EXPERIMENTAL STUDY OF AERODYNAMIC BEHAVIOUR OF STRETCHABLE SPORT FABRICS

A thesis submitted in accordance with the regulations for the degree of Doctor of Philosophy

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DECLARATION OF ORIGINALITY

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.

Hazim Abdulaziz Moria

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<th>Description</th>
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<tbody>
<tr>
<td>$Re$</td>
<td>Reynolds Number</td>
</tr>
<tr>
<td>$V$</td>
<td>Air Velocity, (m/s)</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Dynamic Viscosity, (N.s/m²)</td>
</tr>
<tr>
<td>$v$</td>
<td>Kinematic Viscosity, (m²/s)</td>
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<tr>
<td>$\rho$</td>
<td>Air Density, (kg/m³)</td>
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<tr>
<td>$q$</td>
<td>Dynamic Pressure, (Pa)</td>
</tr>
<tr>
<td>$F_D$</td>
<td>Drag Force, (N)</td>
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<tr>
<td>$C_D$</td>
<td>Drag Force Coefficient</td>
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<tr>
<td>$F_L$</td>
<td>Lift Force, (N)</td>
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<tr>
<td>$C_L$</td>
<td>Lift Force Coefficient</td>
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<tr>
<td>$L/D$</td>
<td>Glide Ratio or Lift/Drag</td>
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<tr>
<td>$F_s$</td>
<td>Side Force, (N)</td>
</tr>
<tr>
<td>$C_s$</td>
<td>Side Force Coefficient</td>
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<tr>
<td>$A$</td>
<td>Projected Frontal Area, (m²)</td>
</tr>
<tr>
<td>$d$</td>
<td>Diameter of Cylinder, (m)</td>
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<td>$l$</td>
<td>Characteristic Length or Length of Cylinder, (m)</td>
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<tr>
<td>$l/d$</td>
<td>Length/Diameter or Aspect Ratio</td>
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<tr>
<td>$\varepsilon$</td>
<td>Relative Roughness</td>
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<tr>
<td>$Ra$</td>
<td>Average Height, (μm)</td>
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<tr>
<td>$k$</td>
<td>Sand Paper Grain Size</td>
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<td>$\alpha$</td>
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<td>$\psi$</td>
<td>Yaw Angle (Degree)</td>
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<tr>
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<tr>
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<tr>
<td>$f$</td>
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<tr>
<td>$t$</td>
<td>Time, (s)</td>
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# LIST OF ABBREVIATIONS AND ACRONYMS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>NPL</td>
<td>National Physical Laboratory</td>
</tr>
<tr>
<td>RMIT</td>
<td>Royal Melbourne Institute of Technology</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>IWT</td>
<td>Industrial Wind Tunnel</td>
</tr>
<tr>
<td>FSM</td>
<td>Full Scale Model</td>
</tr>
<tr>
<td>FM</td>
<td>Fiberglass Model</td>
</tr>
<tr>
<td>MH</td>
<td>Flexible Mannequin of Plastic Construction</td>
</tr>
<tr>
<td>UCI</td>
<td>Union Cycliste Internationale or International Cycling Union</td>
</tr>
<tr>
<td>FIS</td>
<td>Fédération Internationale de Ski or International Ski Federation</td>
</tr>
<tr>
<td>FINA</td>
<td>Fédération Internationale</td>
</tr>
<tr>
<td>UP</td>
<td>upright position</td>
</tr>
<tr>
<td>DP</td>
<td>dropped position</td>
</tr>
<tr>
<td>TTP</td>
<td>time-trial position</td>
</tr>
<tr>
<td>SLR</td>
<td>Single Lens Reflex</td>
</tr>
<tr>
<td>TIFF</td>
<td>Tagged Image File Format</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>SHV</td>
<td>Surface Height Variation</td>
</tr>
<tr>
<td>JPEG</td>
<td>Joint Photographic Experts Group</td>
</tr>
<tr>
<td>BMP</td>
<td>Bit Map Picture</td>
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ABSTRACT

In speed sports, aerodynamics can play a critical role in athletes’ performance. With margins being very small, an athlete’s garment can be the difference between winning and losing. In recent years there has been great interest in the effects of different garments and their aerodynamic characteristics. It is widely believed that the reduction of aerodynamic drag can enhance athlete’s performance. There has been little understanding in the aerodynamic properties and behaviours of athlete’s garment as limited research is reported in the open literature. Without a thorough understanding, it is difficult to develop sports garments that are scientifically proven to be aerodynamically superior.

The primary objective of this research is to understand the aerodynamic characteristics and gain a greater insight in order to establish relations between sports garments’ physical parameters and aerodynamic properties. With a view to achieve this objective, a series of stretchable knitted and woven fabrics used in speed sports garments (e.g., sprint, cycling, speed skating, downhill skiing, ski jumping and swimming) have been studied for a wide range of Reynolds numbers (Re) and angles of attack (α). The aerodynamic investigations were conducted in the wind tunnel environment. The physical surface characteristics of fabrics were determined using optical and electron scanning microscopic techniques. The quantification of the surface profile was undertaken by using an automatic surface tester (Kawabata). The stretchability was measured by using an Instron tensile test machine. For aerodynamic study of sports fabrics, an advanced cylindrical methodology has also been developed. The aerodynamic properties (drag and lift) and fabrics surface characteristic (surface roughness, distance and gap area between yarns) were determined and correlated.

In this study, the drag polar (\(C_L/C_D\) ratio) for 3D circular cylinder with smooth and rough surfaces (varied by knitted and woven fabrics) has been established for a range of Reynolds numbers (\(Re = 5.06 \times 10^4\) to \(2.30 \times 10^5\)) and angles of attack (\(\alpha = 0^\circ\) to \(90^\circ\)). The drag polar allows determining the aerodynamic efficiency of sports fabrics (i.e., garments) and their optimal design. The aerodynamic behaviour of knitted fabrics is found to be quite different to that of woven fabrics. With an increase of stretch (within the elastic zone), the surface morphology of knitted fabrics becomes courser and thereby triggers an early airflow transition (laminar to turbulent flow). In contrast, the stretch on woven fabrics makes the surface morphology smoother which delays the flow transition.
The minimum drag coefficient \( C_{D\text{min}} \) of stretchable knitted fabrics is directly proportional to relative roughness whereas the critical Reynolds numbers is inversely proportional to the relative roughness \( (\varepsilon = 1.39 \times 10^{-4} \text{ to } 7.73 \times 10^{-4}) \) within Reynolds numbers investigated \( (Re_{\text{crit}} = 1.83 \times 10^5 \text{ to } 1.00 \times 10^5) \). On the other hand, the minimum drag coefficient \( C_{D\text{min}} \) of stretchable woven fabrics is proportional to the relative roughness, however the relationship of critical Reynolds number \( (Re_{\text{crit}} = 1.17 \times 10^5 \text{ to } 2.34 \times 10^5) \) with the relative roughness \( (\varepsilon = 3.689 \times 10^{-4} \text{ to } 1.319 \times 10^{-4}) \) is non-linear.

Knitted fabrics with lower relative roughness, distance and gap area between yarns generate greater aerodynamic efficiency \( (C_l/C_D) \) at high Reynolds numbers. Similarly with the higher relative roughness, distance and gap area between yarns, the knitted fabrics offers an aerodynamic benefit at low Reynolds numbers. A notable reduction of aerodynamic benefit in woven fabrics was found under unstretched condition. However with increased stretches, the aerodynamic advantage \( (C_l/C_D) \) increases almost linearly. The stretched woven fabrics are found to be aerodynamically beneficial at high Reynolds numbers whereas the stretched knitted fabrics are at low Reynolds numbers.

The practical implication of these research findings is multi-fold. The drag polar of smooth and rough cylindrical surfaces can be applied not only for the development of engineered sports garments but also for the optimal athlete’s body orientation. Additionally, the findings can be utilised in developments of various projectile shapes for military and sports applications.

This study did not take into account the effect of turbulence and boundary layer interaction on stretchable fabrics. It would be useful to undertake such study. Also, in an open environment, an athlete can experience wind from any direction with varied gustiness that can affect the aerodynamic performance of sports garments. It would be useful to undertake further study of crosswind effect as well.
CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW
1.1 Motivation and Introduction

Aerodynamic behaviour of stretchable sports fabrics can play a significant role in a wide range of speed sports including cycling, downhill-skiing, speed-skating, ski-jumping, sprinting and swimming. The winning time margins are progressively being reduced with the integration of advanced technologies as well as vigorous training regimes. The winning margin can be further decreased by understanding aerodynamic behaviour especially the drag and lift properties of an athlete’s physical body positions and their outfits (Barelle, Ruby, & Tavernier, 2004; Grappe, Candau, Belli, & Rouillon, 1997; Laing & Sleivert, 2002; Lukes, Chin, & Haake, 2005). Elaborate understanding of the aerodynamic behaviour of physiological parameters (such as athlete body position and geometric shape of body parts) as well as fabric parameters (surface roughness, course/wale orientation in knitted fabric, and weft/warp orientation in woven fabric) in high speed sports can lead to higher efficiency and achievement.

Strangwood and Subic (2007) pointed out that the appropriateness of materials for sports applications indicating that they should meet a range of performance parameters depending on the specific requirements imposed by any one application. Technological innovation in both design and materials has played a significant role in sports achieving its current standing in both absolute performance and its aesthetics. Sports garments can affect athletic performance by influencing the aerodynamics of the moving athlete interacting with external air flow. Laing and Sleivert (2002) suggested that drag can be reduced by up to 10% through the appropriate use of garments in sports. Hence, the relationships between stretchable speed sport fabrics and the athletic performance accomplished are a complex and intimate mix where the engineering science can make a significant quantitative contribution.

A number of factors have been identified by previous studies (Barelle et al., 2004; Grappe et al., 1997; Laing & Sleivert, 2002; Lukes et al., 2005) that may contribute to the aerodynamic efficiency of athletes in higher speed sports. These factors are:

- Athlete’s body.
- Sports garments.
- Sport equipment.
As sports garments have direct impact on athletic performance in higher speed sports, it is necessary to identify the important factors that may influence the aerodynamic properties of sports garments. There are several factors that can affect these aerodynamic characteristics of sports garments (Chowdhury, 2012). These factors are:

- **Speed**: The speed has significant influences on the overall aerodynamic efficiency based on body configuration, sports garments and the geometric shapes of sports equipment. The range of variable speeds can have notable effect on the aerodynamic properties of sport garments as the airflow regime can notably change from laminar to turbulent flow. For example, the average air speeds for sprint, cycling, speed-skating, downhill skiing and swimming are 32, 42, 50, 100 and 107 km/h (i.e., 2 m/s in water).

- **Body posture**: Different body parts experience incoming air during sporting events which generate either pure aerodynamic drag or both drag and lift simultaneously. The projected frontal area represents a significant factor in aerodynamic drag generation. During flight phase, the minimisation of drag and maximisation of lift is highly dependent on the body position. Hence, aerodynamic drag reduction is largely based on the position of different body parts.

- **Fabric properties**: The parameters affecting the aerodynamic properties (drag and lift) and flow transitions from laminar to turbulent of fabrics are the surface roughness, seam position, fibre orientation, porosity and the air permeability.

- **Garment construction**: Sports garments are made of multiple panels of fabric joined together by using seams or fasteners. The prominence of the seam (position and size) may have effect on drag and lift since it can change air flow regime locally.

### 1.2 Literature Review

The following subheadings discuss in detail the review of the relevant background literature. The human body parts representation, aspect ratio of length and diameter cylindrical shapes, surface roughness, stretchable fabric, seam position and wale orientation will be discussed here.
1.2.1 Human Body

The configuration of the human body shape is complex and considered to be a bluff body due to the complex physiological shapes and dimension. Many researchers including Hanavan (1964); Weinbach (1938) and Jensen (1978); Hatze (1980); Yeadon (1990) have studied the human body’s anthropometric behaviour and subdivided the human body into multiple cylindrical, conical and other shapes in order to represent the body with minimum anthropometric dimensions (Figure 1.1). Hanavan (1964) suggested a simplified human model with 15 main cylindrical and elliptical segments with a uniform density. The trunk was modelled as an elliptical cylinder; the upper arm, forearm, thigh, shank and feet as frustums of circular cones and the head as a sphere. Weinbach (1938) and Jensen (1978) used stereo photogrammetry to estimate the shape of the body segments. The body is sectioned into elliptical disks of a small width. Hatze (1980) developed a comprehensive model of the human body incorporating 242 anthropometric measurements whereas Yeadon (1990) divided the human body into 40 main body segments involving circular cross section which represented the head, arm and legs. However, this large number of body segments creates complexity in aerodynamics. This segmented simplified human body is well studied in biomechanics as well.

Several researchers Hoerner (1965); Morkovin (1964); (Pugh, 1974); Shanebrook and Jaszczak (1974); Gerrard (1978); Nedina, Sukharev, and Flippov (1983); Coutanceau and Defaye (1991); Williamson (1996) have experimentally measured the aerodynamic characteristics of the human body considering the human body as a circular cylinder or sphere. Shanebrook and Jaszczak (1974) presented a model to determine the aerodynamic forces of the human body for various sports includes running, skating, downhill skiing, ski jumping and long jump. They considered the human body as a multi-jointed mechanical system composed of various segments and showed that the drag assessment applied on an athlete could be realized by considering the athlete's body as a set of cylinders. Their model is thus composed of eight circular cylinders to simulate the lower and upper limbs and the trunk, in addition to a sphere to simulate the head. It is noted that one arm and one leg on opposite sides of the trunk are bent respectively forward and backward whereas the other appendages are extended. This assumption for the running position was determined by analysing photographs taken by Jaszczak as shown in Figure 1.2. However, this study considered only the aerodynamic drag measurement.
Figure 1.1: Geometric model of the human body: (a) Hanavan (1964); (b) Weinbach (1938) and Jensen (1978); (c) Hatze (1980); (d) Yeadon (1990)
Brownlie (1992) have developed four different models to measure the aerodynamic effect on elite athletic performance using a wind tunnel as shown in Figure 1.3. A full scale of human analogues model (FSM) with eleven separate components was made of uniform Aluminium circular cylinders. The height and frontal area of the model were 138.7 cm and 3973.5 cm$^2$ respectively. The segment dimensions were proportionally modelled to match a mature U.S. female. An upright child mannequin of fibreglass construction (FM) was made for running and Nordic ski apparel testing. The mannequin was 138 cm in height and had a frontal area of 3178.9 cm$^2$. The flexible mannequin (MH) ski model and cycle model were made of plastic. Both mannequins used for downhill skiing and cycling simulations (Figure 1.3 c and d).
Figure 1.3: Four different models: (a) full scale model of simplified human body (FSM); (b) upright child fibreglass mannequin (FM); (c) flexible mannequin (MH) of ski model; (d) flexible mannequin (MH) of cycle model (Brownlie, 1992)
An alternative method to experimental study of textile aerodynamics/hydrodynamics can be the Computational Fluid Dynamics (CFD). The CFD study has recently been used in ski jumping (Meile et al. (2006)), cycling (Defraeye et al. (2010); Hanna (2002); Lukes et al. (2004)), swimming (Bixler et al. (2007); Bixler and Riewald (2002); Bixler and Schloder (1996); Gardano and Dabnichki (2006); Lecrivain et al. (2008); Minetti et al. (2009); Rouboa et al. (2006); Zaidi et al. (2008); Zaidi et al. (2010)), soccer (Barber et al. (2009)), bobsleighing (Dabnichki and Avital (2006)). All these studies considered the flow around bluff bodies which mostly represents human’s parts (streamlined shape without sharp edges). Melile et al. (2006) combined the experiment and CFD methods to investigate the aerodynamic behaviour of a full scale model ski jumper. The study focused on the effect of different postures on aerodynamic forces under a wide range of angles of attack. However, the comparison of CFD with experiment results revealed a weak agreement nonetheless a clear outline of simulation potentials and limits. Zaidi et al. (2008) used CFD to evaluate the effect of three different swimmer’s head positions on hydrodynamic performance in swimming. A 2D model was developed to simulate three different head positions: (i) head aligned with the body, (ii) a lower head position, and (iii) a higher head position. The model was fully submerged without angle of attack with different fluid velocities. The results indicated that the higher head position presented larger drag than the lower head position for three different flow velocities. However, no experimental validation of their simulated findings was reported. Marinho et al. (2009) analysed the effect of swimmer’s body positions on hydrodynamic drag during gliding in swimming through CFD methodology. A 3D model representing a male adult swimmer in two gliding positions: (i) a ventral position with the arms extended at the front and (ii) a ventral position with the arms placed alongside the trunk. The simulations were conducted with a model located at a water depth of 0.90 m with different flow velocities. The findings showed that the position with the arms extended at the front produced lower drag than the position with the arms aside the trunk. Bixler et al. (2007) made some contributions to CFD validation in swimming research at different body postures during gliding. The authors compared the drag of a real swimmer, a 3D model of swimmer and a real mannequin based on the digital model. The finding revealed that the drag determined from the digital model using CFD method was to be within 4% of the values measured experimentally for the mannequin, although the mannequin drag was found to be 18% smaller than the real swimmer drag. Defraeye et al. (2010) evaluated the aerodynamics performance on a cyclist using CFD method. A wind tunnel experiment on a scale model of a cyclist (scale1:2) was used to validate the CFD modelling. The computational modelling was
performed using different turbulence schemes such as steady Reynolds Averaged Navier Stokes (RANS), with several $k$-$\varepsilon$ and $k$-$\omega$ turbulence models and unsteady large eddy simulation (LES) and also boundary layer modelling techniques (e.g., wall functions and low Reynolds number modelling (LRNM)). The results revealed that RANS ($k$-$\omega$) obtained the best overall performance followed by more computationally expensive LES. Also, LRNM was clearly preferred over the wall functions to model the boundary layer. Hence, this study was restricted with the upright position and no fabric measurements applied. Blocken et al. (2013) recently analysed the aerodynamic drag of two drafting cyclists in upright position (UP), dropped position (DP) and time-trial position (TTP) using CFD simulations with wind tunnel data. The simulations were made for single cyclist and two drafting cyclists with different bicycle separation distances. The results indicated that the drag reduction of the trailing cyclist is 27.1%, 23.1% and 13.8% for UP, DP and TTP respectively while the drag reduction of the leading cyclist is 0.8%, 1.7% and 2.6% for UP, DP and TTP respectively. Also, the drag reductions decrease with the increasing separation distance. However, this study did not consider the aerodynamic effect of fabrics. The review of CFD studies applied in sports aerodynamics especially in textiles is extremely limited. Additionally, none of these studies are related to textile aerodynamics/hydrodynamics as with current computational power, it difficult to predict accurately the aerodynamic behaviour of surface morphology of textiles. However, this computational tool may provide some insights in textile aerodynamics in the future as the computational power is progressively being increased.

Chowdhury et al. (2008) developed four different standard cylindrical arrangements to provide precise data on aerodynamic drag. This study was carried out experimentally in the wind tunnel at vertical orientation ($\alpha = 90^\circ$) to evaluate the end effect of 3D flow around the active cylinder (see Figure 1.4). The finding showed that at low speed, $C_D$ is highest for the standard configuration without the top section (A) than any other configurations. Also, both the top and bottom sections must be utilized to achieve this uniformity of flow about the active section. Thus, the non-active parts with a 5 mm gap can reduce the 3D flow effect around the cylinder. However, the study did not tackle the aerodynamic properties such as lift at different angles of attack.
Oggiano, Troynikov, Konopov, Subic, and Alam (2009) used both cylinder and leg models to evaluate several fabric samples in the wind tunnel. Figure 1.5 shows a schematic design of the cylinder arrangement and a typical leg model used in this study. Two dummy cylinders, the foot and the knee were used to reduce the 3D flow effect. Here, this study showed the similarity in aerodynamic behaviour between the cylinder model and the leg model. However, this study considered only the aerodynamic drag measurement of both models at vertical orientation ($\alpha = 90^\circ$).

![Figure 1.4: End configurations for the vertical cylindrical methodology (Chowdhury, 2008)](image)

![Figure 1.5: Design and experimental arrangement: (a) plastic cylinder model; (b) a mannequin leg model testing in RMIT Industrial Wind Tunnel (Oggiano et al., 2009)](image)
Underwood and Jermy (2011) have tested three different diameters of cylinder with rounded head at the leading edge. The tests were conducted in the wind tunnel at horizontal and vertical orientations ($\alpha = 0^\circ$ and $90^\circ$) in order to represent the forearm, upper arm and thigh of the cyclist respectively (see Figure 1.6). The finding revealed that there is a significant difference in the drag coefficient for both orientations. They did not take into the account the 3D effect of the different lengths of the rounded heads and angles of attack ($\alpha$).

Figure 1.6: Experimental cylinder with rounded head at the leading edge: (a) horizontal orientation; (b) vertical orientation in the wind tunnel (Underwood and Jermy, 2011)

Kyle (1988); Di Prampero, Cortili, Mognoni, and Saibene (1979) demonstrated that somebody positions are more aerodynamically efficient than others. Here, Chowdhury et al. (2009) developed a simplified human body which has inclined multiple cylindrical segments (angles of attack) as illustrated in Figure 1.7. The cylindrical arrangement allowed for testing at variable angles of attack from $\alpha = 30^\circ$ to $150^\circ$. However, the authors did not evaluate the top effect of the cylinder on the aerodynamic characterisation. Additionally, the part of the rig seems to interfere significantly with flow affecting the aerodynamic properties. Also, the inclined model did evaluate the aerodynamic properties below $\alpha = 30^\circ$. 
From these prior studies, it is clear that in spite of the complex structure of the human body, human body parts may be represented as multiple cylinders for aerodynamic evaluation in wind tunnel experimentation. The number of the cylinders representing the body parts may then be simplified according to the dominant characteristics of the body posture in different sports. The aerodynamic properties of these cylindrical body parts can be evaluated in wind tunnel testing under a range of angles of attack while representing real life body positions in sporting action. Thus, in order to simplify the complex aerodynamic interactions of various body parts, a simplified cylindrical arrangement with different ellipsoidal heads and without heads was developed to evaluate the 3D effect on aerodynamic properties at varied angles of attack. Further information about the cylindrical arrangements is addressed in Chapter 3.

1.2.2 Aspect Ratio of Length and Diameter Cylinders

Depending on the $l/d$ ratio, the flow around the cylinder can be considered 3D or 2D. Hoerner (1965) evaluated the cylindrical bodies in axial flow with a blunt shape and rounded (streamlined head) forms as a function of the fitness ratio ($l/d$). The results as shown in Figure 1.8 revealed that with the blunt shape the drag reduces appreciably upon reaching a certain minimum length ratio $l/d = 1$ then became constant with the increment of length $C_D = 0.81$. The rounded nose reduces the drag to low values (0.195) at $l/d = 2.5$, then a gradual
increase in drag occurred with increasing length. The study also showed that the blunt shape generated four times the drag compared to the rounded shape. However, this study was only considering cylinders in axial orientation (horizontal axis).

！Drag Coefficient of Cylindrical Bodies in Axial Flow

*Figure 1.8: Drag coefficient ($C_D$) of blunt nose (upper part) and rounded nose (lower part) cylinders versus fineness ratio ($l/d$) (Hoerner, 1965)*

Chowdhury (2012) studied two types of aspect ratio of different length and diameter cylinders. The first study developed ten different length cylinders ($l = 30, 50, 80, 100, 200, 300, 400, 600, 800$ and $1000$ mm) with same diameter ($d = 110$ mm). The second study developed seven different diameter cylinders ($d = 90, 110, 120, 130, 140, 150$ and $160$ mm) with same length ($l = 300$ mm). The tests were conducted experimentally in the wind tunnel at vertical orientation ($\alpha = 90^\circ$) over a range of wind speeds. The results as shown in Figure 1.9 illustrated that as the length of the cylinder increases, the $C_D$ value increases. Furthermore, the $C_D$ value reduces with the increment in cylinder diameter with $Re$ beyond a transition point at $Re = 2.6 \times 10^5$. The results obtained for the different lengths agreed well with the Bearman and Harvey (1993); White (2003) and also agreed well with Granger (1985) for the different diameters. However, these studies were only evaluated the aerodynamic drag at vertical orientation.
1.2.3 Surface Roughness

Body parts covered with fabrics can potentially influence the aerodynamic behaviour by altering the air flow characteristics. The air flow characteristics can also be influenced by varying angles of attack. The surface roughness of sports fabrics can potentially exhibit significant influences on aerodynamic properties (lift and drag) and transitional flow from laminar to turbulent due to the transitional properties at the boundary layer. The sport fabrics illustrate a varied range of surface morphologies and wide boundary layer behaviours. A relationship between the surface profile and fabric construction parameters was described by (Dias & Delkumburewatte, 2008). Wieselsberger (1922) indicated that the drag coefficient ($C_D$) of a cylinder was dependent on Reynolds number, and that a drop in drag coefficient at high Reynolds numbers ($Re$) called ‘drag crisis’ was related to the transition to turbulence in the boundary layer around the separation point. Typical influencing parameters for the flow around a cylinder are free steam turbulence, aspect ratio, space boundaries, oscillations and surface roughness (Zdravkovich, 1990, 1997, 2003a, 2003b).

Fage and Warsap (1929) carried out experiments to determine how the drag over a cylinder was influenced by the surface roughness. The roughness was simulated by wrapping the two cylinders in John Oakey’s glass paper (sand paper) of five grades. They reported that as the relative roughness ($\varepsilon$) increases, the fall in minimum drag coefficient ($C_{D_{min}}$) occurs at lower values of critical Reynolds number ($Re_{Crit}$). However, the work of Fage and Warsap (1929)
was corrected for blockage effects by a number of researchers (Achenbach, 1968, 1971, 1972, 1974a, 1977; Güven, Farell, & Patel, 1976; Miller, Salter, & Maybrey, 1975; Szechenyi, 1975) as presented in Figure 1.10. Their studies have agreed well with the work presented by (Fage & Warsap, 1929). Hence, the results revealed that the cylinders with different types of roughness have a strong dependence of drag on the roughness.

Figure 1.10: Compilation of drag coefficients as affected by surface roughness (Guven et al., 1980)

Hoerner (1965); Achenbach (1968); Szechenyi (1975); Kyle and Caiozzo (1986); Spring, Savolainen, Erkkila, Hamalainen, and Pihkala (1988) revealed that with an appropriate surface roughness or placement of boundary layer trip wire, Reynolds number at which flow transition occurs may be reduced to as low as Re = 4 × 10^4. Achenbach (1968) focused on the effect of surface structure on the flow transition from laminar to turbulent and the effect of such transition on the total drag of a circular cylinder. Achenbach noted that the viscous drag to be only about 3% of the total drag for a cylinder under these conditions. Szechenyi (1975) pointed out that the surface characteristics, fluid density, cross flow diameter and air velocity will influence boundary layer flow around a bluff body. Moreover, Güven et al. (1976) did boundary layer measurements on rough cylinders showing the boundary layer growth.
The flow transition around an athlete body from laminar to turbulent flow and the consequent drag reduction was predicted by Pugh (1974). These findings were carried out on spheres and cylinders. The surface roughness of cylinders can shift the transitional flow at lower Reynolds numbers ($Re$) significantly and the higher the roughness of the surface, the lower the value of the critical speed. Since surface roughness generally promotes laminar boundary layer transition to turbulence boundary. The role of the fabric roughness is to reduce the pressure drag thereby possibly promoting aerodynamic efficiency. Simultaneously, the surface roughness in excess of the aerodynamically smooth limit increases viscous drag. The net effect of a particular fabric therefore depends on the relative balance between increased viscous drag and reduced pressure drag.

The surface of fabrics is not absolutely smooth and flat. The geometrical roughness within certain extents is significant. The effects of surface roughness in general are well described (Barelle et al., 2004; Grappe et al., 1997; Laing & Sleivert, 2002; Lukes et al., 2005). The characteristics of the roughness itself also play an important role, influencing how effective the roughness is in working as a turbulence trigger and how it affects the growth of the boundary layer. For fabrics, the surface characteristics are dependent on:

- Yarn size and fibre diameter.
- Tightness and cover factor.
- Porosity.
- Air permeability.
- Fabric construction technique.

The importance of the aerodynamic attributes of the fabric materials used in the garment manufacturing has been highlighted in numerous studies (Brownlie, 1992; Chowdhury, 2012; Kyle, Brownlie, Harber, MacDonald, & Shorten, 2004; Moria et al., 2010; Oggiano, Sætran, Løset, & Winther, 2007; Oggiano & Sætran, 2009). Széchenyi (1975) & Güven et al. (1976) found that a particle Reynolds number ($Re$) encompassed those surfaces which had sufficient roughness to induce transcritical flow. In numerous athletic situations, the $C_{D_{\text{min}}}$ is of greater importance than the transcritical drag. A comparison of the current results with those of Fage and Warsap (1930); Széchenyi (1975); Güven et al. (1976) is impossible because the surface roughness variables described in the work of these investigations were either inferred or indirectly measured through mass flow experiments in pipe and pressure drop experiments in
ducts. The sand grain size has not published equivalent as a standard surface roughness parameter so that any attempt to predict the effect of three dimensional, discrete roughness elements on the basis of sand grain size is impossible.

Van Ingen Schenau (1982) showed that a rough woollen suit actually had less drag than a smooth speed skating skin suit at low speeds (<6.5 m/s) and explained this by an earlier development of a turbulent boundary layer due to the surface roughness. However, speed skating skin suits stayed uniformly smooth for many years. Brownlie, Kyle, Harber, MacDonald, and Shorten (2004) carried out experimental wind tunnel studies on the effect of aerodynamic drag of athletic clothing materials, hair, and shoes used in sprint and distance running. Their investigations were aimed at finding the aerodynamic contribution of the clothing where speeds were less than 10 m/s. The study indicated a possibility to lower the aerodynamic drag of a runner by improving garments or by trimming or covering the hair. They also reported the concept that a small reduction of aerodynamic drag can result in measurably improved performance. The study was established on a human mannequin at four wind speeds (4.7, 7.1, 8.8 and 9.7 m/s). The authors also revealed that tight fitting garments obtained a drag reduction at running speeds. However, the study did not reveal detailed correlation between the surface parameters such as roughness, fibre orientation and seam position with such aerodynamic properties.

Van Ingen Schenau (1982) further noted that a wool cross country ski suit had less drag at a speed below 7 m/s than smooth Lycra but more drag than Lycra at a speeds higher than 7 m/s. Brownlie, Mekjavic, Gartshore, Mutch, and Banister (1987) found that a polyurethane laminated Lycra skin suit would reduce the drag on a sprinter by 7.4% below the nude value and 12.8% below the drag of a Lycra skin suit. Kyle (1988) found that a rubber coated cycling suit and a Lycra suit reduced the drag on a cyclist by 8.4% and 7.5% respectively compared with a wool jersey and Lycra pants. Laing and Sleivert (2002) suggested that drag can be reduced by up to 10% through the appropriate use of garments in sports. Kyle and Caiozzo (1986) also investigated various types of clothing used in athletics. They indicated that the leg model covered with Lycra underwent a reduction in drag at a much lower Reynolds number ($Re = 1 \times 10^5$) than with any other smooth or rough covering. However, the roughness of fabric was not measured. Brownlie et al. (1987) found that in large scale wind tunnel tests with an upright mannequin clothed in a form fitting suit, there was a significant 8.8% reduction in drag with a non-porous, polyurethane coated spandex suit compared with a
porous Lycra suit. Holden (1998) reported that a downhill skier clothed in a porous ski suit has a 5% higher drag than a skier in a non-porous, rubber-coated ski suit. Holden postulated that the increased drag of the porous suit was due to macroscopic flapping of the surface or an adverse change in the position of flow separation, resulting from flow through the suit. Brownlie (1992) suggested that the roughness of the suit benefits airflow around the mannequin and the surface roughness of selected fabrics allowed drag reduction on human bodies in cycling and down-hill skiing. However, the surface measurement used an indirect method and no correlation was established.

Kuper and Sterken (2008) analysed the performance of skating suits by using rough fabrics on the legs of the suits to trip the transition to turbulent at low Reynolds numbers. The study demonstrated that some suits significantly increased the average skating speed in long-distance events. A similar study by Brownlie et al. (2004) demonstrated that the Nike swift skin cycling suit can increase the speed by up to 0.2-0.3 seconds per lap on a 400 m oval track by using different rough fabrics in various zones of the suit. However, the study did not reveal detailed correlation between the surface parameters such as roughness, fibre orientation and seam position with such aerodynamic properties.

Oggiano et al. (2009) presented a detailed methodology which allows the behaviour of a particular type of sports fabric (i.e., single knitted jersey fabric) with different roughness parameters to be established. The study was based on wind tunnel force measurements over a range of speeds (20 to 70 km/h) using both a cylinder model and a simplified leg model. Here, they employed geometric parameters to characterise single knitted jersey fabrics in the investigation aimed at finding the correlations between roughness parameters and aerodynamic properties of fabrics. This study showed that the aerodynamic behaviour of materials determined by using a simplified cylinder and leg model was similar. In this study, only drag forces were analysed with a vertical orientation ($\alpha = 90^\circ$) of cylindrical and leg models. Also, the study was restricted to single knitted jersey fabrics.

Konopov et al. (2010) studied the correlation between the geometrical parameters of double layer knitted fabrics, comfort and aerodynamic properties. The study was based on wind tunnel force measurement for a range of speeds from 20 to 70 km/h with a cylinder model in the vertical position. The main objective of the study was to evaluate the aerodynamic drag of double layer knitted fabrics used in high speed winter sports. The study indicated that the interior layer (base) has limited effects on the aerodynamic drag of the entire knitted fabrics
as the passing airflow had a notable perturbation with all layers of fabrics. The authors did not consider the effects of seam, inclination angles, fibre orientation and microstructure of the fabric surface profile.

Bardal (2010) investigated experimentally in the wind tunnel the aerodynamic effect of two knitted fabrics (wool and polyester) on a circular cylinder. Also, the effects of knitting parameters and type of yarn on the flow field were investigated. The finding showed that both wool and polyester fabrics clearly adding surface roughness which has different influence on the flow field. However, only drag forces were investigated with a vertical orientation ($\alpha = 90^\circ$) of cylindrical model and the study was restricted to two fabrics (wool and polyester).

Underwood and Jermy (2011) carried out experiments in the wind tunnel on four different stretched cycling fabrics at vertical and horizontal orientations. They pointed out that no significant difference in drag force occurred at horizontal orientation while an obvious influence in aerodynamic behaviour was observed. However, the study did not reveal detailed correlation between the surface parameters such as fibre orientation and stretch level with such aerodynamic properties. Also, they did not show how the angles of attack will affect the aerodynamic properties.

Chowdhury (2012) investigated eight fabrics with varied surface profiles (surface roughness and fibre orientation) used in different sports including ski jumping and cycling. These were evaluated across a range of Reynolds numbers ($Re$) within a wind tunnel environment. The fabrics were tested using a simplified cylindrical arrangement with variable angles of attack ($\alpha = 30^\circ$ to $150^\circ$). The Electron Scanning Microscopic (ESM) technique and Alicona Mex software were also used to obtain the 3D measurements of the surface texture of each knitted samples. The results shows that the influence of surface roughness at various inclination angles noted that the rougher surfaces produce an earlier transitional flow compared to the smoother surface at inclination angles between $\alpha = 30^\circ$ and $150^\circ$. However, this study did not consider the effect of fabric stretch as well as an indirect measurement was used to estimate the surface roughness of each knitted fabric.

Hence, aerodynamic properties such as drag and lift are significant factors in elite sports performance. It should also be noted that the impact of surface roughness induced by fabrics has not been previously investigated at variable angles of attack. This impact is difficult to interpret from published data on the model roughness discussed above. Presently, no study
has reported the aerodynamic behaviour of stretchable knitted and woven fabric within different elongations in the open literature. Here, this study will address the transitional effect in the boundary layer which is significantly affected by the surface roughness within different stretch conditions at variable angles of attack ($\alpha$).

### 1.2.4 Stretchable Fabric

Stretchable (tension/compression) garments have become very popular items for sports apparel. To date, few studies exist about whether they influence athletic performance rather than providing freedom in movement necessary in sport (Higgins, Naughton, & Burgess, 2009; Ishtiaque, 2001; Pearce, Kidgell, Gierekelis, & Carlson, 2009; Troynikov et al., 2010). The majority of commercial stretchable garments currently available for sports applications are claimed to provide the athlete with enhanced blood flow, better muscle oxygenation, reduced fatigue, faster recovery, reduced muscle oscillation and reduced muscle injury (Gandhi, Palmar, Lewis, & Schraibman, 1984; O'Donnell Jr, Rosenthal, Callow, & Ledig, 1979; Perlau, Frank, & Fick, 1995; Sigel, Edelstein, Savitch, Hasty, & Felix Jr, 1975; Troynikov et al., 2010; Wanga, Feldera, & Caib, 2011).

Brandon et al. (2003) examined ten male and ten female track athletes to determine how custom-fit compression shorts affect athletic performance and to examine the mechanical properties of the shorts in sprint or jump events. The results reveal that possible reasons for the improvement could be that they reduce muscular fatigue and injuries, which lead to more successful training. The study was limited to biomedical influences and no correlation with the aerodynamic performance. Also, the stretch conditions for short were not measured.

Wanga et al. (2011) studied the physical and mechanical properties of four Nylon/Spandex knitted fabrics as commercial medical compression garments. The authors observed that the compression garment fabrics had an open knitted structure with stable dimensions. Also, the Spandex was only presented in the wale direction (lateral direction). The tensile assessment showed that the compression fabrics were strong and their breaking extension was well beyond 200%. The fabric stretching force had a near linear relationship with its elongation when the fabric was stretched up to 100% extension. After fatigue stretching, the average immediate recovery of compression fabrics examined was more than 95% and the average elastic recovery after an extended period of relaxation was at least 98%. This study was significant from the view of estimating the required compression force for designing individualised compression garments with the medical compression fabrics. However, the
authors did not establish any aerodynamic effect relation with fabric properties at varied stretch conditions.

Troynikov, Ashayeri, and Fuss (2012) investigated and compared the surface characteristics of knitted fabrics suitable for sport compression garments under conditions similar to those when such garments are worn. The study quantitatively studies and evaluates the effects of fabric physical structural parameters and construction. This mainly the elastic deformation on the fabric surface topography as relevant to the practical wear of sport garments with negative fit made from it. The knitted fabric is objectively evaluated for physical properties and surface characteristics in terms of sensorial comfort. However, the authors did not correlate the effect of stretchable knitted fabrics on aerodynamic properties.

1.2.5 Seam Position
The prominence of the seam (position and size) may have effect on drag and lift since it can change the air flow regime locally. The seam in various higher speed sports garments can potentially has significant influence on aerodynamic properties. Brownlie (1992) studied the effect of three styles of seams (flat seam, surged seam and flat taped seam) in the wind tunnel. The seams were sewn as two parallel seams on two sleeves of different fabrics and placed at 81° to the oncoming wind direction, relative to the circumference of the cylinder. The results showed that the surged seam provided more drag than the bare cylinder while the flat seam was found to provide greater drag than the flat taped seam. The results suggested that to be effective, the seam should be thinner than the thickness of fabric. However, in athletic applications, a seam should be sewn from the wind facing side of the body and a low profile; flat taped seam should be used in preference to surged seams.

Chowdhury (2012) carried out experimental wind tunnel studies on the effect of the seam position on aerodynamic performance of the garment. The study evaluated a sleeve with a single seam with a standard cylinder model at vertical orientation. The seam was tested from 0° to 180° with increments of 15°. The results noted that the seam position influences the air flow regime passing over the surface of the cylindrical surface. The seam positions from 45° to 60° underwent a flow transition at an earlier stage at $Re = 0.5 \times 10^5$. In contrast, seam positions from 0° to 15° underwent flow transition at high Reynolds number ($Re = 1.5 \times 10^5$). But seam positions from 90° to 180° underwent flow transition at $Re = 1.4 \times 10^5$. Moreover, Brownlie (1992) pointed out that seam position of fabric sleeve at forward flow separation point 45° to 60° might cause early flow transition. However, the seam position at 45°
triggered the flow separation earlier as the local disturbance due to the seam was more than any other configuration. Also at 60° seam position, the disturbance due to the seam influenced the flow transition at an earlier point. Flow transition behaviour due to fabric seam from this study agreed well with published data (Alam, La Brooy, & Subic, 2007; Brownlie, 1992). This study clearly exhibits the effects of seam on sports garments. As the seam position moved to different orientations from 75° and 90°, the effect on seam was minimal. Also, it is evident that the seam positions below 45° had minimal effect on transitional flow. However, the transitional flow was observed with the seam position at 180° due to the surface roughness of the fabric rather than the seam.

Underwood and Jermy (2011) carried out experimental wind tunnel studies on the effect of seam position on aerodynamic performance of garment with different roughness. The study evaluated the cylinder in a vertical orientation and the seam was placed from 0° to 180° with increments of 30°. The results indicated that the seam placed at 60° and 150° has the lowest drag coefficient ($C_D$) and the highest drag coefficient was found at 90°. Nevertheless, the author did not consider the wale orientation of the fabrics and angles of attack.

The effect of a seam on a spherical object such as a cricket ball has a notable influence on aerodynamic behaviour as studied by (Alam et al., 2007; La-Brooy, Alam, & Watmuff, 2009). The study by Alam et al. (2007) used the flow visualisation technique on a cricket ball to demonstrate the flow behaviour due to the seam using a scaled up cricket ball model ($d = 450$ mm) by artificially creating the surface roughness and seam (see Figure 1.11). The figure illustrates the flow structure around a cricket ball with different seam positions (0°, 30°, 70° and 90°) and surface roughness. The study found that the seam location close to the mean direction of the airflow at 0° (horizontal orientation) which has a similar effects as the smooth sphere without any seams or surface roughness. It also indicated that the seam position at 30° delays flow separation. On the other hand, the seam positions at 70° and 90° have minimal transitional effect. However, the seam positions at other angles (e.g., seam positions between 30° to 70°) were not mentioned in their study.
Figure 1.11: Different seam orientations with flow direction of cricket ball (Alam et al., 2007)

1.2.6 Wale Orientation

Chowdhury, Moria, Alam, and Subic (2011) have conducted experimental wind tunnel tests on the effect of wale orientations on aerodynamic behaviour of fabrics. Three knitted samples of same material but different wale orientations (0°, 45°, and 90°) and the seam placed at the back at 180° with respect to wind flow direction to avoid the flow disturbances due to the seam were evaluated. The results showed that the wale orientation did not have notable effect in subcritical and supercritical flow regimes when the cylinder was at vertical orientation. However, the finding was restricted to one type of knitted fabric.

Figure 1.12: Fabric wale orientations (Chowdhury et al., 2011)
1.2.7 Conclusion from Prior Works

The number of published research articles in this area is significantly limited. The available limited publications may be categorised in accordance with their study parameters. Table 1.1 summarises their major findings and limitations.

Table 1.1: Summary of related published research work

<table>
<thead>
<tr>
<th>Author</th>
<th>Fabric Type</th>
<th>Surface Roughness</th>
<th>Stretch</th>
<th>Seam Orientation</th>
<th>Fibre Orientation</th>
<th>Test Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brownlie (1992)</td>
<td>Knitted</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>90°</td>
</tr>
<tr>
<td>Oggiano et al. (2009)</td>
<td>Knitted</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>90°</td>
</tr>
<tr>
<td>Underwood &amp; Jermy (2011)</td>
<td>Knitted</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>0° &amp; 90°</td>
</tr>
<tr>
<td>Wang et al. (2011)</td>
<td>Knitted</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Troynikov et al. (2012)</td>
<td>Knitted</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Chowdhury (2012)</td>
<td>Knitted</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>30°-150°</td>
</tr>
</tbody>
</table>

Table 1.1 clearly indicates that there is a significant knowledge gap and deficiency in the comprehensive understanding of stretchable speed sport fabrics under a range of aerodynamic conditions. As noted, no study has been undertaken to detail the aerodynamic effect of surface roughness of the stretchable knitted and woven speed sport fabrics at various elongations (stretches) under the imposition of inclination from horizontal to vertical orientations ($\alpha = 0°$ to $90°$).

1.3 Rationale and Scope

Lift and drag optimisation are important parameters for an elite athlete’s performance. The reduction of drag is critical in achieving optimum performance abilities. In high level sports, the aerodynamic characteristics and drag reductions found from different garments have been seen to greatly alter achievable performance (Chowdhury, Alam, & Subic, 2010; Strangwood & Subic, 2007; Vorontsov & Rumyantsev, 2000). As a result a detailed understanding of different garment designs and materials, along with their aerodynamic characteristics, has become critical in modern day sports. This research aims to establish a comprehensive
relationship between the surface parameters of stretchable knitted and woven sport fabrics with its respective aerodynamic properties (drag and lift coefficients). So, it is a new field and little research has been reported in open literature. There are significant knowledge gap in stretchable knitted and woven fabrics. There is no well-developed methodology for determination of aerodynamic behaviour of sport fabrics. Limited information on sport fabrics aerodynamic is available for athletes, coaches and regulatory bodies.

In this research, the drag and lift characteristics of a number of stretchable knitted and woven sports fabrics under different structures and physical parameters will be evaluated. These will be looked at in various arrangements and configurations to determine their drag reduction capabilities and lift improvements, which can be related to possible benefits in high level sports. It was found that the average air speeds of sprinters, cyclists, skaters, skiers and swimmers were 32, 42, 50 95 and 107 km/h (i.e., 2 m/s in water) respectively. Therefore, the fabrics would be tested at a range of speeds from 30 to 140 km/h to ensure a detailed overview for a range of sports. The fabrics need to be tested using a variable angle of attack cylindrical arrangement in RMIT Industrial Wind Tunnel. In unison, a detailed study of the microstructure and surface roughness of the fabrics would be undertaken to relate fabric structures to its aerodynamic characteristics.

1.4 Novel Contribution

Previous research has focused at very preliminary overviews of different commercial fabrics and their aerodynamic characteristics. As a result their research has only looked at minimal angles of attack with a vertical orientation. As well as this, they have only tested fabrics under normal elasticity. Therefore a detailed understanding of the fabrics under the full range of angles of attack and under different elasticity (as would be seen on the human body) has not been investigated. This means much of the research to date is not a good representation of how the fabrics would act in real life use. Additionally no correlation has been made between the impacts of surface roughness induced by stretchable knitted and woven fabrics. This means that some fabrics aerodynamic characteristics have been tested, but no investigation on the understanding of why the flow acts differently for a range of materials has been made. The goal of this research is to better represent the material for real world application and understand how flow characteristics will change with elasticity, fabric structure, surface roughness and angle of attack. In addition, a drag polar curve and glide ratio of smooth cylinder with different configurations, stretchable knitted and woven sports fabrics with roughness's and angles of attack have been established.
1.5 Research Aim and Objective

The research aims to create a new and comprehensive understanding of the aerodynamic behaviour of stretchable knitted and woven fabrics used in speed sports under a range of stretches and various angles of attack. This understanding will translate into a reliable, accurate and widely available aerodynamic performance evaluation tool that can be used as the basis for future innovations in speed sport garments.

The main research objectives are to:

1. Establish a correlation between fabrics physical and aerodynamic parameters for knitted and woven fabrics.
2. Develop drag polar for smooth and rough cylindrical surfaces under variable inclined physiological condition.
3. Design and develop a methodology to evaluate the aerodynamic behaviour of sports fabrics.
4. How does aerodynamic efficiency depend on angle of attack with varied surface roughness?

1.6 Research Questions

In light of the need for a quantitative understanding the stretchable knitted and woven fabrics and their aerodynamic behaviour at various angles of attack, especially in higher speed sports, the research questions in this project are formulated as follows:

1. What relationship does stretchable knitted and woven fabrics surface morphology have with the aerodynamic properties?
2. How can the aerodynamic properties of such fabrics be quantified?
3. What effect physiological orientation can have on aerodynamic properties?

1.7 Thesis Overview

The approach taken to answer the research questions are documented over the following chapters. An overview of these chapters is presented below.

Chapter 1 (current chapter) introduces the detailed review of the relevant background literature. The experimental developments and sport fabrics of the prior studies, the rationale and scope, aim and objectives of the present work are outlined and research questions formulated.
Chapter 2 describes the experimental methodology adopted in this research. Also this chapter describes equipment, instrumentation test and facilities used in the course of the work.

Chapter 3 investigates the aerodynamic behaviour of a smooth cylinder at different cylindrical arrangements and different ellipsoidal heads. A description of the experimental set-up and procedure is given, followed by the results and analysis. A drag polar curve of the smooth cylinder with different configurations is further explained.

Chapter 4 and 5 investigate the aerodynamic behaviour of stretchable knitted and woven speed sport fabrics respectively. A description of the experimental set-up and procedure is given, followed by the results and analysis.

Chapter 6 presents the implications of a cylindrical methodology for stretchable speed sports garments. A drag polar curve and glide ratio of the stretchable knitted and woven sports fabrics with roughness's and angles of attack are discussed.

Chapter 7 discusses the general and specific conclusions from this research and outlines recommendations on how the research could be further developed.

The appendices cover further information including; calibration of instruments, detailed design of experimental arrangements, supplementary results, calculations of error analysis and effect of surface roughness on stretchable knitted and woven sport fabrics at $\alpha = 15^\circ, 30^\circ, 60^\circ$. 
CHAPTER 2

EXPERIMENTAL METHODOLOGY
2.1 **Introduction**

This chapter describes the experimental methodology adopted in this research. A detailed description of research equipment, instrumentation, test procedure and facilities used in the course of the study is given in following sections.

2.2 **Experimental Facilities**

2.2.1 **The RMIT Industrial Wind Tunnel**

The RMIT industrial wind tunnel employed has a rectangular test section of 6 m$^2$. The dimensions of the test section were $2\,\text{m} \times 3\,\text{m} \times 9\,\text{m}$ with a turntable for variable yaw with suitably sized models. The tunnel uses a seven blade fan with the approximate diameter of 3 m, driven by a D.C. electric motor controlled by a tachometer mounted on the output shaft of the motor. The wind tunnel is a subsonic and horizontal structure that can produce a maximum wind speed in the test section up to approximately 150 km/h. A remotely mounted fan drive motor and acoustically treated turning vane minimises the background noise and temperature rise inside the test section. The free stream turbulence intensity was approximately 1.8%. Flow angularity was 3% in both pitch and yaw, making the tunnel suitable for these aerodynamic experiments. An isometric view of the industrial wind tunnel is shown in Figure 2.1. The tunnel was calibrated prior to conduct the experimental works.

![Figure 2.1: An Isometric view of the industrial wind tunnel (Alam et al., 2010)](image_url)
2.2.2 Measurements of Dynamic Pressure, Velocity and Temperature

The air speeds inside the test section of the wind tunnel were measured with a modified National Physical Laboratory (NPL) ellipsoidal head pitot-static tube which is located at the entry of the test section. This was connected through flexible tubing with the Baratron pressure sensor (MKS Instruments, USA) as shown in Figure 2.2. The tested dynamic pressure, air temperature and velocity inside the wind tunnel in real time were acquired from the wind tunnel control panel.

![Figure 2.2: Inside the wind tunnel test section](image)

2.2.3 Industrial Wind Tunnel Calibration

Dynamic pressures \((q = 0.5ρv^2)\) in the wind tunnel were measured vertically from 200 to 1800 mm in increments of 200 mm from the tunnel floor at the location where the experimental arrangements were mounted. The nominal tunnel air speeds were initialized from 10 to 140 km/h in increments of 10 km/h with less than ±1% accuracy. The local pressure was normalised by dividing by the wind tunnel reference pressure \((q_{ref})\) and plotting against the height of the air speeds. This indicated that the local pressure did not vary significantly when referenced to the tunnel wall mounted reference pressure for the given speeds. However, a minor variation of normalised velocity can be seen near the tunnel floor.
(Figure 2.3). No correction of velocity was deemed necessary as local pressure \((q)\) did not vary significantly with wall mounted reference pressure \((q_{ref})\) with height. The accuracy of the pressure measured with various speeds across the plane was estimated to be less than \(\pm 1\%\). Hence, the tunnel reference pressure was used in the calculation of drag and lift coefficients.

![Figure 2.3: Normalised local pressure variation with height in relation to reference pressure (Alam et al., 2001)](image)

2.2.4 Measurements of Aerodynamic Forces and Moments

To measure the forces and moments in real time, a 12 bit data accusation system was used. The system involves of a six-component load sensor, connecting cable, PCI data card (12 bit) and data acquisition PC (Microsoft Windows-7) with custom made software. The experimental arrangement was connected through a mounting strut with the JR3 multi-axis load sensor. The sensor was used to measure the three forces (drag, lift and side forces) and three moments (yaw, pitch and roll moments) simultaneously. The \(C_D\), \(C_L\), \(C_S\) and \(Re\) are calculated by using the following equations:

\[
C_D = \frac{D}{\frac{1}{2} \rho V^2 A}
\]  

(2.1)
\[ C_L = \frac{L}{\frac{1}{2} \rho V^2 A} \]  \hspace{1cm} (2.2)

\[ C_S = \frac{S}{\frac{1}{2} \rho V^2 A} \]  \hspace{1cm} (2.3)

\[ Re = \frac{\rho V d}{\mu} \]  \hspace{1cm} (2.4)

Each data point was recorded for 30 seconds time averaged with a frequency of 20 Hz minimising electrical interference. Multiple data were collected at each speed and the results were averaged minimising further possible errors in the raw experimental data. The JR3 sensor with load rating 200 N was used for the measurement of aerodynamic properties of different experimental arrangements. The test models were mounted below the test section of the wind tunnel floor which allows the test models to have all the measurement instrumentation external from the tunnel test section. These facilities administering a breaking force from a calliper or rope break system. The relevant details of the JR3 sensor can be found in Appendix A.1.

2.3 Fabric Configuration

Fabric is a manufactured by assembling fibres and/or yarns that have substantial surface area in relation to its thickness and sufficient cohesion to give the assembly useful mechanical strength. In this study, ten commercially available stretchable fabrics (five knitted and five woven) were selected. Each sample prepared with 220 mm length (cylinder length) and 300 mm width (cylinder circumference). The fabric tested within varied elongations from 0 mm to 100 mm. The dimensions needed for the normal fit (0 mm) is 220 mm length and 290 mm. The 290 mm is reduced by 20 mm at each stretch sample condition (from 20 mm to 100 mm) as shown in Figure 2.4. The fabric sleeves for the cylinder models were made with plain seams which were machine-sewn (see Figure 2.5). Two opposite edges of a single piece of fabric were stitched together with a single row longitudinal stitch, leaving a seam allowance of 10 mm with raw edges inside the sleeve to conform to sports body regulators. Seam allowance is defined as the area between the edge and the stitching line on two pieces of material being stitched together.
Figure 2.4: Fabric preparation and dimensions

Figure 2.5: Seam joint on rear of test cylinder
2.4 Microscopy and Microanalysis

2.4.1 Optical Microscope

A Digitech-i microscope is a portable magnification device which is used to digitally capture the fabric surface as shown in Figure 2.6. This microscope was used essentially to observe the fabric features (such as number of course/weft per cm and gap between the yarns) under a range of stretches. It also has multiple bright LED white lights which allow enhancement of the fabric image. A 5 megapixel image was taken at various magnification levels (20-200 times magnification). The images were stored in the computer memory with 1024 × 884 pixels and a BMP (Bit Map Picture) format for further analysis. Details of Digitech-i optical microscope are given in Appendix A.2.

![Digital Microscope]

*Figure 2.6: Digitech-i optical microscope*

2.4.2 Scanning Electron Microscope

As shown in Figure 2.7, a scanning electron microscope (Model: FEI Quanta 200) was used to capture the fabric sample surface images with different magnifications. The Quanta 200 SEM is an adaptable high performance, low-vacuum and scanning electron microscope with a tungsten electron source. These have three imaging modes (low vacuum, high vacuum and SEM) to provide various ranges of samples.
Fabric samples with a 10 mm (0.4 inch) were cleaned to remove any foreign materials from the surface and mounted on the sample holder inside the test chamber. Scanning was performed in low vacuum mode with water vapour pressure of approximately 1000 Pascal. The low vacuum detectors are not sensitive to light generated during sample heating. Therefore, the dynamic heating experiments can be imaged and recorded live at temperatures up to 1500° C. The scanned images were stored in computer memory with the 1024 × 884 pixels resolution and TIFF (Tagged Image File Format) format for further analysis. Details of the FEI Quanta 200 are furnished in Appendix A.3.

2.5 Experimental Instruments

2.5.1 Tensile Strength Test Instrument

An Instron universal test machine (Model 4466) with the maximum load rating 10 kN was used to conduct the tensile strength (stretch) test of fabric samples. Two adapters (grips made of aluminium) were designed to hold uniformly the two ends of the fabric. One attachment was used for the upper end of the fabric sample connected to the moving part of the Instron
loading arm while the other attachment was used to hold the base. The rubber slabs were used on the interior side of the aluminium adapter plate to ensure that the fabric will not slip out of the grip. The external dimensions of the plate are 250 mm width, 60 mm length and 10 mm thickness which are larger than the dimensions of each sample. Three samples of each fabric were prepared and tested in order to minimise any error during the experimental measurements. Each sample’s dimension is 220 mm width and 320 mm length. The thicknesses of all samples were entered into the computer before the test. In accordance with the standard test method as described in ASTM Standard D5034-95 for the breaking strength and elongation of fabrics, the loading rate was set at 300 mm/min. As shown in Figure 2.8, each sample stretched in the course (knitted fabric)/ weft (woven fabric) directions until it reached 100 mm extension from zero level. Details of the Instron universal test machine and two aluminium grips designed are shown in Appendix A.4 and Appendix B.2 respectively.

![Experimental setup for tension measurement](image)

*Figure 2.8: Experimental setup for tension measurement*

### 2.5.2 Surface Roughness Measurement

A KESFB4-A (manufactured by KES Kato Tech Co. Ltd., Japan) automatic surface tester was used to measure each fabric’s frictional properties and geometrical surface roughness under various tension levels. The main part of this device is the contactor in the form of a wire of diameter 0.5 mm. This contactor is moved of a constant rate of 1 mm/sec and surface height variation (SHV) is registered on a paper sheet. The KESFB4-A has a maximum 0.5µ
detectable sensitivity in surface contour to provide an accurate measurement. The surface property and low cut filter is set in the circuit for excluding the components over 1 mm wavelength so that data should have correlation with finger feeling. Hence, using this fully automatic machine, the fabric’s surface frictional coefficient and roughness were measured simultaneously in three different areas within a sample of 220 mm width and 320 mm length. Fabric samples were placed on the test bed with appropriate stretch and the measurements were taken three times and averaged in order to minimise any error incurred during the measurement. Each fabric sample was measured in course direction (knitted fabric) and weft direction (woven fabric) from 0 mm to 100 mm in increments of 20 mm extension. The experimental setup for the fabric surface roughness measurement is shown in Figure 2.9. The relative roughness parameter ($\varepsilon$) was measured for each fabric sample and the roughness was normalised dividing by the cylinder diameter using the following equation:

$$\varepsilon = \frac{R_a}{d}$$

(2.5)

where $R_a$ is the average roughness height and $d$ is the diameter of the smooth test cylinder. Details of the automatic surface tester can be found in Appendix A.5 and Appendix D.2.3 and the definition of $R_a$ can be found in (Chowdhury, 2012; Troynikov et al., 2012).

Figure 2.9: Experimental setup for fabric surface roughness measurement
2.5.3 Inclinometer Instrument

The inclinometer application (Tilt-Meter app., version 1.1.2) via iPhone-4s device was used accurately to adjust the inclined cylinder at any angle of attack. Initially, the application is calibrated to obtain the accurate angle. The accuracy of the application is about 0.1°. Figure 2.10 demonstrates the experimental measurement procedure of the inclined angle.

![Image of inclinometer application on iPhone]

*Figure 2.10: Measuring seat angle with my iPhone using the Tilt-Meter app*

2.6 Flow Visualisation

Flow visualisation experiments were conducted in RMIT Industrial Wind Tunnel to obtain a qualitatively understanding of flow over different cylindrical arrangements at variable angles of attack using smoke trails. Smoke is used to provide information about the state of the flow on the surface, detecting separation and reattachment zones. The smoke generator (Figure 2.11) used mineral oil to produce the smoke for the experiment. The injection tube was heated to burn the oil at a certain temperature regulated by a thermostat setting. A pump was used to pressurise the oil to flow through the injector. The diameter of injector tip is 6 mm. The generated smoke was dense enough to enable the visualization of the flow trail at low air speeds (~10 km/h). It may be noted that the smoke trail disappears quickly at higher speeds (over 10 km/h). A Nikon D7000 SLR camera with 30 frames per second form a stationary point (side view) was used to capture the path of the smoke infused within the flow. Slide
projectors were used as a suitable light source as they offered very concentrated light over a small area. A total of two slide projectors and two spot lights were used to generate required lighting. Flow separation and vortex formation were observed at different parts of the smooth cylindrical arrangements as described in Chapter 3.

Figure 2.11: A single point smoke generator
CHAPTER 3

AERODYNAMIC BEHAVIOUR OF CYLINDER
3.1 Introduction

The human body is not a streamlined shape and caused flow separation around it. The drag generated by the body is significantly larger than the drag generated by athlete’s outfit (fabric). Therefore, the drag generated by the sport fabric must be evaluated in isolation by using a macro scale testing. In order to measure the aerodynamic properties, such as drag and lift, two experimental arrangements were developed and used: (a) vertical cylindrical arrangement to measure the drag only and (b) variable angle of attack cylindrical arrangement to measure the drag and lift simultaneously at different angles of attack. Both arrangements have been experimentally tested at RMIT University Industrial Wind Tunnel. The arrangements are further explained in the following sections.

3.2 Vertical Cylindrical Arrangement

The smooth vertical cylinder arrangement is used to evaluate the aerodynamic drag. Here a smooth cylinder and strut are used for conducting the experimental work. The smooth test cylinder was based on a hollow PVC material of 90 mm diameter \(d\) and 220 mm length \(l\) constructed with fillers for structural rigidity. The cylinder was vertically supported on a six component force sensor using a steel strut. The sensor was used to measure the three forces (drag, lift and side forces) and their moments (yaw, pitch and roll moments) simultaneously. The fabrics to be tested were applied over the cylinder. Each stretch level of sport fabric was subjected to a range of wind speeds. A schematic CAD model and the experimental arrangement employed are shown in Figure 3.1.

![Figure 3.1: Vertical smooth cylindrical arrangement: (a) Schematic CAD model; (b) Experimental cylinder installed in the test section of RMIT Wind Tunnel](image-url)
3.3 Variable Angle of Attack Cylindrical Arrangements

Two inclined cylinder arrangements were developed in this study to evaluate the body segments under varied angles of attack with the simultaneous measurement of drag and lift: (a) variable angle of attack cylindrical arrangement without ellipsoidal head and (b) variable angle of attack cylindrical arrangement with different ellipsoidal heads.

3.3.1 Variable Angle of Attack Cylindrical Arrangement without Ellipsoidal Head

The arrangement of this configuration consists of a cylinder, a rotating mechanism and strut with a symmetrical aerofoil canopy. The cylinder was 90 mm diameter \( (d) \) and 220 mm length \( (l) \). The test cylinder was connected to the hinge that was supported by the strut. The rotating mechanism (i.e., hinge) was designed to set a fixed inclination angle of attack from \( \alpha = 0^\circ \) to \( 180^\circ \) relative to the wind direction. The aerofoil canopy was used to cover the strut through the test to minimise the aerodynamic interference. Figure 3.2 shows the CAD model of the experimental arrangement. The positioning of the test cylinder at different angles of attack in the industrial wind tunnel is shown Figure 3.3. The relevant details of the cylindrical arrangement with variable angles of attack can be found in Appendix B.1.

Figure 3.2: Schematic CAD model for the cylinder without ellipsoidal head at variable angle of attack
3.3.2 Variable Angle of Attack Cylindrical Arrangement with Ellipsoidal Head

This arrangement involves an additional ellipsoidal head to the same cylinder used in the arrangement of variable angle of attack without an ellipsoidal head. The semi-major radius \(a\) and semi-minor radius \(b\) of the ellipsoidal head is illustrated in Figure 3.4. Three different semi-major radii were developed at 40, 60 and 110 mm in this study. The same semi-minor radius of ellipsoidal head \((b)\) was held constant, while the length of \((b)\) was equal to half of the cylinder diameter \((d = 90 \text{ mm})\).
As shown in Figure 3.5 each ellipsoidal head was attached to the test cylinder through a 40 mm length and 8 mm diameter of thread rod located in the centre to avoid any gap between the ellipse and test cylinder. The dimensions of the three ellipsoidal heads (a) that were used in this study are illustrated in Figure 3.6. Further details about the three ellipsoidal head configurations are provided in Appendix B.2.

Figure 3.5: Schematic CAD model of variable angle of attack cylindrical arrangement with three ellipsoidal heads used in this study: (a) 40mm; (b) 60mm; (c) 110mm

Figure 3.6: Combination of three ellipsoidal head configurations used in this study (all the dimensions are in mm)
3.4 Aerodynamic Results of Vertical Cylinder

The aerodynamic drag forces were measured vertically at 90° under a range of wind speeds starting from 30 to 140 km/h with 10 km/h increments. These drag forces are converted to dimensionless drag coefficients \((C_D)\) while Reynolds numbers \((Re)\) were calculated based on the cylinder diameter. Figure 3.7 shows the plots of the variation of \(C_D\) with \(Re\) for the smooth vertical cylinder. Experimental data in this study shows that a data variation was less than ±1%. The projected frontal area for the vertical cylinder configuration was considered as described in equation 3.1:

\[
A = l \times d \quad \text{(3.1)}
\]

Results obtained from this study revealed that there is no apparent flow transition occurring for the smooth cylinder under the range of \(Re\) tested. Generally, flow transition (from the laminar to turbulent regimes) for the smooth cylinder occurs at \(Re \geq 3 \times 10^5\). Here, the maximum \(Re = 2.3 \times 10^5\) which covers the wind speeds for most speed sports and also the maximum speed limit for the RMIT Industrial Wind Tunnel. The results obtained from this
experimental study agreed well with the published data of flow transition point of a smooth cylinder (Achenbach, 1968, 1971, 1972, 1974a, 1974b, 1977; Achenbach & Heinecke, 1981; Granger, 1985; Hoerner, 1965; White, 2003). However, prior studies Bearman and Harvey (1993); Chowdhury et al. (2009) have studied the influence of aspect ratio (l/d) on the flow past a smooth cylinder. The ratio (l/d) of this arrangement was 2.44 which represent a 3D flow around the smooth vertical cylinder at critical flow regime. However, a cylinder with a rough surface may not follow the same trend.

3.5 Aerodynamic Results of Variable Angle of Attack for Cylinder without Ellipsoidal Head

The athlete’s body parts may be represented by cylindrical shapes having various angles of attack (α). These equivalent cylinders submerged in fluids experience flow transitional effects (laminar to turbulent flow regimes) depending on their inclination angles. Hence, the cylindrical arrangement of variable angle of attack with a rotating mechanism is used to evaluate the flow characteristics on a smooth cylinder. Details of the arrangements can be found in Section 3.3.1. The drag and lift forces were measured on the smooth cylinder without ellipsoidal head (d = 90 mm and l = 220 mm) over a range of angles of attack from α = (0° to 90°) and wind speeds starting from 30 to 140 km/h. In order to determine the effect of inclination angles of attack, Figure 3.8 and Figure 3.9 show the plots of the drag coefficient (C_D) and lift coefficient (C_L) variation with Reynolds numbers (Re) at different angles of attack (α) tested. Experimental data in these studies show that a data variation is less than ±1%. It may be noted that in the calculation of C_D and C_L values for the various α values, the projected frontal area is described in equation 3.2:

\[ A = (l \times d \times \sin \alpha) + (\pi r^2 \times \cos \alpha) \quad (3.2) \]

End plates (top and bottom ends) of the cylinder play a significant role in the aerodynamic properties. The projected frontal area of the plates decreases with the increase of α and it is zero at α = 90°. Hence, with an increase of α, the flow separation at the end plates of the cylinder was delayed whereas the flow separation behind the cylinder occurred earlier. As a result, the maximum value of C_D was obtained at α = 0° whereas the lowest C_D value was found at α = 30° as shown in Figure 3.8. It is found that the C_D variation with Re as a function of α indicates that with the increase of α, the C_D value increases. However, for α = 0°, the projected frontal area was considered as a cross sectional area of the cylinder (i.e., πr^2).
Therefore, despite having the lowest drag experienced by the cylinder at $\alpha = 0^\circ$, the $C_D$ value is highest. The $C_D$ value at $\alpha = 0^\circ$ and $\alpha = 90^\circ$ agreed well with the published data (Achenbach, 1968; Chowdhury et al., 2009; Granger, 1985; Hoerner, 1965; White, 2003). It is interesting to note that an early flow transition has been noted for the smooth cylinder at an angle of attack between $60^\circ$ to $75^\circ$. Additionally, it is not clear what triggered this flow transition. It is believed that the oblique flow generated by the variable angle of attack, the cylinder might cause this early transition. The similar behaviour of the smooth cylinder for the $C_L$ was noted as shown in Figure 3.9. The $C_L$ behaviour at low $Re$ value is believed to be experimental error. However, the maximum $C_L$ value was found at $\alpha = 45^\circ$ and values decreased with the further increase or decrease of angles of attack. Furthermore, for the $C_L$ values at $\alpha = 15^\circ$ and $30^\circ$, the direction is negative at low $Re$, however, the $C_L$ values increases with the increase of up to 70 km/h ($Re = 1.18 \times 10^5$).

![Figure 3.8: The variation of $C_D$ with $Re$ for the cylinder without ellipsoidal head at variable angles of attack](image-url)
Figure 3.9: The variation of $C_L$ with $Re$ for the cylinder without ellipsoidal head at variable angles of attack

Figure 3.10 and Figure 3.11 show the variations of $C_D$ and $C_L$ with angles of attack ($\alpha$) at different speeds for the smooth cylinder. As shown in Figure 3.10, for all wind speeds tested, the magnitude of $C_D$ values at $\alpha = 0^\circ$ is uniformly 0.81 and it is 0.70 at $\alpha = 90^\circ$. A significant variation in $C_D$ values was found at $\alpha = 30^\circ$, $45^\circ$, $60^\circ$ and $75^\circ$ compared to the slight change in $C_D$ values that occurred at $\alpha = 0^\circ$, $15^\circ$ and $90^\circ$. It is clearly evident that with an increase in angle of attack ($\alpha > 15^\circ$), the $C_D$ values gradually increase respectively with wind speeds. However, the $C_L$ value increases consistently with a peak value at an angle of attack of $45^\circ$. Thereafter, the $C_L$ value gradually decreases with the increase of angle of attack as shown in Figure 3.11. Again it is found that low wind speeds of 30–50 km/h seem to inhibit some experimental error due to the aerodynamic interference induced by the end plates. In agreement with Bearman and Harvey (1993) it is found that the $C_L$ value of a circular cylinder at $\alpha = 0^\circ$ and $90^\circ$ is zero.
Figure 3.10: The variation of $C_D$ with angles of attack of the cylinder without ellipsoidal head at different speeds

Figure 3.11: The variation of $C_L$ with angles of attack of the cylinder without ellipsoidal head at different speeds
With a view to understand the flow behaviour of the cylindrical arrangement without ellipsoidal head, a smoke flow visualisation tests were undertaken at variable angles of attack ($\alpha = 0^\circ$, $45^\circ$ and $90^\circ$). Figure 3.12 demonstrates that the flow separation of the cylinder without ellipsoidal head at horizontal orientation ($\alpha = 0^\circ$) became more turbulent due to the effect of end plate. A significant drop in the flow separation was observed with inclined positions while the flow became more turbulent at vertical orientation ($\alpha= 90^\circ$). However, the projected frontal area of the top end reduces with the increase of $\alpha$ and it is zero at $\alpha = 90^\circ$. Thus, with an increase of $\alpha$, the flow separation at the top end of the cylinder delayed whereas the flow separation behind the cylinder occurred earlier as observed in the flow visualisation test.

Figure 3.12: Flow visualisation using smoke generation of cylindrical arrangement without ellipsoidal head at $\alpha = 0^\circ$, $45^\circ$ and $90^\circ$
The majority of the aerodynamic drag is generated by the body shape which is predominantly pressure induced drag. The projected frontal area represents a significant factor in aerodynamic drag generation. In aeronautics and many speed sports applications, the lift-to-drag \( (L/D) \) ratio is considered fundamental. Here, \( L/D \) relationships are plotted for the smooth cylinder under the same test conditions as mentioned earlier (see Figure 3.13). The maximum value of \( L/D \) was obtained at \( \alpha = 45^\circ \) whereas the lowest \( C_D \) value was found at \( \alpha = 15^\circ \) for the smooth cylinder.

![Graph showing variation of L/D with Re at different angles of attack for the smooth cylinder without ellipsoidal head](image)

**Figure 3.13: The variation of L/D with Re at different angles of attack for the smooth cylinder without ellipsoidal head**

Figure 3.14 shows the average \( C_D \) and \( C_L \) variation with angle of attack. The \( C_D \) rapidly decreases with the increase of \( \alpha \). Thereafter, with an increase of \( \alpha \), the \( C_D \) value gradually increases. As a result, the cylinder at angles of attack (i.e., \( \alpha = 15^\circ \) and \( 30^\circ \)) created a minimum value in \( C_D \) while the maximum lift was found at \( \alpha = 45^\circ \). At the same time, the \( C_L \) value rises steadily with a peak value at an angle of attack of \( 45^\circ \) and gently decreases with the increase of \( \alpha \). As explained previously, the extreme parts of \( \alpha = 0^\circ \) and \( 90^\circ \) did not create
lift and between these values the variations in uplift depicted in Figure 3.14. Figure 3.15 is illustrated by drag polar plot of $C_L$ vs. $C_D$, which indicates that the maximum lift can be found at $\alpha = 45^\circ$ with a finite length circular cylinder. However, a sudden reduction in $C_D$ value obtained when the cylinder tilted from $\alpha = 0^\circ$ to $15^\circ$. A slight difference in $C_D$ value was also obtained between $\alpha = 15^\circ$ to $45^\circ$. Nonetheless, a significant difference in $C_L$ value was found between $\alpha = 15^\circ$ and $45^\circ$ and a sharp decrease in $C_L$ then occurred after the peak value. However, this arrangement did not provide a complete drag polar curve from $\alpha = 0^\circ$ to $90^\circ$ due to the effect of end plates. Flow visualisation tests were carried out to demonstrate the flow behaviour around the cylinder at different angles of attack (see Figure 3.12). Also, further studies have been undertaken to investigate the effect of end plates in the subsequent sections.

![Figure 3.14: Average $C_D$ and $C_L$ variation with angles of attack for the smooth cylinder without ellipsoidal head](image.png)
Figure 3.15: The variation of $C_L$ with $C_D$ for the variable angles of attack for smooth cylinder without ellipsoidal head

3.1 Aerodynamic Results of Variable Angles of Attack for Cylinder with Ellipsoidal Head

This study was carried out to investigate the effect of various radii of ellipsoidal heads on the aerodynamic properties at a range of angles of attack. As mentioned earlier, the semi-minor radius of the ellipsoidal head was kept constant ($b = 45$ mm) and the semi-major radius of the ellipsoidal head was varied ($a = 40, 60$ and $110$ mm). Table 3.1 gives the ratio of $(l+a)/d$ which represents three ellipsoidal heads ($a$) including cylinder length ($l$) over the cylinder diameter ($d$).

Table 3.1: Aspect Ratio of $(l+a)/d$ for three ellipsoidal head configurations

<table>
<thead>
<tr>
<th>Ellipsoidal Head, mm</th>
<th>$(l+a)/d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>2.92</td>
</tr>
<tr>
<td>60</td>
<td>3.15</td>
</tr>
<tr>
<td>110</td>
<td>3.71</td>
</tr>
</tbody>
</table>
It is important to note that all three ellipsoidal head configurations have been conducted at a range of angles of attack from $\alpha = 0^\circ$ to $90^\circ$ with an increment of $15^\circ$. The wind speeds ranged from 30 to 140 km/h in increments of 10 km/h. It may be noted that in the calculation of $C_D$ and $C_L$ values for the three ellipsoidal heads under a range of $\alpha$, the projected frontal area is described in Equation 3.3

$$A = (l \times d \times \sin \alpha) + (\pi ab \times \cos \alpha)$$  \hspace{1cm} (3.3)

In following sections, the effect of aspect ratio and effects of 3D flow around the cylinder with three ellipsoidal heads with respect to the variable angles of attack are discussed.

### 3.1.1 40 mm Ellipsoidal Head

In order to evaluate the aerodynamic behaviour around the smooth cylinder, a 40 mm of semi-major radius ($a$) of ellipsoidal head was used. The 40 mm ellipsoidal head radius was developed to compare the aerodynamic effect with the cylinder without ellipsoidal head. However, this ellipsoidal head is the shortest radius amongst others. Figure 3.16 and Figure 3.17 show the plots of the $C_D$ and $C_L$ variation with $Re$ for different values of $\alpha$. Experimental data in these studies show that a data variation is less than $\pm 1\%$.

From Figure 3.16, it is clearly evident that the ellipsoidal head changed the aerodynamic behaviour around the cylinder at different angles. As a result, the magnitude of the $C_D$ value at $\alpha = 0^\circ$ reduced to 0.2 compared to 0.81 in the cylinder arrangement without ellipsoidal head. The $C_D$ value is more than 3 times less. Also, the $C_D$ value at $\alpha = 90^\circ$ is about 0.57 compared to 0.7 in cylinder without head. Between $\alpha = 0^\circ$ and $90^\circ$ orientations, the variations in $C_D$ values were also changed. However, the maximum value of $C_D$ was obtained at $\alpha = 75^\circ$ whereas the lowest $C_D$ value was found at $\alpha = 15^\circ$. The $C_D$ value at $\alpha = 0^\circ$ agreed with the published data of (Hoerner, 1965). Simultaneously, the $C_L$ values were enhanced more than 2 times for all angles except $\alpha = 0^\circ$ and $90^\circ$ orientations. The maximum value of $C_L$ was obtained at $\alpha = 45^\circ$ whereas the lowest $C_L$ value was found at $\alpha = 15^\circ$. 

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Figure 3.16: The variation of $C_D$ with $Re$ for the cylinder with ellipsoidal head ($a = 40$ mm) at variable angles of attack

Figure 3.17: The variation of $C_L$ with $Re$ for the cylinder with ellipsoidal head ($a = 40$ mm) at variable angles of attack
The $C_D$ values as a function of angle of attack ($\alpha$) with respect to the wind speeds is shown in Figure 3.18. The figure indicates that a slight decrease in $C_D$ value was obtained with an increase of angle of attack to 15° and then gradually increased at 30°. After that a dramatic growth occurred with a peak value at an angle of attack of 75°. However, a sudden drop was obtained at 90°. Moreover, the magnitude of $C_D$ values reduces with the increase of wind speeds $\alpha = 45°$, 60° and 75°. On the other hand, the $C_L$ value increases sharply with a peak value at an angle of attack of 45° and decreases with the increase of angle of attack (see Figure 3.19). It is also found that the $C_L$ value of a circular cylinder with 40 mm ellipsoidal head at streamwise and spanwise orientations ($\alpha = 0^\circ$ and 90°) did not generate lift.

*Figure 3.18: The variation of $C_D$ with angles of attack of the cylinder with ellipsoidal head ($a = 40 \text{ mm}$) at different speeds*
Figure 3.19: The variation of $C_L$ with angles of attack of the cylinder with ellipsoidal head ($a = 40$ mm) at different speeds

Figure 3.20 demonstrates the flow characteristics of the cylindrical arrangement with ellipsoidal head ($a = 40$ mm) at $\alpha = 0^\circ$, $45^\circ$ and $90^\circ$ using smoke flow visualisation. It is evident that the ellipsoidal head enhanced the flow separation at various $\alpha$. The flow separation at the horizontal orientation $\alpha = 0^\circ$ became streamlined and attached. However, with an increase of angle of attack at $\alpha = 45^\circ$ and $90^\circ$ the flow separation at the top end of the cylinder delayed whereas the flow separation behind the cylinder occurred earlier as shown in the flow visualisation.
Figure 3.20: Flow visualisation using smoke generation of cylindrical arrangement with ellipsoidal head (d = 40 mm) $\alpha = 0^\circ$, $45^\circ$ and $90^\circ$
Figure 3.21 shows the ratio of lift-to-drag (L/D) verses Re under the same test conditions as mentioned earlier. The maximum value of L/D was obtained at $\alpha = 45^\circ$ whereas the lowest $C_D$ value was found at $\alpha = 75^\circ$.

![Figure 3.21: The variation of L/D with Re at different angles of attack for the smooth cylinder with ellipsoidal head (a = 40 mm)](image)

Figure 3.22 shows the $C_D$ and $C_L$ variation with angle of attack. From the figure, it is evident that the drag and lift are maximum at $\alpha = 75^\circ$ and $45^\circ$ respectively. Figure 3.23 is a drag polar curve of $C_L$ vs. $C_D$, which indicates that the maximum lift can be found at $\alpha = 45^\circ$ with an advantage in drag compared to $\alpha = 60^\circ$. At lower angle of attack, there was a slight decrease in $C_D$ compared to the increment in $C_L$, while a huge change in $C_D$ and $C_L$ values was observed at $\alpha = 45^\circ$. However, this study revealed that the ellipsoidal head enhanced the aerodynamic flow behaviours around the cylinder at different angles of attack particularly at $\alpha = 0^\circ$ and $90^\circ$ orientations. Also, 40 mm ellipsoidal head improved the magnitude of aerodynamic parameter (drag and lift) values more than two times compared to the cylinder without ellipsoidal head configuration.
Figure 3.22: Average $C_D$ and $C_L$ variation with angles of attack for the smooth cylinder with ellipsoidal head ($a = 40$ mm)

Figure 3.23: The variation of $C_L$ with $C_D$ for the variable angles of attack for smooth cylinder with ellipsoidal head ($a = 40$ mm)
3.1.2 60 mm Ellipsoidal Head

A 60 mm ellipsoidal head radius was developed to study and compare the aerodynamic behaviour with the 40 mm ellipsoidal head. The radius of ellipsoidal head ($a = 60$ mm) represents one-third the length of the test cylinder. Figure 3.24 and Figure 3.25 show the plots of the $C_D$ and $C_L$ variation with $Re$ at different values of $\alpha$ tested. The experimental data variation is less than ±1% is noted.

The results indicate that the 60 mm ellipsoidal head changed the aerodynamic behaviour around the cylinder at different angles of attack compared to aforementioned configurations. The magnitude of the $C_D$ value at $\alpha = 0^\circ$ reduced slightly to 0.192 compared to 0.2 in 40 mm ellipsoidal head orientation. The $C_D$ value at $\alpha = 90^\circ$ is about 0.56 compared to 0.57 in cylinder without head. Between $\alpha = 0^\circ$ and $90^\circ$ orientations, the variations in $C_D$ values were also changed. However, the maximum values of $C_D$ and $C_L$ were obtained at $\alpha = 75^\circ$ and $45^\circ$ respectively. The lowest $C_D$ and $C_L$ values were found at $\alpha = 15^\circ$. The $C_D$ value at $\alpha = 0^\circ$ agreed with the published data (Hoerner, 1965).

![Figure 3.24: The variation of $C_D$ with $Re$ for the cylinder with ellipsoidal head ($a = 60$ mm) at variable angles of attack](image-url)
Figure 3.25: The variation of $C_L$ with $Re$ for the cylinder with ellipsoidal head ($a = 60$ mm) at variable angles of attack

Figure 3.26 illustrates the $C_D$ values as a function of angle of attack with respect to the wind speeds. The figure indicates that a slight decrease in $C_D$ value was found with an increase of angle of attack to 15° and then gradually increased at 30°. Subsequently, a dramatic growth occurred with a peak value at an angle of attack of 75°. However, a sudden drop was obtained at 90°. Conspicuously, the magnitude of $C_D$ values reduces with the increase of wind speeds at $\alpha = 60°$ and 75°. A slight variation was observed in $C_D$ values at $\alpha = 15°$, 30° and 45°. On the other hand, the $C_L$ value increases sharply with a peak value at an angle of attack of 45° and decreases gradually with the increase of angle of attack of 75° as shown in Figure 3.27. Also, it is found that low wind speeds of 30 to 50 km/h seem to inhibit some experimental error due to the aerodynamic interference induced by the end plates. It is also found that the $C_L$ value of a circular cylinder with 60 mm ellipsoidal head at $\alpha = 0°$ and 90° did not generate lift.
Figure 3.26: The variation of $C_D$ with angles of attack of the cylinder with ellipsoidal head ($a = 60 \text{ mm}$) at different speeds

Figure 3.27: The variation of $C_L$ with angles of attack of the cylinder with ellipsoidal head ($a = 60 \text{ mm}$) at different speeds
As shown in Figure 3.28, the smoke flow visualisation of the cylindrical arrangement with ellipsoidal head \((a = 60\, \text{mm})\) at numerous angles of attack \((\alpha = 0^\circ, 45^\circ \text{ and } 90^\circ)\) was carried out. The figure expound with an increase of ellipsoidal head to \(a = 60\, \text{mm}\), the flow of the smoke generation at the horizontal orientation \((\alpha = 0^\circ)\) became more attached to the cylinder and smoother (less turbulent) compared to the aforementioned configurations. Also, rising the test cylinder at angular and vertical orientations \((\alpha = 45^\circ \text{ and } 90^\circ)\), the flow separation at the top end of the cylinder delayed more whereas the flow separation behind the cylinder occurred earlier. As a result, 60 mm ellipsoidal head enhanced the aerodynamic properties \((C_D \text{ and } C_L)\) at different angles of attack as observed in the flow visualisation.

Figure 3.28: Flow visualisation using smoke generation of cylindrical arrangement with ellipsoidal head \((a = 60\, \text{mm})\) \(\alpha = 0^\circ, 45^\circ \text{ and } 90^\circ\)
Figure 3.29 shows the ratio of lift-to-drag ($L/D$) verses $Re$ under the same test conditions as mentioned earlier. The maximum value of $L/D$ was obtained at $\alpha = 30^\circ$ and $45^\circ$ whereas the lowest $C_D$ value was found at $\alpha = 75^\circ$.

Figure 3.29: The variation of $L/D$ with $Re$ at different angles of attack for the smooth cylinder with ellipsoidal head ($a = 60$ mm)

Figure 3.30 illustrates the $C_D$ and $C_L$ variation with angle of attack. From the figure, it is evident that the drag and lift is maximum at $\alpha = 75^\circ$ and $45^\circ$ respectively. Figure 3.31 is a drag polar plot of $C_L$ verses $C_D$, which obtained a consistent drag polar curve at different angles of attack. The maximum lift was found at $\alpha = 45^\circ$ with an advantage in drag compared to $\alpha = 60^\circ$. At lower angle of attack, a slight decrease in drag compared to the increment in lift while a huge change in drag and lift value was observed at $\alpha = 45^\circ$. However, this study revealed that the 60 mm ellipsoidal head enhanced the aerodynamic flow behaviour at different angles of attack.
Figure 3.30: Average $C_D$ and $C_L$ variation with angles of attack for the smooth cylinder with ellipsoidal head ($a = 60$ mm)

Figure 3.31: The variation of $C_L$ with $C_D$ for the variable angles of attack for smooth cylinder with ellipsoidal head ($a = 60$ mm)
3.1.3 110 mm Ellipsoidal Head

The 110 mm ellipsoidal head radius was developed to study and compare the aerodynamic effect of the cylinder with 40 and 60 mm ellipsoidal head and without ellipsoid head. The radius of ellipsoidal head \((a = 110 \text{ mm})\) represents half the length of the test cylinder. Figure 3.32 and Figure 3.33 illustrate the plots of the \(C_D\) and \(C_L\) variation with \(Re\) at different \(\alpha\).

The results show that the 110 mm ellipsoidal head also changed the aerodynamic behaviour around the cylinder at different angles of attack. The magnitude of \(C_D\) value at \(\alpha = 0^\circ\) reduced slightly to 0.190. This value is less than that of the aforementioned configurations of the 40 and 60 mm ellipsoidal head which were 0.199 and 0.192 respectively. The \(C_D\) value at \(\alpha = 90^\circ\) is about 0.54 compared to 0.57 and 0.56 of ellipsoidal heads with 40 and 60 mm respectively. Between \(\alpha = 0^\circ\) and \(90^\circ\) orientation, the variations in \(C_D\) values were also affected by the change in ellipsoidal head. However, the maximum values of \(C_D\) and \(C_L\) were obtained at \(\alpha = 75^\circ\) and \(60^\circ\) respectively while the lowest \(C_D\) and \(C_L\) values were found at \(\alpha = 15^\circ\). The \(C_D\) value at \(\alpha = 0^\circ\) agreed with the published data (Hoerner, 1965).

![Graph showing the variation of \(C_D\) with \(Re\) for the cylinder with ellipsoidal head \((a = 110 \text{ mm})\) at variable angles of attack.](image)

*Figure 3.32: The variation of \(C_D\) with \(Re\) for the cylinder with ellipsoidal head \((a = 110 \text{ mm})\) at variable angles of attack*
Figure 3.33: The variation of $C_L$ with $Re$ for the cylinder with ellipsoidal head ($a = 110$ mm) at variable angles of attack.

Figure 3.34 shows the variation of $C_D$ values for the cylinder with ellipsoidal head 110 mm as a function of angle of attack with respect to wind speeds. A close examination from the figure, it can deduce that as the angle of attack is increased, there is a gradual reduction in $C_D$ valid between angles ranging between 0° and 30°. The peak $C_D$ values were noted at 75° for all wind speeds; followed by a significant drop in $C_D$ across all wind speeds at 90°. Also, the magnitude of $C_D$ values reduces with an increase in wind speeds between 60° and 75° with a minor variation in $C_D$ values observed between 30° and 45°. Additionally, Figure 3.35 shows a very gradual increase in $C_L$ between 0° and 30°. This then corresponds to a sharp rise in $C_L$ values from 30° to 45°. A close inspection from figure, it is evident that at low wind speeds ranging between 30 to 50 km/h, the experimental errors attributed by the end plates hinder the results. It was also found that the $C_L$ value of a circular cylinder with 110 mm ellipsoidal head at angle of attack 0° and 90° did not generate lift.
Figure 3.34: The variation of $C_D$ with angles of attack of the cylinder with ellipsoidal head ($a = 110$ mm) at different speeds

Figure 3.35: The variation of $C_L$ with angles of attack of the cylinder with ellipsoidal head ($a = 110$ mm) at different speeds
In order to understand the flow characteristics of the cylindrical arrangement with ellipsoidal head \((a = 110 \text{ mm})\), a smoke flow visualisation tests were executed at variable angles of attack. Figure 3.36 demonstrates the flow characteristics at different orientations. The figure reveals that the flow at horizontal orientation \((\alpha = 0^\circ)\) is attached to the test cylinder and became much smooth (less turbulent) compared to previous configurations. In addition, the angular position at \(\alpha = 60^\circ\) became more turbulent and generated less flow separation at vertical orientation \(\alpha = 90^\circ\). As a result, with an increase of ellipsoidal head \((a = 110 \text{ mm})\), a significant flow separation was created at horizontal and vertical orientations \((\alpha = 0^\circ \text{ and } 90^\circ)\) however a notably smaller flow separation was found at intermittent angles.

*Figure 3.36: Flow visualisation using smoke generation of cylindrical arrangement with ellipsoidal head \((a = 110 \text{ mm})\) \(\alpha = 0^\circ, 60^\circ \text{ and } 90^\circ\)*
Figure 3.37 shows the ratio of lift-to-drag (L/D) verses Re under the same test conditions as mentioned earlier. The maximum value of L/D was obtained at $\alpha = 30^\circ$ and $45^\circ$ whereas the lowest $C_D$ value was found at $\alpha = 75^\circ$.

![Graph showing L/D vs Re for different angles of attack](image)

**Figure 3.37:** The variation of L/D with Re at different angles of attack for the smooth cylinder with ellipsoidal head ($a = 110$ mm)

Figure 3.38 illustrates the $C_D$ and $C_L$ variation with angle of attack. From the figure, it is clearly evident that the drag and lift is maximum at $\alpha = 75^\circ$ and $60^\circ$ respectively. Also, the peak values of $C_L$ at $60^\circ \pm 15^\circ$ were very close. Figure 3.39 is a drag polar plot of $C_L$ verses $C_D$, which obtained a consistent drag polar curve at different angles of attack. The maximum lift was found at $\alpha = 60^\circ$. At lower angles of attack, there was a slight decrease in $C_D$ compared to the increment value in $C_L$ while a huge change in $C_D$ and $C_L$ values were created at $\alpha = 60^\circ$. 
Figure 3.38: Average $C_D$ and $C_L$ with angles of attack for the smooth cylinder with ellipsoidal head ($a = 110$ mm)

Figure 3.39: The variation of $C_L$ with $C_D$ for variable angles of attack for smooth cylinder with ellipsoidal head ($a = 110$ mm)
3.2 Effect of Aspect Ratio

To determine the effect of aspect ratio \((l/d)\), the vertical cylinder with three ellipsoidal heads \((a = 40, 60\) and \(110\) mm) was conducted in the wind tunnel over a range of wind speeds (30 to 140 km/h). As mentioned earlier in Table 3.1, the aspect ratio of \((l+a)/d\) represents three ellipsoidal heads radii \((a)\) including cylinder length \((l)\) over the cylinder diameter \((d)\).

Figure 3.40 shows the \(C_D\) variation with \(Re\) for the smooth cylinder at \(\alpha = 90^\circ\) orientation with three ellipsoidal heads. It is clearly noted that as the \((l+a)/d\) ratio increases, the \(C_D\) value decreases due the effect of 3D. Also, the \(C_D\) value remains almost constant throughout the \(Re\) range evaluated. In addition, a linear relation \(C_D\text{min} = (-0.0376 \times Re) + (0.6781)\) and the correlation coefficient is \(R^2 = 0.9978\) were obtained with the increase of ellipsoidal head \((a)\) as represented in Figure 3.41.

![Figure 3.40: The variation of \(C_D\) with \(Re\) for smooth cylinder with three ellipsoidal heads at vertical orientation](image-url)
3.3 Effects of 3D Flow around the Ends

To establish the effect of the 3D flow around the ends of the cylinder, three ellipsoidal heads $(a = 40, 60$ and $110$ mm) were evaluated in the wind tunnel over a range of wind speeds (30 to 140 km/h). Figure 3.42 represents the drag polar plot of $C_L$ verses $C_D$ at different angles of attack investigated.

From the figure, it is clearly evident that the ellipsoidal head arrangement has a significant effect on the aerodynamic flow around the cylinder at different angles of attack. The cylinder without ellipsoidal head produced higher drag compared to the three ellipsoidal heads whereas the lift was two times lower. Also, the cylinder without ellipsoidal head did not provide a consistent drag polar curve. Due to the end effect of the cylinder without ellipsoidal head, a sudden reduction in $C_D$ value occurred from $a = 0^\circ$ to $15^\circ$. Also, a huge drop in $C_L$ value obtained after the peak angle of attack at $a = 45^\circ$. On the other hand, the three ellipsoidal heads totally enhanced the aerodynamic flow behaviour around the cylinder at different angles of attack. The results indicate that these three ellipsoidal heads produced less $C_D$ and high $C_L$. Slight variations in $C_D$ values at $a = 0^\circ$ and $90^\circ$ orientations were observed.
At lower angle of attack from $\alpha = 15^\circ$ to $75^\circ$, an obvious variation was found. The ellipsoidal head ($a = 40$ mm) produced the highest $C_D$ compared to 60 and 110 mm ellipsoidal heads from $\alpha = 30^\circ$ to $60^\circ$, while the $C_D$ value of $a = 40$ mm decreased at $\alpha = 75^\circ$. The ellipsoidal head ($a = 60$ mm) has similar aerodynamic parameter results of $a = 110$ mm. Nonetheless, $a = 60$ mm created optimal $C_L$ values at different angles of attack while a minor improvement in $C_D$ was found for $a = 110$ mm. At $\alpha = 75^\circ$, it was found that $a = 60$ mm produced less $C_D$ compared to $a = 110$ mm. The maximum difference in $C_D$ values among the three ellipsoidal heads was found between $\alpha = 45^\circ$ and $60^\circ$ whereas the minimum variation was observed at $\alpha = 0^\circ$ and $90^\circ$.

Figure 3.42: Comparison of variation of $C_L$ with $C_D$ for variable angles of attack smooth cylinder without ellipsoidal head and with ellipsoidal head ($a = 40$, 60 and 110 mm)
Table 3.2 shows the variation of $C_L$ with $C_D$ for variable angles of attack without and with three different ellipsoidal head configurations. The comparison revealed that the optimal arrangement for the further studies of speed sports fabrics is the 60 mm ellipsoidal head. As the 60 mm ellipsoidal head obtained the maximum $C_L/C_D$ which has the lowest drag and maximum lift compared to the aforementioned cylinder with other ellipsoidal heads and without an ellipsoidal heads at various angles of attack. Although the end effects are measurable, it is not critical for fabric studies. Here, the experimental investigation of the stretchable speed sport fabric tests are based on the 60 mm ellipsoidal head at variable angles of attack. These studies are discussed in detail in Chapter 4 and Chapter 5.

Table 3.2 Comparison of variation of $C_L$ with $C_D$ for variable angles of attack for without ellipsoidal head and with ellipsoidal head smooth cylinder

<table>
<thead>
<tr>
<th>Angle of Attack (°)</th>
<th>$C_L/C_D$, Ellipsoidal Head (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without</td>
</tr>
<tr>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>15</td>
<td>0.124</td>
</tr>
<tr>
<td>30</td>
<td>0.281</td>
</tr>
<tr>
<td>45</td>
<td>0.474</td>
</tr>
<tr>
<td>60</td>
<td>0.394</td>
</tr>
<tr>
<td>75</td>
<td>0.307</td>
</tr>
<tr>
<td>90</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.580</strong></td>
</tr>
</tbody>
</table>
3.4 Summary

Two inclined cylindrical test methodologies were developed in this study to evaluate the body segments under varied angles of attack ($\alpha = 0^\circ$ to $90^\circ$ with an increment of $15^\circ$) for drag and lift measurements: (a) variable angle of attack cylindrical arrangement without ellipsoidal head and (b) variable angle of attack cylindrical arrangement with three ellipsoidal heads. Three different semi-major radii were developed at 40, 60 and 110 mm in this study. The semi-minor radius of ellipsoidal head (b) was held constant, while the length of (b) was equal to half of the cylinder diameter ($d = 90$ mm). All aerodynamic investigations were conducted in RMIT University Industrial Wind Tunnel. The drag and lift forces were measured on the smooth cylinder over a range of wind speeds starting from 30 to 140 km/h in an increment of 10 km/h. These drag and lift forces are converted to dimensionless drag and lift coefficients ($C_D$ and $C_L$) while Reynolds numbers ($Re$) were calculated based on the cylinder diameter and wind speeds. The aerodynamic investigations reveal that the variable angle of attack of the cylindrical arrangement with ellipsoidal heads altered the aerodynamic properties ($C_D$ and $C_L$). The $60$ mm ellipsoidal head allowed obtaining the maximum $C_L/C_D$ ratio that is the lowest drag and maximum lift compared to the cylinder with $40$ and $110$ mm ellipsoidal heads at various angles of attack. The flow visualization using smoke generation of cylindrical arrangement without ellipsoidal head and three ellipsoidal heads was undertaken. The flow visualization reveals that the cylindrical arrangement without ellipsoidal head created more turbulent at all angles of attack. On the other hand, three ellipsoidal heads significantly altered the aerodynamic properties at different angles of attack. Hence, the experimental investigations of the stretchable speed sport fabrics are based on the $60$ mm ellipsoidal head under variable angles of attack as described in Chapters 4 and 5.
CHAPTER 4

AERODYNAMIC BEHAVIOUR OF STRETCHABLE SPORTS KNITTED FABRICS
Aerodynamic behaviour of speed sports knitted fabrics is believed to play a significant role in a wide range of speed sports including sprinting, cycling, speed-skating, downhill-skiing and ski-jumping. In speed sports, knitted garments are skin-fitted with reasonable tension. Here, investigation is undertaken to quantify the effects of five different stretchable knitted speed sport fabrics. These including, surface roughness, distance and gap area between courses on aerodynamic properties (drag and lift) and their correlations at varied elongations (0 to 100 mm). As mentioned previously in Chapter 3, the variable angle of attack cylindrical arrangement with 60 mm ellipsoidal head is used in this study to develop correlation between the aerodynamic parameters with the physical parameters of five stretchable knitted speed sports fabrics under varied angles of attack ($\alpha = 0^\circ$ to $90^\circ$).

### 4.1 Knitted Fabric Characterisation

Knitting is a process of manufacturing textile structures with a single yarn or set of yarns moving in only one direction (Raz, 1987; Spencer, 2001). Knitted fabrics are produced by looping the yarn through itself to make a chain of stitches which are then connected together. Figure 4.1 illustrates the structure of a common knitted fabric where the stitch density of the fabric is expressed as the number of courses and wales per unit length. Course can be defined as the row of loops or stitches running across the width of a fabric (crosswise), where the wale represents a sequence of stitches in which each stitch is suspended from the next (lengthwise).

![Figure 4.1: Structure of a common knitted fabric stitch](image-url)
4.2 Photographic Characterisation of Stretchable Knitted Fabrics

Five commercially available knitted stretchable fabrics (as samples K1, K2, K3, K4 and K5) were selected for this study. Each of the knitted fabric has different properties that are useful in sportswear. Figure 4.2 illustrates the photographs of the smooth cylinder and five samples examined in this study. The yellow line indicates the wale direction (vertical) while the fabric stretched in the course direction with red line (horizontal). Table 4.1 provides the material composition, thickness and course direction of each sample fabric.
Table 4.1: Material composition, thickness and course direction of five sport knitted fabrics

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Material composition</th>
<th>Thickness, (mm)</th>
<th>Course direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>92% Polyester and 8% Spandex</td>
<td>0.40</td>
<td>0°</td>
</tr>
<tr>
<td>K2</td>
<td>80% Nylon and 20% Spandex</td>
<td>0.55</td>
<td>0°</td>
</tr>
<tr>
<td>K3</td>
<td>85% Nylon and 15% Spandex</td>
<td>0.60</td>
<td>0°</td>
</tr>
<tr>
<td>K4</td>
<td>95% Polyester and 5% Spandex</td>
<td>0.65</td>
<td>0°</td>
</tr>
<tr>
<td>K5</td>
<td>50% Nylon, 45% Polyester and 5% Spandex</td>
<td>0.50</td>
<td>0°</td>
</tr>
</tbody>
</table>

4.3 Microstructural Analysis of Stretchable Knitted Fabrics

In order to understand the surface morphology such as yarn and fibre size, and stitch pattern of five stretchable knitted fabrics at varied elongations (stretches), an optical and electron microscopic study were performed.

4.3.1 Optical Image Analysis

The optical microscope was used to study the fabric surface morphology under different elongations starting from 0 mm (normal fit) to 100 mm (maximum fit) with an increment of 20 mm elongation. As mentioned earlier, the maximum elongation level (100 mm) is located within the elastic condition for all knitted fabric samples. A hysteresis analyse for all knitted fabrics was undertaken.
Figure 4.3: Optical images of knitted fabrics surface at 0(left), 50(middle) and 100mm (right)
As shown in Figure 4.3, optical images with 15 times magnification illustrated the numbers of courses and wales per cm, the distance and gap area between courses at unstretched and stretched conditions 0 mm (left side), 50 mm (middle) and 100 mm (right side) respectively. The elongation applied in the course direction (lateral axis) in order to obtain the maximum elongation. In addition, Table 4.2 and Table 4.4 represent the obtained data from optical image analyses. Further images about knitted fabrics at 20, 40, 60 and 80 mm elongations are giving in Appendix E.1.

Table 4.2: Number of courses and wales per cm of five sport knitted fabrics with optical image analysis

<table>
<thead>
<tr>
<th>Fabric</th>
<th>No. of Courses per cm</th>
<th>No. of Wales per cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K1</td>
<td>K2</td>
</tr>
<tr>
<td>Elongation (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>21</td>
<td>25</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>23</td>
</tr>
<tr>
<td>40</td>
<td>19</td>
<td>22</td>
</tr>
<tr>
<td>60</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>80</td>
<td>17</td>
<td>19</td>
</tr>
<tr>
<td>100</td>
<td>16</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 4.3: Fabrics characterization of five sport knitted fabrics with optical image analysis

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Gap Area, (μm² × 10^3)</th>
<th>Course to Course, (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K1</td>
<td>K2</td>
</tr>
<tr>
<td>Elongation (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>30.42</td>
<td>35.53</td>
</tr>
<tr>
<td>20</td>
<td>36.11</td>
<td>41.65</td>
</tr>
<tr>
<td>40</td>
<td>40.85</td>
<td>47.78</td>
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<tr>
<td>60</td>
<td>45.15</td>
<td>55.21</td>
</tr>
<tr>
<td>80</td>
<td>51.63</td>
<td>62.72</td>
</tr>
<tr>
<td>100</td>
<td>56.25</td>
<td>68.45</td>
</tr>
</tbody>
</table>
4.3.2 Electron Microscopic Image Analysis

Optical images did not provide detailed information of the surface including the yarn and fibre sizes and knitting pattern. Therefore, high resolution (1886 × 2048 pixels) digital images (TIF format) of fabric surface were acquired with a scanning electron microscope (SEM) at different magnification for the analysis. The surface of the fabric samples were cleaned from any foreign material and mounted on the sample holding stubs. The surfaces of all test fabric samples were examined at magnification of 100 and 1000. The yarn size and fibre diameter can be estimated from Figure 4.4 and Figure 4.5 for each fabric sample. Table 4.4 shows the individual yarn size, fibre size and stitch pattern for all stretchable fabrics used.
Figure 4.4: SEM images of five stretchable knitted fabric surfaces with 100X magnification, (left side) unstretched fabric and (right side) stretched fabric.
Figure 4.5: SEM images of five knitted fabric surfaces with 1000X magnification
Table 4.4: Five knitted fabrics characterization with SEM image

<table>
<thead>
<tr>
<th>Fabric No.</th>
<th>Yarn size (μm)</th>
<th>Fibre size (μm)</th>
<th>Stitch pattern</th>
<th>Unstretched</th>
<th>Stretched</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>138</td>
<td>16.67</td>
<td>V-shaped</td>
<td>Circular loop</td>
<td></td>
</tr>
<tr>
<td>K2</td>
<td>114</td>
<td>21.11</td>
<td>V-shaped</td>
<td>Circular loop</td>
<td></td>
</tr>
<tr>
<td>K3</td>
<td>146</td>
<td>24.22</td>
<td>V-shaped</td>
<td>V-shaped</td>
<td></td>
</tr>
<tr>
<td>K4</td>
<td>184</td>
<td>11.99</td>
<td>Circular loop</td>
<td>Circular loop</td>
<td></td>
</tr>
<tr>
<td>K5</td>
<td>246</td>
<td>18.33</td>
<td>Circular loop</td>
<td>Circular loop</td>
<td></td>
</tr>
</tbody>
</table>

4.4 Knitted Fabric Surface Profile

All the knitted fabric samples were prepared at the same dimensions (220 mm width and 320 mm length) and three samples of each fabric were measured. Each sample stretched in the course direction till it reached 100 mm extension from zero. The KESFB4-A automatic surface tester was used to measure each fabric’s frictional properties and geometrical surface roughness under various tension levels as mentioned in Section 2.5.2. The average height of the surface area (Ra) then obtained from the fabric surface profile measurement. Surface roughness measurements are based on the surface profile measurement. The error margin in this measurement was also calculated. Table 4.5 shows the average value of all stretchable knitted fabric heights with standard deviation and elongation from 0 mm to 100 mm. The maximum error was found to be approximately ±4%. Further information for each knitted fabric is given in Appendix D.2.1.

Table 4.5: Average height of sample knitted fabric surface measurement

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Average height of knitted fabric surface Ra, (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 mm</td>
</tr>
<tr>
<td>K1</td>
<td>12.06±0.49</td>
</tr>
<tr>
<td>K2</td>
<td>18.07±0.09</td>
</tr>
<tr>
<td>K3</td>
<td>23.41±0.06</td>
</tr>
<tr>
<td>K4</td>
<td>27.33±0.57</td>
</tr>
<tr>
<td>K5</td>
<td>41.67±0.69</td>
</tr>
</tbody>
</table>
4.5 Measurement of Knitted Fabric Stretchability

In order to study the stretchability of knitted sample fabrics an Instron universal test machine was used as mentioned in Section 2.5.1. Initially, all the fabric samples were prepared at the same dimensions of 220 mm width and 320 mm length and the thickness of fabrics are shown in Table 4.1. In accordance with the standard test method as described in ASTM Standard D5034-95 for the breaking strength and elongation of knitted fabrics, the loading rate was set at 300 mm/min. Each sample was measured three times and stretched in the course direction till it reached 100 mm extension from zero. Troynikov et al. (2010) determined the range of practical extension for sport compression garments to be within 10–70%, which determined the selection of chosen elastic strains for experimental samples. The variations of tensile force with fabric elongation for all stretchable knitted fabrics are shown in Figure 4.6. Detailed about fibres and their properties are pointed out in (Wardiningsih, 2009).

\[\text{Figure 4.6: The variation of tensile force with fabric elongation of five stretchable knitted fabric}\]
4.6 Aerodynamic Characterisation of Stretchable Knitted Sports Fabrics

With a view to evaluate the aerodynamic characterisation of all stretchable knitted fabrics, a variable angles of attack cylindrical arrangement with 60 mm ellipsoidal head was used for this study. It is important to note that all the knitted fabrics have been conducted at varied elongations from 0 mm to 100 mm and angles of attack from $\alpha = 0^\circ$ to $90^\circ$ with an increment of $15^\circ$ for the following sections. The wind speeds ranged from 30 to 140 km/h in increments of 10 km/h. The aerodynamic parameter will be then correlated with the physical parameters. The principle aerodynamic parameters used in this study where drag ($F_D$) and lift ($F_L$) and their non-dimensional coefficient ($C_D$) and ($C_L$). The physical parameters of the fabrics are the surface roughness, course to course distance and gap area between the courses at varied elongations. The correlations of the aerodynamic and physical parameter are discussed in the following sections.

4.6.1 Effect of Surface Roughness on Stretchable Knitted Sport Fabrics

The structural pattern of knitted fabric depends on the appearance of course and wale on their surface. Fabric structural patterns characteristics are important from the view of the influence on the surface roughness. Fabric surface roughness is an important parameter which affects the critical Reynolds number appreciably (Achenbach, 1971, 1972, 1974a, 1977; Achenbach & Heinecke, 1981; Hoerner, 1965; Kyle & Caiozzo, 1986; Spring et al., 1988; Szechenyi, 1975). Table 4.6 shows the average relative roughness of all stretchable knitted fabrics. The relative roughness parameter ($\varepsilon$) was estimated for each fabric sample at specific elongation. The roughness was normalized dividing by the cylinder diameter ($d$) of the test cylinder.

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Average relative roughness of knitted fabric surface, ($\varepsilon = Ra/d$)$\times 10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 mm</td>
</tr>
<tr>
<td>K1</td>
<td>1.39</td>
</tr>
<tr>
<td>K2</td>
<td>2.03</td>
</tr>
<tr>
<td>K3</td>
<td>2.63</td>
</tr>
<tr>
<td>K4</td>
<td>3.07</td>
</tr>
<tr>
<td>K5</td>
<td>4.68</td>
</tr>
</tbody>
</table>
From Table 4.6, it is clearly evident that each fabric sample has different relative roughness ($\varepsilon$). This study points out that the value of relative roughness of each knitted fabric sample elongated within the elastic region significantly increases. However, the following sections are discussing the effect of the surface roughness ($\varepsilon$) of all stretchable knitted speed sport fabrics on aerodynamic parameters (drag and lift). Here, 0°, 45° and 90° angle of attack ($\alpha$) are presented whereas 15°, 30°, 60° and 75° are provided in Appendix F.

4.6.1.1 Surface Roughness $\alpha = 90^\circ$

To understand the effect of surface texture, the cylinder fitted with knitted fabrics at varied fabric elongations were initially tested at $\alpha = 90^\circ$. As the incoming air flow is perpendicular to the cylinder, the drag force is more dominant. Figure 4.7 shows the variation of $C_D$ with Reynolds number for all knitted fabric with different relative roughness and the bare cylinder at $\alpha = 90^\circ$.

The curves of all stretchable knitted fabric samples exhibit different behaviours in different ranges of Reynolds numbers ($Re$). The air flow transition (from laminar to turbulent) was observed with all stretchable knitted fabric samples at different elongations. The transitional effects vary differently depending on the surface roughness over a range of $Re$ from $(1.00 \times 10^5$ to $1.83 \times 10^5$). The rough surface triggers the flow separation earlier than the smooth surface of the bare cylinder (Achenbach, 1971, 1974a, 1977; Achenbach & Heinecke, 1981; Blevins, 1984, 1985). No flow transition from the laminar to turbulent was observed with the bare cylinder due to the smooth surface of the cylinder in the $Re$ range tested and value of 0.56. However, all stretchable fabric samples from 0 mm (normal fit) to 100 mm (maximum fit) underwent a flow transition. Depending on the surface roughness, different fabric exhibited sequence backward of flow transitions occurred. All stretchable knitted fabrics have the same flow characterisations at different elongations. For example, K5 ($Ra = 41.67$ to $68.76 \mu m$) at varied elongations underwent the flow transition earlier (from $Re = 1.33 \times 10^5$ to $1.00 \times 10^5$) compared to all other knitted samples whereas the late transition occurred at K1 ($Ra = 12.06$ to $30.70 \mu m$) from $Re = 1.35 \times 10^5$ to $1.83 \times 10^5$. Among all cases, unstretched fabrics have the lowest $C_D$ values while the 100 mm elongation has the highest $C_D$ value. Since all samples are knitted fabrics, it is evident that there is a direct relationship between the $C_{D_{min}}$ and fabric elongation. In general, the rougher surface of the fabric extends the turbulent boundary layer by reducing the length of laminar boundary and ultimately delays the flow separation in comparison with the smooth surface of the test cylinder. As the knitted fabric samples elongated, the critical Reynolds number ($Re_{critical}$) decreases and the
minimal coefficient of drag ($C_{D_{min}}$) increases as shown in Figure 4.7. The findings agreed well with the related studies undertaken by (Achenbach, 1971, 1974a, 1977; Batham, 1973; Bearman & Harvey, 1993; Blevins, 1984, 1985; Chowdhury, 2012; Fage & Warsap, 1929; Fage & Warsap, 1930; Hoerner, 1965; Hughes & Brighton, 1967).

Figure 4.7: The variation of $C_D$ with Reynolds number for five knitted fabric with different relative roughness and the bare cylinder at $\alpha = 90^\circ$
Relative roughness ($\varepsilon$) has significant impact on air flow characteristics at $\alpha = 90^\circ$. The increased relative roughness enhances earlier transition from laminar to turbulent flow. However, it increases the magnitude of the minimum drag coefficient ($C_{D_{\text{min}}}$) value. A plot between the $C_{D_{\text{min}}}$ value and relative roughness ($\varepsilon$) of all stretchable fabric surfaces is shown in Figure 4.8. The figure indicates that the overall of knitted fabrics represent a linear relation between the relative roughness ($\varepsilon$) and the $C_{D_{\text{min}}}$. The linear equation which fits the data is minimum drag coefficient, $C_{D_{\text{min}}} = (0.0168 \times \varepsilon) + (0.3123)$ and the correlation coefficient is $R^2 = 0.9067$. Generally, with the decrease of relative roughness, the magnitude of $C_{D_{\text{min}}}$ value decreases as indicated previously (Achenbach, 1971, 1974a, 1977; Batham, 1973; Bearman & Harvey, 1993; Blevins, 1984, 1985; Chowdhury, 2012; Fage & Warsap, 1929; Fage & Warsap, 1930; Hoerner, 1965; Hughes & Brighton, 1967; Miller et al., 1975). Although, K1 had the minimum $\varepsilon$ value ranged from $1.39 \times 10^{-4}$ to $3.45 \times 10^{-4}$ while the maximum $\varepsilon$ value was obtained from $4.68 \times 10^{-4}$ to $7.73 \times 10^{-4}$ for K5. However, the lower $\varepsilon$ values (e.g., K1 and sample at lower elongation) can provide an aerodynamic advantage by reducing the drag at lower speeds. The higher relative roughness ($\varepsilon$) values (e.g., K5 and sample at maximum elongation) are advantage at higher speeds.

---

**Figure 4.8**: The minimum drag coefficient ($C_{D_{\text{min}}}$) variation with relative roughness ($\varepsilon$) of five knitted fabrics with different elongations at $\alpha = 90^\circ$. 
Figure 4.9 depicts a relationship of relative roughness ($\varepsilon$) of all knitted fabrics and $Re_{critical}$ based on $C_{Dmin}$ values obtained. The linear equation which fits the data is critical Reynolds number, $Re_{critical} = (-15125 \times \varepsilon) + (204980)$ and the correlation coefficient is $R^2 = 0.8929$. The standard regression value indicates a linear relation between the relative roughness and $Re_{critical}$. However, the figure shows that with the increase of relative roughness, the magnitude of $Re_{critical}$ value decreases. Also, with the sample elongated the magnitude of $Re_{critical}$ value decreases. Optical (Figure 4.3) and microscopic (Figure 4.4) analyses have revealed that the surface roughness of each knitted fabric is slightly altered with the distance from course to course and gap area between the courses. As a result, each knitted fabric with different elongations obtained different magnitude value of aerodynamic drag varied between 0.320 and 0.429 at $\alpha = 90^\circ$.

Figure 4.9: Critical Reynolds number ($Re_{critical}$) variation with relative roughness ($\varepsilon$) of five knitted fabrics at varied elongations at $\alpha = 90^\circ$
4.6.1.2 Surface Roughness $\alpha = 45^\circ$

The inclination angle of $45^\circ$ represents the half way of $\alpha = 0^\circ$ and $90^\circ$. In order to understand the effect of surface roughness at $\alpha = 45^\circ$, this study was conducted with all stretchable knitted fabrics at varied elongations. Figure 4.10 shows the variation of $C_D$ (left side) and $C_L$ (right side) with $(Re)$ for all knitted fabric with different relative roughness and the smooth cylinder.

The curves of all stretchable knitted fabric samples show different behaviours in different ranges of $(Re)$ for drag and lift as expected. Again, the air flow transition (from laminar to turbulent) was observed with all stretchable knitted fabric samples at different elongations. At laminar flow, the magnitude of $C_D$ (0.40) at $\alpha = 45^\circ$ was the lowest value compared to other aforementioned angles. The $C_D$ curve of the smooth cylinder gradually decreases at $Re = 1.34 \times 10^5$. All the stretchable knitted fabrics have the same flow characterisations at different elongations. The drag transitional effects vary differently depending on the surface roughness over a range of $Re$ from $(8.42 \times 10^4$ to $1.50 \times 10^5$). For example, K5 ($Ra = 41.67$ to $68.76 \mu m$) at varied elongations underwent the flow transition earlier (from $Re = 1.01 \times 10^5$ to $8.42 \times 10^4$) compared to all other knitted samples whereas the late transition occurred at K1 ($Ra = 12.06$ to $30.70 \mu m$) from $Re = 1.50 \times 10^5$ to $1.00 \times 10^5$. On the other hand, a continuing decreases of $C_L$ value was observed with the smooth cylinder at $Re = 1.34 \times 10^5$. However, all stretchable knitted fabrics have the same flow characterisations at different elongations.

With decrease of angle of attack, $C_L$ values at $\alpha = 45^\circ$ is higher than other aforementioned angles. Notably, the magnitude of $C_L$ generated higher values than the $C_D$ values at $\alpha = 45^\circ$. However, K5 ($Ra = 41.67$ to $68.76 \mu m$) at varied elongations underwent the flow transition earlier (from $Re = 1.01 \times 10^5$ to $8.42 \times 10^4$) compared to all other knitted samples whereas the late transition occurred at K1 ($Ra = 12.06$ to $30.70 \mu m$) from $Re = 1.50 \times 10^5$ to $1.00 \times 10^5$. 
The variation of minimum drag coefficient ($C_{D_{\text{min}}}$) with relative roughness ($\varepsilon$) of knitted fabrics with different elongations at $\alpha = 45^\circ$ is shown in Figure 4.11. However, the magnitude of the $C_{D_{\text{min}}}$ obtained lower values compared to the aforementioned angles due to the reduction of the projected frontal area. A direct relationship between the $C_{D_{\text{min}}}$ and fabric elongation was observed. The linear equation which fits the data is minimum drag coefficient, $C_{D_{\text{min}}} = (0.0142 \times \varepsilon) + (0.2423)$ and the correlation coefficient is $R^2 = 0.9581$. The unstretched fabrics have the lowest $C_{D_{\text{min}}}$ values while with the elongation to 100 mm the $C_{D_{\text{min}}}$ value increased. For example, K1 has the lowest $C_{D_{\text{min}}}$ values where the value increases consistent with K2, K3, K4 and K5 respectively due to increase in relative roughness. At the same time, the linear equation which fits the data is minimum lift coefficient, $C_{L_{\text{min}}} = (0.0152 \times \varepsilon) + (0.3544)$ and the correlation coefficient is $R^2 = 0.853$. However, unstretched fabrics have the lowest $C_{L_{\text{min}}}$
values while with the elongation to 100 mm $C_{Lmin}$ values increased. K1 has the lowest $C_L$ values where K2, K3, K4 and K5 obtained the higher $C_{Lmin}$ values as shown in Figure 4.12.

**Figure 4.11:** The minimum drag coefficient ($C_{Dmin}$) variation with relative roughness ($\epsilon$) of five knitted fabrics with different elongations at $\alpha = 45^\circ$

**Figure 4.12:** The minimum drag coefficient ($C_{Lmin}$) variation with relative roughness ($\epsilon$) of five knitted fabrics with different elongations at $\alpha = 45^\circ$
Figure 4.13 illustrates the relationship of relative roughness ($\varepsilon$) of all knitted fabrics and $Re_{critical}$ based on $C_{Dmin}$ values. The figure shows that a linear relationship between the relative roughness and the $Re_{critical}$. The linear equation which fits the data is critical Reynolds number, $Re_{critical} = (-12758 \times \varepsilon) + (164474)$ and the correlation coefficient is $R^2 = 0.8103$. All stretchable knitted fabric with different elongations obtained different magnitude value of $Re_{critical}$ varied between $1.50 \times 10^5$ and $8.42 \times 10^4$. The lowest $Re_{critical}$ was found at K5 while the highest $Re_{critical}$ obtained at K1.

Figure 4.13: Critical Reynolds number ($Re_{critical}$) variation with relative roughness ($\varepsilon$) of five knitted fabrics at varied elongations at $\alpha = 45^\circ$

Figure 4.14 indicates the variation of $L/D$ with relative roughness ($\varepsilon$) of all knitted fabrics at varied elongations $\alpha = 45^\circ$. A linear relationship between the relative roughness and the $L/D$ was observed. The linear equation which fits the data is critical glide ration, $L/D = (-0.0151 \times \varepsilon) + (1.4499)$ and the correlation coefficient is $R^2 = 0.6091$. The maximum value of $L/D$ was found at K1 and maximum elongation for each fabric while the lowest $L/D$ obtained at K5 and minimum elongation for each fabric. This study revealed that this angle with the surface roughness is a critical angle which changed the aerodynamic glide ration. Also, the effect of ellipsoidal head might change the effect of surface roughness. Therefore, the surface
roughness and the angle of attack affect the aerodynamic properties and can obtain the optimum outcome for the elite athlete.

![Graph showing the variation of L/D with relative roughness (ε) of five knitted fabrics at varied elongations at α = 45°](image)

**Figure 4.14: The variation of L/D with relative roughness (ε) of five knitted fabrics at varied elongations at α = 45°**

### 4.6.1.3 Surface Roughness α = 0°

This study carried out to examine the effect of surface roughness at streamwise orientation (α = 0°). Figure 4.15 illustrates the variation of $C_D$ (left side) and $C_L$ (right side) with Reynolds number for five knitted fabric with different relative roughness and the bare cylinder at α = 0°.

The curves of all stretchable knitted fabric samples show similar aerodynamic behaviours. No flow transition from the laminar to turbulent was observed with the smooth cylinder due to the boundary layer effect. However, all stretchable fabric samples from 0 mm (normal fit) to 100 mm (maximum fit) did not have flow transition. Depending on the surface roughness, different fabric obtained different magnitude of $C_D$ values. Also, all stretchable knitted fabrics have the same flow characterisation at different elongations. For example, the K1 ($Ra = 12.06$ to $30.70 \ \mu m$) at varied elongations generated the lowest magnitude of $C_D$ values (0.195 to}
0.210) compared to all other knitted samples whereas K5 (Ra = 41.67 to 68.76 μm) obtained the highest $C_D$ values varied from 0.202 to 0.217.

![Graphs showing $C_D$ vs. $Re$ for K1, K2, K3, K4, and K5](image)

Figure 4.15: The variation of $C_D$ (left side) and $C_L$ (right side) with Reynolds number for five knitted fabric with different relative roughness and the bare cylinder at $\alpha = 0^\circ$
The variation of minimum drag coefficient \((C_{D_{\text{min}}})\) with relative roughness \((\varepsilon)\) of knitted fabrics with different elongations at \(\alpha = 0^\circ\) is shown in Figure 4.16. The magnitude of the \(C_D\) value is higher than the \(C_D\) values at \(\alpha = 15^\circ\) and \(30^\circ\). However, a direct linear relationship between the \(C_{D_{\text{min}}}\) and fabric elongation was observed. The linear equation which fits the data is minimum drag coefficient, \(C_{D_{\text{min}}} = (0.0033 \times \varepsilon) + (0.1935)\) and the correlation coefficient is \(R^2 = 0.7342\). Again, unstretched fabrics have the lowest \(C_{D_{\text{min}}}\) values while with the elongation to 100 mm the \(C_{D_{\text{min}}}\) value increased. For example, K1 has the lowest \(C_{D_{\text{min}}}\) values (0.195) where the value increases consistently with K2, K3, K4 and K5 due to increase in relative roughness.

Figure 4.16: The minimum drag coefficient \((C_{D_{\text{min}}})\) variation with relative roughness \((\varepsilon)\) of five knitted fabrics with different elongations at \(\alpha = 0^\circ\)
Figure 4.17 represents the relationship of relative roughness ($\varepsilon$) of all knitted fabrics and $Re_{critical}$ based on $C_{Dmin}$ values. The figure shows that a linear relationship between the relative roughness and the $Re_{critical}$. The linear equation which fits the data is critical Reynolds number, $Re_{critical} = (-85.786 \times \varepsilon) + (167687)$ and the correlation coefficient is $R^2 = 0.2685$. All stretchable knitted fabric with different elongations obtained different magnitude value of $Re_{critical}$ varied between $1.678 \times 10^5$ and $1.669 \times 10^5$. However, the highest $Re_{critical}$ obtained at K1 and due the increment of relative roughness the $Re_{critical}$ decreased (K2, K3, K4 and K5 respectively).

![Figure 4.17: The minimum drag coefficient ($C_{Lmin}$) variation with relative roughness ($\varepsilon$) of five knitted fabrics with different elongations at $\alpha = 0^\circ$](image-url)
4.6.2 Effect of Distance between Courses on Stretchable Knitted Sport Fabrics

The distance between courses is an important parameter which affects the critical Reynolds number appreciably. As demonstrated earlier in the optical and electron analysis that the elongation of knitted fabrics changes the microstructure of each sample. It is believed that the fabric structural patterns characteristics are important from the view of the influence on the fabric distance from course to course. However, the non-dimensional elongation (course to course distance) of stretchable sport knitted fabrics with an optical image analysis at varied elongations (0 to 100 mm) is illustrated earlier in Table 4.3 and Figure 4.3. The variation of $C_{Dmin}$ with the fabric non-dimensional elongation (distance between courses) at variable angles of attack ($\alpha = 0^\circ$ to $90^\circ$) are shown in Figure 4.18.

From the figure, it is clearly evident that the $C_{Dmin}$ correlates linearly with non-dimensional elongation (course to course distance) of stretchable knitted fabrics used in this study at varied angles of attack. The $C_{Dmin}$ values increase continuously with the amount of fabric elongations without any sudden drop. The relationship at different inclination angles also indicates that K1 (smooth surface) with lowest non-dimensional elongation (course to course distance) has the minimum values of $C_{Dmin}$. Conversely, K5 (rough surface) obtained the maximum values of $C_{Dmin}$ due to the increment in distance between courses. However, the distance between courses is so important in terms of flow transition at specific Reynolds numbers ($Re$). It is believed that there is a strong relationship between the surface roughness (average height) and the distance between courses. As a result, as the distance between courses increases, the minimal coefficient of drag ($C_{Dmin}$) increases and the critical Reynolds number ($Re_{critical}$) decreases.
Figure 4.18: Variation of $C_{D\text{min}}$ with non-dimensional elongation (course to course distance), $X_n/X_1$ of five stretchable knitted fabrics.
4.6.3 Effect of Gap Area between Courses on Stretchable Knitted Sport Fabrics

The gap area between the courses is also an important aspect for stretchable knitted sport fabrics. In elongation cases, the gap area between courses changed and affected the aerodynamic properties at specific Reynolds number ($Re$). The angle of attack of the cylinder also generated different magnitudes of aerodynamic drag and lift. Figure 4.19 illustrates the investigation of the effect of gap area between the courses in stretchable knitted fabrics on the aerodynamic performance at variable angles of attack ($\alpha = 0^\circ$ to $90^\circ$). The fabric non-dimensional elongation (gap area between courses) of stretchable sport knitted fabrics varied from 0 to 100 mm is shown earlier in Table 4.3.

It is noted that the gap area between the courses in knitted fabric also influences the air flow regime passing over the surface of the cylindrical surface. Also, a linear correlation between the $C_{D_{\text{min}}}$ and non-dimensional elongation (gap area) of all stretchable knitted fabrics at varied angles of attack. The $C_{D_{\text{min}}}$ values increase continuously with the amount of fabric elongations without any sudden drop. The relationship at different inclination angles also indicates that K1 (smooth surface) with lowest non-dimensional elongation (gap area) has the minimum values of $C_{D_{\text{min}}}$. Whereas K5 (rough surface) obtained the maximum values of $C_{D_{\text{min}}}$ due to the increments in the gap area between courses. At the same time, elongated the fabric also increase the magnitude to $C_{D_{\text{min}}}$. Therefore, the gap area between the courses is so important in terms of flow transition at specific Reynolds number ($Re$). It is believed that there is a strong relationship between the surface roughness (average height) and the gap area between courses in stretchable knitted fabrics. As a result, as the gap area between courses increases, the minimal coefficient of drag ($C_{D_{\text{min}}}$) increases and the critical Reynolds number ($Re_{\text{critical}}$) decreases.
Figure 4.19: Variation of $C_{D_{\text{min}}}$ with non-dimensional elongation (gap area), $A_n/A_1$ of five stretchable knitted fabrics
4.7 Summary

The surface morphology of all stretchable knitted fabrics produced a notable effect on the aerodynamic properties (drag and lift) and is directly dependent on the surface roughness, distance and gap area between courses. As the knitted fabric is elongated laterally from 0 mm (normal fit) to 100 mm (maximum fit), the increment of $C_{D_{\min}}$ values increases respectively without any sudden change. However, the knitted fabric with lower relative roughness, distance and gap area between courses can create an advantage in aerodynamic properties by reducing the drag at higher speeds. In contrast, the higher relative roughness, distance and gap area between courses can also provide an aerodynamic advantage by reducing drag at lower Reynolds numbers. The surface texture can be utilized to maximize the aerodynamic benefit for various speed ranges. By increasing the surface roughness of knitted fabrics (stretch), the flow can be tripped into turbulence at lower Reynolds numbers, potentially decreasing drag. It also shows however, that after the initial reduction in drag coefficient the drag then increases quickly with increasing Reynolds number due to high levels of friction drag associated with turbulent flow. Thus increasing the surface roughness can significantly increase the total drag if the flow is tripped prematurely due to increasing the roughness of the surface already in turbulent flow. A suitable selection of stretchable sport knitted fabric and garment fit for elite athletes is vital for achieving aerodynamic advantages. Similarly, the angle of attack is crucial in term of speed sport applications to maintain the maximum glide ratio and obtain the appropriate posture for the elite athlete.
CHAPTER 5
AERODYNAMIC BEHAVIOUR OF
STRETCHABLE SPORTS WOVEN FABRICS
Aerodynamic behaviour of speed sports woven fabrics can play a significant role in a wide range of speed sports including downhill skiing, ski-jumping and swimming. In speed sports, woven garments are skin-fitted with reasonable tension. The main objective of this chapter is to investigate the effects of different stretchable woven speed sport fabrics. These including, surface roughness, distance and gap area between wefts on aerodynamic properties (drag and lift) and their correlations at varied elongations (0 to 100 mm). As mentioned earlier in Chapter 3, the variable angle of attack cylindrical arrangement with 60 mm ellipsoidal head is used in this study to develop correlation between the aerodynamic parameters with the physical parameters of five stretchable woven speed sports fabrics under varied angles of attack ($\alpha = 0^\circ$ to $90^\circ$).

5.1 Woven Fabric Characterisation

Woven fabric unlike the knitted fabric where the yarns crossover one another (Lord, 1973; Shishoo, 2005; Tokarska & Gniotek, 2005). The woven fabric is produced by a series of parallel yarns placed perpendicularly to another set of parallel yarns (right angle). The yarns that go down the length of the fabric defined as warp (lengthwise) where the weft is that yarns threaded from side to side, over and underneath warp yarns to make fabric (crosswise). Figure 5.1 illustrates the structure of a common woven fabric stitch.

![Structure of a common woven fabric stitch](image_url)
5.1 Photographic Characterisation of Stretchable Woven Fabrics

Five commercially available woven stretchable fabrics (W1, W2, W3, W4 and W5) were selected for this study. Each of the woven fabric has different properties that are useful in sportswear. Figure 5.2 illustrates photographs of the smooth cylinder and five samples examined in this study. The yellow line indicates the warp direction (vertical) while the fabric stretched in the weft direction with red line (horizontal). Table 4.1 provides the material composition, thickness and weft direction of each sample fabric.
5.2 Microstructural Analysis of Stretchable Woven Fabrics

With a view to understand the surface morphology such as yarn and fibre size, and stitch pattern of five stretchable woven fabrics at varied elongations (stretches), an optical and electron microscopic study were performed.

5.2.1 Optical Image Analysis

The optical microscope was used to study the fabric surface morphology under different elongations staring from 0 mm (normal fit) to 100 mm (maximum fit) with an increment of 20 mm extension. As mentioned earlier, the maximum elongation level (100 mm) is located within the elastic condition for all woven fabric samples. A hysteresis analyse for all woven fabrics was undertaken.

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**Table 5.1: Material composition and thickness of five sport woven fabrics**

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Material composition</th>
<th>Thickness, (mm)</th>
<th>Weft direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>70% Polyamide and 30% Elastane</td>
<td>0.27</td>
<td>0°</td>
</tr>
<tr>
<td>W2</td>
<td>66% Polyamide and 34% Elastane</td>
<td>0.27</td>
<td>0°</td>
</tr>
<tr>
<td>W3</td>
<td>64% Polyamide and 36% Elastane</td>
<td>0.27</td>
<td>0°</td>
</tr>
<tr>
<td>W4</td>
<td>87% Cotton and 13% Elastane</td>
<td>0.36</td>
<td>0°</td>
</tr>
<tr>
<td>W5</td>
<td>60% Rayon, 32% Polyester and 8% Elastane</td>
<td>0.55</td>
<td>0°</td>
</tr>
</tbody>
</table>
Figure 5.3: Optical images of woven fabrics surface at 0(left), 50(middle) and 100mm (right)
As shown in Figure 5.3, optical images with 15 times magnification illustrated the numbers of weft and warp per cm and the gaps between the wefts during the elongation process at 0, 50 and 100 mm extension respectively. The stretch direction applied in the weft direction in order to obtain the maximum fabric elongation. In addition, Table 5.2 and Table 5.3 represent the obtained data from optical image analyses. Further images about the woven fabrics at 20, 40, 60 and 80 mm elongations are giving in Appendix E.2.

Table 5.2: Number of wefts and warps per cm of five sport woven fabrics with optical image analysis

<table>
<thead>
<tr>
<th>Fabric Elongation (mm)</th>
<th>No. of Wefts per cm</th>
<th>No. of Warps per cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W1</td>
<td>W2</td>
</tr>
<tr>
<td>0</td>
<td>43</td>
<td>41</td>
</tr>
<tr>
<td>20</td>
<td>39</td>
<td>37</td>
</tr>
<tr>
<td>40</td>
<td>37</td>
<td>35</td>
</tr>
<tr>
<td>60</td>
<td>35</td>
<td>33</td>
</tr>
<tr>
<td>80</td>
<td>33</td>
<td>31</td>
</tr>
<tr>
<td>100</td>
<td>31</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 5.3: Fabrics characterization of five sport woven fabrics with optical image analysis

<table>
<thead>
<tr>
<th>Fabric Elongation (mm)</th>
<th>Gap Area, (μm² × 10^3)</th>
<th>Weft to Weft, (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W1</td>
<td>W2</td>
</tr>
<tr>
<td>0</td>
<td>14.32</td>
<td>15.12</td>
</tr>
<tr>
<td>20</td>
<td>17.6</td>
<td>18.87</td>
</tr>
<tr>
<td>40</td>
<td>18.78</td>
<td>20.15</td>
</tr>
<tr>
<td>60</td>
<td>20.31</td>
<td>21.73</td>
</tr>
<tr>
<td>80</td>
<td>21.68</td>
<td>23.15</td>
</tr>
<tr>
<td>100</td>
<td>22.64</td>
<td>24.44</td>
</tr>
</tbody>
</table>
5.2.2 Electron Microscopic Image Analysis

A scanning electron microscope (SEM) was used to examine the surface structure of all stretchable woven fabrics at varied magnification at 100 and 1000. The yarn size and fibre diameter are shown in Figure 5.4 and Figure 5.5. Table 5.4 illustrates the individual yarn size, fibre diameter and stitch pattern for all stretchable woven fabrics used in this study.
Figure 5.4: SEM images of five stretchable woven fabric surfaces with 100X magnification, (left side) unstretched fabric and (right side) stretched fabric
Figure 5.5: SEM images of five woven fabric surfaces with 1000X magnification
Table 5.4: Five woven fabrics characterization with SEM image

<table>
<thead>
<tr>
<th>Fabric No.</th>
<th>Yarn size (μm)</th>
<th>Fibre size (μm)</th>
<th>Stitch pattern</th>
<th>Unstretched</th>
<th>Stretched</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>100</td>
<td>18.89</td>
<td>Rectangular</td>
<td>Rectangular</td>
<td>Rectangular</td>
</tr>
<tr>
<td>W2</td>
<td>106</td>
<td>19.05</td>
<td>Rectangular</td>
<td>Rectangular</td>
<td>Rectangular</td>
</tr>
<tr>
<td>W3</td>
<td>110</td>
<td>19.11</td>
<td>Rectangular</td>
<td>Rectangular</td>
<td>Rectangular</td>
</tr>
<tr>
<td>W4</td>
<td>122</td>
<td>16.13</td>
<td>Rectangular</td>
<td>Rectangular</td>
<td>Rectangular</td>
</tr>
<tr>
<td>W5</td>
<td>178</td>
<td>22.22</td>
<td>Rectangular</td>
<td>Rectangular</td>
<td>Rectangular</td>
</tr>
</tbody>
</table>

5.3 Woven Fabric Surface Profile

All five woven fabric samples were prepared at the same dimensions (220 mm width and 320 mm length) and three samples of each fabric were measured. Each sample stretched in the weft direction till it reached 100 mm extension from zero. The KESFB4-A automatic surface tester was used to measure each fabric’s frictional properties and geometrical surface roughness under various tension levels as mentioned in section 2.5.2. The average height of the surface area ($Ra$) then obtained from the fabric surface profile measurement. Surface roughness measurements are based on the surface profile measurement. Characteristic of roughness is a variation coefficient of the surface height. The error margin in this measurement was also calculated. Table 5.5 shows the average value of five stretchable woven fabric heights with standard deviation and elongation from 0 mm to 100 mm. The maximum error was found to be approximately ±4%. Further information for each woven fabric can be found in Appendix D.2.2.

Table 5.5: Average height of five woven fabric surface measurement

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Average height of woven fabric surface $Ra$, (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 mm</td>
</tr>
<tr>
<td>W1</td>
<td>14.56±0.77</td>
</tr>
<tr>
<td>W2</td>
<td>16.85±0.13</td>
</tr>
<tr>
<td>W3</td>
<td>19.49±0.57</td>
</tr>
<tr>
<td>W4</td>
<td>23.22±0.65</td>
</tr>
<tr>
<td>W5</td>
<td>32.83±0.17</td>
</tr>
</tbody>
</table>
5.4 Measurement of Woven Fabric Stretchability

In order to study the stretchability of commercially woven fabric samples, an Instron universal test machine was used as mentioned in section 2.5.1. Initially, all the fabric samples were prepared at the same dimensions of 220 mm width and 320 mm length and the thickness of fabrics are shown in Table 5.1. According to the standard test method as described in ASTM Standard D5034-95 for the breaking strength and elongation of woven fabrics, the loading rate was set at 300 mm/min. Each sample was measured three times and stretched in the weft direction till it reached 100 mm extension from zero. The variations of tensile force with fabric elongation for all stretchable woven fabrics are shown in Figure 5.6. Detailed about the fibres and their properties are described in (Wardiningsih, 2009).

![Figure 5.6: The variation of tensile force with fabric elongation of five stretchable woven fabrics](image-url)
5.5 Aerodynamic Characterisation of Stretchable Woven Sports Fabrics

In order to evaluate the aerodynamic characterisation of stretchable woven fabrics, a variable angles of attack cylindrical arrangement with 60 mm ellipsoidal head was used for this study. It is important to note that all the woven fabrics have been conducted at varied elongations from 0 mm to 100 mm and angles of attack from $\alpha = 0^\circ$ to $90^\circ$ with an increment of $15^\circ$ for the following sections. The wind speeds ranged from 30 to 140 km/h in increments of 10 km/h. The aerodynamic parameters are then correlated with the physical parameters. The principle aerodynamic parameters used in this study where drag ($F_D$) and lift ($F_L$) and their non-dimensional coefficient ($C_D$) and ($C_L$). The physical parameters of the fabrics are the surface roughness, course to course distance and gap area between the wefts at varied elongations. The correlations of the aerodynamic and physical parameter are discussed in the following subsections.

5.5.1 Effect of Surface Roughness on Stretchable Woven Sport Fabrics

The structural pattern of woven fabric depends on the appearance of weft and warp on their surface. Fabric structural patterns characteristics are important from the view of the influence on the surface roughness. Fabric surface roughness is an important parameter which affects the critical Reynolds number appreciably (Achenbach, 1968, 1971, 1974a, 1977; Hoerner, 1965; Kyle & Caiozzo, 1986; Spring et al., 1988; Szechenyi, 1975). Table 5.6 shows the average relative roughness of five stretchable woven fabrics. The relative roughness parameter ($\varepsilon$) was estimated for each fabric sample at specific elongation. The roughness was normalized dividing by the test cylinder diameter ($d$).

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Average relative roughness of woven fabric surface, ($\varepsilon = Ra/d$)$\times 10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>1.636</td>
</tr>
<tr>
<td>W2</td>
<td>1.893</td>
</tr>
<tr>
<td>W3</td>
<td>2.190</td>
</tr>
<tr>
<td>W4</td>
<td>2.610</td>
</tr>
<tr>
<td>W5</td>
<td>3.689</td>
</tr>
</tbody>
</table>

Table 5.6 indicates that each fabric sample has different relative roughness ($\varepsilon$). This study shows that the value of ($\varepsilon$) of each woven fabric sample elongated within the elastic region

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significantly decreases. Hence, the following sections are discussing the effect of the surface roughness ($\varepsilon$) of all stretchable woven speed sport fabrics on aerodynamic parameters (drag and lift). Only, 0°, 45° and 90° angle of attack ($\alpha$) are presented here whereas 15°, 30°, 60° and 75° are provided in Appendix G.

5.5.1.1 Surface Roughness $\alpha = 90^\circ$

To understand the effect of surface texture, the cylinder fitted with woven fabrics at varied fabric elongations were tested at $\alpha = 90^\circ$. As the incoming air flow is perpendicular to the cylinder, the drag force is more dominant. Figure 4.7 shows the variation of $C_D$ with Reynolds number for all woven fabric with different relative roughness and the bare smooth cylinder at $\alpha = 90^\circ$.

The graphical display of all stretchable woven fabric samples exhibit different behaviours in different ranges of Reynolds numbers. The air flow transition (from laminar to turbulent) was observed with five stretchable woven fabric samples at different elongations. The transitional effects vary differently depending on the surface roughness over a range of $Re$ from $(1.17 \times 10^5$ to $2.34 \times 10^5)$. The rough surface triggers the flow separation earlier than the smooth surface of the bare cylinder (Achenbach, 1968, 1971, 1974a, 1977; Blevins, 1984, 1985; Güven et al., 1976; Hoerner, 1965; Kyle & Caiozzo, 1986; Spring et al., 1988; Szechenyi, 1975). No flow transition from the laminar to turbulent was observed with the bare cylinder due to the smooth surface of the cylinder in the $Re$ range tested and value of 0.56. All stretchable woven fabric samples from 0 mm (normal fit) to 100 mm (maximum fit) underwent a flow transition. All stretchable woven fabrics have the same flow characterisations at different elongations. Notably, the stretchable woven fabric samples exhibit a slight reduction in relative roughness values within elongation applied. However, each fabric at 0 mm elongation generated an early flow transition and then jump to late transition til 20 mm elongation. Then, sequence backward flow transitions occurred with the increase in fabric elongations. However, depending on the surface roughness at normal fit (0 mm), W5 ($Ra = 32.83$ μm) underwent the flow transition earlier at $Re = 1.17 \times 10^5$ compared to all other woven samples whereas the late transition occurred with W1 ($Ra = 14.56$ μm) at $Re = 2.34 \times 10^5$. Among all the fabrics elongated from 20 to 100 mm, W5 ($Ra = 30.81$ to 25.98 μm) generated early flow transition from $Re = 2.00 \times 10^5$ to 1.69 $\times 10^5$ whereas W1 ($Ra = 13.53$ to 11.74 μm) obtained late transition at $Re = 2.34 \times 10^5$ to 2.01 $\times 10^5$. Since all samples are woven fabrics, it is evident that there is a direct relationship between the $C_{D_{min}}$ and fabric elongation. The rougher surface of all stretchable woven fabrics at normal fit (0
mm) extends the turbulent boundary layer by reducing the length of laminar boundary and ultimately delays the flow separation in comparison with the smooth surface of the test cylinder. Although, a slight reduction in relative roughness was found with woven fabric elongation to 100 mm, the critical Reynolds number \( (Re_{\text{critical}}) \) decreases and the minimal coefficient of drag \( (C_{D_{\text{min}}}) \) increases.

**Figure 5.7:** The variation of \( C_D \) with Reynolds number for five woven fabric with different relative roughness and the bare cylinder at \( \alpha = 90° \)
Relative roughness ($\varepsilon$) has significant impact on air flow characteristics at $\alpha = 90^\circ$. For example, the fabric at 0 mm elongation, an increase in relative roughness enhances earlier transition from laminar to turbulent flow. However, it increases the magnitude of the minimum drag coefficient ($C_{D_{min}}$) value. However, a sudden late jump in flow transition and drop in $C_{D_{min}}$ was obtained at 20 mm elongation. A plot between $C_{D_{min}}$ value and relative roughness ($\varepsilon$) of all stretchable fabric surfaces is shown in Figure 5.8. The figure indicates that the overall of all woven fabrics after 0 mm, represent a linear relation between the relative roughness ($\varepsilon$) and the $C_{D_{min}}$. The linear equation which fits the data is minimum drag coefficient, $C_{D_{min}} = (0.0321 \times \varepsilon) + (0.3272)$ and the correlation coefficient is $R^2 = 0.3162$. W1 obtained the lower $C_{D_{min}}$ values at 20 mm which can provide an aerodynamic advantage by reducing the drag at higher speeds while W5 at 20 mm has an advantage at lower speeds.

![Figure 5.8: The minimum drag coefficient ($C_{D_{min}}$) variation with relative roughness ($\varepsilon$) of five woven fabrics with different elongations at $\alpha = 90^\circ$](image_url)
Figure 5.9 depicts a relationship of relative roughness ($\epsilon$) of all woven fabrics and $Re_{critical}$ based on $C_{D_{min}}$ values obtained. The linear equation which fits the data is critical Reynolds number, $Re_{critical} = (-24464 \times \epsilon) + (248996)$ and the correlation coefficient is $R^2 = 0.2647$. The standard regression value indicates a linear relation (starts at 20 mm elongation) between the relative roughness and the $Re_{critical}$. However, the figure shows that with the increase of relative roughness at 0 mm, the magnitude of $Re_{critical}$ value decreases. Also, when the sample elongated the magnitude of $Re_{critical}$ value decreases. Optical (Figure 5.3) and microscopic (Figure 4.4) analyses have revealed that the surface roughness of each woven fabric is slightly altered with the distance from course to course and gap area between the courses. As a result, each woven fabric with different elongations obtained different magnitude value of aerodynamic drag varied between 0.330 and 0.488 at $\alpha = 90^\circ$. However, due the limit of speed at RMIT Industrial Wind Tunnel, the finding of W1 and W2 from 20 to 60 mm elongations did not show $Re_{critical}$ values.

![Figure 5.9: Critical Reynolds number ($Re_{critical}$) variation with relative roughness ($\epsilon$) of five woven fabrics at varied elongations at $\alpha = 90^\circ$](image-url)
5.5.1.2 Surface Roughness $\alpha = 45^\circ$

The inclination angle of $45^\circ$ represents the half way of $\alpha = 0^\circ$ and $90^\circ$. In order to understand the effect of surface roughness at $\alpha = 45^\circ$, this study was conducted at varied elongations. Figure 5.10 shows the variation of $C_D$ (left side) and $C_L$ (right side) with Reynolds number for all woven fabrics with different relative roughness and the smooth cylinder.

The curves show different behaviours in different ranges of Reynolds numbers for drag and lift as expected. The air flow transition (from laminar to turbulent) was observed with five stretchable woven fabric samples at different elongations. At laminar flow, the magnitude of $C_D$ (0.40) at $\alpha = 45^\circ$ was the lowest value compared to other aforementioned angles. The $C_D$ curve of the smooth cylinder gradually decreases at $Re = 1.34 \times 10^5$. All stretchable woven fabrics have the same flow characterisations at different elongations over a range of $Re$ from $(1.00 \times 10^5$ to $2.34 \times 10^5)$. All the fabrics at 0 mm elongation created an early flow transition and then jump for late transition within 20 mm elongation. Then, sequence backward flow transitions occurred with the increase in fabric elongation. However, depending on the surface roughness at normal fit (0 mm), W5 ($Ra = 32.83 \, \mu m$) underwent the flow transition earlier at $Re = 1.00 \times 10^5$ compared to all other woven samples whereas the late transition occurred with W1 ($Ra = 14.56 \, \mu m$) at $Re = 2.34 \times 10^5$. Among all the fabrics elongated from 20 to 100 mm, W5 ($Ra = 30.81$ to $25.98 \, \mu m$) generated early flow transition from $Re = 1.86 \times 10^5$ to $1.33 \times 10^5$ whereas W1 ($Ra = 13.53$ to $11.74 \, \mu m$) obtained late transition at $Re = 2.34 \times 10^5$ to $1.84 \times 10^5$. At the same time, a continuing decreases of $C_L$ value was observed with the smooth cylinder at $Re = 1.31 \times 10^5$. However, all stretchable woven fabrics have the same flow characterisations at different elongations. The magnitude of $C_L$ values is two times less than the $C_D$ values due the higher angle of attack. Again, at normal fit (0 mm), W5 ($Ra = 32.83 \, \mu m$) underwent the flow transition earlier at $Re = 1.00 \times 10^5$ compared to all other woven samples whereas the late transition occurred with W1 ($Ra = 14.56 \, \mu m$) at $Re = 2.34 \times 10^5$. Among all the fabrics elongated from 20 to 100 mm, W5 ($Ra = 30.81$ to $25.98 \, \mu m$) generated early flow transition from $Re = 1.84 \times 10^5$ to $1.34 \times 10^5$ whereas W1 ($Ra = 13.53$ to $11.74 \, \mu m$) obtained late transition at $Re = 2.34 \times 10^5$ to $1.84 \times 10^5$. 
The variation of minimum drag coefficient ($C_{D_{\text{min}}}$) with relative roughness ($\varepsilon$) with different elongations at $\alpha = 45^\circ$ is shown in Figure 5.11. However, the magnitude of the $C_{D_{\text{min}}}$ generated lower values compared to the aforementioned angles due to the reduction in the projected frontal area. A direct linear relationship (starts at 20 mm) between the $C_{D_{\text{min}}}$ and fabric elongation was observed. The linear equation which fits the data is minimum drag coefficient, $C_{D_{\text{min}}} = (0.0258 \times \varepsilon) + (0.2108)$ and the correlation coefficient is $R^2 = 0.3145$. Again, in this study, the unstretched fabrics at 0 mm elongation have the highest $C_{D_{\text{min}}}$ values while the 20 mm elongation has the lowest $C_{D_{\text{min}}}$ value. With applying elongation on the fabric after 20 mm, the $C_{D_{\text{min}}}$ values increases. W1 has the lowest $C_{D_{\text{min}}}$ values where the value increases consistent with W2, W3, W4 and W5. On the other hand, unstretched fabrics have the highest $C_{L_{\text{min}}}$ values while 20 mm elongation has the lowest $C_{L_{\text{min}}}$ values as shown in Figure 5.12. Again, with the elongation of the fabric after 20 mm, the $C_{L_{\text{min}}}$ values increases.
A direct linear relationship (starts from 20 mm elongation) between the $C_{L_{min}}$ and fabric elongation was obtained. The linear equation which fits the data is minimum lift coefficient, $C_{L_{min}} = (0.0338 \times \varepsilon) + (0.23)$ and the correlation coefficient is $R^2 = 0.2937$. However, W1 obtained the lowest $C_{L_{min}}$ values where W2, W3, W4 and W5 obtained higher $C_{L_{min}}$ values constantly.

Figure 5.11: The minimum drag coefficient ($C_{D_{min}}$) variation with relative roughness ($\varepsilon$) of five woven fabrics with different elongations at $\alpha = 45^\circ$

Figure 5.12: The minimum drag coefficient ($C_{L_{min}}$) variation with relative roughness ($\varepsilon$) of five woven fabrics with different elongations at $\alpha = 45^\circ$
Figure 5.13 illustrates the relationship of relative roughness ($\varepsilon$) and $Re_{critical}$ based on $C_{D_{min}}$ values. The figure shows that a linear relationship (starts from 20 mm) between the relative roughness and the $Re_{critical}$. The linear equation which fits the data is critical Reynolds number, $Re_{critical} = (-26571 \times \varepsilon) + (237194)$ and the correlation coefficient is $R^2 = 0.2972$. All stretchable woven fabric with different elongations obtained different magnitude value of $Re_{critical}$ varied between $1.00 \times 10^5$ and $2.34 \times 10^5$. The lowest $Re_{critical}$ was found at W5 while the highest $Re_{critical}$ obtained at W1.

Figure 5.13: Critical Reynolds number ($Re_{critical}$) variation with relative roughness ($\varepsilon$) of five woven fabrics at varied elongations at $\alpha = 45^\circ$

Figure 5.14 illustrates the variation of $L/D$ with relative roughness ($\varepsilon$) of all woven fabrics at varied elongations $\alpha = 45^\circ$. A linear relationship (starts from 20 mm) between the relative roughness and the $L/D$ was observed. The linear equation which fits the data is critical glide ratio, $L/D = (0.0151 \times \varepsilon) + (1.1012)$ and the correlation coefficient is $R^2 = 0.1702$. The maximum value of $L/D$ was found at W5 and normal fit (0 mm elongation) while the lowest $L/D$ obtained at W1 and 20 mm elongation. As a result, the surface roughness and the angle of attack affect the aerodynamic properties and can obtain the optimum outcome for the elite athlete. This study revealed that this angle with the surface roughness is a critical angle which
changed the aerodynamic glide ratio. Also, the effect of ellipsoidal head might change the effect of surface roughness. As a result, the surface roughness and the angle of attack affect the aerodynamic properties.

![Graph showing the variation of L/D with relative roughness for five woven fabrics at varied elongations at α = 45°](image)

**Figure 5.14:** The variation of L/D with relative roughness ($\varepsilon$) of five woven fabrics at varied elongations at $\alpha = 45^\circ$

### 5.5.1.3 Surface Roughness $\alpha = 0^\circ$

This study carried out to investigate the effect of surface roughness at streamwise orientation ($\alpha = 0^\circ$). Figure 5.15 illustrates the variation of $C_D$ (left side) and $C_L$ (right side) with Reynolds number with different relative roughness and the bare cylinder.

The curves show similar aerodynamic behaviour. No flow transition from the laminar to turbulent was observed with the smooth cylinder due to the boundary layer effect. However, fabrics from 0 mm (normal fit) to 100 mm (maximum fit) did not show flow transition. However, depending on the surface roughness at varied elongations, W5 ($Ra = 32.83$ to $25.98 \mu m$) obtained higher $C_D$ values compared to all other woven samples whereas the minimum was found in W1 ($Ra = 14.56$ to $11.74 \mu m$).
Figure 5.15: The variation of $C_D$ (left side) and $C_L$ (right side) with Reynolds number for five woven fabric with different relative roughness and the bare cylinder at $\alpha = 0^\circ$
The variation of minimum drag coefficient \( (C_{D_{\text{min}}}) \) with relative roughness \( (\varepsilon) \) with different elongations at \( \alpha = 0^\circ \) is shown in Figure 5.16. The magnitude of the \( C_D \) value is higher than the \( C_D \) values at \( \alpha = 15^\circ \) and 30\(^\circ\). However, a direct linear relationship between the \( C_{D_{\text{min}}} \) and fabric elongation was observed. The linear equation which fits the data is minimum drag coefficient, \( C_{D_{\text{min}}} = (0.0036 \times \varepsilon) + (0.1965) \) and the correlation coefficient is \( R^2 = 0.1964 \). Again, unstretched fabrics have the highest \( C_{D_{\text{min}}} \) values while with the 20 mm elongation obtained the lowest \( C_{D_{\text{min}}} \) values. For example, W1 has the lowest \( C_{D_{\text{min}}} \) values (0.194) where the value increases consistently with W2, W3, W4 and W5 due to increase in relative roughness.

**Figure 5.16:** The minimum drag coefficient \( (C_{D_{\text{min}}}) \) variation with relative roughness \( (\varepsilon) \) of five woven fabrics with different elongations at \( \alpha = 0^\circ \)
Figure 5.17 illustrates the relationship of relative roughness ($\varepsilon$) and $Re_{critical}$ based on $C_{D_{\text{min}}}$ values. The figure shows that a linear relationship between the relative roughness and the $Re_{critical}$. The linear equation which fits the data is critical Reynolds number, $Re_{critical} = (-9.1498 \times \varepsilon) + (165383)$ and the correlation coefficient is $R^2 = 0.0043$. All woven fabrics with different elongations obtained different magnitude value of $Re_{critical}$ varied between $1.652 \times 10^5$ and $1.655 \times 10^5$.

Figure 5.17: The minimum drag coefficient ($C_{L_{\text{min}}}$) variation with relative roughness ($\varepsilon$) of five woven fabrics with different elongations at $\alpha = 0^\circ$.
5.5.2 Effect of Distance between Wefts on Stretchable Woven Sport Fabrics

The distance from weft to weft is a significant parameter which influences the critical Reynolds numbers \((Re)\). As demonstrated earlier in the optical and electron analysis that elongate the woven fabric alters the microstructure of each sample. It is believed that fabric structural pattern characteristics are important from the view of effect on the distance between wefts. The non-dimensional elongation (distance between wefts) of all stretchable sport woven fabrics with an optical image analyse at varied elongations varied from 0 to 100 mm is illustrated earlier in Table 5.3 and Figure 5.3. The variation of \(C_{Dmin}\) with the fabric non-dimensional elongation (distance between wefts) at variable angles of attack \((\alpha = 0^\circ \text{ to } 90^\circ)\) are shown in Figure 5.18.

It is noted that the \(C_{Dmin}\) correlates linearly with non-dimensional elongation (distance between wefts) at varied angles of attack. However, a suddenly drop in \(C_{Dmin}\) value at 20 mm elongation followed with continuously increments with an increase in fabric elongation til 100 mm. The relationship at different angles of attack indicates that W1 (smooth surface) with lowest non-dimensional elongation (distance between wefts) has minimum values of \(C_{Dmin}\). The W5 (rough surface) obtained the maximum values of \(C_{Dmin}\) due to the increment in the distance between wefts. The distance between wefts is critical to obtain a flow transition at specific Reynolds number. A close inspection with the optical analysis shows that the woven structure at 0 mm has unsteady pattern while after 20 mm elongation the pattern became steady. Moreover, it is believed that there is a strong relationship between the surface roughness (average height) and the distance between wefts. Thus as the distance between wefts increases, the minimal coefficient of drag \((C_{Dmin})\) increases and the critical Reynolds number \((Re_{critical})\) decreases after 20 mm elongation.
Figure 5.18: Variation of $C_{D_{min}}$ with non-dimensional elongation (weft to weft distance), $X_w/X_1$ of five stretchable woven fabrics
5.5.3 Effect of Gap Area between Wefts on Stretchable Woven Sport Fabrics

The gap between wefts is an important aspect for stretchable woven sport fabrics. In different elongation cases, the gap area between wefts influences the aerodynamic properties (drag and lift) at specific Reynolds number ($Re$). The angle of attack of the cylinder generated different magnitudes of aerodynamic darg and lift. Figure 5.19 illustrates the study of the effect of gap area between wefts in stretchable woven fabrics on aerodynamic characteristics at variable angles of attack ($\alpha = 0^\circ$ to $90^\circ$). All stretchable woven fabrics properties in terms of gap area between wefts are shown previously in Table 5.3.

It is evident that the gap area between wefts in woven fabric also affects the air flow regime passing over the surface of the cylindrical surface. The relation between the $C_{D_{min}}$ and non-dimensional elongation (gap area) of all stretchable woven fabrics at different angles of attack is linear. The $C_{D_{min}}$ obtained a suddenly drop after normal fit (0 mm elongation) and continuously rises with fabric elongations til 100 mm (maximum fit). The relationship at different inclination angles also indicates that W1 (smooth surface) with lowest non-dimensional elongation (gap area between wefts) has minimum values of $C_{D_{min}}$. While W5 (rough surface) gained the maximum values of $C_{D_{min}}$ due to the increments in gap area between wefts.

Therefore, the gap area between the wefts is important in terms of transitional flow at specific Reynolds number. There is a significant relationship between the surface roughness (average height) and the gap area between wefts in the stretchable woven fabrics. As a result, as the gap area between wefts increases, the minimal coefficient of drag ($C_{D_{min}}$) increases and the critical Reynolds number ($Re_{critical}$) decreases.
Figure 5.19: Variation of $C_{D_{min}}$ with non-dimensional elongation (gap area), $A_n/A_1$ of five stretchable woven fabrics.
5.6 Summary
The surface texture of all stretchable woven fabrics caused a notable influence on the aerodynamic properties (drag and lift) and directly dependent on the surface roughness, distance and gap area between wefts. All stretchable woven fabrics are unlike knitted fabrics in structural patterns and physical properties. However, all woven fabric underwent a sudden drop in $C_{D_{\text{min}}}$ values after 20 mm elongation followed by linear increment to maximum fit. At normal fit (0 mm), the fabric with a lower relative roughness, distance and gap area between wefts provides an aerodynamic advantage by reducing drag at higher speeds. On the other hand, the higher relative roughness, distance and gap area between wefts also provide a benefit in aerodynamic properties by reducing the drag at lower speeds. Also, the surface texture can be utilised to maximize aerodynamic properties for various speed ranges. Therefore, the study revealed that after 20 mm elongation, with an increase of relative roughness, distance and gap area between wefts, the critical Reynolds number ($Re_{\text{critical}}$) decreases and the minimal coefficient of drag ($C_{D_{\text{min}}}$) increases. Optimal selection of speed sport woven fabric and garment fit for the elite athletes is of utmost important for achieving aerodynamic advantages. In addition, the angle of attack is vital in terms of speed sport applications to maintain the maximum glide ratio and obtain the appropriate posture for the elite athlete.
CHAPTER 6

IMPLICATION OF CYLINDRICAL METHODOLOGY FOR STRETCHABLE SPORTS GARMENTS
6.1 Introduction

Currently, there is no standard test methodology available for the evaluation of stretchable knitted and woven fabrics used in higher speed sports on aerodynamic parameters. Understanding the right stretch level and athlete’s body position either for optimising or selection of appropriate fabrics for the better outcome is paramount. As the winning position in the world class competitions is decided with a fraction of time difference, apart from the athletic physical endeavour, an engineered sport fabric can enhance the overall performance. Also, the selection of optimal stretchable fabric parameters (surface roughness, gap area and distance between yarns) for the aerodynamic performance of sport garments, cylindrical methodology is useful during the initial design stage. However, this chapter is discussing the implication of the cylindrical methodology for stretchable knitted and woven fabrics used in high speed sports. The implication will point out the aerodynamic effect at various fabric elongations at different angles of attack.

6.2 Implication of Stretchable Knitted Sport Fabrics

Table 6.1 shows the comparison of total variation of $C_L/C_D$ with different elongations of five knitted fabric samples at various angles of attack. Figure 6.1 illustrates the variations of drag polar curves ($C_L$ Vs. $C_D$) of the 60 mm ellipsoidal head and stretchable knitted fabric from 0 to 100 mm elongation at different angles of attack ($\alpha = 0^\circ$ to $90^\circ$).

<table>
<thead>
<tr>
<th>Knitted fabric sample</th>
<th>$C_l/C_D$, Knitted Fabric Elongation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>K1</td>
<td>5.257</td>
</tr>
<tr>
<td>K2</td>
<td>5.349</td>
</tr>
<tr>
<td>K3</td>
<td>5.420</td>
</tr>
<tr>
<td>K4</td>
<td>5.491</td>
</tr>
<tr>
<td>K5</td>
<td>5.571</td>
</tr>
</tbody>
</table>

It is clearly evident that the stretchable knitted fabric samples (K1, K2, K3, K4 and K5) have a significant influence on aerodynamic properties. Each knitted samples revealed that as the sample stretches (elongate) the glide ratio ($C_l/C_D$) increases linearly. Also, when the surface
roughness increases, the $C_L/C_D$ increases linearly. The fabric at 100 mm elongation has the maximum value of $C_L/C_D$ while the minimum value found at 0 mm among all the tested angles. As a result, the highest value of $C_L/C_D$ was found at K5 (rounder knitted fabric). Further calculation for each knitted fabric is shown in Appendix C.1.

From the figure, the optimal angle was found at $\alpha = 45^\circ$ and slightly lower at $\alpha = 60^\circ$. As mentioned earlier all the knitted fabrics produced the same aerodynamic behaviour with different magnitudes. By covering the smooth cylinder with a knitted fabric (K5) with different stretch cases leads to change the aerodynamic behaviour with different $C_L$ and $C_D$. The fabric at 0 mm elongation generated the lowest value of $C_L$ and $C_D$ whereas the magnitude of $C_L$ and $C_D$ rises with the fabric elongation respectively. Nonetheless, a significant observation was prominent between $\alpha = 45^\circ$ to $75^\circ$ when the knitted fabric elongated. However, a slight variations in $C_L$ was noted at $\alpha = 15^\circ$ and $30^\circ$ and minor changes also occurred at $\alpha = 0^\circ$ and $90^\circ$. 

Figure 6.1: Variations of drag polar curves of 60 mm ellipsoidal head and stretchable knitted fabric from 0 to 100 mm elongation at different angles of attack
6.3 Implication of Stretchable Woven Sport Fabrics

Table 6.2 shows the comparison of total variation of $C_L/C_D$ with different elongations of five woven fabric samples at various angles of attack. Figure 6.3 illustrates the variations of drag polar curves ($C_L$ Vs. $C_D$) of the 60 mm ellipsoidal head and stretchable woven fabric from 0 to 100 mm elongation at different angles of attack ($\alpha = 0^\circ$ to $90^\circ$).

Table 6.2: Comparison of total variation of $C_L$ with $C_D$ for variable angles of attack for different elongation of five woven fabric samples

<table>
<thead>
<tr>
<th>Woven fabric sample</th>
<th>$C_L/C_D$, Woven Fabric Elongation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>W1</td>
<td>5.094</td>
</tr>
<tr>
<td>W2</td>
<td>5.193</td>
</tr>
<tr>
<td>W3</td>
<td>5.276</td>
</tr>
<tr>
<td>W4</td>
<td>5.378</td>
</tr>
<tr>
<td>W5</td>
<td>5.574</td>
</tr>
</tbody>
</table>

The result obtained from all stretchable woven fabric samples (W1, W2, W3, W4 and W5) shows a significant influence on the aerodynamic properties. The maximum value of ($C_L/C_D$) was found at 0 mm elongation while the minimum value obtained at 20 mm among all the tested angles. The $C_L/C_D$ increases after the minimum value (20 mm) then the increment of $C_L/C_D$ was found linearly. However, the woven fabric also revealed that the rougher woven fabric has the highest value of $C_L/C_D$. Further calculation for each woven fabric is shown in Appendix C.2.

Figure 6.3 shows the variations of drag polar curves of 60 mm ellipsoidal head and stretchable woven fabric from 0 to 100 mm elongation at different angles of attack. Unlike the knitted fabric, the woven fabric at 0 mm elongation obtained the highest value of $C_L$ and $C_D$ then a sudden reduction (lowest $C_L$ and $C_D$ values) was found at 20 mm elongation. Then, the magnitude of $C_L$ and $C_D$ rises gradually with the fabric elongation after 20 mm till the maximum fit. Again, a similar variation was occurred between $\alpha = 15^\circ$ and $30^\circ$ and minor changes also arose at $\alpha = 0^\circ$ and $90^\circ$ for the woven fabric at different elongations.
Figure 6.2: Variations of drag polar curves of 60 mm ellipsoidal head and stretchable woven fabric from 0 to 100 mm elongation at different angles of attack

6.4 Comparison of Stretchable Knitted and Woven Sport Fabrics

Figure 6.3 shows the comparison of maximum total variation of $C_l/C_D$ for variable angles of attack of knitted fabric samples at different elongation. The finding shows that the knitted fabric increases linearly from 0 mm to 100 mm while the woven fabric decreases at 20 mm elongation then linearly increased. However, the knitted fabric obtained advantaged in $C_l/C_D$ at varied fabric elongations.
Figure 6.3: Comparison of total $C_L/C_D$ between knitted and woven fabrics for variable angles of attack (maximum glide ratio)

6.5 Summary

It is significant to understand the aerodynamic behaviour of different stretchable fabrics which are used in various speed sports. Therefore, a reliable methodology for evaluating garment aerodynamic performance would be extremely useful to guide innovation in design and manufacture of the future stretchable speed sport fabrics. It can also serve as a useful tool to examine sports compliance and as a tool for training and coaching elite athletes to enhance their performance. In order to establish an acceptable speed sport suit evaluation tool, input on lift and drag characteristics is required. These can be obtained in the wind tunnel and/or in the computer simulations as part of the program development. So, the performance evaluation tool will need to account for surface morphology, realignment of fabric and change in surface roughness with fit. The methodology can be developed to allow for changes in the material’s surface property, and dimensions data, aerodynamic characteristics data, initial settings (velocity, angle of attack, etc.), and field conditions. The reliability of the methodology needs to be tested and benchmarked using the simplified human body and live athlete.
CHAPTER 7

CONCLUSIONS & SUGGESTIONS FOR FURTHER WORKS
7.1 Conclusions

The main objective of this research was to develop a comprehensive understanding of the aerodynamic behaviour of stretchable knitted and woven fabrics used in high speed sports under a range of stretches and various angles of attack. Several parameters such as, surface roughness, distance between yarns and gap area between yarns were considered and correlated with aerodynamic properties. The following general and specific conclusions stem from this research.

7.1.1 General Conclusions

A series of drag polar curves for 3D circular cylinders with smooth and rough surfaces for a range of Reynolds numbers (Re) and angles of attack (α) was established in this research. These drag polar curves are pioneering in the aerodynamics field of cylindrical surfaces and shapes. The significance of aerodynamic properties is expressed by the drag polar curve which constitutes two dimensionless quantities; lift coefficient (CL) and drag coefficient (CD) varied by angles of attack (α) and Reynolds numbers (Re). The drag polar curve provides the required information to analyse the aerodynamic performance and hence the prediction of optimal shape design.

An advanced ‘cylindrical test methodology’ with the minimal 3D aerodynamic effect for macro scale investigation of sports fabric has been developed and benchmarked. The amount of drag and lift generated by sports fabrics is significantly lower compared to the overall aerodynamic drag and lift of the athlete. The methodology developed here will provide an important means to determine the aerodynamic properties (drag and lift) of sports garments with higher aerodynamic efficiency.

The aerodynamic behaviour of stretchable knitted fabrics tends to be different to that of woven fabrics. With an increase of stretch (within the elastic zone), the surface morphology of knitted fabrics becomes courser thereby causes an early airflow transition (laminar to turbulent flow regime). In contrast, the stretch on woven fabrics makes the surface morphology smoother which delays the flow transition.

7.1.2 Specific Conclusions

For stretchable knitted fabrics, the minimum drag coefficient (C_{D_{min}}) is directly proportional to relative roughness (ε) whereas the critical Reynolds numbers (Re_{crit}) is inversely
proportional to relative roughness ($\varepsilon = 1.39 \times 10^{-4}$ to $7.73 \times 10^{-4}$) within Reynolds numbers investigated ($Re_{\text{crit}} = 1.83 \times 10^5$ to $1.00 \times 10^5$). Knitted fabrics with lower relative roughness, distance and gap area between yarns provides an advantage in aerodynamic efficiency ($C_l/C_D$) at higher Reynolds numbers ($Re$). Similarly with higher relative roughness, distance and gap area between yarns, the knitted fabrics offers an aerodynamic benefit at lower Reynolds numbers ($Re$).

For stretchable woven fabrics, the minimum drag coefficient ($C_{D_{\text{min}}}$) is proportional to the relative roughness ($\varepsilon$) however the relationship of critical Reynolds number ($Re_{\text{crit}} = 1.17 \times 10^5$ to $2.34 \times 10^5$) with the relative roughness ($\varepsilon = 3.689 \times 10^{-4}$ to $1.319 \times 10^{-4}$) is non-linear. A significant drop of aerodynamic benefit was noted at the initial fabric elongation. However with further elongations, the aerodynamic advantage ($C_l/C_D$) increases in approximately linear fashion.

For the smooth cylinder the favourable glide ratio is found between $\alpha = 30^\circ$ and $37^\circ$ whereas for woven and knitted fabrics, the favourable glide ratios are between $\alpha = 30^\circ$ and $45^\circ$. However, the glide ratio for knitted fabrics is higher compared to woven fabrics between $\alpha = 45^\circ$ and $75^\circ$. The glide ratios for all knitted and woven fabrics at all stretched conditions above $\alpha = 45^\circ$ have lower magnitudes compared to the smooth cylinder.

The optical and electron scanning microscope studies have shown that with the increase of stretch of knitted and woven fabrics, the distance and gap area between yarns increases despite woven fabrics having more than twice the number of yarns. The surface roughness measurement has revealed that the relative roughness of knitted fabrics increases with an increase of stretch whereas for woven fabrics it decreases.

The stretched woven fabrics can provide an aerodynamic benefit at higher Reynolds numbers ($Re$) whereas the stretched knitted fabrics provides aerodynamic advantages at lower Reynolds numbers ($Re$). The stretched knitted fabrics reduces the aerodynamic drag over 30% while the stretched woven fabrics reduces the aerodynamic drag at around 38% at high Reynolds numbers ($Re$).

The selection of stretchable knitted and woven sport fabrics used in speed sports should be based on Reynolds numbers (i.e., speed range), magnitude of stretches and angles of attack ($\alpha$) for achieving maximum aerodynamic benefits.
7.2 Suggestions for Further Work

After conducting the work presented here and reviewing the literature available in the public domain, the following areas have been identified for future work:

1. With increasing computational capabilities, it may be useful to develop Computational Fluid Dynamics (CFD) modelling of various sports garments with varied surface roughness.
2. It would be worth looking further into the effect of turbulence on the aerodynamic characteristics of the fabrics. Surface roughness can alter the turbulence levels.
3. In an open environment, the athlete can experience wind from any directions with varied gustiness which can have effect on aerodynamic parameters crosswind conditions. Therefore, it would be useful to undertake further study on crosswinds effect.
4. It was found that different fabrics achieved different results at different angles of attack and at different stretches. Therefore, the influence of average inclination angle and stretch levels on knitted and woven fabrics aerodynamic behaviour is worthy of further investigation.
REFERENCES


Spencer, D. J. (2001). *Knitting technology: a comprehensive handbook and practical guide: CRC.*


The following is a list of publications arisen from this work:


A. Load Sensor Specification

The JR3 sensor is a monolithic aluminium (optionally stainless steel or titanium) device instrumented with metal foil strain gages which sense the loads imposed on the sensor. The strain gage signals are connected to the external amplifier and signal conditioning equipment through the sensor cable. In the external electronic system the strain gage signals are amplified and combined to produce signals representing the force and moment loads for all axes.

Sensors are produced in a wide variety of load ratings and bolt patterns. The physical size of the sensor varies, depending on factors such as force and moment ratings and required mounting dimensions.

The axes on standard JR3 sensors are oriented with the X and Y axes in the plane of the sensor body, and the Z axis perpendicular to the X and Y axes. The reference point for all loading data is the geometric centre of the sensor. When viewed from the Robot Side of the sensor the forces and moments are related by the Right Hand Rule.

![Sensor axis orientation](image)

*Figure A.1: Sensor axis orientation*

All JR3 sensors use captive button-head bolts to mount the sensor with recommended torque. Sensors transmit digital output data to the receiver electronics in a synchronous serial format.
All low level analogue signals and the Analogue to Digital (A/D) circuitry are within the sensor body, shielded from electromagnetic interference by the metallic sensor body. Data for all six axes is returned to the receiver at a rate of 8 kHz. The data stream also includes feedback monitoring the sensor power supply voltage and information about sensor characteristics and calibration. Transmission of sensor calibration data from the sensor allows sensors to be interchanged with no need for any adjustment of the receiver circuitry. Feedback of the sensor power voltage allows use of long lengths of small gage wire in the sensor cable. Sensor power and data signals can be passed through slip rings with no increase in noise or loss of accuracy. Standard digital output sensors utilise either a 6 pin RJ-11 or an 8 pin RJ-45 modular style jack depending on the sensor model.

The nominal load rating of JR3 sensors is the X or Y axis force rating. The Z axis rating is twice the X or Y axis rating. The torque rating for all axes is the X or Y axis force rating times the sensor diameter.

Typical features and options for our "M" sensors include:

- Internal electronics for enhanced noise immunity
- Digital output option for use with a JR3 DSP-based receiver card
- Analogue output option for use with pre-existing data acquisition systems
- Half-bridge strain gage configuration for cost-effectiveness
- Fewer internal loading flexures for cost-effectiveness
- ISO 9409 standard bolt patterns with captive screws for easy, no-adapter-plate-needed installation

Typical specifications:

- Accuracy of nominally 1% of Full Scale (FS)
- Repeatability better than absolute accuracy
- Linearity of 0,5% of FS from +FS to -FS
- and 0,1% of FS at loading below 1/4 FS
- Resolution of 1/4000 FS

JR3 sensors (M series) with load rating 200N, 400N and 1000N were used for the measurement of aerodynamic properties of different experimental arrangements.
A.2 Digitech-i Optical Microscope Specification

This Digitech-i optical microscope was used to digitally capture images of the fabric and other materials. The technical specifications are as follows:

Table A. 1: Optical Microscope Specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model no</td>
<td>Digitech-i optical</td>
</tr>
<tr>
<td></td>
<td>2 megapixel digital microscope</td>
</tr>
<tr>
<td>Magnification ratio</td>
<td>20x - 200x</td>
</tr>
<tr>
<td>Image sensor</td>
<td>2MP CMOS - interpolated: 5MP</td>
</tr>
<tr>
<td>Colour</td>
<td>24 bit</td>
</tr>
<tr>
<td>Applications</td>
<td>Great for science projects, home experiments and for the study of insects</td>
</tr>
<tr>
<td>Capture resolutions</td>
<td>1600 x 1200, 1280 x 1024, 1024 x 768, 800 x 600, 640 x 480, 352 x 288, 320 x 240, 160 x 120</td>
</tr>
<tr>
<td>Focus range</td>
<td>manual focus from 10mm to infinity</td>
</tr>
<tr>
<td>Flicker frequency</td>
<td>50Hz / 60Hz</td>
</tr>
<tr>
<td>Frame rate</td>
<td>Max. 30fps under 600 brightness</td>
</tr>
<tr>
<td>Shutter speed</td>
<td>1 sec to 1/1000 sec</td>
</tr>
<tr>
<td>Video format</td>
<td>AVI</td>
</tr>
<tr>
<td>Still image format</td>
<td>JPG and BMP</td>
</tr>
<tr>
<td>Light source</td>
<td>8 white LED lights</td>
</tr>
<tr>
<td>PC interface</td>
<td>mini USB 2.0</td>
</tr>
<tr>
<td>Power supply</td>
<td>5V DC from USB port</td>
</tr>
</tbody>
</table>
A.3 Scanning Electron Microscope Specification

This instrument was used for acquiring high quality magnified images of the fabric and other materials. The technical specifications are as follows:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model no</td>
<td>FEI Quanta 200</td>
</tr>
<tr>
<td>Electron optics</td>
<td>High-performance thermal emission- SEM column with dual-anode source emission geometry, fixed objective aperture and through-the-lens differential pumping Filament lifetime &gt; 100 hours</td>
</tr>
<tr>
<td>Resolution</td>
<td></td>
</tr>
<tr>
<td>High-vacuum</td>
<td>3.0nm at 30kV (SE)</td>
</tr>
<tr>
<td></td>
<td>4.0nm at 30kV (BSE)</td>
</tr>
<tr>
<td></td>
<td>10nm at 3kV (SE)</td>
</tr>
<tr>
<td>Low-vacuum</td>
<td>3.0nm at 30kV (SE)</td>
</tr>
<tr>
<td></td>
<td>4.0nm at 30kV (BSE)</td>
</tr>
<tr>
<td></td>
<td>&lt; 12nm at 3kV (SE)</td>
</tr>
<tr>
<td>Extended vacuum mode</td>
<td>3.0nm at 30kV (SE)</td>
</tr>
<tr>
<td></td>
<td>Accelerating voltage: 200V – 30kV</td>
</tr>
<tr>
<td></td>
<td>Probe current: up to 2μA – continuously adjustable</td>
</tr>
<tr>
<td>Chamber vacuum</td>
<td></td>
</tr>
<tr>
<td>High-vacuum</td>
<td>&lt; 6e-4 Pa</td>
</tr>
<tr>
<td>Low-vacuum</td>
<td>10 to 130 Pa</td>
</tr>
<tr>
<td>ESEM-vacuum</td>
<td>10 to 2600 Pa</td>
</tr>
<tr>
<td>Chamber</td>
<td>284mm left to right</td>
</tr>
<tr>
<td></td>
<td>10mm analytical work distance (WD)</td>
</tr>
<tr>
<td></td>
<td>8 ports EDX take-off angle: 35°</td>
</tr>
<tr>
<td>Image processor</td>
<td>Resolution Up to 4096 x 3536 pixels</td>
</tr>
<tr>
<td></td>
<td>File type TIFF (8- or 16-bit), BMP or JPEG</td>
</tr>
</tbody>
</table>
A.4 Instron Universal Test Machine

This machine was used to evaluate the mechanical properties of materials and components using tension, compression, flexure, fatigue, impact, torsion and hardness tests. The technical specifications are as follows:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model no</td>
<td>4466</td>
</tr>
</tbody>
</table>
| Power Requirements | +5 Vd.c.  
+15 Vd.c.  
-15 Vd.c. |
| Operating Performance | ±0.01% of full scale or ±0.5% of reading (whichever is greater) ±1 count on the load display.  
Load weighing system meets or surpasses the following standards: ASTM E4, BS1610, DIN 51221, ISO 7500/1, EN10002-2, AFNOR AO3-501 |
| Accuracy      | ±0.05% of full scale or ±0.5% of reading (whichever is greater) ±1 count on the strain display  
Strain measurement system meets or surpasses the following standards: ASTM E83, BS3846, ISO 9513, EN1002-4 |
| Operating temperature: | +10 to +38 °C (+50 to +100°F)  
(other ranges available on request) |
| Storage temperature: | -40 to +60 °C (-40 to +140°F) |
| Relative Humidity: | 10% to 90% non-condensing |
| Atmosphere: | Use in normal laboratory conditions. |
| Dimensions | H × W × D: 406.4 mm × 280 mm × 58.2 mm |
| File type | TIFF (8- or 16-bit), BMP or JPEG |
| Maximum Load | 10 KN |
A.5 KESFB4-A Automatic Surface Tester Machine

This tester machine was used to measure each fabric’s frictional properties and geometrical surface roughness under various tension levels. The technical specifications are as follows:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension/Weight</td>
<td><strong>Measuring unit:</strong> 624 (W) x 600 (D) x 430 (H) mm/58kg</td>
</tr>
<tr>
<td></td>
<td><strong>Electronic unit:</strong> 180 (W) x 400 (D) x 397 (H) mm/11kg</td>
</tr>
<tr>
<td>Power source</td>
<td>Adjustable by transformer 60Hz/50Hz, 60W (maximum)</td>
</tr>
<tr>
<td>Accessories</td>
<td>A pulley for calibration: 1pce</td>
</tr>
<tr>
<td></td>
<td>20g/10g weight for calibration: 10g: 1pce each</td>
</tr>
<tr>
<td></td>
<td>3 different screw drivers: 1pce each</td>
</tr>
<tr>
<td>Measuring conditions</td>
<td>20-30 ºC, 50-70% RH</td>
</tr>
<tr>
<td></td>
<td>Avoid dew condensation Keep the conditions stable.</td>
</tr>
<tr>
<td></td>
<td>(Standard condition: 20 ºC /65%RH)</td>
</tr>
<tr>
<td>Surface friction detection</td>
<td><strong>Surface friction force detector:</strong> Ring type force sensor with differential transformer.</td>
</tr>
<tr>
<td></td>
<td><strong>Friction force sensitivity:</strong> 20gf = IV output in measurement sensitivity.</td>
</tr>
<tr>
<td></td>
<td><strong>Accuracy:</strong> Less than ±0.5% in full-scale Non-linearity is less than 0.5% in entire range</td>
</tr>
<tr>
<td></td>
<td><strong>Force calibration:</strong> Calibrate it at 1V when hanging 20g weight to the load cell via pulley.</td>
</tr>
<tr>
<td></td>
<td>Contacting area of friction contactor: 5mm x 5mm (0.25cm^2).</td>
</tr>
<tr>
<td>Surface roughness detection</td>
<td><strong>Surface roughness detector:</strong> Spring board type detector with differential transformer.</td>
</tr>
<tr>
<td></td>
<td><strong>Surface roughness sensitivity:</strong> 1V output at 40 microns.</td>
</tr>
<tr>
<td></td>
<td><strong>Accuracy:</strong> Less than ±0.5% in full-scale Non-linearity is less than 0.50% in entire range.</td>
</tr>
<tr>
<td></td>
<td><strong>Roughness displacement calibration:</strong> Calibrate the contactor as 1V = 0.04mm by adjusting micrometre</td>
</tr>
<tr>
<td></td>
<td><strong>Shape of roughness contactor:</strong> Using 0.5mm wire,</td>
</tr>
</tbody>
</table>

167
contacting area length of 5mm.

*Roughness spring force calibration*: 10V output at 10gf compression (full-scale).

<table>
<thead>
<tr>
<th>Detection of surface measurement movement</th>
<th>Detector of surface measurement movement: Potentiometer.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sensitivity of surface measurement movement: Proportional system (0.5V at 10mm).</td>
</tr>
<tr>
<td></td>
<td>Accuracy: Less than ±0.5% in full-scale Non-linearity is less than 0.2% in entire range.</td>
</tr>
<tr>
<td></td>
<td>Displacement calibration: Calibrate the chuck’s movement by dial gage.</td>
</tr>
<tr>
<td></td>
<td>Maximum moving distance: 30mm Effective measuring distance 20mm.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen moving rate</th>
<th>1mm/sec</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Condition of surface measurement</th>
<th>Tension of specimen: 400g tension against 20cm width.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Friction measurement load: 50gf vertical direction load (including weight of contactor).</td>
</tr>
<tr>
<td></td>
<td>Roughness measurement load: 10gf against a specimen by spring contacting pressure.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanical units Measuring unit</th>
<th>Electronic unit</th>
</tr>
</thead>
</table>
B.1 Variable Angle of Attack Cylindrical Arrangement

Figure B.1: Variable angle of attack cylindrical arrangement: (a) side view; (b) front view
B.2 Ellipsoidal Heads

Figure B.2: Geometry of ellipsoidal heads (Side view): (a) 40 mm; (b) 60 mm; (c) 110 mm
B.2 Aluminium Grip

Figure B.3: Geometry of aluminium grips: (a) front view; (b) side view
APPENDIX C: Additional Results

C.1: Implication of Stretchable Knitted Speed Sport Fabrics

Table C. 1: Total variation of $C_L$ with $C_D$ for variable angles of attack for different elongation of knitted fabric sample 1 (K1)

<table>
<thead>
<tr>
<th>Angle of Attack (°)</th>
<th>Knitted Fabric Elongation, K1 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>15</td>
<td>1.019</td>
</tr>
<tr>
<td>30</td>
<td>1.371</td>
</tr>
<tr>
<td>45</td>
<td>1.429</td>
</tr>
<tr>
<td>60</td>
<td>0.909</td>
</tr>
<tr>
<td>75</td>
<td>0.529</td>
</tr>
<tr>
<td>90</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5.257</strong></td>
</tr>
</tbody>
</table>

Table C. 2: Total variation of $C_L$ with $C_D$ for variable angles of attack for different elongation of knitted fabric sample 2 (K2)

<table>
<thead>
<tr>
<th>Angle of Attack (°)</th>
<th>Knitted Fabric Elongation, K2 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>15</td>
<td>1.078</td>
</tr>
<tr>
<td>30</td>
<td>1.409</td>
</tr>
<tr>
<td>45</td>
<td>1.412</td>
</tr>
<tr>
<td>60</td>
<td>0.911</td>
</tr>
<tr>
<td>75</td>
<td>0.539</td>
</tr>
<tr>
<td>90</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5.349</strong></td>
</tr>
</tbody>
</table>
Table C. 3: Total variation of $C_L$ with $C_D$ for variable angles of attack for different elongation of knitted fabric sample 3 (K3)

<table>
<thead>
<tr>
<th>Angle of Attack (°)</th>
<th>Knitted Fabric Elongation, K3 (mm)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
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<td>1.393</td>
</tr>
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<td>1.479</td>
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</tr>
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<td>1.392</td>
<td>1.393</td>
<td>1.396</td>
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<td>0.916</td>
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<td>0.550</td>
<td>0.553</td>
<td>0.558</td>
<td>0.560</td>
</tr>
<tr>
<td>90</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>5.420</td>
<td>5.494</td>
<td>5.583</td>
<td>5.662</td>
<td>5.744</td>
<td>5.845</td>
</tr>
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</table>

Table C. 4: Total variation of $C_L$ with $C_D$ for variable angles of attack for different elongation of knitted fabric sample 4 (K4)

<table>
<thead>
<tr>
<th>Angle of Attack (°)</th>
<th>Knitted Fabric Elongation, K4 (mm)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
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<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>15</td>
<td>1.167</td>
<td>1.210</td>
<td>1.264</td>
<td>1.315</td>
<td>1.371</td>
<td>1.431</td>
</tr>
<tr>
<td>30</td>
<td>1.475</td>
<td>1.498</td>
<td>1.523</td>
<td>1.543</td>
<td>1.569</td>
<td>1.599</td>
</tr>
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<td>45</td>
<td>1.379</td>
<td>1.379</td>
<td>1.380</td>
<td>1.381</td>
<td>1.382</td>
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</tr>
<tr>
<td>60</td>
<td>0.917</td>
<td>0.918</td>
<td>0.919</td>
<td>0.920</td>
<td>0.921</td>
<td>0.921</td>
</tr>
<tr>
<td>75</td>
<td>0.553</td>
<td>0.554</td>
<td>0.557</td>
<td>0.561</td>
<td>0.569</td>
<td>0.571</td>
</tr>
<tr>
<td>90</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>5.491</td>
<td>5.560</td>
<td>5.643</td>
<td>5.720</td>
<td>5.812</td>
<td>5.904</td>
</tr>
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</table>
Table C. 5: Total variation of $C_L$ with $C_D$ for variable angles of attack for different elongation of knitted fabric sample 5 (K5)

<table>
<thead>
<tr>
<th>Angle of Attack (°)</th>
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<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>15</td>
<td>1.213</td>
<td>1.265</td>
<td>1.317</td>
<td>1.372</td>
<td>1.421</td>
<td>1.475</td>
</tr>
<tr>
<td>30</td>
<td>1.516</td>
<td>1.550</td>
<td>1.571</td>
<td>1.596</td>
<td>1.611</td>
<td>1.628</td>
</tr>
<tr>
<td>45</td>
<td>1.340</td>
<td>1.343</td>
<td>1.346</td>
<td>1.346</td>
<td>1.347</td>
<td>1.348</td>
</tr>
<tr>
<td>60</td>
<td>0.931</td>
<td>0.933</td>
<td>0.934</td>
<td>0.937</td>
<td>0.939</td>
<td>0.940</td>
</tr>
<tr>
<td>75</td>
<td>0.571</td>
<td>0.576</td>
<td>0.580</td>
<td>0.582</td>
<td>0.587</td>
<td>0.591</td>
</tr>
<tr>
<td>90</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5.571</strong></td>
<td><strong>5.667</strong></td>
<td><strong>5.748</strong></td>
<td><strong>5.832</strong></td>
<td><strong>5.906</strong></td>
<td><strong>5.981</strong></td>
</tr>
</tbody>
</table>
C.2: Implication of Stretchable Woven Speed Sport Fabrics

*Table C. 6: Total variation of $C_L$ with $C_D$ for variable angles of attack for different elongation of woven fabric sample 1 (W1)*

<table>
<thead>
<tr>
<th>Angle of Attack ($^\circ$)</th>
<th>Knitted Fabric Elongation, W1 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>15</td>
<td>1.158</td>
</tr>
<tr>
<td>30</td>
<td>1.411</td>
</tr>
<tr>
<td>45</td>
<td>1.167</td>
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<tr>
<td>60</td>
<td>0.861</td>
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<tr>
<td>75</td>
<td>0.495</td>
</tr>
<tr>
<td>90</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5.094</strong></td>
</tr>
</tbody>
</table>

*Table C. 7: Total variation of $C_L$ with $C_D$ for variable angles of attack for different elongation of woven fabric sample 2 (W2)*

<table>
<thead>
<tr>
<th>Angle of Attack ($^\circ$)</th>
<th>Knitted Fabric Elongation, W2 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
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<tr>
<td>0</td>
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</tr>
<tr>
<td>15</td>
<td>1.220</td>
</tr>
<tr>
<td>30</td>
<td>1.431</td>
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<td>45</td>
<td>1.176</td>
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<td>60</td>
<td>0.866</td>
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<tr>
<td>75</td>
<td>0.500</td>
</tr>
<tr>
<td>90</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5.193</strong></td>
</tr>
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</table>
Table C. 8: Total variation of $C_L$ with $C_D$ for variable angles of attack for different elongation of woven fabric sample 3 (W3)

<table>
<thead>
<tr>
<th>Angle of Attack ($^\circ$)</th>
<th>Knitted Fabric Elongation, W3 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
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<tr>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>15</td>
<td>1.275</td>
</tr>
<tr>
<td>30</td>
<td>1.446</td>
</tr>
<tr>
<td>45</td>
<td>1.179</td>
</tr>
<tr>
<td>60</td>
<td>0.870</td>
</tr>
<tr>
<td>75</td>
<td>0.506</td>
</tr>
<tr>
<td>90</td>
<td>0.000</td>
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<tr>
<td><strong>Total</strong></td>
<td>5.276</td>
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</table>

Table C. 9: Total variation of $C_L$ with $C_D$ for variable angles of attack for different elongation of woven fabric sample 4 (W4)

<table>
<thead>
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<th>Angle of Attack ($^\circ$)</th>
<th>Knitted Fabric Elongation, W4 (mm)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
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<tr>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>15</td>
<td>1.336</td>
</tr>
<tr>
<td>30</td>
<td>1.460</td>
</tr>
<tr>
<td>45</td>
<td>1.193</td>
</tr>
<tr>
<td>60</td>
<td>0.876</td>
</tr>
<tr>
<td>75</td>
<td>0.513</td>
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<tr>
<td>90</td>
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<tr>
<td><strong>Total</strong></td>
<td>5.378</td>
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</table>
Table C. 10: Total variation of $C_L$ with $C_D$ for variable angles of attack for different elongation of woven fabric sample 5 (W5)

<table>
<thead>
<tr>
<th>Angle of Attack (°)</th>
<th>Knitted Fabric Elongation, W5 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
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<tr>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>15</td>
<td>1.449</td>
</tr>
<tr>
<td>30</td>
<td>1.510</td>
</tr>
<tr>
<td>45</td>
<td>1.202</td>
</tr>
<tr>
<td>60</td>
<td>0.884</td>
</tr>
<tr>
<td>75</td>
<td>0.528</td>
</tr>
<tr>
<td>90</td>
<td>0.000</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>5.574</strong></td>
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APPENDIX D: Error Analysis

D.1: Wind Tunnel

In this study, all experimental investigations were conducted on cylindrical arrangement with variable angles of attack in industrial wind tunnels environment. Also, the three different ellipsoidal heads were tested at varied inclination angles. Experimental errors were determined during the measurements. During the measurement of dynamic pressure, velocity, forces and moments using the industrial wind tunnel, random errors may occur due to alignment errors and slow changes in tunnel speed. However, these errors were assessed by the degree of data repeatability.

D.1.1: Repeatability of Results: Each wind tunnel test was performed at least three times on different date to verify the repeatability of the experimental data. The data were analysed with standard deviations. The maximum variation was found less than ±1%. If the variations were found more than ±1%, repeats were performed to confirm the data. Tables H1 and H2 shows the two repeatability results of drag measurements taken three times in different period and day.

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>Speed m/s</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.70</td>
<td>8.53</td>
<td>0.731</td>
<td>0.732</td>
<td>0.739</td>
</tr>
<tr>
<td>40.86</td>
<td>11.35</td>
<td>1.249</td>
<td>1.255</td>
<td>1.267</td>
</tr>
<tr>
<td>51.44</td>
<td>14.29</td>
<td>1.993</td>
<td>1.995</td>
<td>2.014</td>
</tr>
<tr>
<td>60.99</td>
<td>16.94</td>
<td>2.762</td>
<td>2.772</td>
<td>2.799</td>
</tr>
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<td>19.78</td>
<td>3.783</td>
<td>3.791</td>
<td>3.828</td>
</tr>
<tr>
<td>81.26</td>
<td>22.57</td>
<td>4.799</td>
<td>4.801</td>
<td>4.849</td>
</tr>
<tr>
<td>92.00</td>
<td>25.55</td>
<td>5.987</td>
<td>5.992</td>
<td>5.961</td>
</tr>
<tr>
<td>102.56</td>
<td>28.49</td>
<td>7.392</td>
<td>7.392</td>
<td>7.465</td>
</tr>
<tr>
<td>112.57</td>
<td>31.27</td>
<td>8.7</td>
<td>8.709</td>
<td>8.796</td>
</tr>
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<td>122.07</td>
<td>33.91</td>
<td>10.132</td>
<td>10.142</td>
<td>10.243</td>
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<td>36.71</td>
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<td>11.306</td>
<td>11.419</td>
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<td>12.257</td>
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<td>12.381</td>
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### Table D. 2: Second drag force measurement

<table>
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<th>Speed m/s</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.70</td>
<td>8.53</td>
<td>0.746</td>
<td>0.749</td>
<td>0.744</td>
</tr>
<tr>
<td>40.86</td>
<td>11.35</td>
<td>1.274</td>
<td>1.264</td>
<td>1.265</td>
</tr>
<tr>
<td>51.44</td>
<td>14.29</td>
<td>2.008</td>
<td>2.017</td>
<td>2.006</td>
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<tr>
<td>60.99</td>
<td>16.94</td>
<td>2.853</td>
<td>2.859</td>
<td>2.805</td>
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<tr>
<td>71.20</td>
<td>19.78</td>
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<td>3.84</td>
<td>3.839</td>
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<td>81.26</td>
<td>22.57</td>
<td>4.869</td>
<td>4.886</td>
<td>4.892</td>
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<td>7.41</td>
<td>7.396</td>
<td>7.459</td>
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<td>31.27</td>
<td>8.745</td>
<td>8.79</td>
<td>8.827</td>
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<td>10.119</td>
<td>10.208</td>
<td>10.112</td>
</tr>
<tr>
<td>132.14</td>
<td>36.71</td>
<td>11.301</td>
<td>11.392</td>
<td>11.393</td>
</tr>
<tr>
<td>142.00</td>
<td>39.44</td>
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<td>12.199</td>
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</table>

### Table D. 3: Error variations

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<th>Drag Force 2</th>
<th>%</th>
</tr>
</thead>
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<td>0.7463</td>
<td>0.7340</td>
<td>1.6525</td>
</tr>
<tr>
<td>1.2677</td>
<td>1.2570</td>
<td>0.8414</td>
</tr>
<tr>
<td>2.0103</td>
<td>2.0007</td>
<td>0.4808</td>
</tr>
<tr>
<td>2.8390</td>
<td>2.7777</td>
<td>2.1603</td>
</tr>
<tr>
<td>3.8510</td>
<td>3.8007</td>
<td>1.3070</td>
</tr>
<tr>
<td>4.8823</td>
<td>4.8163</td>
<td>1.3518</td>
</tr>
<tr>
<td>6.0727</td>
<td>5.9800</td>
<td>1.5259</td>
</tr>
<tr>
<td>7.4217</td>
<td>7.4163</td>
<td>0.0718</td>
</tr>
<tr>
<td>8.7873</td>
<td>8.7350</td>
<td>0.5955</td>
</tr>
<tr>
<td>10.1463</td>
<td>10.1723</td>
<td>0.2562</td>
</tr>
<tr>
<td>11.3620</td>
<td>11.3437</td>
<td>0.1613</td>
</tr>
<tr>
<td>12.1933</td>
<td>12.2993</td>
<td>0.8693</td>
</tr>
</tbody>
</table>

**Variation** 0.7519
D.1.2: Wind-Tunnel Speed Errors: During the test, the air speed in the wind tunnel was measured with a NPL modified ellipsoidal head Pitot-static tube connected to a MKS Baratron-reference pressure transducer. The air speed was also measured with a Honeywell (160 PC) pressure transducer to compare the data with MKS Baratron pressure transducer. The air speed was also measured with a Betz manometer. The deviation of tunnel air speed measurements was less than ±1% from the nominal value.

D.1.3: Solid Blockage Correction: This effect of solid blockage ratio defined as the ratio of the projected frontal area of the experimental arrangement and cross-sectional area of the wind tunnel test section. Tunnel blockage can cause the drag coefficient to be overestimated. As the solid blockage ratio for all the experimental arrangements used in this work is less than 10%, no corrections were required.

D.1.4: Temperature and Pressure Errors: Slow fluctuations of tunnel temperature and ambient pressure were accounted for in the acquisition systems and proper corrections were made (where needed) during the data processing.

D.1.5: Data Acquisition: Dynamic pressure and velocity inside the wind tunnel during experiment was recorded with MKS Baratron pressure transducer which was calibrated against a precision inclined-manometer. Highly sensitive JR3 sensors were used to measure the forces and moments. Data acquisition was fully computerised and without human intervention.

D.1.6: Alignment Errors: Changing angles of attack in the wind tunnel were determined by inclinometer scale. Alignment errors were minimised by taking extra care during tithing the lock in the rotating mechanics. The error is about 0.1°.
**D.2: Surface Roughness Measurements**

Each surface roughness test was performed at least three times on different dates to verify the repeatability of the experimental data. The data were analysed with standard deviations. The maximum variation was found less than ±1%. If the variations were found more than ±1%, repeats were performed to confirm the data.

**D.2.1 Knitted Fabric**

*Table D. 4: Surface roughness measurement for five stretchable knitted fabrics*

<table>
<thead>
<tr>
<th>Elongation</th>
<th>0 mm</th>
<th>20 mm</th>
<th>40 mm</th>
<th>60 mm</th>
<th>80 mm</th>
<th>100 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric</td>
<td>Ra (μm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K1</td>
<td>11.915</td>
<td>15.051</td>
<td>17.224</td>
<td>20.960</td>
<td>24.628</td>
<td>30.702</td>
</tr>
<tr>
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<td>12.877</td>
<td>15.051</td>
<td>17.224</td>
<td>19.354</td>
<td>23.528</td>
<td>29.702</td>
</tr>
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<td>17.986</td>
<td>20.318</td>
<td>23.349</td>
<td>25.489</td>
<td>29.929</td>
<td>36.298</td>
</tr>
<tr>
<td></td>
<td>18.167</td>
<td>20.591</td>
<td>22.115</td>
<td>25.825</td>
<td>30.250</td>
<td>37.775</td>
</tr>
<tr>
<td>Average</td>
<td>18.065</td>
<td>20.457</td>
<td>23.182</td>
<td>26.056</td>
<td>29.961</td>
<td>37.869</td>
</tr>
<tr>
<td>K3</td>
<td>23.472</td>
<td>25.504</td>
<td>27.535</td>
<td>31.808</td>
<td>36.482</td>
<td>44.274</td>
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### D.2.2 Woven Fabric

Table D. 5: Surface roughness measurement for five stretchable woven fabrics

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<th>Elongation</th>
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<th>40 mm</th>
<th>60 mm</th>
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<th>100 mm</th>
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<tr>
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<td>30.807</td>
<td>29.277</td>
<td>27.921</td>
<td>26.835</td>
<td>25.978</td>
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</tbody>
</table>
D.2.3 Fabric Sample Measurement

Figure D. 1 demonstrates the operation of measuring the fabric surface roughness which moved 30 mm forward and backward.

![Figure D. 1: Example of fabric frictional properties and geometrical surface roughness measurement](image)

Figure D. 1: Example of fabric frictional properties and geometrical surface roughness measurement
E.1 Knitted Fabrics

E.1 Knitted Fabrics

20 mm

40 mm

60 mm

80 mm
Figure E.1: Optical images of five knitted fabrics surface at 20, 40, 60 and 80 mm
E.2 Woven Fabrics
Figure E. 2: Optical images of five knitted fabrics surface at 20, 40, 60 and 80 mm
APPENDIX F: Effect of Surface Roughness on Stretchable Knitted Sport Fabrics

As mentioned in Chapter 4, the following sections are presenting the effect of surface roughness on stretchable knitted sport fabrics at $\alpha = 75^\circ$, 60°, 30° and 15°.

F.1 Surface Roughness $\alpha = 75^\circ$

The flow around an inclined cylinder varied between 15° and 75° can be complex, showing vortex structures and mechanisms with different properties and different behaviours. Here, Figure F. 1 shows the variation of $C_D$ (left side) and $C_L$ (right side) with Reynolds number of five knitted fabrics with different relative roughness and the bare cylinder at $\alpha = 75^\circ$.

The curves of all stretchable knitted fabric samples illustrate different behaviours in different ranges of Reynolds numbers for drag and lift as expected. Again, the air flow transition (from laminar to turbulent) was observed with all stretchable knitted fabric samples at different elongations. At laminar flow, the magnitude of $C_D$ value at $\alpha = 75^\circ$ was higher than $\alpha = 90^\circ$. Here, a gradual decreases of $C_D$ value (0.83) was observed with the smooth cylinder at $Re = 1.31 \times 10^5$. All stretchable knitted fabrics have the same flow characterisations at different elongations. The drag transitional effects vary differently depending on the surface roughness over a range of $Re$ from $(1.00 \times 10^5$ to $1.67 \times 10^5$). For example, K5 ($Ra = 41.67$ to $68.76 \mu m$) at varied elongations underwent the flow transition earlier (from $Re = 1.33 \times 10^5$ to $1.00 \times 10^5$) compared to all other knitted samples whereas the late transition occurred at K1 ($Ra = 12.06$ to $30.70 \mu m$) from $Re = 1.17 \times 10^5$ to $1.67 \times 10^5$. At the same time, a continuing decreases of $C_L$ value was observed with the smooth cylinder at $Re = 1.31 \times 10^5$. However, all stretchable knitted fabrics have the same flow characterisations at different elongations. The magnitude of $C_L$ values is two times less than the $C_D$ values due the higher angle of attack. For example, K5 ($Ra = 41.67$ to $68.76 \mu m$) at varied elongations underwent the flow transition earlier (from $Re = 1.33 \times 10^5$ to $1.00 \times 10^5$) compared to all other knitted samples whereas the late transition occurred at K1 ($Ra = 12.06$ to $30.70 \mu m$) from $Re = 1.67 \times 10^5$ to $1.17 \times 10^5$. Present investigation found similar trends with the previously published data (Chowdhury, 2012).
(a) K1 (Drag)  
(b) K1 (Lift)  
(c) K2 (Drag)  
(d) K2 (Lift)  
(e) K3 (Drag)  
(f) K3 (Lift)

Wind
α=75°
Due to the effect of ellipsoidal head and cylinder at $\alpha = 75^\circ$, the magnitude of the aerodynamic drag has the highest value compared to other angles of attack. As shown in Figure F. 2, unstretched fabrics have the lowest $C_{D_{\text{min}}}$ values while the 100 mm elongation has the highest $C_{D_{\text{min}}}$ value. However, a direct linear relationship between the $C_{D_{\text{min}}}$ and fabric elongation was obtained. The linear equation which fits the data is minimum drag coefficient, $C_{D_{\text{min}}} = (0.0196 \times \varepsilon) + (0.469)$ and the correlation coefficient is $R^2 = 0.8601$. On the other hand, K1 has the lowest $C_{D_{\text{min}}}$ values where the value increases consistent with K2, K3, K4 and K5 respectively. As shown in Figure F. 3, unstretched fabrics have the lowest $C_{L_{\text{min}}}$ values while the 100 mm elongation has the highest $C_{L_{\text{min}}}$ values. A direct linear relationship between the $C_{L_{\text{min}}}$ and fabric elongation was obtained. The linear equation which fits the data is minimum lift coefficient, $C_{L_{\text{min}}} = (0.0165 \times \varepsilon) + (0.2401)$ and the correlation coefficient is $R^2 = 0.9103$.

Figure F. 1: The variation of $C_D$ (left side) and $C_L$ (right side) with Reynolds number of five knitted fabric with different relative roughness and fabric elongations at $\alpha = 75^\circ$.
coefficient is $R^2 = 0.9473$. However, K1 at the lowest $C_{L_{\text{min}}}$ values where K2, K3, K4 and K5 obtained the higher $C_{L_{\text{min}}}$ values consistently.

Figure F. 2: The minimum drag coefficient ($C_{D_{\text{min}}}$) variation with relative roughness ($\varepsilon$) of five knitted fabrics with different elongations at $\alpha = 75^\circ$

Figure F. 3: The minimum drag coefficient ($C_{L_{\text{min}}}$) variation with relative roughness ($\varepsilon$) of five knitted fabrics with different elongations at $\alpha = 75^\circ$
A relationship of relative roughness ($\varepsilon$) of all knitted fabrics and $Re_{\text{critical}}$ based on $C_{D\text{min}}$ values is illustrated in Figure F. 4. The figure shows that a linear relationship between the relative roughness and the $Re_{\text{critical}}$. The linear equation which fits the data is critical Reynolds number, $Re_{\text{critical}} = (-11909 \times \varepsilon) + (179540)$ and the correlation coefficient is $R^2 = 0.7591$. All stretchable knitted fabric with different elongations obtained different magnitude value of $Re_{\text{critical}}$ varied between $6.79 \times 10^5$ and $1.68 \times 10^5$. The lowest $Re_{\text{critical}}$ was found at K5 while the highest $Re_{\text{critical}}$ obtained at K1.

![Figure F. 4: Critical Reynolds number ($Re_{\text{critical}}$) variation with relative roughness ($\varepsilon$) of five knitted fabrics at varied elongations at $\alpha = 75^\circ$](image)

The majority of the aerodynamic drag is generated by the body shape which is predominantly pressure drag. The projected frontal area represents a significant factor in aerodynamic drag generation. In many speed sports, glide ratio ($L/D$) is considered fundamental. Figure F. 5 illustrates the variation of $L/D$ with relative roughness ($\varepsilon$) of all knitted fabrics at varied elongations. A linear relationship between the relative roughness and the $L/D$ was observed. The linear equation which fits the data is critical glide ration, $L/D = (0.0101 \times \varepsilon) + (0.5179)$ and the correlation coefficient is $R^2 = 0.9558$. The maximum value of $L/D$ was found at K5 and maximum elongation while the lowest $L/D$ obtained at K1 and minimum elongation. As a
result, the surface roughness and the angle of attack affect the aerodynamic properties and can obtain the optimum outcome for the elite athlete.

![Graph showing the variation of L/D with relative roughness (ε) of five knitted fabrics at varied elongations at α = 75°](image)

**Figure F. 5**: The variation of L/D with relative roughness (ε) of five knitted fabrics at varied elongations at α = 75°

### F.2 Surface Roughness α = 60°

As mentioned earlier, the study was conducted with five stretchable knitted fabrics at varied elongations at α = 60°. In the previous section, the cylinder with ellipsoidal head at α = 75° generated drag and lift as expected. Here, the variation of $C_D$ (left side) and $C_L$ (right side) with Reynolds number for five knitted fabric with different relative roughness and the bare cylinder at α = 60° is shown in Figure F. 6.

The curves of all stretchable knitted fabric samples shows different behaviours in different ranges of Reynolds numbers for drag and lift as expected. Again, the air flow transition (from laminar to turbulent) was observed with all stretchable knitted fabric samples at different elongations. At laminar flow, the magnitude of $C_D$ (0.63) at α = 60° was lower value than α = 75° and higher than α = 90°. The $C_D$ curve the smooth cylinder gradually decreases at $Re = 1.33 \times 10^5$. All stretchable knitted fabrics have the same flow characterisations at different elongations. The drag transitional effects vary differently depending on the surface roughness
over a range of \( Re \) from \((8.41 \times 10^4 \text{ to } 1.50 \times 10^5)\). For example, K5 \((Ra = 41.67 \text{ to } 68.76 \mu m)\) at varied elongations underwent the flow transition earlier (from \( Re = 1.17 \times 10^5 \text{ to } 8.41 \times 10^4 \)) compared to all other knitted samples whereas the late transition occurred at K1 \((Ra = 12.06 \text{ to } 30.70 \mu m)\) from \( Re = 1.50 \times 10^5 \text{ to } 1.01 \times 10^5 \). On the other hand, a continuing decreases of \( C_L \) value was observed with the smooth cylinder at \( Re = 1.33 \times 10^5 \). However, all stretchable knitted fabrics have the same flow characterisations at different elongations. With decrease of angle of attack, \( C_L \) values at \( \alpha = 60^\circ \) is higher than \( \alpha = 75^\circ \). Also, the magnitude of \( C_L \) values obtained a slightly lower than the \( C_D \) values. However, K5 \((Ra = 41.67 \text{ to } 68.76 \mu m)\) at varied elongations underwent the flow transition earlier (from \( Re = 1.17 \times 10^5 \text{ to } 8.41 \times 10^4 \)) compared to all other knitted samples whereas the late transition occurred at K1 \((Ra = 12.06 \text{ to } 30.70 \mu m)\) from \( Re = 1.50 \times 10^5 \text{ to } 1.01 \times 10^5 \). Findings have similar trend with the published data (Chowdhury, 2012).
Figure F. 6: The variation of $C_D$ (left side) and $C_L$ (right side) with Reynolds number for five knitted fabric with different relative roughness and the bare cylinder at $\alpha = 60^\circ$
The variation of minimum drag coefficient ($C_{D_{\text{min}}}$) with relative roughness ($\varepsilon$) of all knitted fabrics with different elongations at $\alpha = 60^\circ$ is shown in Figure F. 7. A direct linear relationship between the $C_{D_{\text{min}}}$ and fabric elongation was observed. The linear equation which fits the data is minimum drag coefficient, $C_{D_{\text{min}}} = (0.0143 \times \varepsilon) + (0.3588)$ and the correlation coefficient is $R^2 = 0.8134$. However, the magnitude of the $C_D$ obtained lower than $\alpha = 75^\circ$ due the reduction of the projected frontal area. Again, unstretched fabrics have the lowest $C_D$ values while with the elongation to 100 mm the $C_{D_{\text{min}}}$ value increased. For example, K1 has the lowest $C_{D_{\text{min}}}$ values where the value increases consistent with K2, K3, K4 and K5 respectively. As shown in Figure F. 8, a direct linear relationship between the $C_{L_{\text{min}}}$ and fabric elongation was obtained. The linear equation which fits the data is minimum lift coefficient, $C_{L_{\text{min}}} = (0.0153 \times \varepsilon) + (0.3213)$ and the correlation coefficient is $R^2 = 0.8943$. At the same time, unstretched fabrics have the lowest $C_{L_{\text{min}}}$ values while with the elongation to 100 mm $C_{L_{\text{min}}}$ values increased. K1 has the lowest $C_{L_{\text{min}}}$ values where K2, K3, K4 and K5 obtained the higher $C_{L_{\text{min}}}$ values consistently.

![Figure F. 7: The minimum drag coefficient ($C_{D_{\text{min}}}$) variation with relative roughness ($\varepsilon$) of five knitted fabrics with different elongations at $\alpha = 60^\circ$](image-url)
Figure F. 8: The minimum drag coefficient ($C_{L_{\text{min}}}$) variation with relative roughness ($\varepsilon$) of five knitted fabrics with different elongations at $\alpha = 60^\circ$.

Figure F. 9 illustrates the relationship of relative roughness ($\varepsilon$) of all fabrics and $Re_{\text{critical}}$ based on $C_{D_{\text{min}}}$ values. The figure shows that a linear relationship between the relative roughness and the $Re_{\text{critical}}$. The linear equation which fits the data is critical Reynolds number, \[ Re_{\text{critical}} = (-11593 \times \varepsilon) + (161736) \] and the correlation coefficient is $R^2 = 0.7563$. All stretchable knitted fabric with different elongations obtained different magnitude value of $Re_{\text{critical}}$ varied between $1.50 \times 10^5$ and $8.41 \times 10^4$. The lowest $Re_{\text{critical}}$ was found at K5 while the highest $Re_{\text{critical}}$ was obtained at K1.
Figure F. 9: Critical Reynolds number ($Re_{\text{critical}}$) variation with relative roughness ($\varepsilon$) of five knitted fabrics at varied elongations at $\alpha = 60^\circ$

Figure F. 10 shows the variation of $L/D$ with relative roughness ($\varepsilon$) of all knitted fabrics at varied elongations $\alpha = 60^\circ$. A linear relationship between the relative roughness and the $L/D$ was observed. A linear relationship between the relative roughness and the $L/D$ was observed. The linear equation which fits the data is critical glide ration, $L/D = (0.0053 \times \varepsilon) + (0.8987)$ and the correlation coefficient is $R^2 = 0.7844$. The maximum value of $L/D$ was found at K5 and maximum elongation for each fabric while the lowest $L/D$ obtained at K1 and minimum elongation for each fabric. As a result, the surface roughness and the angle of attack affect the aerodynamic properties and can obtain the optimum outcome for the elite athlete.
Figure F.10: The variation of L/D with relative roughness (ε) of five knitted fabrics at varied elongations at α = 60°

F.3 Surface Roughness α = 30°

With a view to understand the effect of surface roughness lower than 45° inclination angle, α = 30° was carried out. Here, Figure F.11 shows the variation of $C_D$ (left side) and $C_L$ (right side) with Reynolds number for five knitted fabric with different relative roughness and the smooth cylinder at α = 30°.

The curves of all stretchable knitted fabric samples shows different behaviours in different ranges of Reynolds numbers for drag and lift as expected. At laminar flow, the magnitude of $C_D$ (0.20) at α = 30° was the lowest value compared to other aforementioned angles. A sudden drop in $C_D$ occurred at $Re = 1.17 \times 10^5$ is evident for the smooth cylinder. All stretchable knitted fabrics have the same flow characterisations at different elongations. The drag transitional effects vary differently depending on the surface roughness at $Re = 1.33 \times 10^5$. For example, the K1 ($Ra = 12.06$ to $30.70$ μm) at varied elongations generated the lowest magnitude of $C_D$ values (0.174 to 0.181) compared to all other knitted samples whereas K5 ($Ra = 41.67$ to $68.76$ μm) obtained the highest $C_D$ values varied from 0.183 to 0.194. At the same time, a continuing decreases of $C_L$ value was observed with the smooth cylinder at $Re = 1.34 \times 10^5$. However, all stretchable knitted fabrics have the same flow characterisations at different elongations. At laminar flow regime, with decrease the angle of attack to 30°, the $C_L$
value (0.276) is higher than $C_D$ values (0.20). Also, the magnitude of $C_L$ is significantly lower than the $C_L$ values compared to other aforementioned angles of attack. However, as the fabric elongated the magnitude of the $C_L$ value increases as well as the higher relative roughness, the higher $C_L$ value obtained. For example, K5 ($Ra = 41.67$ to $68.76 \, \mu m$) at varied elongations has the highest $C_L$ values varied from $0.277$ to $0.316$ while the lowest $C_L$ values are found at K1 ($Ra = 12.06$ to $30.70 \, \mu m$) from $0.239$ and $0.279$. 

\[ \text{value increases as well as the higher } \]
Figure F. 11: The variation of \( C_D \) (left side) and \( C_L \) (right side) with Reynolds number for five knitted fabric with different relative roughness and the bare cylinder at \( \alpha = 30^\circ \)

The variation of minimum drag coefficient \( (C_{D_{\text{min}}}) \) with relative roughness \( (\varepsilon) \) of knitted fabrics with different elongations at \( \alpha = 30^\circ \) is shown in Figure F. 12. The magnitude of the \( C_D \) obtained is the lowest values compared to the aforementioned angles due the reduction of the projected frontal area (angle of attack). However, a direct linear relationship between the \( C_{D_{\text{min}}} \) and fabric elongation was observed. The linear equation which fits the data is minimum drag coefficient, \( C_{D_{\text{min}}} = (0.0031 \times \varepsilon) + (0.1702) \) and the correlation coefficient is \( R^2 = 0.9719 \). Again, unstretched fabrics have the lowest \( C_{D_{\text{min}}} \) values while with the elongation to 100 mm the \( C_{D_{\text{min}}} \) value increased. For example, K1 has the lowest \( C_{D_{\text{min}}} \) values where the value increases consistent with K2, K3, K4 and K5 respectively due to increase in relative roughness. At the same time, the linear equation which fits the data is minimum lift coefficient, \( C_{L_{\text{min}}} = (0.0115 \times \varepsilon) + (0.2327) \) and the correlation coefficient is \( R^2 = 0.9226 \). The unstretched fabrics have the lowest \( C_{L_{\text{min}}} \) values while with the elongation to 100 mm \( C_{L_{\text{min}}} \)
values increased. K1 has the lowest $C_L$ values where K2, K3, K4 and K5 obtained the higher $C_{L\text{min}}$ values as shown in Figure F. 13.

**Figure F. 12:** The minimum drag coefficient ($C_{D\text{min}}$) variation with relative roughness ($\varepsilon$) of five knitted fabrics with different elongations at $\alpha = 30^\circ$

**Figure F. 13:** The minimum drag coefficient ($C_{L\text{min}}$) variation with relative roughness ($\varepsilon$) of five knitted fabrics with different elongations at $\alpha = 30^\circ$
Figure F. 14 illustrates the relationship of relative roughness ($\varepsilon$) of all stretchable fabrics and $Re_{critical}$ based on $C_{Dmin}$ values. The figure shows that a linear relationship between the relative roughness and the $Re_{critical}$. The linear equation which fits the data is critical Reynolds number, $Re_{critical} = (-88.771 \times \varepsilon) + (217941)$ and the correlation coefficient is $R^2 = 0.372$. All stretchable knitted fabric with different elongations obtained different magnitude value of $Re_{critical}$ varied between $2.179 \times 10^5$ and $2.172 \times 10^5$. As mentioned earlier, a slight difference in $Re_{critical}$ was found due the reduction of projected frontal area and enhancement of flow by the ellipsoidal head. However, the highest $Re_{critical}$ obtained at K1 and due the increment of relative roughness the $Re_{critical}$ decreased K2, K3, K4 and K5 respectively.

![Graph showing the relationship between relative roughness and critical Reynolds number](image)

**Figure F. 14: Critical Reynolds number ($Re_{critical}$) variation with relative roughness ($\varepsilon$) of five knitted fabrics at varied elongations at $\alpha = 30^\circ$**

Figure F. 15 shows the variation of $L/D$ with relative roughness ($\varepsilon$) of all knitted fabrics at varied elongations $\alpha = 30^\circ$. A linear relationship between the relative roughness and the $L/D$ was observed. The linear equation which fits the data is critical glide ration, $L/D = (0.0371 \times \varepsilon) + (1.376)$ and the correlation coefficient is $R^2 = 0.8445$. The maximum value of $L/D$ was found at K5 and maximum elongation for each fabric while the lowest $L/D$ obtained at K1 and minimum elongation for each fabric.
Figure F. 15: The variation of L/D with relative roughness (ε) of five knitted fabrics at varied elongations at α = 30°.

**F.4 Surface Roughness α = 15°**

Figure F. 16 depicts the variation of $C_D$ (left side) and $C_L$ (right side) with Reynolds number for five knitted fabric with different relative roughness and the smooth cylinder at α = 15°.

The curves of all stretchable knitted fabric samples show different behaviours in different ranges of Reynolds numbers for drag and lift as expected. At laminar flow, the magnitude of $C_D$ (0.171) at α = 15° is the lowest value compared to other aforementioned angles. A sudden drop in $C_D$ occurred at $Re = 1.17 \times 10^5$ is evident for the smooth cylinder. All stretchable knitted fabrics have the same flow characterisations at different elongations. The drag transitional effects vary differently depending on the surface roughness at $Re = 1.17 \times 10^5$. For example, the K1 ($Ra = 12.06$ to $30.70 \mu m$) at varied elongations generated the lowest magnitude of $C_D$ values (0.156 to 0.160) compared to all other knitted samples whereas K5 ($Ra = 41.67$ to $68.76 \mu m$) obtained the highest $C_D$ values varied from 0.160 to 0.164. At the same time, a slight increases with stability of $C_L$ value was observed with the smooth cylinder at $Re = 1.17 \times 10^5$. At laminar flow regime, with decrease the angle of attack to 15°, the $C_L$ value (0.165) is lower than $C_D$ values (0.169). Nonetheless, the $C_D$ value after the transition
obtained the same magnitude of $C_L$. However, all stretchable knitted fabrics have the same flow characterisations at different elongations. As the fabric elongated the magnitude of the $C_L$ value increases as well as the higher relative roughness, the higher $C_L$ value obtained. For example, K5 ($Ra = 41.67$ to 68.76 μm) at varied elongations has the highest $C_L$ values varied from 0.195 to 0.242 while the lowest $C_L$ values are found at K1 ($Ra = 12.06$ to 30.70 μm) from 0.159 and 0.207.
Figure F. 16: The variation of $C_D$ (left side) and $C_L$ (right side) with Reynolds number for five knitted fabric with different relative roughness and the bare cylinder at $\alpha = 15^\circ$.

The variation of minimum drag coefficient ($C_{D_{\text{min}}}$) with relative roughness ($\varepsilon$) of all knitted fabrics with different elongations at $\alpha = 15^\circ$ is shown in Figure F. 17. However, the magnitude of the $C_D$ obtained is the lowest values compared to the aforementioned angles due the reduction of the projected frontal area (angle of attack). A direct relationship between the $C_{D_{\text{min}}}$ and fabric elongation was observed. The linear equation which fits the data is minimum drag coefficient, $C_{D_{\text{min}}} = (0.0012 \times \varepsilon) + (0.1553)$ and the correlation coefficient is $R^2 = 0.9459$. Again, unstretched fabrics have the lowest $C_{D_{\text{min}}}$ values while with the elongation to 100 mm the $C_{D_{\text{min}}}$ value increased. For example, K1 has the lowest $C_{D_{\text{min}}}$ values (0.156) where the value increases consistent with K2, K3, K4 and K5 respectively due to increase in relative roughness. At the same time, the linear equation which fits the data is minimum lift coefficient, $C_{L_{\text{min}}} = (0.0123 \times \varepsilon) + (0.1533)$ and the correlation coefficient is $R^2 = 0.8417$. The unstretched fabrics have the lowest $C_{L_{\text{min}}}$ values while with the elongation to
100 mm $C_{L_{min}}$ values increased. K1 has the lowest $C_L$ values (0.159) where K2, K3, K4 and K5 obtained the higher $C_{L_{min}}$ values as shown in Figure F. 18.

Figure F. 17: The minimum drag coefficient ($C_{D_{min}}$) variation with relative roughness ($\varepsilon$) of five knitted fabrics with different elongations at $\alpha = 15^\circ$.

Figure F. 18: The minimum drag coefficient ($C_{L_{min}}$) variation with relative roughness ($\varepsilon$) of five knitted fabrics with different elongations at $\alpha = 15^\circ$. 
Figure F. 19 represents the relationship between the relative roughness ($\varepsilon$) of all knitted fabrics and its critical Reynolds number ($Re_{critical}$) based on a minimum drag coefficient value ($C_{Dmin}$). A linear relationship exists between the relative roughness of the fabrics and the critical Reynolds number. The linear equation which fits the data is the critical Reynolds number of $Re_{critical} = (-114.51 \times \varepsilon) + (217659)$ and a correlation coefficient of $R^2 = 0.3452$. The magnitude value of $Re_{critical}$ of all knitted fabrics with different elongation, varies between $2.177 \times 10^5$ and $2.168 \times 10^5$. As mentioned earlier, a slight variation in $Re_{critical}$ was observed due the reduction of projected frontal area and enhancement of flow by the ellipsoidal head. The highest $Re_{critical}$ was obtained at K1 and because of the increment added to the relative roughness, the $Re_{critical}$ decreased K2, K3, K4 and K5 respectively.

![Graph showing the relationship between relative roughness and critical Reynolds number for five knitted fabrics at varied elongations at $\alpha = 15^\circ$.](image)

*Figure F. 19: Critical Reynolds number ($Re_{critical}$) variation with relative roughness ($\varepsilon$) of five knitted fabrics at varied elongations at $\alpha = 15^\circ$*
Figure F. 20 illustrates the variation of lift to drag ratio ($L/D$) with respect to relative roughness ($\varepsilon$) of all knitted fabrics at varied elongations of $\alpha = 15^\circ$. A linear relationship between the relative roughness and $L/D$ was noted. The linear equation which fits the data is critical glide ratio, $L/D = (0.0674 \times \varepsilon) + (0.9939)$ and a correlation coefficient of $R^2 = 0.8173$. The heights value of $L/D$ was found at K5 and maximum fabric elongation of each fabric. The lowest $L/D$ was obtained at K1 and minimum fabric elongation of each fabric.

Figure F. 20: The variation of $L/D$ with relative roughness ($\varepsilon$) of five knitted fabrics at varied elongations at $\alpha = 15^\circ$
APPENDIX G: Effect of Surface Roughness on Stretchable Woven Sport Fabrics

As mentioned in Chapter 5, the following sections are presenting the effect of surface roughness on stretchable woven sport fabrics at \( \alpha = 75^\circ, 60^\circ, 30^\circ \) and \( 15^\circ \).

**G.1 Surface Roughness \( \alpha = 75^\circ \)**

The flow around an inclined cylinder varied between \( 15^\circ \) and \( 75^\circ \) can be complex, showing vortex structures and mechanisms with different properties and different behaviours. Here, Figure G. 1 shows the variation of \( C_D \) (left side) and \( C_L \) (right side) with Reynolds number of five woven fabrics with different relative roughness and the bare cylinder at \( \alpha = 75^\circ \).

The curves of all stretchable woven fabric samples illustrate different behaviours in different ranges of Reynolds numbers for drag and lift as expected. Again, the air flow transition (from laminar to turbulent) was observed with all stretchable woven fabric samples at different elongations. At laminar flow, the magnitude of \( C_D \) value at \( \alpha = 75^\circ \) was higher than \( \alpha = 90^\circ \). Here, a gradual decreases of \( C_D \) value (0.83) was observed with the smooth cylinder at \( Re = 1.31 \times 10^5 \). All stretchable woven fabrics have the same flow characterisations at different elongations. However, each fabric at 0 mm elongation created an early flow transition and then jump for late transition within 20 mm elongation. Then, sequence backward flow transitions occurred with the increase in fabric elongation. However, depending on the surface roughness at normal fit (0 mm), W5 (\( Ra = 32.83 \mu m \)) underwent the flow transition earlier at \( Re = 1.17 \times 10^5 \) compared to all other woven samples whereas the late transition occurred with W1 (\( Ra = 14.56 \mu m \)) at \( Re = 2.34 \times 10^5 \). Among all the fabrics elongated from 20 to 100 mm, W5 (\( Ra = 30.81 \) to 25.98 \( \mu m \)) generated early flow transition from \( Re = 2.00 \times 10^5 \) to 1.52 \( \times 10^5 \) whereas W1 (\( Ra = 13.53 \) to 11.74 \( \mu m \)) obtained late transition at \( Re = 2.34 \times 10^5 \) to 2.01 \( \times 10^5 \). At the same time, a continuing decreases of \( C_L \) value was observed with the smooth cylinder at \( Re = 1.31 \times 10^5 \). However, all stretchable woven fabrics have the same flow characterisations at different elongations. The magnitude of \( C_L \) values is two times less than the \( C_D \) values due the higher angle of attack. Again, at normal fit (0 mm), W5 (\( Ra = 32.83 \mu m \)) underwent the flow transition earlier at \( Re = 1.17 \times 10^5 \) compared to all other woven samples whereas the late transition occurred with W1 (\( Ra = 14.56 \mu m \)) at \( Re = 2.34 \times 10^5 \). Among all the fabrics elongated from 20 to 100 mm, W5 (\( Ra = 30.81 \) to 25.98 \( \mu m \))
generated early flow transition from $Re = 2.00 \times 10^5$ to $1.52 \times 10^5$ whereas W1 ($Ra = 13.53$ to 11.74 $\mu$m) obtained late transition at $Re = 2.34 \times 10^5$ to $2.01 \times 10^5$. 

(a) W1 (Drag)  
(b) W1 (Lift)  
(c) W2 (Drag)  
(d) W2 (Lift)  
(e) W3 (Drag)  
(f) W3 (Lift)
Due to the effect of ellipsoidal head and cylinder at $\alpha = 75^\circ$, the magnitude of the aerodynamic drag has the highest value compare to other angles of attack. As shown in Figure G. 2, unstretched fabrics have the highest $C_{D_{\text{min}}}$ values while the 20 mm elongation has the lowest $C_{D_{\text{min}}}$ value. With applying elongation on the fabric after 20 mm, the $C_{D_{\text{min}}}$ values increases further. However, a direct linear relationship (starts from 20 mm elongation) between the $C_{D_{\text{min}}}$ and fabric elongation was obtained. The linear equation which fits the data is minimum drag coefficient, $C_{D_{\text{min}}} = (0.0433 \times e) + (0.3819)$ and the correlation coefficient is $R^2 = 0.2237$. On the other hand, W1 has the lowest $C_{D_{\text{min}}}$ values where the value increases consistent with W2, W3, W4 and W5 respectively. As shown in Figure G. 3, unstretched fabrics have the highest $C_{L_{\text{min}}}$ values while 20 mm elongation has the lowest $C_{L_{\text{min}}}$ values. Again, apply elongation on the fabric after 20 mm, the $C_{L_{\text{min}}}$ values increases. A direct linear relationship (starts from 20 mm elongation) between the $C_{L_{\text{min}}}$ and fabric elongation was
obtained. The linear equation which fits the data is minimum lift coefficient, $C_{L_{min}} = (0.0308 \times \varepsilon) + (0.1752)$ and the correlation coefficient is $R^2 = 0.301$. However, W1 obtained the lowest $C_{L_{min}}$ values where W2, W3, W4 and W5 obtained higher $C_{L_{min}}$ values constantly.

**Figure G. 2: The minimum drag coefficient ($C_{D_{min}}$) variation with relative roughness ($\varepsilon$) of five woven fabrics with different elongations at $\alpha = 75^\circ$**

**Figure G. 3: The minimum drag coefficient ($C_{L_{min}}$) variation with relative roughness ($\varepsilon$) of five woven fabrics with different elongations at $\alpha = 75^\circ$**
A relationship of relative roughness (ε) of all stretchable woven fabrics and $Re_{critical}$ based on $C_{Dmin}$ values is illustrated in Figure G. 4. The figure shows that a linear relationship (starts from 20 mm elongation) between the relative roughness and the $Re_{critical}$. The linear equation which fits the data is critical Reynolds number, $Re_{critical} = (-26383 \times \varepsilon) + (249774)$ and the correlation coefficient is $R^2 = 0.2939$. All stretchable woven fabrics with different elongations obtained different magnitude value of $Re_{critical}$ varied between $2.390 \times 10^5$ and $1.173 \times 10^5$. The lowest $Re_{critical}$ was found at W5 and sequence increases W4, W3, W2 and W1.

Figure G. 4: Critical Reynolds number ($Re_{critical}$) variation with relative roughness ($\varepsilon$) of five woven fabrics at varied elongations at $\alpha = 75^\circ$

Figure G. 5 illustrates the variation of $L/D$ with relative roughness (ε) of all woven fabrics at varied elongations. A linear relationship (starts from 20 mm elongation) between the relative roughness and the $L/D$ was observed. The linear equation which fits the data is critical glide ratio, $L/D = (0.0185 \times \varepsilon) + (0.4667)$ and the correlation coefficient is $R^2 = 0.241$. The maximum value of $L/D$ was found at W5 and maximum elongation while the lowest $L/D$ obtained at W1 with minimum elongation (20 mm). As a result, the surface roughness and the angle of attack affect the aerodynamic properties.
Figure G. 5: The variation of L/D with relative roughness ($\varepsilon$) of five woven fabrics at varied elongations at $\alpha = 75^\circ$

G.2 Surface Roughness $\alpha = 60^\circ$

All stretchable woven fabrics were tested at varied elongations at $\alpha = 60^\circ$. In the previous section, the cylinder with ellipsoidal head at $\alpha = 75^\circ$ generated drag and lift as expected. Here, the variation of $C_D$ (left side) and $C_L$ (right side) with Reynolds number for five woven fabric with different relative roughness and the bare cylinder at $\alpha = 60^\circ$ is presented in Figure G. 6.

The curves shows different behaviours in different ranges of Reynolds numbers for drag and lift as expected. Again, the air flow transition (from laminar to turbulent) was observed at different elongations. At laminar flow, the magnitude of $C_D$ (0.63) at $\alpha = 60^\circ$ was lower value than $\alpha = 75^\circ$ and higher than $\alpha = 90^\circ$. The $C_D$ curve the smooth cylinder gradually decreases at $Re = 1.33 \times 10^5$. All stretchable woven fabrics have the same flow characterisations at different elongations over a range of $Re$ ($1.173 \times 10^5$ to $2.354 \times 10^5$). Again in this study, each fabric at 0 mm elongation created an early flow transition and then jump for late transition within 20 mm elongation. Then, sequence backward flow transitions occurred with the increase in fabric elongation. However, depending on the surface roughness at normal fit
(0 mm), W5 ($Ra = 32.83 \mu m$) underwent the flow transition earlier at $Re = 1.17 \times 10^5$ compared to all other woven samples whereas the late transition occurred with W1 ($Ra = 14.56 \mu m$) at $Re = 2.354 \times 10^5$. Among all the fabrics elongated from 20 to 100 mm, W5 ($Ra = 30.81$ to $25.98 \mu m$) generated early flow transition from $Re = 1.83 \times 10^5$ to $1.34 \times 10^5$ whereas W1 ($Ra = 13.53$ to $11.74 \mu m$) obtained late transition at $Re = 2.34 \times 10^5$ to $1.84 \times 10^5$. At the same time, a continuing decreases of $C_L$ value was observed with the smooth cylinder at $Re = 1.31 \times 10^5$. However, all stretchable woven fabrics have the same flow characterisations at different elongations. The magnitude of $C_L$ values is two times less than the $C_D$ values due the higher angle of attack. Again, at normal fit (0 mm), W5 ($Ra = 32.83 \mu m$) underwent the flow transition earlier at $Re = 1.17 \times 10^5$ compared to all other woven samples whereas the late transition occurred with W1 ($Ra = 14.56 \mu m$) at $Re = 2.34 \times 10^5$. Among all the fabrics elongated from 20 to 100 mm, W5 ($Ra = 30.81$ to $25.98 \mu m$) generated early flow transition from $Re = 1.83 \times 10^5$ to $1.34 \times 10^5$ whereas W1 ($Ra = 13.53$ to $11.74 \mu m$) obtained late transition at $Re = 2.34 \times 10^5$ to $1.84 \times 10^5$. 

![Diagram](image-url)
Figure G.6: The variation of $C_D$ (left side) and $C_L$ (right side) with Reynolds number for five woven fabric with different relative roughness and the bare cylinder at $\alpha = 60^\circ$. 

Figure G.6 (continued)
The variation of minimum drag coefficient \((C_{D_{\text{min}}})\) with relative roughness \((\varepsilon)\) with different elongations at \(\alpha = 60^\circ\) is shown in Figure G. 7. A direct linear relationship (starts at 20 mm) between the \(C_{D_{\text{min}}}\) and fabric elongation was observed. The linear equation which fits the data is minimum drag coefficient, \(C_{D_{\text{min}}} = (0.0313 \times \varepsilon) + (0.3124)\) and the correlation coefficient is \(R^2 = 0.2263\). However, the magnitude of the \(C_D\) obtained lower than \(\alpha = 75^\circ\) due the reduction of the projected frontal area. Again, unstretched fabrics obtained highest \(C_{D_{\text{min}}}\) values while the 20 mm elongation has the lowest \(C_{D_{\text{min}}}\) value. With applying elongation on the fabric after 20 mm, the \(C_{D_{\text{min}}}\) values increases. W1 has the lowest \(C_{D_{\text{min}}}\) values where the value increases consistent with W2, W3, W4 and W5. On the other hand, unstretched fabrics have the highest \(C_{L_{\text{min}}}\) values while 20 mm elongation has the lowest \(C_{L_{\text{min}}}\) values as shown in Figure G. 8. Again, apply elongation on the fabric after 20 mm, the \(C_{L_{\text{min}}}\) values increases. A direct linear relationship (starts from 20 mm elongation) between the \(C_{L_{\text{min}}}\) and fabric elongation was obtained. The linear equation which fits the data is minimum lift coefficient, \(C_{L_{\text{min}}} = (0.0327 \times \varepsilon) + (0.2587)\) and the correlation coefficient is \(R^2 = 0.276\). However, W1 obtained the lowest \(C_{L_{\text{min}}}\) values where W2, W3, W4 and W5 obtained higher \(C_{L_{\text{min}}}\) values constantly.

![Figure G. 7: The minimum drag coefficient \((C_{D_{\text{min}}})\) variation with relative roughness \((\varepsilon)\) of five woven fabrics with different elongations at \(\alpha = 60^\circ\)](image-url)
A relationship of relative roughness ($\varepsilon$) of all woven fabrics and $Re_{critical}$ based on $C_{Dmin}$ values is illustrated in Figure G. 9. The figure shows that a linear relationship (starts from 20 mm elongation) between the relative roughness and the $Re_{critical}$. The linear equation which fits the data is critical Reynolds number, $Re_{critical} = (-26536 \times \varepsilon) + (239898)$ and the correlation coefficient is $R^2 = 0.2957$. The stretchable woven fabrics with different elongations obtained different magnitude value of $Re_{critical}$ varied between $2.354 \times 10^5$ and $1.173 \times 10^5$. The lowest $Re_{critical}$ was found at W5 and sequence increases W4, W3, W2 and W1.
Figure G. 9: Critical Reynolds number ($Re_{critical}$) variation with relative roughness ($\varepsilon$) of five woven fabrics at varied elongations at $\alpha = 60^\circ$.

Figure G. 10 illustrates the variation of $L/D$ with relative roughness ($\varepsilon$) of all woven fabrics at varied elongations. A linear relationship (starts from 20 mm elongation) between the relative roughness and the $L/D$ was observed. The linear equation which fits the data is critical glide ratio, $L/D = (0.0147 \times \varepsilon) + (0.8338)$ and the correlation coefficient is $R^2 = 0.4875$. The maximum value of $L/D$ was found at W5 and maximum elongation while the lowest $L/D$ obtained at W1 and 20 mm elongation. As a result, the surface roughness and the angle of attack affect the aerodynamic properties.
G.3 Surface Roughness $\alpha = 30^\circ$

Figure G. 11 shows the variation of $C_D$ (left side) and $C_L$ (right side) with Reynolds number with different relative roughness and the smooth cylinder. The curves of all stretchable woven fabric samples shows different behaviours in different ranges of Reynolds numbers for drag and lift as expected. At laminar flow, the magnitude of $C_D$ (0.20) at $\alpha = 30^\circ$ was the lowest value compared to other aforementioned angles. A sudden drop in $C_D$ occurred at $Re = 1.17 \times 10^5$ is evident for the smooth cylinder. All stretchable woven fabrics have the same flow characterisations at different elongations. The drag transitional effects vary differently depending on the surface roughness at $Re = 1.33 \times 10^5$. For example, the W1 ($Ra = 14.56$ to $11.74 \ \mu m$) at varied elongations generated the lowest magnitude of $C_D$ values (0.174 to 0.188) compared to all other woven samples whereas W5 ($Ra = 32.83$ to $25.98 \ \mu m$) obtained the highest $C_D$ values varied from 0.186 to 0.197. At the same time, a continuing decrease of $C_L$ value was observed with the smooth cylinder at $Re = 1.34 \times 10^5$. However, all stretchable woven fabrics have the same flow characterisations at different elongations. At laminar flow regime, with the decrease of the angle of attack to $30^\circ$, the $C_L$ value (0.276) is higher than $C_D$ values (0.20). Also, the magnitude of $C_L$ is significantly lower than the $C_L$ values compared...
to other aforementioned angles of attack. However, as the woven fabric elongated the magnitude of the $C_L$ value increases after a sudden drop after 0 mm. For example, W5 ($Ra = 32.83$ to $25.98 \mu m$) at varied elongations has the highest $C_L$ values varied from 0.264 to 0.298 while the lowest $C_L$ values are found at W1 ($Ra = 14.56$ to $11.74 \mu m$) from 0.236 and 0.266.
The variation of minimum drag coefficient ($C_{D_{min}}$) with relative roughness ($\varepsilon$) with different elongations at $\alpha = 30^\circ$ is shown in Figure G. 12. The magnitude of the $C_D$ obtained is the lowest values compared to the aforementioned angles due to the reduction of the projected frontal area (angle of attack). However, a direct linear relationship (starts from 20 mm) between the $C_{D_{min}}$ and fabric elongation was observed. The linear equation which fits the data is minimum drag coefficient, $C_{D_{min}} = (0.0051 \times \varepsilon) + (0.175)$ and the correlation coefficient is $R^2 = 0.3703$. Again, unstretched fabrics have the highest $C_{D_{min}}$ values while the 20 mm elongation has the lowest $C_{D_{min}}$ value. With applying elongation on the fabric after 20 mm, the $C_{D_{min}}$ values increases. W1 has the lowest $C_{D_{min}}$ values where the value increases consistent with W2, W3, W4 and W5. At the same time, the linear equation which fits the data is minimum lift coefficient, $C_{L_{min}} = (0.014 \times \varepsilon) + (0.2345)$ and the correlation coefficient is $R^2 = 0.4214$. Again, unstretched fabrics have the highest $C_{L_{min}}$ values while 20 mm
elongation has the lowest $C_{L\text{min}}$ values. W1 has the lowest $C_L$ values where W2, W3, W4 and W5 obtained the higher $C_{L\text{min}}$ values respectively as shown in Figure G. 13.

**Figure G. 12:** The minimum drag coefficient ($C_{D\text{min}}$) variation with relative roughness ($\varepsilon$) of five woven fabrics with different elongations at $\alpha = 30^\circ$

**Figure G. 13:** The minimum drag coefficient ($C_{L\text{min}}$) variation with relative roughness ($\varepsilon$) of five woven fabrics with different elongations at $\alpha = 30^\circ$
Figure G. 14 illustrates the relationship of relative roughness ($\varepsilon$) and $Re_{critical}$ based on $C_{D_{min}}$ values. The figure shows that a linear relationship between the relative roughness and the $Re_{critical}$. The linear equation which fits the data is critical Reynolds number, $Re_{critical} = (-15.936 \times \varepsilon) + (217653)$ and the correlation coefficient is $R^2 = 0.0022$. The stretchable woven fabric with different elongations obtained different magnitude value of $Re_{critical}$ varied between $2.172 \times 10^5$ and $2.179 \times 10^5$. As mentioned earlier, a slight difference in $Re_{critical}$ was found due the reduction of projected frontal area and enhancement of flow by the ellipsoidal head.

![Graph](image)

**Figure G. 14:** Critical Reynolds number ($Re_{critical}$) variation with relative roughness ($\varepsilon$) of five woven fabrics at varied elongations at $\alpha = 30^\circ$

Figure G. 15 illustrates the variation of $L/D$ with relative roughness ($\varepsilon$) of woven fabrics at varied elongations $\alpha = 30^\circ$. A linear relationship (starts from 20 mm) between the relative roughness and the $L/D$ was observed. The linear equation which fits the data is critical glide ratio, $L/D = (0.036 \times \varepsilon) + (1.3449)$ and the correlation coefficient is $R^2 = 0.4588$. The maximum value of $L/D$ was found at W5 and normal fit elongation for each fabric while the lowest $L/D$ obtained at W1 and 20 mm elongation for each fabric.
Figure G. 15: The variation of L/D with relative roughness (ε) of five woven fabrics at varied elongations at α = 30°

G.4 Surface Roughness α = 15°

Figure G. 16 illustrates the variation of $C_D$ (left side) and $C_L$ (right side) with Reynolds number with different relative roughness and the smooth cylinder at $α = 15°$. The curves show different behaviours in different ranges of Reynolds numbers for drag and lift. At laminar flow, the magnitude of $C_D$ (0.171) is the lowest value compared to other aforementioned angles. A sudden drop in $C_D$ occurred at $Re = 1.17 \times 10^5$ is evident for the smooth cylinder. All stretchable woven fabrics have the same flow characterisations at different elongations. The drag transitional effects vary differently depending on the surface roughness at $Re = 1.17 \times 10^5$. For example, the W1 ($Ra = 14.56$ to $11.74 \ \mu m$) at varied elongations generated the lowest magnitude of $C_D$ values (0.157 to 0.162) compared to all other woven samples whereas W5 ($Ra = 32.83$ to $25.98 \ \mu m$) obtained the highest $C_D$ values varied from 0.163 to 0.168. At the same time, a slight increase with stability of $C_L$ value was observed with the smooth cylinder at $Re = 1.17 \times 10^5$. At laminar flow regime, with decrease the angle of attack to 15°, the $C_L$ value (0.165) is lower than $C_D$ values (0.169). Nonetheless, the $C_D$ value after the transition obtained the same magnitude of $C_L$. However, all stretchable
woven fabrics have the same flow characterisations at different elongations. As the woven fabric elongated the magnitude of the $C_L$ value increases after a sudden drop after 0 mm. For example, W5 ($Ra = 32.83$ to $25.98$ μm) at varied elongations has the highest $C_L$ values varied from $0.198$ to $0.243$ while the lowest $C_L$ values are found at W1 ($Ra = 14.56$ to $11.74$ μm) from $0.159$ and $0.188$. 

(a) W1 (Drag)

(b) W1 (Lift)

(c) W2 (Drag)

(d) W2 (Lift)

(e) W3 (Drag)

(f) W3 (Lift)
Figure G. 16: The variation of $C_D$ (left side) and $C_L$ (right side) with Reynolds number for five woven fabric with different relative roughness and the bare cylinder at $\alpha = 15^\circ$

The variation of minimum drag coefficient ($C_{D_{\text{min}}}$) with relative roughness ($\varepsilon$) $\alpha = 15^\circ$ is shown in Figure G. 17. However, the magnitude of the $C_D$ obtained is the lowest values compared to the aforementioned angles due the reduction of the projected frontal area (angle of attack). A direct relationship between the $C_{D_{\text{min}}}$ and fabric elongation was observed. The linear equation which fits the data is minimum drag coefficient, $C_{D_{\text{min}}} = (0.0026 \times \varepsilon) + (0.1569)$ and the correlation coefficient is $R^2 = 0.4467$. Again, unstretched fabrics have the highest $C_{D_{\text{min}}}$ values while the 20 mm elongation has the lowest $C_{D_{\text{min}}}$ value. With applying elongation on the fabric after 20 mm, the $C_{D_{\text{min}}}$ values increases. W1 has the lowest $C_{D_{\text{min}}}$ values where the value increases consistently with W2, W3, W4 and W5. At the same time, the linear equation which fits the data is minimum lift coefficient, $C_{L_{\text{min}}} = (0.0226 \times \varepsilon) + (0.148)$ and the correlation coefficient is $R^2 = 0.5413$. Again, unstretched fabrics have the highest $C_{L_{\text{min}}}$ values while 20 mm elongation has the lowest $C_{L_{\text{min}}}$ values. W1 has the lowest $C_L$ values where W2, W3, W4 and W5 obtained the higher $C_{L_{\text{min}}}$ values respectively as shown in Figure G. 18.
Figure G. 17: The minimum drag coefficient ($C_{D\text{min}}$) variation with relative roughness ($\varepsilon$) of five woven fabrics with different elongations at $\alpha = 15^\circ$.

Figure G. 18: The minimum drag coefficient ($C_{L\text{min}}$) variation with relative roughness ($\varepsilon$) of five woven fabrics with different elongations at $\alpha = 15^\circ$. 
Figure G. 19 illustrates the relationship of relative roughness ($\varepsilon$) and $Re_{\text{critical}}$ based on $C_{D\text{min}}$ values. The figure shows that a linear relationship between the relative roughness and the $Re_{\text{critical}}$. The linear equation which fits the data is $Re_{\text{critical}} = (-54.622 \times \varepsilon) + (217602)$ and the correlation coefficient is $R^2 = 0.0117$. All stretchable woven fabric with different elongations obtained different magnitude value of $Re_{\text{critical}}$ varied between $2.168 \times 10^5$ and $2.179 \times 10^5$. As mentioned earlier, a slight difference in $Re_{\text{critical}}$ was found due the reduction of projected frontal area and enhancement of flow by the ellipsoidal head.

Figure G. 19: Critical Reynolds number ($Re_{\text{critical}}$) variation with relative roughness ($\varepsilon$) of five woven fabrics at varied elongations at $\alpha = 15^\circ$

Figure G. 20 illustrates the variation of $L/D$ with relative roughness ($\varepsilon$) at varied elongations $\alpha = 15^\circ$. A linear relationship (starts from 20 mm) between the relative roughness and the $L/D$ was observed. The linear equation which fits the data is critical glide ratio, $L/D = (0.1192 \times \varepsilon) + (0.9517)$ and the correlation coefficient is $R^2 = 0.5495$. The maximum value of $L/D$ was found at W5 and normal fit elongation for each fabric while the lowest $L/D$ obtained at W1 and 20 mm elongation for each fabric.
Figure G.20: The variation of L/D with relative roughness ($\varepsilon$) of five woven fabrics at varied elongations at $\alpha = 15^\circ$