact. This data reveals new information about foot to ball dynamic parameters during a curved kick measured in this study for the first time and have not been previously described in the literature.

The system is portable, low cost and with a sufficient sampling rate frequency for initial measuring of foot to ball impact forces. The sensor has high resolution, is thin/flexible, wearable and light weight. Further experiments to study different types of kicks and accuracy are needed in the future to establish better understanding of the foot to ball impact phase using this fairly inexpensive approach and subsequently to improve the kicking skill in different level soccer athletes. The COP data recorded here by the boot can potentially be used to assemble athlete specific signature-COP values that can be amalgamated to form a “COP library”. The same can also be done with kick force data.
9. References


LAWSON; B G., 1978, Kicking shoe, US patent 4123856 A.


