A method of using computer simulation to assess the functional performance of football boots

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A Method of Using Computer Simulation to Assess the Functional Performance of Football Boots

by

Samuel Fraser

A Doctoral Thesis
Submitted in Partial Fulfilment of the Requirements
for the award of

Doctor of Philosophy
of
Loughborough University

June 2015

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Abstract

This thesis details the development of Finite Element Analysis (FEA) techniques to simulate assembly and functional performance of football boots within a virtual environment. With a highly competitive market and seasonal changes in boot design common, the current design process can require numerous iterations, each adding time and cost to the development cycle. Using a reliable model allows evaluation of novel design concepts without the necessity to manufacture physical prototypes, and thus has potential financial benefits as well as reducing development time.

A modelling approach was developed to construct a three dimensional boot model using FEA techniques, simulating the assembly of representative boot constituent parts based on manufacturing patterns, geometries and materials. Comparison between the modelled and physical boots demonstrated good agreement. Assessment of physical boot manufacture enabled the validation of the simulated assembly techniques, with digital image correlation hardware and software used to provide experimental measurements of the surface deformation. Good agreement was reported, demonstrating the predictive capabilities of FEA.

Extensive review of literature provided applicable loading conditions of the boot during game play, with bending and torsional stiffness identified as important parameters. Boundary conditions associated with the foot during these movements provided a platform from which mechanical tests were used and developed to quantify boot function. Modelling techniques were developed and applied to the assembled FEA boot model, simulating the loading conditions to verify the validity when compared with experimental measurements. Bending and torsional stiffness extracted from the model were compared with the physical equivalent, demonstrating good predictive capabilities. The model was able to represent bending stiffness of the physical equivalent within 5.6% of an accepted boot range up to 20°, with torsional stiffness represented within the accepted range between 10° inversion to 7.5° eversion, corresponding to a large proportion of match play. Two case studies proved the applicability of the FEA techniques to simulate assembly and determine mechanical functionality virtually through a combination of automated modelling methods and a bespoke framework, demonstrating how it could be implemented within the industrial design process.
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I would like to thank my supervisors at the industrial collaborator, adidas, Dr Tim Lucas, Mr Paul Smith and Dr Chris Holmes for their knowledge and input throughout the project. I enjoyed every placement and learned a great deal whilst working in the adidas innovation team. I would also like to thank the rest of the team, making my time in Germany very enjoyable.

I have thoroughly enjoyed my time working at the Sports Technology Institute, with the support of the academic staff, technicians and fellow researchers making a fun and exciting environment to work in. I would especially like to thank Steve Carr for his help in creating the bespoke testing rig documented in the thesis. I made a lot of good friends and memories throughout my time.

I also owe a lot to my friends and family, with their continued support throughout the highs and lows experienced throughout the PhD. I couldn't have got this far without them.
Publications Arising from this Work


Fraser, S., Harland, A., Smith, P. and Lucas, T. 2015. Predicting mechanical function using a finite element approach; determining the impact of manufacturing processes on material behaviour in football boot uppers - Under Review
“Perfection is not attainable, but if we chase perfection we can catch excellence.”

- Vince Lombardi
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Chapter 1:
Introduction

1.1 Research Context

Association football is the most watched, most played and highest revenue-generating sport in
the world (Hennig 2011), with approximately 265 million active participants globally (FIFA 2006).
The scale of footballers actively involved with the sport has led to a highly competitive market for
associated products, with the football athletic footwear industry alone worth $278 million in 2009
(SGMA, 2010). With seasonal changes in footwear design common throughout the industry,
brands are keen to create innovative products that follow current trends. Brands seek shorter
development time from concept to finalised product to remain competitive within the market.

Whilst the competitive nature of the market has led to new technologies being implemented
within football boot design, the approach used to create products has remained relatively
consistent. New products, based on new designs, must be well evaluated prior to market release
not only for aesthetic appeal, but also for function. Adjustments made to aspects of production,
such as manufacturing patterns and geometries, materials and mouldings typically require the
manufacture of physical prototypes to evaluate functional performance through physical testing.
This process can require numerous iterations, each adding time and cost to the development
cycle.

Each brand will carry out functional testing, typically involving laboratory-based mechanical tests,
used to quantify performance. The process provides accepted benchmarks based on successful
products, against which new physical prototypes can be evaluated. Finding an alternative to the
need for physical creation of prototypes could potentially provide a competitive advantage and
financial benefits.

Finite Element Analysis (FEA) is a technique used to model physical phenomena within a virtual
environment, predicting and quantifying the outcome of a specific scenario. Whilst primarily used
in the automotive, aeronautical and defence industries, the reduction in computation cost has led
to FEA being used more expansively, providing engineering insight to a range of complex
problems across a variety of applications. Although high initial costs are associated with
generating a model, the long term costs of operation can be relatively low. With a reliable model,
the evaluation of novel design concepts without the necessity to manufacture physical prototypes
has potential financial benefits as well as shortening the design process.
The research presented in this thesis explores the potential to exploit FEA capabilities to form a football boot from its discrete constituent parts and evaluate its function within a virtual environment. Consideration is given to the level of agreement required from such a process to justify the value of this approach. ABAQUS CAE v6.13 FEA software package was used throughout this research project. With a highly competitive industry, access to detailed information regarding design and manufacture of football boots was limited. Collaboration with an industrial partner (adidas) provided a range of components, manufacturing patterns, material samples and access to manufacturing procedures integral to the aims of this research project. For consistency, a single specific boot was used as a case study throughout the thesis.

1.2 Research Aim

The aim of the FE model was to represent the mechanical characteristics of a physical boot, from which its functional performance could be determined. Ideally, this would provide a link between constituent parts and final product performance. Therefore the aim of this research was to answer the following question:

*Can FEA methods be used to model a football boot constructed from its constituent parts in order to predict mechanical function?*

1.2.1 Research Objectives

Pursuit of this aim is reliant on addressing the following objectives:

1. Create a FEA model from the individual boot constituent parts using manufacturing patterns, geometries and materials
2. Simulate the assembly of the individual constituent parts into a representative boot, comparing the resulting geometry with the physical equivalent
3. Develop methods to assess physical boot manufacture, comparing acquired experimental measurements with FEA boot model
4. Determine appropriate boundary conditions associated with boot function to use existing and where necessary develop mechanical test devices to provide comparable experimental measurements of the physical equivalent
5. Generate models of the mechanical test devices to extract outputs from the simulated loading condition for comparison with measurements taken from the physical equivalent
6. Consider levels of agreement required for simulations to be deemed useful and how the modelling techniques can be applied
The objectives were broken down into the following series of activities that are reported in the chapters of this thesis:

**Literature Review** – Assessment of current knowledge related to the area of research in terms of mechanical function, biomechanics and the application of FEA techniques, identifying the most applicable to football boots. Interrogation of literature would indicate boot constituent parts and manufacturing processes, performance objectives and boot function.

**FE Boot Model Creation** – Development of modelling approaches to determine whether FEA techniques can be used to construct a specific football boot. If successful, modelling the virtual assembly of a boot from its raw constituents would enable factors such as initial geometry and materials to be related to subsequent modelling outcomes when measuring boot function. Methods would be established through the use of simple design concepts, prior to the application of manufacturing patterns and material samples to generate the virtual boot.

**Experimental Measurement of Boot Mechanical Functionality** – Laboratory based mechanical tests would be used to quantify boot function based on identified boundary conditions outlined in the literature review. Measurements of boot function using existing and, where necessary, the development of new experimental test devices would provide quantifiable benchmarks from which the validity of the FE models could be determined.

**Functional Analysis of FE Boot Model** – Application of modelling methods to measure boot function based on experimental test devices. Appropriate abstractions would be required to simplify the experimental tests, with comparable measured outcomes required. If possible, the validity and applicability of the FE boot model could be determined by relating the measured outputs of physical boots and the virtual model based on the respective experimental test.

**Influence of Manufacturing Processes on Boot Function** – With the FE boot model constructed from constituent parts, the potential to draw relative comparisons between virtual and physical assembly processes could be beneficial to understand the impact of manufacturing on boot function. Measurement of physical parameters during boot manufacture would provide quantifiable data to compare with the modelled assembly method.

**Application of FEA Functional Analysis** – Establish a framework to enable the automatic assembly and functional analysis of football boots, permitting the impact of specific input parameters in the boot design process to be quantified in terms of boot function. Conclusions from this objective would indicate how the techniques developed in the thesis can be used within the boot design process.
To meet the research aim and objectives, this thesis is structured to reflect the schematic diagram denoted in Figure 1-1. The thesis starts by reviewing current literature (Chapter 2) acquiring relevant knowledge to model and simulate the assembly of a football boot from its constituent parts (Chapter 3). Comparison between simulation outputs of the constructed FEA boot and experimental measurements will be reported in Chapter 4. Investigating the potential influence manufacturing processes have on the constituent part behaviour will be documented in Chapter 5, providing quantifiable data to relate with the FEA model. Chapter 6 reports an expansion of experimental tests to measure boot function highlighted in the literature review, using mechanical tests to quantify physical boots. Creation of representative FEA models to simulate the experimental tests enabled comparisons to be drawn between simulated outputs and measured data from physical boots, determining the modelling approaches usefulness (Chapter 7). An automated approach to simulate boot function, relating input parameters with measured outputs through an established framework is proposed, enabling the potential applicability of FEA models within the design process to be demonstrated (Chapter 8). The research conclusions and further work are stated in Chapter 9 and Chapter 10 respectively.

![Figure 1-1: Schematic diagram displaying the interlinking structure between physical and virtual evaluation of football boots used to meet the research aim and objectives; Processes signify necessary work flow, translations represent transfer of information and validation involves the comparison between measured and simulated outputs.](image-url)
Chapter 2: Literature Review

2.1 Introduction to Football Boots

An understanding of the individual constituent parts and manufacturing processes to acquire the relevant knowledge to construct a representative FEA boot model was an integral aspect of the research. This section provides an overview of football boot anatomy describing relevant details of constituent parts and manufacturing methods in physical boot assembly.

2.1.1 Boot Constituent Parts

Boot design has transformed since the inception of Association Football, with players originally opting to wear traditional ankle high steel toe capped work boots when playing surfaces were often sodden muddy pitches (Soar and Tyler 1986). Factors such as the professionalism of the sport, magnitude of active participation and advancements in the understanding of materials and manufacturing techniques have been prominent in the gradual change in boot construction throughout the 20th century, with features such as screw in studs and boots cut below the ankle now common in market available boots.

Modern day boots are generally assembled from two major components; the outsole and the upper (displayed in Figure 2-1). The outsole provides an interface between the foot and the ground, designed to provide support to the plantar region of the foot. Through design procedures, the outsole geometry and material selection dictates the range of motion possible, enabling the component to deform in specific regions during player movements (Lees 1996), providing support to the foot.

![Figure 2-1: Example of a Modern Football Boot Constructed from the Upper and Outsole Component.](Image from adidas (2012))

Published academic studies have investigated the role of outsole architecture (stud length and configuration) on different playing surfaces, informing boot manufacturers of the most appropriate in terms of injury prevention and playing performance (Murphy et al. 2003; Kirk et al. 2007; Wannop et al. 2010; Hennig and Sterzing 2010; Twomey et al. 2012; Galbusera et al. 2013). Knowledge acquired through these studies has led to defined outsole constructions across the market, depending on the playing surface as demonstrated in Figure 2-2. The outsole architecture
varies depending on the penetrative nature of the playing surface; selecting the wrong outsole construction can lead to isolated peak pressures experienced on the foot, as well as players slipping if the tractional need is not met (Hennig and Sterzing 2010; Bentley et al. 2011).

**Figure 2-2**: Example of Different Outsole Constructions within same boot type; Futsal (a), Astro-Turf (b), Hard Ground (c), Firm Ground (d) and Soft Ground (e). (adidas 2014)

The upper is assembled from a series of constituent parts, encompassing the foot to provide a robust, durable surface for protection from the environment (Lees 1996). Whilst boot design influences the configuration of constituent parts, those used to create the specific boot modelled in this thesis were documented below in Figure 2-3, providing a visual representation of the parts. The last defines the assembled boot’s curvature, with the lasting board used as an anchor for other parts to be attached. The length of the lasting board varies depending on the construction approach, with a half lasting board displayed in Figure 2-3. The pattern piece is the largest single component, generally covering the outer surface of the last once assembled. This can be combined from a series of different materials to create a single component. The presence of a heel pad is common within the design, but can be factored into the pattern piece design. An opening in the dorsal region of the midfoot allows the foot to be placed into the boot, with a tongue and lace structure providing a protective layer and tightening mechanism respectively.

**Figure 2-3**: Diagram to show Constituent parts of the Upper Component of the specific Boot Type Reported in this Thesis.

There has been a noticeable change from natural leather to synthetic leather materials, with benefits including weight reduction, less variability in playing conditions and manufacturing, as
well as bonding of reinforcement layers (Hilgers and Walther 2011). Knitted uppers were released to the market at the time of writing this thesis. Whilst they have not been comprehensively evaluated, it has the potential to offer variable stiffness across the upper, as well as a reduction in waste during manufacture.
2.1.2 Boot Manufacture

The general process of boot manufacture has been largely unchanged for many decades. However, the competitive nature of the industry has led to limited sources of current information on the design and manufacturing processes of football boots. For the purpose of this research project, the industrial collaborator, adidas, allowed the manufacturing process of physical boots to be witnessed.

Observation of the physical manufacturing process enabled key stages of boot construction to be identified, creating a representative FEA model from the constituent parts. The overall process to build the boot required four stages as outlined below:

**Preparation of constituent parts** – Cutting dies, based on manufacturing patterns, were used to cut individual materials with each part prepared by applying heat, adhesive and/or stitching where required. In this example, the pattern piece consisted of a single primary material with additional reinforcement materials bonded to its surface prior to any surface coatings applied and eyelet holes cut out.

**Rearfoot Assembly** – Generally the rearfoot was stitched together, joining edge pairings of the pattern piece, heel pad, tongue and lasting board parts. Stitching lines, printed onto the pattern piece, were aligned by the seamstress. A method termed as ‘stitch and turn’ involved the heel region of the medial and lateral sides being stitched together inside out, following two pin holes used for alignment. Foam was added to provide a soft interaction when shod with a protective heel lining adhered to the outside of the foam layer. The tongue and heel pad were stitched to the pattern piece and lasting board, completing the rearfoot assembly stage (Figure 2-4).

![Figure 2-4: Rearfoot Assembly; Heel Pad (Left), Tongue (Middle) and Lasting Board Stitching (Right).](image)
**Forefoot Assembly** – The final process associated with upper manufacture involved the application of heat and pressure, attaching the pattern piece’s forefoot to the lasting board. Markings on the lasting board enabled alignment between the component and the base of the last prior to the shoe being heated to a surface temperature of 85° monitored using a hand held temperature sensor (Figure 2-5). Once at the required temperature, the shoe was placed into another machine, clamping the rear of the upper in place before attaching the forefoot to the lasting board (Figure 2-5). Pressure was applied to the dorsal region of the forefoot during this process. With the tip of the forefoot fixed, glue was applied to the remaining unattached edges, before the manual attachment to complete the assembly process.

![Figure 2-5: Upper Forefoot Heating (Left), Forefoot Forming Process (Middle) and Manual Application of Bonding Margin (Right).](image)

**Outsole Attachment** - the final stage in boot manufacture was the attachment of the outsole. The outsole was constructed separately by injection moulding. Due to the overlapping regions caused by the forefoot assembly process, excess material was removed using an industrial sanding machine. Adhesive was applied to the adjoining regions, before force was applied from the top of the last, pressing the upper downwards on to the outsole, completing the boot manufacture process.
2.2 The Functional Requirements of a Football Boot within the Game

Mechanical testing devices enable the measurement of physical samples, generally under simplified loading conditions based on a real system. Measurements obtained from these test devices enable load response to be quantified, providing comparative data for analysis in the development process of new concepts. With the ‘best-case’ or ‘optimum’ value not necessarily known, measuring physical samples can provide comparative data to which the accuracy and applicability of the model can be determined. For greater applicability, mechanical tests would be based on frequent player related loading conditions. Simplification of the often complex loading conditions offers the opportunity to ensure reliable and repeatable experimental test data. The process to investigate how the boot is typically loaded and the subsequent methods to measure this through mechanical tests will be explored.

2.2.1 Analysis of Player Movements in Football

Traditionally, the football boot must function to provide protection to the foot from the environment without inhibiting performance (Hilgers and Walther 2011; Villwock et al. 2009). Evolutional change to modern boot design suggests that the focus has moved away from protection and towards performance; key factors for this could be the improvements in sports facilities and equipment. Establishing how boot function relates to player performance is an important factor in defining appropriate boundary conditions for the experimental mechanical tests.

Throughout the majority of a competitive game, players do not contact the ball (Hilgers and Walther 2011). When contact does occur between the boot and ball, the average aggregate interaction time has been calculated to be between 2% and 2.4% of the game, approximately 1.18 minutes (Dellal and Lago-Penas 2011; Di Salvo et al. 2007). Furthermore, in elite competitions, players have been observed to take fewer touches of the ball per possession in order to increase the pace of the match (Dellal and Lago-Penas 2011). Despite the infrequent occurrence of the boot and ball contact, the role of kicking has been researched with regards to player technique, playing conditions and equipment (Lees et al. 2010; Andersen 1999; Dörge et al. 2002; Sterzing and Hennig 2008; Nunome et al. 2006; Shinkai et al. 2009; Ishii et al. 2009; Ishii et al. 2014; Kellis and Katis 2007; Katis et al. 2013). Contact between the boot and ball defines the initial ball velocity and spin rate, which, in addition to surface roughness of the ball, influences its flight path (Carre et al. 2002; Myers and Mitchell 2012; Lees et al. 2010; Kellis and Katis 2007; Mehta and Pallis 2001; De Witt and Hinrichs 2012). At impact, the velocity of the ball after contact depends
on the mass of the ball, initial velocity of the ball, impact velocity of the foot, effective striking mass of the foot and the coefficient of restitution between the foot and ball (Andersen 1999). Spin rate has been shown to primarily be defined by the impact location relative to the centre of the ball (Asai et al. 2002) with players developing different techniques to manipulate the ball flight to meet the players’ needs (Sterzing 2010).

Biomechanical analysis of player kicking technique has been extensively researched with measureable parameters, such as ball velocity and spin rate, used to evaluate the skill. For the purpose of analysing boot to ball interaction, clear definitions of kick types are required in combination with Figure 2-6. Instep kicking involves contact along the curved arch of the foot; medial dorsal region of the boot. Striking the ball with this part can cause the ball to curve in flight (Asai et al. 2002; Carre et al. 2002). Whilst spin can be imparted on the ball during this kick type, forced plantar flexion of the foot around the ankle joint during kicking is common during ball striking, reducing the energy transferred to the ball (Asami and Nolte 1983). Side foot kicks involve contact between the medial side of the boot, with the impact reported to increase the rigidity of the ankle, transferring more energy to the ball than during instep kicking, thus creating a greater foot to ball velocity ratio (Sakamoto et al. 2010). Impact location relative to the centre of the ball has been shown to have a greater effect on ball spin, with friction between the dorsal surface of the upper also important (Asai et al. 2002). However, by impacting the ball with the instep or outstep of the upper, the resulting ball velocity fell (Neilson and Jones, 2005). Imposing an accuracy constraint on subjects (players required to hit a target) resulted in the reduction in ball velocity to 85% and 80% of the velocity when the constraint was removed (Andersen and Dörge (2011) and Asami and Nolte (1983) respectively).

**Figure 2-6: Typical Impact location during Boot to Ball interaction; Side Foot (a), Instep (b), Dorsal (c), Toe (d) and Outstep (e). Boot image taken from manufactures website (adidas).**

Published literature suggests that during ball contact boot constituent parts have little significant influence compared with player technique. Variation in outsole stiffness and changing the effective mass of the boot were found to have no significant influence on ball velocity (Sterzing and Hennig 2008). Reduction in pressure gradients across the dorsal region of the upper led to small improvements in accuracy during instep kicks (Hennig et al. 2009). Kuo and Shiang (2007) supported this, reporting that ball accuracy was improved when the lace structure was moved away from the area of contact. However, numerical analysis using FEA reported that changing the
material stiffness in the upper had no influence on ball velocity (Ishii et al. 2009). With boot to ball contact one aspect of match play, the role of boots on player movements requires consideration.

Footwear plays an important role in player movements, facilitating sharp accelerations and decelerations as well as during multi-directional movements (Hennig and Sterzing 2010). As players remain active throughout the majority of the game, whether it’s changing direction or intensity, the boot undergoes variable loading (Mayhew and Wenger 1985). Player movements within a game have been reported and documented in literature, with multiple studies compiled to classify player movements into specific categories to identify common deformation mechanisms the boot undergoes during a game (Taskin 2008; Dellal and Lago-Penas 2011; O’Donoghue et al. 2005; Bloomfield et al. 2007; Lees and Kewley 1993; Bangsbo et al. 2006; Mohr et al. 2003; Grehaigne et al. 1997; Hennig and Sterzing 2010). Movements are grouped into two distinct classifications with regards to player motion; linear and multi-directional. Linear motion is defined as players following a straight path, involving players walking, jogging, running, sprinting, braking, jumping and landing. Multi-directional movements involve players changing their angle of motion, including turning, cutting, and shuffling motions (Lees and Kewley 1993).

Understanding common deformation mechanisms of the boot requires the evaluation of player movements in terms of these linear and non-linear movements. The accepted average range for player running distance during a game has been reported to be between 10 and 12 km (Bangsbo et al. 2006; Hilgers and Walther 2011; Hennig and Briehle 2000; Di Salvo et al. 2007). Statistical analysis of elite level match play has shown that the majority of distance covered during a game is generally associated with low intensity movements; three different studies reported low intensity movements of 83.6%, 86% and 90.9% (Withers et al. 1982; Ali and Farrally 1991; Mayhew and Wenger 1985). However, the timing of the higher intensity movements had a dominant role in the outcome of a game, with players changing intensity to find space to receive the ball, drag players out of position or sprinting behind defenders to have a shot on goal. These high intensity movements generally last for short periods of time, with 98% of sprints lasting less than 10 seconds (O’Donoghue 2002), with elite match analysis documenting players to have the capacity to sprint between 193.6m and 278.2m at speeds greater than 24.1kmph, and cover between 226.1m and 334m at high-intensity running per game (21-24kmph) (Dellal and Lago-Penas 2011). However, increasing the intensity was found to come at a cost, requiring greater levels of energy production (Bangsbo et al. 2006). Players were reported to sprint only once every 90 seconds lasting less than 4 seconds, with sprint distances lasting an average of 15m with a maximum distance of 40m (Taskin 2008). The number of high intensity movements was reported to increase
during elite matches, highlighting the importance of finding space during match play (Mohr et al. 2003). After high intensity movements, players would then drop to low intensity movements to recover with these movements requiring low energy turnover (Bangsbo et al. 2006). Reilly and Thomas reported a ratio of 2.2:1 for low to high intensity movements observed during match play. Statistical data has reported more than 700 turns and 30-40 jumps by elite players per game (Bloomfield et al. 2007).

Dynamic movements generally involve a succession of linear and multi-directional movements such as a player jogging, followed by a sudden 45° cut to change direction which led into a short sprint (Bloomfield et al. 2008). Forty percent of decelerations after a sprint led to a shuffle movement, resulting in a change of eccentric to concentric movements, argued to be a potential cause of injury (Bloomfield et al. 2008). The loading on the boot is an important consideration during these movement types, with regard to performance and injury reduction.

It is apparent from the literature discussed in this section that during boot to ball contact, the role of boot properties has little significance when defining the resulting ball flight. However, with player movements constantly loading the boot throughout a game, the potential impact the boot has on these movements is more prominent. With this in mind, the focus of boot functionality will be on player movements. Understanding how the boot is loaded during linear and multi-directional movements is required to define boundary conditions for representative mechanical tests.
2.2.2 Analysis of Foot Biomechanics during Football Movements

Understanding functions of the foot and ankle with regards to human locomotion is necessary to comprehend how the boot deforms during player movements defined previously.

Foot and Ankle Joint

A complex structure of 26 bones and 19 large muscles forms the foot, as well as over a hundred ligaments (Hamill, J. & Knutzen 2003; Floyd 2004). The skeletal structure is shown in Figure 2-7.

Figure 2-7: Anatomical Diagram to Detail Bone Structure of Foot (Marieb, 2006).

The foot has two primary functions; propulsion and support. Body mass and its motion is typically transferred through the tibia down into the talus and Calcaneus (Floyd 2004). The joint between these bones is known as the subtalar joint (Floyd 2004). This joint allows the talus and calcaneus bones to articulate due to the concave surface of the talus and the convex surface of the calcaneus (Floyd 2004). The role of the joint is to absorb the rotation of the lower extremity during the stance phase of human gait locomotion (Hamill and Knutzen 2003). Pronation of the foot involves a combination of eversion, dorsiflexion and abduction (Sammarco, G. J. & Hockenbury 2001). Supination has been documented as the opposite which involved inversion, plantar flexion and adduction (James et al. 1978). The Achilles tendon is attached to the posterior surface of the Calcaneus, due to its prominent shape.

The intricate structure of the foot enables articulation of specific bones to facilitate human locomotion. The navicular links the talus to the medial, intermediate and lateral cuneiforms with the proximal end of the fourth and fifth metatarsals joined to the cuboid. The cuboid also interacts with the lateral cuneiforms and the navicular (Floyd 2004). The metatarsophalangeal joint (MPJ) is located between the metatarsals and phalanges, permitting articulations of flexion, extension abduction and adduction. The condyloid-type joint consists of 5 separate joints due to the number of phalanges and metatarsals. The metatarsal break can be described as the axis between the second metatarsal head and the fifth metatarsal head, with the angle between the longitudinal axis and the metatarsal break ranging between 50° and 70°. Mann (1975) measured a range of between 53.5° and 72.5° with an average of 62° (Figure 2-8).

Figure 2-8: Metatarsal Break Angle between Longitudinal axis (Blue) and Metatarsal Break (Red).
Three arches (antero-posterior, longitudinal and transverse arch) are formed by the complex ligament and tendon network to create an elastic shock-absorbing system (Hamill and Knutzen 2003), capable of supporting the body mass during human locomotion. The muscles around the foot and ankle are grouped into four individual segments to allow different rotations (Floyd 2004). Plantar flexion is generated by the contraction of the Gastrocnemius and the Soleus, located on the posterior side of the tibia (Marieb, 2006). Three fibularis muscles also aid planter flexion as well as evasion of the foot. Dorsiflexion of the foot is achieved by the tibialis anterior muscle, in combination with the extensor digitorum longus.

The ankle joint has been documented to allow approximately 50 degrees of plantar flexion and 20 degrees of dorsiflexion, limited by the talus and the tibia (Floyd 2004). Inversion and eversion rotations occur around the subtalar and transverse tarsal joints, where the bones glide past each other. Up to 30 degrees inversion and 15 degrees of eversion around these joints has been reported (Floyd 2004). The MPJ can allow between 40 degrees of flexion and extension of the phalanges and 45 degrees of flexion and 70 degrees of extension in the joint between the first metatarsal and the big toe (Floyd 2004).

**Linear motion**

Bipedal locomotion, referred to as the human gait, has been defined as a functional task requiring complex interactions and co-ordination between most of the major joints in the body (Barr and Backus, 2001). The greatest range of motion is found to occur in the sagittal plane with smaller movements in the frontal and transverse plane (Barr and Backus, 2001). Human gait has been divided into two primary phases; stance and swing (Floyd (2004), Barr and Backus (2001)). The stance phase is considered to consist of three components: the heel strike, midstance and toe off. The swing phase involves three stages: the internal, mid and terminal swing. During walking, generally the stance phase lasts for 60% of the stride, providing support during locomotion (Barr and Backus, 2001). The remaining 40% occurs as the foot is repositioned for the next contact point (Figure 2-9).

**Figure 2-9:** Schematic Diagram of the Gait Cycle showing the right foot and left foot (TO=toe off, HC=heel contact) (Barr and Backus, 2001).
During the stance phase, the foot contacts the ground, causing it to pronate and supinate (Cavanagh, 1989). As the heel becomes fixed to the floor during stance, ankle dorsiflexion leads to an internal rotation of the tibia and pronation of the foot (Novacheck, 1998). Pronation occurs as the limb contacts the ground, with the foot supinating as the stance phase increases, forming a stable lever for toe off (Novacheck, 1998). This results in supination and pronation around the sartorius joint, with peak pronation occurring around 40% of the stance phase (Novacheck, 1998). After this point, the foot supinates until around 70% of the stance phase, where it is classed as being in a neutral position. The joint loses rigidity at initial contact, allowing this mechanism to take place. The joint then becomes rigid around 70% of the stance phase, providing a lever for the toe off phase (Novacheck, 1998). The three states of the foot during contact can be seen in Figure 2-10.

**Figure 2-10: Stages of Foot-Ground Contact Demonstrating the Foot Rotation; Diagram displays rotation for right foot (Hamill and Knutzen, 2003).**

During the foot-strike, the rotation of the forefoot relative to the rearfoot has been quantified through biomechanical studies (Stacoff et al. 1991). The forefoot and rearfoot can be viewed as loosely coupled during small angles of torsional movements (Stacoff et al. 1989), with the torsional angle, defined as the angle between the forefoot and rearfoot, used to indicate whether footwear caused over pronation, by relating torque and angular rotation. Between 13° eversion and up to 20° inversion was documented in a study involving barefoot running, whilst the peak torsional rotation was significantly reduced to 7° eversion and up to 6° inversion when the athlete wore running footwear (Stacoff et al. 1989). When testing individuals whom have excessive pronation, eversion ranged between 3.07° to 15.46° for males and between 2.07° to 11.14° for females when wearing football boots (Sandrey et al. 2001). It was suggested that a football boot, due to its stiff outsole, might force the foot into eversion at a faster rate (Stacoff et al. 1991). Reasons for over-pronation reported were related to weak heel counters and high torsional stiffness (Stacoff et al. 1989).

During toe-off, the heel is raised, resulting in the extension of the MPJ, transferring energy from the proximal joints to the ankle and further on to the MPJ (Goldmann et al. 2013). It has been estimated that the MPJ force amounts to 86% body weight during the second peak in the gait cycle (Jacob 2001). Goldmann et al. (2013), compiled the maximal moment around the MPJ from multiple studies. They documented a range between 20 and 40 Nm in walking and running, and
between 75 and 150 Nm in vertical and horizontal jumping. MPJ peak moments in excess of 60 Nm in running (4 ± 0.4 m/s) and 100 Nm in sprinting (7.1 - 8.4 m/s) were found (Stefanyshyn and Nigg 1997). During sprinting (7.1 - 8.4 m/s), the MPJ had the lowest ratio between energy generated and energy lost (6.0 ± 3.1 J and 47.8 ± 16.6 J respectively) when compared to the ankle, knee and hip joint (Stefanyshyn and Nigg 1997). During sprinting, the MPJ has been shown to be a large dissipater of energy during the stance phase, yielding changes in shoe design to reduce the loss (Stefanyshyn and Nigg 1997). The toe-off phase itself has been split into two phases; digitigrade and unguligrade (Bojsen-Møller and Lamoreux 1979). The digitigrade phase involves rotation around the lateral MPJ axis up to 60 degrees, with the toes remaining fixed to the floor whilst the heel was raised. Unguligrade phase has a 90 degree rotation of the MPJ around the tip of the big toe, resulting in the plantar flexion of the toe, leading to the straightening of the joint to its undeformed shape (Figure 2-11).

Figure 2-11: MPJ Extension During Toe-Off; a-b: Digitigrade Phase, b-c: Unguligrade Phase.

Speed of the movement has two effects on the metatarsophalangeal joint; the motion possible and the axis of rotation. The position of the joint can be split into two axes; the transverse and oblique axis (Bojsen-Møller 1978). The transverse axis is located between the first and second metatarsal heads, with the oblique axis located between the second and fifth metatarsal heads (Figure 2-12). Depending on the intensity of the movement type (low or high speed) the mechanical demands will determine about which axis the MPJ rotated.

Figure 2-12: Location of Transverse Axis and Oblique Axis of the MPJ.

During the toe-off phase in human gait, active and passive functions of the foot occur. The active function involves the foot being driven by the foot and ankle muscles. However the passive function results in the stiffening of the foot, known as the windlass effect (Hicks 1954). High-gear and low-gear push off are governed by the passive function of plantar aponeurosis.

As the movement speed influences the loading of the joint, the level of dorsi-flexion changes (Hopson et al. 1995). At low speeds, push off around the oblique axis means that the contact area moves from the heel pad to the lateral side of the forefoot. As a result, the distance between the tuber calcanei to the MPJ reduces and the plantar aponeurosis becomes slack and unable to support the arch (Bojsen-Møller 1978). High gear involves dorsiflexion about the transverse axis.
Dorsi-flexion of the toes during the terminal phase of stance places traction on the plantar aponeurosis, elevating the arch of the foot. As a result, the plantar aponeurosis stretches across the 1st and 2nd metatarsal heads during dorsiflexion of the MPJ, becoming tightened, leading to a passive lever for propulsion. During high gearing, the plantar aponeurosis was pre-tensioned, causing the windlass effect to start as soon as the heel was raised. During low gear movements, the plantar aponeurosis was not pre-tensioned, so the dorsi-flexion must first take up the slack of the plantar aponeurosis (Bojsen-Møller 1978). Hicks (1954) used a triangular truss model to demonstrate the phenomenon (Figure 2-13). The system used two struts to simulate the medial longitudinal arch with a tie rod connected to each end of the struts, which replicated the plantar aponeurosis. As the toes became dorsally flexed, the traction of the plantar aponeurosis around the metatarsal heads led to the shortening of the aponeurosis, resulting in the elevation of the arch. This created a lever used for propulsion. Factors such as the playing surface conditions and direction of propulsion have an effect on which gearing system is used. At low speeds such as walking, a common movement in soccer, the low gear system will be used, with sprints resulting in the high gear system being required.

Figure 2-13: Triangular Truss Model for Windlass Effect Explanation (Hicks 1954).

With reference to the human gait, linear movement types involve bending of the foot in the forefoot (rotation at the rearfoot about the MPJ) during toe-off at the end of the stance phase. When the foot impacts the ground, it pronates and supinates (Cavanagh, 1989), which involves inversion and eversion of the foot; termed torsion. With linear movements common throughout the game, both bending and torsion of the foot are important considerations with regards to loading of the boot.

Multi-Direction Movements

Multi-directional movements enable the player to change direction, avoiding obstacles during match play. Changing direction requires the player’s centre of mass to be shifted into the intended movement path through a combination of reorienting the body and the associated impulse vector (Mornieux et al. 2014). Through motion analysis of multi-directional movements, three factors have been reported to be integral when changing the movement path; preparatory positioning of the foot, trunk and head (Patla et al. 1999; Vallis and McFadyen 2003; Hicheur et al. 2005; Sreenivasa et al. 2008; Wheeler and Sayers 2010; Mornieux et al. 2014). Foot placement defines the direction the centre of mass will be accelerated in, based on the foot’s centre of
pressure. The head enables the initial reorientation of the body based on the visual field, whilst the trunk rotation about the long axis of the body orientates the body. Anticipatory postural adjustments (APAs) - the term given to these preparatory strategies – have been associated with successful movement execution, thus improving the APAs can have performance benefits (Jindrich and Qiao 2009; Patla et al. 1999). Although all three factors are important in directional change, the role the boot has during these movements is of interest to this research project.

Player multi-directional movements observed during match play include cutting, turning and shuffling, of which can be performed differently (Mornieux et al. 2014). The ability of a player to change direction is an important factor in football, enabling the player to modify their movement pattern when reacting to stimuli within the environment (Mornieux et al. 2014; Marshall et al. 2014; Kim et al. 2014). In rugby, higher skilled players demonstrated faster directional change than less skilled (Gabbett and Benton 2009), suggesting the boot must function to enable the player to initially position the foot to meet performance related objectives. It has been suggested that reducing the execution time of cutting motions is imperative in performance success (Marshall et al. 2014).

Multi-directional movements are dependent on the level of change required by the player, with studies generally defining a movement path to which subjects follow. Biomechanical studies have investigated the kinematics of cutting motions to evaluate boot design, primarily focused on traction properties of the shoe, with a 45° directional change common (Kim et al. 2014; Mornieux et al. 2014; Wong et al. 2007; Park et al. 2009; Stefanyshyn et al. 2010). During cutting motions, the impact phase of a lateral cut involved the medial side of the foot impacting the ground. A larger lever arm due to athletic footwear construction led to an increased moment around the subtalar joint (Figure 2-14). The authors reported that after touchdown, an inversion moment occurred in all but one shoe, reducing the lateral stability during cutting (Stacoff et al. 1996). It was suggested that this finding should be considered in football boot design, signifying why outsole design generally consists of thin constructions.

Figure 2-14: Diagram to show extended lever arm at touch down between barefoot (a) and shod (b) (Stacoff et al. 1996).

This research project will look to develop mechanical tests to experimentally measure boot properties, thus traction properties were not investigated, but will be discussed briefly. Traction between the outsole and ground provides a platform to which the player can change direction,
with studs used to penetrate the ground followed by pushing off. Lack of traction can lead to the player slipping whilst too much traction can lead to injuries during movements (Stacoff et al. 1996; Wong, Chamari, Mao, et al. 2007; Park et al. 2009). As the traction can be perceived by a player (Sterzing et al., 2009b), they slow down their speed in an attempt to remain upright; lack of confidence would lead to slower times.

2.2.3 Analysis of Bending and Torsional Requirements of Footwear in Sport

With linear and multi-directional movements resulting in bending and torsion of the foot, thus deforming the boot, determining the relevance of these deformation mechanisms required further analysis. The boot provides resistance to the foot in bending and torsion based on its construction, thus bending and torsional stiffness properties were used to investigate boot function, identifying boundary conditions to apply to mechanical tests.

**Bending Stiffness**

Bending stiffness has been identified as an important parameter in sport shoe design (Park et al. 2007). However, there have been conflicting reports in literature regarding the influence of bending stiffness on performance. It has been documented that more flexible footwear allows a larger range of motion and power generation, leading to an increased step length and gait velocity (Cikajlo and Matejacić 2007). However, an increase in performance has been reported by changing the mechanical properties of sprint spikes, documented to influence performance (Stefanyshyn and Fusco 2004; Toon et al. 2011). Studies into running shoes reported that running economy improved due to a stiffer midsole when compared to a commercially available midsole (Roy and Stefanyshyn 2006), whilst muscle work was shown to be influenced by modifications to mechanical variables of the shoe (Nigg 2001).

When designing sporting footwear, increasing energy generation and/or decreasing energy dissipation at joints has been shown to be an important consideration (Tinoco et al. 2010). By increasing the bending stiffness of footwear (insertion of carbon fibre inserts to the midsole), energy loss at the MPJ was reduced (Stefanyshyn and Nigg 1997; Stefanyshyn and Nigg 1998; Stefanyshyn and Fusco 2004). Mechanical tests used in these studies involved the footwear being supported at the heel, with the forefoot loaded, much like a simply supported cantilever beam. Performance improvements have been reported by changing the mechanical bending stiffness of sprint spikes (Stefanyshyn and Fusco 2004; Tinoco et al. 2010). On average, a reduction of 0.02 seconds was achieved using a plate with a stiffness of 42 N/mm when compared to the shoe
without the insert (Stefanyshyn and Fusco 2004), whilst 10 out of 12 participants had a performance improvement when a stiff midsole was worn (Tinoco et al. 2010).

Measuring bending stiffness of footwear through simple mechanical tests demonstrated how shoe properties could be quantified prior to human testing to establish the relationship with athletic performance. Shoe testing involved force measurements taken at 30° dorsiflexion of the midsole, with a last placed within the shoe cut off at the MPJ (unspecified distance) (Tinoco et al. 2010). The two shoes used in the test varied between 103.8 ± 0.9N for the stiff shoe and 70.5 ± 1.4N for the compliant shoe.

**Torsional Stiffness**

Torsional stiffness is a measurable property in footwear, defined as the stiffness of the shoe during relative motion between the rearfoot and forefoot about its longitudinal axis (Stacoff et al. 1991). Biomechanical analysis of running footwear has shown that inversion during the stance phase has to be controlled and reduced, stabilising the foot and reducing the risk of injury (Stacoff et al. 1996). Stabilisers have been built into running shoes to reduce over pronation, increasing the stiffness of the shoe (Stacoff et al. 1989). Overuse injuries, due to the repeated impact caused by movement types (James et al. 1978), and excessive pronation injuries (Cavanagh and Lafortune 1980; Reinschmidt and Nigg 2000; Hintermann and Nigg 1998; Sandrey et al. 2001; Stacoff et al. 1989) have been documented as key considerations in running footwear design. Increased pronation has been associated with injuries, such as shin splints (medial tibial stress syndrome), tibial posterior tendonitis, Achilles bursitis and tendonitis (Hintermann and Nigg 1998). Loading from the medial or lateral direction showed a significant effect on injury rate when compared to anterior or posterior direction, suggesting the importance of torsional stiffness on footwear (Giza et al. 2003).

Rearfoot and forefoot strikers have been documented to have different mechanics during running (McClay and Manal 1995). Rearfoot strikers were shown to land at approximately 5° rearfoot inversion, but forefoot strikers land at higher angles of inversion. As both rearfoot and forefoot strikers evert to the similar angles during midstance, forefoot strikers have to rotate at a faster rate. In a different study, rearfoot striking led to the torsional rotation of the forefoot relative to the rear foot being greatly reduced in relation to the barefoot condition, whilst less eversion was found in forefoot runners when compared to rearfoot strikers (Stacoff et al. 1989). Stacoff et al. (1991) suggested that torsional movement may be influenced by the stiffness of the shoe sole construction when rearfoot striking. A review into current literature by Cheung et al. (2011), documented that motion control footwear was an effective approach to reduce the level of foot..
pronation and peak vertical impact during running. Whilst the interaction of running shoes involved contact with a harder surface that in football, the principles of how footwear influenced linear running biomechanics was important. The torsional stiffness of the shoe reduced over pronation and thus must be considered in football footwear.

Lateral stability of the shoe was influenced by the torsional stiffness, increasing or reducing the moment around the subtalar joint (Stacoff et al. 1996). Lateral stability had to be provided by the shoe, through appropriate design of the shoe sole (Stacoff et al. 1996). Loading of the lateral side of the upper was caused by the forefoot abducting at midstance forcing the 5th metatarsal head to press on the upper (Cole, 2001). If the vamp was too stiff, high loads caused discomfort when running, but reduced the level of pronation of the foot. Ankle taping, used to reduce the range of motion at the joint, was found to decrease the risk of ankle injury in players who had a history of ankle injuries (McKay et al. 2001). Ankle braces and high-cut shoes were used to improve ankle stability in sports such as basketball (Stacoff et al. 1996). Fixing over the ankle reduced the movement of the subtalar joint.

With regard to different components of the shoe, Stacoff et al. (1996), reported supination was decreased due to the high-cut shoe during sideward cutting movements, suggesting the influence of the upper on lateral stability. The rotational stiffness may be influenced by changing the materials used to construct the upper (Villwock et al. 2009). During V-cuts and side shuffling, the levels of inversion can be reduced by ankle high upper designs (Stacoff et al., 1996). Research into inversion during these movement types in basketball has led to these findings, and although football uppers cease below the ankle, it is still an important consideration. High top shoes provides a partial mechanical coupling between the leg and rearfoot during V-cuts (Stacoff et al., 1996). Basketball shoes with uppers that go above the ankle, provide a resistance to the inversion moment by 29% when compared to a low cut shoe (Ottaviani et al., 1995). However, when wearing an ankle high upper, it reduced the inverted position of the foot at contact (Brizuela et al., 1997).

Literature reported in this section demonstrates the importance of these mechanical properties in footwear design, but without sufficient published data their direct influence on playing performance in football could not be obtained. Mechanical testing will enable these properties in football boots to be quantified from which FEA models will be created and validated against.
2.3 Application of Finite Element Analysis Techniques

With the aim of this research project to investigate the use of FEA techniques to create representative models and simulations, this section provides an understanding of relevant governing principles with examples of pertinent applications necessary to build a knowledge base.

2.3.1 Introduction to Finite Element Analysis

Finite Element Analysis involves the use of a technique known as the finite element method (FEM). Its purpose is to obtain approximate solutions to a wide variety of engineering problems, where exact solutions are not possible (Huebner et al. 2001). Started in the mid-1960s, FEM utilised mathematical methods to transform differential equations into numerical solutions (Lewis and Ward 1991). The method has typically been used in the automotive and aeronautical industry, due to the high costs associated with manufacturing developmental prototypes. Meshing the solution domain divides it up into finite segments, termed elements, with each element behaviour calculated (Becker 2004). Consumer demand has led to FEA software establishing numerous different element types, with each coded to model a specific object as demonstrated in Figure 2-15.

![Figure 2-15: Applicable Element Types available in ABAQUS CAE (Abaqus 2014).](image)

ABAQUS CAE groups these elements into “families” in which there are different “classes” – shell elements (family) has three classes for example (Abaqus 2014). Selecting the most applicable element type is important in achieving accurate and reliable solutions. Nodes, located and specified based on the element type, calculate the displacement or other degrees of freedom. Displacements occurring along the elements are determined by interpolating from the associated nodes. The distribution of mesh is an important factor in FEA, dictating the number of nodes present within the modelling space. Increasing the number of nodes increases the numerical computational time cost, however, too few nodes can lead to inaccurate results. Mathematical theory defines the element’s behaviour in combination with the nodal displacements (Abaqus 2014). Lagrangian elements use the specified material definition in combination with the nodal displacement to determine the physical loading of the element, whereas Eulerian element, typical in fluid mechanic simulations, are fixed in space whilst material flows through them (Abaqus 2014). Numerical techniques integrate quantities across the volume of each element, calculating the material response at each integration point within the element (Abaqus 2014).
The physical response of the model requires material models to be clearly defined within the FEA solver. Applied to the associated elements within the modelling space, material models can consist of a combination of material behaviours, such as elasticity and plasticity (Abaqus 2014). An extensive range of material behaviours are possible within ABAQUS v6.13, prescribing relative coefficients based on raw data measured through standardised experimental tests. The material must have at least the relevant behaviour defined within the model as required by the analytical step, for example a thermal analysis requires the thermal properties of the model to be stated in the material definition. Material behaviour can be characterised by importing experimental test data, to which existing hyperelastic response curves are fitted to define the strain energy potential of the material. Selection of the material model is based on the relative hyperelastic behaviour of the response curve and test data. It is recommended that the response curve must be stable during the expected strain range of the material (Abaqus 2014). This process facilitates experimental measurement of physical materials to be represented within the model.

With the application of material behaviour to the meshed solution domain, the model requires known factors to be defined for the analytical process; contact criterion, boundary conditions with relevant loading conditions and constraints applied within the solution domain (Rao 2005). Basic continuum mechanics were used to create a series of differential equations across the domain at each node, generating an approximate solution (Becker 2004). FEM has become the most popular method in both research and industrial numerical simulations (Sun et al. 2000). Implicit and explicit algorithms had been developed, depending on the particular problem; selecting the most appropriate algorithm was important for accuracy and CPU cost. The implicit approach was generally used to solve linear and non-linear static problems, as well linear and low speed dynamic problems. The explicit approach was more applicable to high speed dynamic and large non-linear quasi-static analyses. The implicit method was based on static equilibrium and was characterised by the simultaneous solution for a set of linear equations (Vegte and Makino 2004). The algorithm worked based on the model being in equilibrium; the net force \( \mathbf{F} \) equalled zero on each node within the mesh. Solved simultaneously, the known nodal displacements \( \mathbf{U} \) were calculated, based on equation 2.1. The global stiffness \( \mathbf{K} \) matrix was important for the implicit solution.

\[
\mathbf{F} = \mathbf{KU}
\]

**Eqn 2.1**

The explicit procedure was outlined by Vegte and Makino (2004); the solution of displacements, velocities and accelerations of each node though time. With time split into increments, the state of the model at the end of an increment \( t+\Delta t \) was solely based on the displacements, velocities
and accelerations at the beginning of the time increment ($t$). It was assumed that the nodal accelerations were constant during the time increment, allowing the nodal velocities to be obtained at the end of the increment. The displacement of the node during the time increment was added to its position before the increment, creating the total displacement at the end of the increment ($t$). A global stiffness was not used in the explicit method. The explicit integration rule calculated at each node, consisted of the nodal acceleration ($\ddot{u}$), mass matrix ($M^N$), applied load vector ($P^f$) and the internal force vector ($I^f$), detailed in equation 2.2 (Abaqus 2014). To ensure that the solution was not influenced by dynamic effects in quasi-static tests, the kinematic energy had to be less than 5% of the strain energy (Sun et al. 2000).

$$\ddot{u}^N_{(i)} = (M^N)^{-1} \left( P^f_{(i)} - I^f_{(i)} \right)$$  \textit{Eqn 2.2}

### 2.3.2 Application of FEA techniques

FEA has been used in the sports industry to help develop equipment, such as athletic footwear, enabling approximate solutions of complex loading conditions to be quantified (Ishii et al. 2014; Hannah et al. 2012; Rupérez et al. 2010). Biomechanical simulation of foot models had been used to evaluate and optimise footwear design. Computational modelling of the foot-shoe interaction served as an objective tool when considering biomechanical influences of shoe design (Cheung et al. 2009).

Integration of computer-aided engineering (CAE) within footwear design has been possible using FEA modelling approaches, relating design factors to measurable effects. With the focus on the shoe-foot interaction, Cheung et al. (2009) documented a review of numerous studies into computational modelling of this interaction. A general work-flow was generated starting with geometrical acquisition, pre-processing of the model followed by post-processing (Figure 2-16) (Cheung et al. 2009). The work flow described how computer aided engineering (CAE) can be introduced into the design process, providing meaningful results within a virtual environment. Modelling approaches have been documented in running midsole development, involving the use of CAD geometries or scanned data to which loads were applied and analysed with regards to pressure distribution and impact forces. This concept demonstrates the potential to evaluate boot function from constituent parts within a virtual environment.

\textit{Figure 2-16: Suggested Work-flow approach for Footwear Design (Cheung et al. 2009).}
Similar modelling approaches had been used to investigate the shoe to foot interaction in high-heeled footwear, highlighting the influence of high-heels on peak pressures experienced by the foot, without extrusive measurements (Yu et al. 2008; Yu et al. 2013). An approach documented both shoe fit and dynamic movement modelling in FEA (Yu et al. 2013). A human foot was generated using MR images, which consisted of the bone structure, ligaments and tendons, encapsulated by soft tissue. The shoe itself was created using custom shoe design software (ShoeCAD, Excel-Last, Hong Kong) to which a layer of elements were applied to form the outsole and upper (Figure 2-17). A process was used to fit the foot to the shoe (Figure 2-17), followed by a subsequent simulation to replicate walking. The study proved that the application of FEA in footwear was possible. However, the approach did not assemble the upper, with only a layer of elements and a simple single material model attributed to CAD geometry.

Figure 2-17: FE Model of Foot and High Heel (Left) and Foot-Shoe Fitting Process (Right) (Yu et al. 2013)

Generally the interaction between the foot and ground has led to the modelling of the midsole, with a few peer review studies looking at the interaction of the entire shoe configuration (Cheung et al. 2009). To reduce impact loading of the rearfoot, a sliding of a base unit, located in the heel of the midsole, was modelled using FEA, showing the displacement of the heel counter using a coupling system based on biomechanical impact between the rearfoot and ground at heel-strike (Figure 2-18). The process allowed virtual testing of components and materials to aid the functional development of this technology.

Figure 2-18: Shoe Structure of Heel Component (Left), with images of FEA model displaying the displacement of the sliding component to reduce impact loading (Cheung et al. 2009)

Hannah et al. (2012) demonstrated how FEA techniques can be developed to incorporate biomechanical data, captured through human kinematic trials, evaluating the function of running shoe midsoles. Three independent segments, coupled with the midsole and foot geometry, were driven by assigning kinematic data to model the foot-strike. Whilst the model only used one human trial and detailed the significant influence of ground location on measured contact forces, the scope for future development in footwear confirmed the potential of virtual testing methods. Again, the upper was not considered when modelling the shoe.
In current literature, there were limited studies documenting approaches to model the function of uppers. Of the studies published, the boot to ball interaction of a curve kick in football was investigated through the use of FEA, demonstrating the potential to evaluate parameters such as material properties and their impact during match play (Ishii et al. 2014). The boot was generated by scanning a physical boot when shod under static conditions using a 3D foot laser scanner. Linear material models with approximate Young’s moduli were assigned to the upper (10MPa – leather), outsole (25MPa – Polyurethane) and foot (7300MPa – Bone). The study concluded changing the upper’s Young’s modulus between 5MPa to 50MPa had little effect on the ball’s launch angle, ball velocity and ball rotation. Whilst the model was validated against human trial data, the authors made simplifications to reduce the model complexity, assigning a single material for bone to the entire foot, thus the relative stiffness of the foot could have resulted in the considerably weaker material used to model the upper to have little effect.

SIMUCAL was developed to act as a virtual simulator for the qualitative and quantitative evaluation of footwear virtual prototypes (Rupérez et al. 2008; Rupérez et al. 2010; SIMUCAL 2014). The software interface was shown in Figure 2-20. The software was designed to align the virtual shoe with human scanned data, followed by an algorithm to evaluate the node to node contact between the two meshed data (Rupérez et al. 2010). The modelling approach used a Lagrange multiplier method to model the contact, with the mesh constructed from shell elements to which elastic material models were used. Both static and dynamic analyses were completed, with only the toe-off phase (midstance to toe-off) being modelled based on kinematic data from known landmarks on the foot. Shoe deformation and surface forces were measurable using the software (Figure 2-20). It claimed that the software was the first simulator that used virtual reality with this aim. The limitations of the modelling approach meant that only elastic materials could be used, with the shoe weight neglected based on the foot upper interaction being the main reason for upper deformation (Rupérez et al. 2008). The influences of manufacturing processes were not investigated. Stress/strain relationships of the materials within the shoe was not measurable; FEA models would be able to capture this relationship through virtual assembly and functional testing.

Figure 2-19: Foot-Strike Modelling; Driven Segments (Left) and Validation (Right) (Hannah et al. 2012)

Figure 2-20: SIMUCAL Visualisation of Comfort Analysis displaying Pressure (a-c) and aesthetic and functional evaluation (d-f) (Rupérez et al. 2010)
Published literature in the assembly of garments has documented the principle of creating 3D shapes from 2D geometries. Tarrier et al. (2010) detailed a process to form the garment around a human body scan using FEA. The study used ABAQUS Explicit, modelling the material with membrane elements based on 2D IGES geometries. An assembly process using connector elements joined the edge pairs together, typical in manufacture. Surface deformation was compared together to validate the fitting procedure, highlighting the potential for virtual fitting using FEA (Figure 2-21). Other computational processes had been documented to relate garment geometry to contact pressure, changing the pattern design based on a 3D mesh and tensile strain (Wang and Tang 2010).

**Figure 2-21: Geometrical positioning of instances for apparel fitting (Left) and Strain analysis of fitting garment (Right) (Tarrier et al. 2010)**

The studies documented in this section demonstrate that through appropriate application of relevant FEA techniques, representative models can be created and used in the development of sports equipment. Cheung et al. (2009) reported a work-flow system to demonstrate how FEA can be introduced within the design process. With limited published studies documenting the application of FEA techniques in football boots, the potential to construct 3D geometries from manufacturing patterns has been demonstrated through garment assembly. These concepts could be further developed to meet the research aim of this thesis.
2.4 Summary

The purpose of the literature review was to acquire relevant knowledge to construct and evaluate a representative model of a football boot from its constituent parts, determining the predictive capabilities when simulating boot mechanical function. Through extensive analysis of existing literature, observations of physical boot manufacture enabled the processes to be classified into four fundamental stages. The constituent parts of the specific boot on which the model would be based consisted of the outsole, pattern piece, tongue, lasting board and lace structure all formed around the shoe-last.

A representative FEA model of a physical boot would require material models characterised through experimental measurement, assignment of appropriate element types and applicable boundary conditions to first construct the boot followed by subsequent predictive simulations. Techniques developed to assemble garments demonstrated the applicability of connector elements to join edges together, with athletic footwear models detailing the potential to simulate experimental tests. Evidence was shown to suggest the implementation of developed FEA techniques within the design process was a feasible concept.

Mechanical functionality of a football boot was identified by understanding common deformation mechanisms of the foot through the analysis of game related activity. It was apparent from literature that the role of boot properties had little influence when defining the resulting ball flight, whereas with players consistently load the boot throughout a game, the potential impact the boot has on these movements could be more prominent. Monitoring of player movements indicated that the main deformation mechanisms involved bending and torsion of the boot, with the respective stiffness property defining the level of rotation possible. Whilst there were limited publications on the role of boot stiffness on player movements, studies reporting other athletic footwear which involve similar movement types as those observed in football, suggested that both bending and torsional stiffness were important factors in performance and injury reduction.

The literature documented within this section will be used in subsequent chapters within this thesis, providing a basis on which the FE boot model would be constructed through the understanding of the constituent parts and physical manufacturing processes (Chapter 3). Boundary conditions identified in deformation mechanisms of the foot would be used to develop and use existing testing devices to experimentally measure bending and torsional stiffness of physical boots equivalent to the model (Chapter 6).
Chapter 3: Simulation of Football Boot Assembly using Finite Element Analysis Techniques

3.1 Introduction

Development of a boot model using FEA techniques was required to address research objectives 1 and 2 of this thesis. Through the use of concept models, preliminary approaches on simple geometries would enable appropriate techniques to be developed, outlining the methods required to virtually assemble constituent parts generated from manufacturing patterns and geometries with experimental measurement of material behaviour to represent a physical boot.

3.1.1 Aims and Objectives

The aim of the study reported in this chapter was to explore the possibility of constructing a three dimensional football boot model using FEA techniques. The chapter will document the modelling approaches and measurable outcomes obtainable through the development of an FE model.

In the pursuit of this aim, the subsequent objectives were followed:

1. Outline the model requirements necessary to facilitate boot construction using FEA
2. Investigate applicable modelling techniques to represent the individual constituent parts
3. Develop representative material models through experimental measurement of material behaviour using standardised protocols
4. Use simple concepts to develop modelling techniques to assemble a 3D geometry
5. Model boot constituent parts based on manufacturing patterns and geometries, moulds and materials
6. Simulate boot assembly process from constituent parts
7. Demonstrate measurable outcomes from generated boot model
3.2 Principle to Model Constituent Parts and Simulate Boot Assembly

The principle of the modelling approach was to pursue the potential to represent boot constituent parts based on manufacturing geometries and experimental capture of material properties such that under specific loading conditions, the model can provide useful and reliable predictions. This section gives a brief overview of the important stages required to model boot manufacture within FEA, addressing objectives 1 and 2.

3.2.1 Model Requirements

The requirements of the virtual model were outlined below:

- Model geometries based on CAD patterns used in manufacture
- Use appropriate elements types for modelling approach and contact
- Create single components from multiple material layers
- Form 3D shape from 2D geometries
- Visualise and export 3D geometry based on virtual assembly methodology

3.2.2 Modelling of Constituent Parts - Element Selection and Material Assignment

It was important to select the most applicable element types to accurately represent the individual constituent parts within the model. The specific boot modelled in this project consisted of a two part construction, with the upper formed from flat patterns and the outsole injection moulded. Material models were characterised through standardised testing protocols and assigned to the elements through a section property. Both parts required different element types based on their specific application, as discussed further in this section.

Outsole

As the outsole was injection moulded, the generation of a mesh based on CAD geometry of the moulded shape was implemented. Continuum solid elements were applied to the mesh. The most applicable element type for the outsole was documented in Chapter 4.

Upper

The upper consisted of multiple constituent parts; pattern piece, tongue, lasting board, heel pad and lace structure. Consideration of each part was important to represent the boot. One-dimensional elements were used to model the lace structure and will be discussed later on in the chapter. The remaining upper parts consisted of thin structures, with thickness in one dimension significantly smaller than in the other dimensions. Common problems when modelling these
geometries with solid elements involves volumetric and shear locking, resulting in increased localised stiffness (Abaqus 2014). Volumetric locking and shear locking occurs when the elements become too stiff due to the number of integration points, leading to the shear stiffness dominating the solution leading to the mesh becoming ‘locked’. Reduced integration is a technique used to overcome these issues in ABAQUS (Abaqus 2014). Conventional (S3R) and continuum shell (SC6R) elements were more applicable to model upper components based on their geometry (Figure 3-1).

![Figure 3-1: Comparison between Conventional vs Continuum Shell Elements to Model the Upper Constituent Parts (Abaqus 2014).](image)

With conventional shell elements, the thickness was specified through a section property, applied to the geometry. Continuum shell elements involved the extrusion of element layers, defining the thickness through nodal geometry rather than the section property. Whilst their appearance resembled continuum solid elements, their kinematic and constitutive behaviour was similar to conventional shell elements. Only displacement degrees of freedom were calculated with continuum shells, whereas conventional shells calculated both displacement and rotational degrees of freedom. Theoretical analysis of these two element types was investigated later on this chapter with regards to their application.

The lace structure in football uppers generally consisted of a single component fed through holes in the upper material, known as eyelets. Tension applied to the lace structure pulls the upper around the foot followed by the lace being fixed together commonly forming a knot. The application of one-dimensional elements to the wires was used to model this component.

3.2.3 Modelling Assembly Process - Edge Pairings

Previous examples of joining mesh nodes along geometrical edges have been documented in the virtual assembly process of apparel patterns (Tarrier et al. 2010). Axial connector elements were used to pull membrane elements, with a lock function to ensure the nodes remained a fixed distance apart. With upper manufacture involving stitching and adhesion to form the assembled geometry, this approach was trialled. Different conditions could be applied to the connector elements, such as axial springs and dashpots, with the node-to-node contact the primary purpose in this application (Abaqus 2014). Axial connector elements were applied to wires (geometrical features designed to link two nodes together) with the distance between the nodes changed by applying either connector loads or displacements.
3.2.4 Analytical Steps and Contact Conditions

The ABAQUS explicit solver was used to model the assembly process, due to the application of loads and boundary conditions on the axial connector elements; these element types were only supported for explicit analysis. Multiple steps were used during the forming process, with the general process split into three major steps. The material was displaced around the last before the connector elements were activated to bring edge pairs together, wrapping and joining the components holding the part formed shoe in shape. With loads and boundary conditions applied throughout the assembly process, a relaxation step was used to enable the upper and outsole elements to be unconstrained whilst the last was held fixed. A general contact algorithm was used, enabling the model to be solved across multiple processors, reducing the overall computational time.

3.2.5 Application of Boundary Conditions, Loads and Constraints

Boundary conditions and loads were applied to both the material edges and the connector elements to form the three dimensional shape. The forming modelling process was dependant on the complexity of the geometry, with relevant boundary conditions and loads applied in different analysis steps. Rigid tie constraints were commonly used within the modelling process where required.

3.2.6 Visualisation and Analytical Results

Field outputs were requested during the analytical steps dependant on the variables required by the user. A variety of options were available for visual and analytical inspection, such as material stress, strain and displacement during the forming process. Virtual testing of the manufactured boot was an integral part of the project, thus the requirement of the deformed geometry of boot was necessary. The last stage of the geometrical forming model was used for subsequent virtual testing approaches.
3.3 Modelling Material Behaviour in FEA

Material models are required by the ABAQUS solver to define the response of the model based on experimental capture of material behaviour. To meet objective 3, this section details the protocol used to capture material behaviour based on experimental tests.

3.3.1 Experimental Measurement of Material Behaviour

Physical material samples used in the modelled boot construction were supplied by the industrial collaborator, enabling their material behaviour to be quantified and imported into ABAQUS CAE. Standardised testing protocols are common when characterising material behaviour, detailing technical procedures to measure their physical response. Material behaviour was captured by following an ISO 527 testing standard to characterise tensile properties in plastics (BSI ISO-527 2012). Dog bone samples (40mm gauge length) ensured consistency between specimens, with an Intron 5569 uni-axial screw driven machine used to quantify the material’s stress/strain relationship (Figure 3-2). Large clamps were used to hold the specimen, avoiding any slip which would influence the data. A 1kN load cell was used to measure the force during the tensile test.

Characterising material behaviour through experimental tests required the understanding of deformation response which could potentially affect the recorded data. The materials were assumed to be homogenous. Mullins Effect is a physical phenomenon in which deformation leads to softening of filled and non-filled rubber-like material, with the initial stress-strain relationship unique and cannot be retraced (Mullins 1969). Uni-axial tensile tests are common in the characterisation of material behaviour, with cyclic analysis used to quantify the Mullins effect (Diani et al. 2009). Most of the softening occurs after the first cycle of loading, with the material response of subsequent cycles coinciding – between 5 and 10 cycles are common during testing.
(Diani et al. 2009). If the extension exceeds maximum extension of the previous cycle, the material follows the monotonous stress-strain relationship, as shown in Figure 3-3. Whilst no single deformation mechanism was sufficient to account for this phenomena, it was suggested that the fine structure changed, altering the material properties (Mullins 1969; Diani et al. 2009).

**Figure 3-3 Stress - Strain response of a rubber like material under simple uniaxial tension and cyclic uniaxial tension increasing every 5 cycles (Diani et al. 2009).**

Accounting for the Mullins effect involved incremental extension, with 5 cycles for each 0.1% increase in strain. Each material was analysed up to 25% strain, capturing material data to characterise material behaviour based on the raw samples.

The specific boot constructed in this research project consisted of eleven different materials; ten within the upper component and a single material used throughout the outsole component. Access to raw material samples for the outsole was not possible, thus material data supplied by the manufacturer was used to create an initial material model. The accuracy of the material data provided will be assessed through mechanical tests applied to the outsole component. Uni-axial tensile tests were conducted on the physical upper material samples, with the geometrical dimensions used to calculate the stress-strain relationship. Of the upper’s constituent parts, the pattern piece construction involved a number of reinforcement regions bonded to a single material (Synthetic Leather). With a high number of materials requiring characterisation, the synthetic leather material was prioritised in terms of material behaviour investigation. With continuum shell elements limited by only allowing isotropic material models to be applied, only one orientation was measured for each material type. Whilst material orientation is an important concept when defining the material behaviour, the focus of the chapter was to establish whether a boot could be assembled within FEA. Further analysis of material behaviour in different orientations would be conducted in subsequent chapters where necessary.

### 3.3.2 Material Model Generation using Finite Element Techniques

Material behaviour captured through experimental uniaxial tests demonstrated non-linear hyperelastic behaviour. Generation of material models required importing a single set of data in terms of nominal stress and strain. The peak load at each increment of the 5th cycle and its respective extension was used to generate a stress-strain relationship for each trial.
The uni-axial test data was imported for each material with hyperelastic response curves fitted to define the strain energy potential of the material. Selection of the material model was based on the relative hyperelastic behaviour of the response curve and test data, with stable behaviour during the expected strain range of the material (Abaqus 2014). Figure 3-4 displays an example of the stress-strain relationship of experimental test data and three stable reduced polynomial response curves to represent the physical response of synthetic leather. Evaluation of different response curves of the synthetic leather material will be evaluated in Chapter 4. Each material had a prescribed material model based on the stability and fit of the response curves. The material models created from uni-axial tensile tests by importing the data into ABAQUS prior to the fitting of hyperelastic response curves, as stated in Table 3-1.

![Stress-strain relationship](image)

**Figure 3-4:** Example of material model response curves to represent experimental test data; Reduced Polynomial (RP) response curves and Mean Experimental Test Data of Synthetic Leather material.
<table>
<thead>
<tr>
<th>Material Name</th>
<th>ABAQUS Defined Material Model</th>
<th>Mass Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toe Reinforcement</td>
<td>Neo-Hookeon</td>
<td>725</td>
</tr>
<tr>
<td>Heel Lining</td>
<td>Neo-Hookeon</td>
<td>579</td>
</tr>
<tr>
<td>Synthetic Leather</td>
<td>Neo-Hookeon</td>
<td>729</td>
</tr>
<tr>
<td>TPU</td>
<td>Yeoh</td>
<td>2229</td>
</tr>
<tr>
<td>Eyestay Lining</td>
<td>Mooney-Rivilin</td>
<td>904</td>
</tr>
<tr>
<td>Eyestay Reinforcement</td>
<td>Neo-Hookeon</td>
<td>222</td>
</tr>
<tr>
<td>Reinforcement Loch</td>
<td>Yeoh</td>
<td>1366</td>
</tr>
<tr>
<td>Foam</td>
<td>Neo-Hookeon</td>
<td>54</td>
</tr>
<tr>
<td>Lasting Board</td>
<td>Neo-Hookeon</td>
<td>900</td>
</tr>
<tr>
<td>Lace Material</td>
<td>Elastic (1.12 GPa)</td>
<td>912</td>
</tr>
</tbody>
</table>

Table 3-1: Material definitions used in ABAQUS to Model Constituent Parts
3.4 Concept Modelling of Constituent Parts and Assembly Process

With regards to objective 4, a simple concept model was generated to demonstrate the application of the modelling principle. During boot manufacture, the constituent parts of the upper were deformed from 2D to a 3D geometry. It was important to complete this process with sufficient accuracy to allow meaningful simulations to be carried out, thus a concept model was developed. To represent the assembly of the boot simply, a sheet and cylinder was used to outline the general approach.

3.4.1 Validation of Shell Element Type

During football boot manufacture, the upper was formed around a mould – known as the last. Whilst different element types were available to model each part, it was important to select the most appropriate to meet the modelling requirement. Due to the large deformation expected during upper manufacture, an evaluation of the most appropriate element type to model the upper component was required. Both continuum and conventional shell types were evaluated for both loading and contact based tests to indicate accuracy of each element type. The loading test involved a pressure applied across a steel plate, with the vertical displacement at the centre of the plate calculated (Figure 3-5). With the theoretical deflection calculated as 0.4328mm, the difference between the models with the two element types and theoretical values compared.

The model was developed by partitioning a 2D planar plate (radius of 0.2m) with a circle with a radius of 0.15 m to generate an inner region to which the pressure was applied (Figure 3-6). The edge region was held fixed in all degrees of freedom for the analysis. The simulation used a dynamic explicit step with a 1 MPa pressure applied. The vertical displacement of the node at the centre of the plate was outputted and compared to the theoretical deflection for both shell element types.
The creation of a continuum shell part required the extrusion of an existing two dimensional mesh. The process involved extruding the triangular shell elements by the desired thickness as a solid layer, one element thick (Figure 3-7). Multiple layers were added to the component where necessary by selecting the relevant surface from which the extrusion was required. Assignment of material properties to the part was conducted through the relevant section.

Both element types were representative of the theoretical displacement with a difference of 1.35% compared to 1.49% for continuum and conventional shells respectively (Table 3-2).

<table>
<thead>
<tr>
<th>Vertical Displacement</th>
<th>Theoretical Equation</th>
<th>Conventional Shell Elements (S3R)</th>
<th>Continuum Shell Elements (SC6R)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.4328 mm</td>
<td>0.4392 mm</td>
<td>0.4387 mm</td>
</tr>
</tbody>
</table>

Table 3-2: Vertical Deflection of Plate Centre for Theoretical and Shell Element Type.

Contact was another factor in determining the best shell element type when modelling the upper. The principle to evaluate the element type on contact was based on the compression of the

Figure 3-6: Plate Geometry (Left) displaying Pressure Application (Purple) and Fixed Region (Grey).

Figure 3-7: Continuum Shell Element Generation; Native Mesh (Left), Orphaned Mesh (Middle) and Continuum Shell extrusion (Right).
cylindrical layer of elements against a rigid plate. With a rigid cylinder lining the inner surface, both surfaces of the cylindrical elements were impacted. A general contact algorithm was used, with hard contact and frictionless tangential interaction between the surfaces. The same thickness was applied for both element types, with the continuum shell elements extruded to give the desired thickness (1mm). The inner rigid cylinder was vertically displaced, which led to contact between the outer surface of the elements and with the rigid plate (Figure 3-8).

![Figure 3-8: Contact Analysis Pre-Displacement; Shells (Left) and Continuum Shells (Right).](image)

Conventional shell elements were found to be less effective at modelling contact (Figure 3-9). Initial buckling of these elements was observed, due to contact irregularities between the rigid cylinder and inner shell nodes. Penetration of the rigid plate was also observed. Continuum shells were shown to simulate contact between both surfaces of the elements (inner and outer) with no penetration of either the rigid cylinder or plate.

![Figure 3-9: Contact of Element Types; Conventional Shells (Left) and Continuum Shells (Right) Demonstrating the Discrepancy of Modelling using the Respective Shell Elements.](image)
The application of continuum shell elements to model the upper components was shown, with accurate representation of both contact between the inner and outer surfaces, as well as the analytical analysis of bending in circular plates.

### 3.4.2 Development of Methodology to Model Simple Components

The model consisted of simplified geometries; flat material (upper components) to be wrapped around a rigid cylinder (last). The sheet geometry was created using a 2D planar deformable part, with dimensions specified in Figure 3-10. Partitioned regions, 5 mm thick, were required along the edge pairs. This was to ensure consistency between the number of mesh nodes on each edge after they were joined together using connector elements. A discrete rigid part was used for the cylinder, with all nodes within the part constrained to a single reference point, fixed in all degrees of freedom during the assembly process. Continuum shell elements were created by extruding triangular shell elements as a solid mesh one element thick. A shell section was applied, with the thickness determined by the nodal distance of the element. Abstractions were applied to the model to reduce the complexity and develop a method, thus a simple linear elastic material model was prescribed to the section.

![Concept Model - 2D Sheet (Red) and Rigid Cylinder (Grey) (Left), with Dimensions (Right).](image)

Generation of wire features required the selection of each node based on the edge pair. With many edge pairs required and the potential for iterations in upper design, a method was created to reduce the user time for model generation. A quicker method was developed by generating
wires based on two sets of attachment points aligned to geometrical edges. Facilitating this approach required an identical geometry used to generate the continuum shell elements for the sheet. The geometry had no thickness, positioned with the outer surface of the continuum shell mesh (Figure 3-11). Importantly both the number of attachment points had to match the number of mesh nodes along the edge. The direction of the attachment points, from one end to the other, had to be the same between the two edge pairs.

![Figure 3-11: Position of Geometry and Mesh Parts (Left) and Attachment Point Generation (Right)](image)

A plug-in, created by ABAQUS in partnership with the industrial collaborator, was used to generate wires between pairs of attachment points. Axial connector elements were applied to these wires, with a lock used to act as a permanent attachment between the edge pairs – simulating a stitch. A tie was used to constrain the attachment points to the mesh nodes, thus connector element displacement resulted in the edge nodes being moved.

A general contact algorithm was used, with hard normal contact and frictionless tangential behaviour. Within the algorithm, the surface interaction between the geometrical surface and the material was excluded during the analysis, as the function of the geometrical surface was only for wire generation. The simulation consisted of three explicit steps; displacement of the edge nodes beyond the rigid cylinder, the application of a load to the axial connector elements followed by a relaxation step (Figure 3-12).
Surface deformation of the continuum shell elements was demonstrated in Figure 3-12. Strain (a ratio of the material extension relative to its original length) calculated as a result of the assembly process was compared with 2D cross-sectional theoretical calculations based on the outer surface dimensions shown in Figure 3-10 and the locking distance of 0.5 mm for the connector elements. Close agreement between the analytical and theoretical approaches was found, with a difference of 5.5% (12.0% mean principal strain of sheet material elements for the model and 12.7% strain for the theoretical values). This added further evidence that both the method and the use of continuum shell elements were applicable for upper modelling.

3.4.3 Development of Methodology to Model Multi-Material Components

Reinforcement materials were present within the pattern piece part, depending on the specific region within the boot. To account for the layering of these materials, an approach was developed to generate multiple layers of continuum shells elements in specific regions of the pre-assembled part. The method involved splitting the part into different regions using partitioning techniques, followed by extruding both regions separately. The same part was used as for the previous sheet material, with regions created at either ends of the component (Figure 3-13). Region two was constructed from two materials, the base material (Material 1) - as used in the previous example - and a new material (Material 2). Material 2 was half the thickness of Material 1.
Figure 3-13: Component Partitioning with Region 1 in Blue (2 Materials) and Region 2 in Cream (1 Material) (Left) and Mesh Parts created based on Regions; Region 1 (Middle) and Region 2 (Right).

The method involved the creation of two separate mesh parts from the same component (Figure 3-13). By meshing the specific region constructed from the same material layering, continuum shells were generated on each part before being incorporated in a single component. When generating multi-layered continuum shell elements, the based mesh was extruded using a solid mesh, one element thick. Subsequent layering was possible by selecting the surface from which the layer was extruded from, and again stating the thickness for the new material (Figure 3-14).

Figure 3-14: Extrusion of Elements for Region 2; Material 1 (Right) and addition of Material 2 (Right).

As both components were created from the same original 2D mesh, they did not require any alignment when importing into the model assembly. Incorporation of both regions as a new part enabled adjacent mesh nodes to be merged together, generating a single part (Figure 3-15).
The same loading conditions and constraints as the previous concept model were used, in addition to the analytical step time. The result of the forming process was displayed in Figure 3-16. The method demonstrated how multi-layered materials were generated on a single two dimensional geometry, from which continuum shell elements were extruded and two different material models were applied to the relevant elements. Where required, more regions and material layers could be used, with the process forming a single part to which boundary conditions, loading and constraints would be applied to form a 3D shape.
3.4.4 Development of Methodology to Model Lace Structure

Generally used in footwear, a single lace structure fed through eyelets located along an open section of the upper is common. The presence of a tongue provides a protective layer to the foot, whilst contacting the lace structure to ensure the foot remains within the boot. Within ABAQUS CAE, generating a single lace structure fed through eyelets was not appropriate. An approach was taken to create single wire structures between the eyelets, following the lace pattern. Beam elements were used to model the lace structure due to their function; one dimensional line element, with a stiffness associated with the beam’s axis, as well as providing tangential contact (Abaqus 2014). Eyelets were created in the sheet part using partitioning techniques, with the region within the hole removed, as demonstrated in Figure 3-17. Generally eyelets regions within boot construction consist of reinforced regions, thus an addition material layer was introduced.

![Figure 3-17: Sketch of Partitioned Geometry for Eyelets.](image)

Formation of the lace structure involved axial connector elements being assigned to the beam end nodes and reference points position at the associated eyelet. Activation of the connector elements through a boundary condition resulted in the two parts being pulled together, allowing them to interact and form the lace structure. The model was constructed with two instances of the same part, with one rotated relative to the other to align the eyelets as demonstrated in Figure 3-18.
Forming the lace structure involved two steps; the first joined the beam elements with the eyelet centres before a relaxation step. The two sheet parts were constrained as rigid, fixed in all degrees of freedom. Connector loads were applied to the connector elements in sequence, joining the lateral lace structures to the eyelets before the medial laces were formed (Figure 3-19). Different load amplitudes were introduced to avoid node snagging between the beam elements and the two sheet parts; a phenomenon associated when contact between nodes resulted in them not separating.

The formed lace structured was imported as a new part, created based on the output database file (ODB) generated by the previous modelling approach. The ODB file is created as a result of the simulation, enabling numerical interrogation. A new mesh part was created from each beam element, creating a single part, to which beam element sections were applied. Both sheet materials were positioned in the same location as the lace forming model, thus the imported lace structure and the sheet parts were aligned together (Figure 3-20).
Figure 3-20: Concept Model Alignment with lace structure and material components.

Tie constraints were used to model the interaction between the lace structures; end nodes of the beam elements were tied to the inner surface of the eyelets. Determining the master and slave relationship was important as each eyelet was tied to two beam elements; one beam element was aligned to the top surface and the other aligned to the bottom surface (Figure 3-21). Where the beam structure was aligned to the top surface (Coloured Cream in Figure 3-21), the beam end was assigned the master with the eyelet nodes assigned the slave. The master slave relationship was reversed for the beam structures aligned to the bottom surface (Coloured Green in Figure 3-21).

Figure 3-21: Tie Constraint at Eyelets; Master (Red) and Slave (Pink) Relationship.

The same approach was taken to form the 3D shape, wrapping the material and lace structure around the cylinder (Figure 3-22). The method demonstrated how modelling approaches were
applicable to virtually form 3D shapes from flat geometries based on typical structures associated with football boot uppers.

Figure 3-22: Lacing Forming Process; Initial alignment (Left), Displacement (Middle) and 3D Shape (Right).

Material stiffness assigned to the lace structure determined the space between the two sheets. With consideration to how lace structures function in practice, typically the player tensions the laces manually, tightening the upper around the foot. As the lace was created from many beam elements, applying tension in the same manor would not suffice. A modelling approach was developed using a linear thermal expansion principle; expansion or contraction of the material due to changes in temperature (Callister 2000). With a given thermal expansion coefficient, defined within a material property, the change in temperature would result in the beam changing length (Eqn. 3.1) (Abaqus 2014). Therefore if the beam element had a negative thermal expansion coefficient, an increase in temperature applied to the elements resulted in the lace length
reducing. Changing the magnitude of the temperature influenced the length of the beam element. A thermal expansion coefficient was set to -0.05 at a temperature of 10° was applied to lace material model.

\[
\text{Thermal Expansion Coefficient} = \alpha = \frac{1}{L} \frac{\Delta L}{\Delta T} \quad \text{Eqn. 3.1}
\]

The same approach was used to assemble the individual components into the 3D geometry. However, an additional step was introduced prior to relaxation, in which a temperature was applied to the laces. A peak temperature of 40° was applied to the beam elements using a pre-defined field with smooth step amplitude lasting the step time. The effect of lace tension was demonstrated in Figure 3-23.

![Figure 3-23: Application of Temperature to Beam Elements to Tension Lace Structure; Before and After Beam Element Temperature Application (Left and Right respectively).](image)

The modelling approach developed in this section created a formed 3D shape based on flat geometries, to which multiple regions constructed from continuum shell elements with different materials and relative thicknesses were generated to form a single component. Lace structure was modelled, linking two material components together typically observed in football uppers. Thermal expansion of beam elements was introduced to tension the lace structure.
3.5 Modelling and Simulation of Football Boot Assembly

The principle of forming 3D shapes from flat components using Finite Element methods had been demonstrated using simplified geometries. With regards to objectives 4 and 5, further development of these materials involved applying the techniques to generate a three dimensional representation of a football boot based on manufacturing patterns, geometries and materials.

3.5.1 Football Boot Case Study

An existing product was modelled to verify the techniques developed in the thesis. The upper was forefoot lasted, cut from synthetic leather with reinforcement regions bonded to its surface. The outsole was injection moulded from a thermo-plastic material, with an external heel counter built into its construction (Figure 3-24).

![Figure 3-24: Upper and Boot Assembly of Football Boot Case Study.](image)

3.5.2 Constituent Parts Modelling - Integration of Manufacturing CAD Geometries

An important factor in the development of the modelling approach was to use geometries used in the manufacture of real football footwear products, essentially virtually simulating their assembly. CAD data, supplied as drawing files (DWG), were imported into HYPERMESH software to generate surfaces to which elements were applied. Unnecessary surface details such as logo printing and surface textures were removed, reducing the complexity of the model and computational time. It was assumed that these features would have little significance on the response of the shoe, due to the material and thickness; these features were screen printed on the constituent part (Figure 3-25).
These components were exported as individual IGES files, before being imported into ABAQUS CAE as parts. Partitioning and virtual topology tools were used to generate surface meshes to which continuum shell elements were generated. Virtual topology is a defeaturing tool used to remove unnecessary surface detail that unduly constrains the mesh generation whilst having an insignificant effect on the mechanics of the model (Abaqus 2014). With the part’s topology created from a series of faces and edges, the tool enables adjacent features to be merged together whilst maintaining the overall shape. Virtual topology was also important in ensuring edge pairs had the exact node and attachment points, essential when assembling the constituent parts. The transformation of each part from the imported CAD surfaces into continuum shell elements was discussed separately. Material models were applied to their respective regions, assigned through section properties.

3.5.3 Constituent Parts Modelling - Edge Pairing Partitioning Method

Modelling manufacture involved joining edge pairs around a mould, creating the desired three dimensional shape. Generally in manufacture, these edges were brought together either by hand or using machinery and permanently fixed together by glue or stitching. As detailed in the concept model, a partitioning technique was used to offset the edges, enabling the edge nodes to be changed without influencing mesh density within the component. Edge pairs within the upper components were colour coded, displaying which regions were joined together (Figure 3-26).
With axial connector elements used to join these edges, the number of mesh nodes along each pairing had to be equal. If nodes were not associated with a connector element, it could not be fixed in place during assembly and was free to rotate. As the edge nodes were limited by the number of attachment points, a partitioned region within the component was created, allowing the mesh density within the part to be varied without affecting the assembly process (Figure 3-27). The principle was used for all components in which edge pairs were present.
3.5.4 Constituent Parts Modelling – Representative Geometry

Pattern Piece

The pattern piece used for the case study consisted of one main material to which reinforcing materials were bonded. To permanently fix the pattern piece forefoot and lasting board, adhesive was applied to a bonding margin to overlay adjoining surfaces. Once fixed in place, excess material was removed using an industrial sander, creating a smooth surface to which the outsole was attached (Figure 3-28).

Figure 3-28: Smoothing bonding region of upper for outsole attachment.

Modelling this process was difficult using FEA techniques due to discontinuity between the bonding margin and the lasting board, thus a simplification was introduced. By removing the bonding margins, a smooth surface on the plantar region of the formed upper was modelled. The bonding margin removed from the pattern piece was highlighted in blue in Figure 3-29.

Figure 3-29: Bonding Margin (Blue) located in forefoot of Pattern Piece.

The creation of the pattern piece part within ABAQUS CAE involved two processes. The first process involved the part being imported based on the IGES geometry created in HYPERMESH. The pattern piece consisted of six regions (Figure 3-30).
Due to the complexity of the part, irregularities during the import process of the multi-surface geometry resulted in difficult meshing conditions. A second process was introduced which involved the multi-surface geometry being saved as two separate sketches within ABAQUS CAE; outline edges and detailed edges (Figure 3-31). A new part was created using the outline edges before partitioning the part based on the detailed edges imported from the sketch. This divided the single surface into different faces, generating the virtual pattern piece. Faces within the eyelets were removed from the component.

The partitioning process split the single part into multiple regions, to which different properties, such as material behaviour and thicknesses, were applied. The upper construction modelled consisted of 9 regions built from 8 different materials as displayed in Figure 3-32.
Creation of continuum shell elements with multiple materials involved each region being extruded as separate parts. Region 2, detailed in Figure 3-32, was used to demonstrate the method, with Figure 3-33 providing visual support of the process. Started by meshing only the required regions on the original pattern piece geometry, the process involved creating a new mesh part based on the region’s surface mesh, with extrusion of layers in accordance with the material thickness. Each layer was assigned a shell section, consisting of the correct material property.

Figure 3-32: Section Assignment for Pattern Piece.

Figure 3-33: Continuum Shells Creation of Specific Region; Surface Mesh (a), Extrusion of Solid Layers (b), Completed Part (c) and Meshed Region Relative to Pattern Piece Geometry (d).
All 9 regional parts were incorporated into a single new mesh part, with adjacent nodes merged within a tolerance of 0.001mm. The section properties of each region were imported, generating a single component with each material assigned to its relevant layer, as denoted in Figure 3-34.

![Figure 3-34: Modelled Representative Pattern Piece Component Formed From 9 Regional Parts.](image)

**Tongue and Heel Pad**

The creation of representative tongue and heel pad constituent parts used the same method described to create the pattern piece. Virtual topology was used to create single edges, to ensure mesh consistency between edge pairs. With axial connector elements used to pull the regions together and ties used to act as the stitches, regions within the parts were partitioned, enabling wires to be generated from attachment points (Figure 3-35). Both parts consisted of a single material, thus a simple solid layer of elements were extruded from surface mesh, generating 3D continuum shell element parts (Figure 3-35).

![Figure 3-35: Tongue (Top) and Heel Pad Components (Bottom); 2D Meshed Surface with Partitioned Regions (Left) and Continuum Shell Element Parts (Right).](image)
Last

The last CAD geometry was supplied by the industrial collaborator in IGES format and imported into HYPERMESH. Rigid tetrahedral elements were assigned to the mesh based on the assumption that the last geometry would not change during manufacture, reducing assembly modelling CPU time. The last was imported into ABAQUS CAE (Figure 3-36).

![Figure 3-36: Representative Last Geometry constructed from tetrahedral rigid elements.](image)

Lasting Board

In football boot manufacture, the curvature of the lasting board was based on the last’s plantar surface, thus a modelling approach to represent this involved a partitioning technique. The approach extended the face of the 2D lasting board CAD onto the plantar region of the last, with the remaining surfaces outside of the lasting board removed, forming the geometry shown in Figure 3-37.

![Figure 3-37: Lasting Board Based on Last Curvature.](image)
Virtual topology and partitioning techniques were applied to the created surface, enabling the associated edge pairs to be created. Again, consistency between the mesh nodes and attachment points of the respective edge pairs was necessary. Continuum shell elements were extruded based on the 2D mesh, with the material assigned using a section property (Figure 3-38).

![Figure 3-38: Partitioned Lasting Board (Left) and Continuum Shell Lasting Board (Right).](image)

**Lace Structure**

The lace structure was formed using beam elements associated with wire features, based on the position of the eyelets in the pattern piece. Demonstrated by the concept model, the beam elements were aligned at an angle, with axial connector elements assigned to wires generated between the beam end node and the reference point positioned at its respective eyelet. The same modelling approach developed in the concept model was used, demonstrated in Figure 3-39.

![Figure 3-39: Lace Forming Process; Pre-Alignment (Left), Stage 1 (Middle) and Stage 2 (Right).](image)

The deformed elements from the lace forming model were imported as a new part into the boot assembly model, with ties used between eyelet and lace end nodes. A simple elastic material was prescribed to the beam elements.
Outsole

A representative outsole constituent part was constructed from the injection mould CAD, supplied by the industrial collaborator. A defeaturing procedure removed surface details such as logos, which could potentially increase numerical analysis whilst remaining redundant during the simulation (Abaqus 2014). Tetrahedral elements were constructed from the CAD surfaces generating a 3D mesh. Checks were carried out on the 3D elements, ensuring their angles were within 20° and 120° to avoid element distortion during analytical solving of the model (Abaqus 2014). The outsole’s 3D mesh and CAD were displayed in Figure 3-40.

Figure 3-40: Outsole CAD (Left) and Representative Meshed Component (Right).

3.5.5 Modelling Football Boot Assembly

Demonstrated through concept modelling, application of loads and displacements to axial connector elements joined edge pairs, forming a 3D model from constituent parts. Attachment points could only be offset based on geometrical edges, resulting in both the geometry (from which the continuum shells were built) and the continuum shell parts being used in the model assembly. Both geometrical and continuum shell components were aligned within the assembly module, based on the initial position of the last (Figure 3-41). To facilitate the assembly process, the tongue was positioned below the pattern piece with the heel pad horizontally aligned to the lateral region of the pattern piece. The lace structure was positioned with the beam end nodes aligned to the eyelet holes. The lasting board was situated under the forefoot of the last.
The sole purpose of the geometrical components was to facilitate wire generation, thus no contact was allowed between them and the upper components throughout the simulation. Wires are geometrical features to which axial connector elements were assigned to enable the joining of the edge pairs. The wire features define the two nodes to which the assigned element will connect. The geometrical components were constructed from simple rigid elements with no thickness, demonstrated in Figure 3-42. Individual attachment point sets were offset from the geometrical components, followed by generating of wires between these sets.

Tie constraints were used to ensure that the wire ends remained fixed to the respective node on the continuum shell component. The nodes on the continuum shell element were set as the master with the attachment points the slave, thus the shortening of the wire’s length resulted in the corresponding node on the continuum shell component being displaced. Wire sets were generated between their respective attachment point pairs, creating six major regions (Figure 3-43). Each wire set enabled the edge pairs to be connected during the assembly process.
3.5.6 Simulation of Football Boot Assembly

Demonstrated in the concept model, the simulation to form the virtual boot was split into a series of steps, in which boundary conditions were applied to the constituent parts within the model. All steps used in the simulation were dynamic explicit; axial connector elements only functioned within the explicit solver. A total of 6 steps were required to form the upper. The first step was required to displace components from their initial positions around the last, whilst the second and third steps applied boundary conditions to the connector elements, locking them in place. The beam elements used to model the laces were tensioned in the fourth step before the attachment of the outsole to the formed upper in the fifth step. The material was allowed to relax in the last step. Mass scaling was an artificial factor within the modelling step which was used to reduce computation time. Applying mass scaling to the model increased the minimum stable time increment, which governs computational time, thus speeding up the solving time. This effect prescribed a large mass to the system and influenced measurements such as force and moments. With the principle of the forming model to simply approximate the manufacturing process, mass scaling was used to reduce computational costs associated with continuum shell elements. ABAQUS user manual states the ratio between the kinetic energy and internal energy must be below 10% (Abaqus 2014) and less than 5% (Sun et al. 2000); this was observed in all steps during the virtually assembly of the boot. Different smooth step amplitudes were applied within the boundary conditions, enabling a series of events to occur within each step. A general contact algorithm was used, based on it allowing the model to be solved using multiple domains. A ‘hard’
normal interaction and frictionless tangential behaviour was applied to the algorithm. All nodes within the lasting board component remained fixed in space during the forming process, with the board pinned in place during manufacture. The initial part of the first step involved connector displacement of the tongue and medial heel pad connector elements, fixing the nodes along the edge pairs together (Figure 3-44).

![Figure 3-44: Application of Tongue and Medial Heel Pad Connector Elements; Before (Left) and after activation (Right).](image)

Nodes located along the edge of the pattern piece were displaced around the last, with contact between the last and upper components experienced during this step, with the connector elements in the forefoot locking (Image A in Figure 3-45). The remaining edge pairs were joined using two steps, in which boundary conditions were applied to the connector elements, with amplitudes dependant on the assembly sequence. The first of these steps involved the joining of connector elements between the heel pad and both the lateral edge of the pattern piece and rear of the (Image B in Figure 3-45). In the third of the assembly steps, connector displacements were applied to the remaining connector elements at the heel. This process resulted in the forming of the upper (Image C in Figure 3-45).

Lace tension was applied during the modelling process to account for the discrepancy between the modelled assembly process and the physical manufacturing process. Applied to the beam element, a prescribed temperature enabled the contraction of the lace structure due to the negative thermal expansion coefficient defined in the material model. The application of a positive change in temperature resulted in the lace length shortening, pulling the eyestay regions together (Image D in Figure 3-45). Aligned below the base of the last based on the heel counter (Image D in Figure 3-45), a pressure was applied to the inner surface of the heel counter whilst the virtual upper was vertically displaced to initiate contact between the adjoining surfaces of the
two components. Boot assembly was completed by attaching the outsole to the upper (Image E in Figure 3-45).

Figure 3-45: Stages of Virtual Upper Manufacture; Displacement of upper components around last (a), connecting underside of upper (b), heel assembly and lace tensioning (c), Relaxed Upper state prior to outsole attachment (d) and assembled boot (e).
3.5.7 Assembled Football Boot Model

The modelling approach facilitated the construction of a representative 3D model of a football boot from constituent parts based on manufacturing patterns, geometries and materials; upper constituent parts were modelled by generating material models based on uni-axial test data prescribed to continuum shell elements, with the outsole modelled using solid continuum elements (Figure 3-46). Residual stresses were present in the material due to the application of hyperelastic material models, thus removing the interaction between the assembled boot and last led to the elements contracting. An approach to import the assembled geometry without residual stresses for subsequent mechanical evaluation will be documented in Chapter 4.

![Figure 3-46: Finite Element Modelling Approach of Virtually Assembled Football Boot.](image)

Interrogation of the FE boot model enabled visualisation of material stress and strain as a result of the assembly process, addressing objective 7. With the upper component being formed from two dimensional flat geometries, surface deformation was quantified through maximum principal strain of the elements, shown in Figure 3-47. This demonstrates the potential to predict how the material will deform due to physical manufacture, visualising and identifying the influence on specific regions within the formed geometry where high stresses and strains are experienced.

![Figure 3-47: Maximum Principal Strain Measured during Virtual Manufacture of Upper Component.](image)
3.6 Chapter Summary

The modelling approach documented a method to construct a 3D boot model from constituent parts based on manufacturing patterns, geometries and materials, addressing the chapter aim.

Development of FEA techniques to meet objectives 1-4 involved the creation of a concept model, assembling a sheet material around a cylinder to form a simple 3D geometry, demonstrating a method to facilitate the assembly of a football boot. Incorporating real manufacturing patterns, geometries and experimental measurement of material behaviour, constituent parts were modelled by assigning continuum shells (upper) and solid (outsole) elements. Modelling techniques were used to join edge pairings, forming a representative 3D football boot, meeting objectives 5 and 6. Interrogation of the model demonstrated the potential to identify regions of high material deformation as a result of constituent parts, in addition to the deformed geometry answering objective 7 stated in the chapter introduction.

With the overall research aim of the thesis to determine the applicability and validity of constructing a football boot using FEA techniques through functional tests, subsequent geometric analysis and load response of the representative football boot model will be required to determine the validity of the approach.
Chapter 4:
Simulation of Load and Deformation Response of Football Boot Model

4.1 Introduction

Acquiring quantifiable data was essential in determining the validity of the FE boot model, with experimental measurement of the physical boot’s response under loading providing comparable data to indicate FEA techniques and permit reliable prediction of mechanical functionality. The process of evaluating the model through geometrical analysis as well as comparative load and deformation response will be documented in this chapter.

4.1.1 Aims and Objectives

The aim of the study reported in this chapter was to evaluate whether the assembled FEA boot model was representative of the physical boot in terms of overall geometry and load response. To meet this aim, the following objectives were pursued:

1. Create a method to import the assembled boot as a 3D geometry for subsequent geometrical and load response analysis
2. Identify a method to compare geometrical differences between the modelled and physical boots
3. Use a simple mechanical test to experimentally measure load and deformation response of physical boots
4. Extract simulated outputs to quantify load and deformation response of the virtual boot
5. Compare experimental measurements of physical boots with model outputs to explore validity of FEA approach
4.2 Geometrical Evaluation of Football Boot Model

This section documents an approach to provide analytical confidence of the 3D representative boot model by comparing it with surface scan data of a physical boot, determining the geometrical accuracy to address objectives 1 and 2.

4.2.1 Surface Evaluation Methodology

Surface scan data of a single physical boot specimen was captured using a GOM ATOS measurement system. The system was based on the triangulation principle; projection of different fringe patterns onto the object recorded by two different cameras (GOM ATOS 2014). Up to 4 million data points were created for each single measurement, with multiple angles used to generate a full 3D scan, creating a Stereolithography (STL) file format.

The process to create a surface from the assembled FE boot model involved importing the upper and outsole as parts based on their final state during virtual boot assembly without residual stresses. An STL file was created by exporting the parts within ABAQUS CAE - beam elements were not compatible with this file format, so the lace structure was not included in the surface comparison. The two surfaces used for the geometrical analysis were displayed in Figure 4-1.

![Figure 4-1: Representative surfaces for Geometrical Analysis; FEA Boot Model Surface (Left), Surface Scan Data of Physical Boot (Middle) with Both Surfaces Aligned (Right). Pre-alignment Node highlighted in Red](image)

GOM Inspect software computed the relative perpendicular distance between two sets of data points, with one set defined as the reference. In this case, the FE boot model was classed as the reference, from which the perpendicular distance between it and the physical boot scan data was computed. After being preliminary aligned manually within ABAQUS CAE, subsequent alignment processes were used within GOM Inspect to reduce potential errors. The first stage involved pre-alignment of the two data sets, arranging both geometries based on the medial eyelet in the first row. A second alignment involved a best-fit method relating the two surfaces together.
(Figure 4-1). The two surfaces were evaluated using a surface comparison based on the CAD geometry, with the relative distance plotted onto the reference.

4.2.2 Surface Evaluation Results

Qualitative analysis of the relative distance between the representative FE model and physical boot scan data can be seen in Figure 4-2. High deviation was measured in the eyestay region, based on the exclusion of the lace structure from the FE boot surface. With the scanned data sets captured from the outer surface, the missing elements resulted in the high deviation. Other regions of high variation were observed between the heel collar and last. Limitations of the physical boot scanning process resulted in poor surface data being captured at this region. These regions were highlighted in Figure 4-3, displaying the high levels of surface difference related to a ± 4mm deviation.

Figure 4-2: Contour plot to show perpendicular distance between Scanned Physical Boot Surface FEA Boot Surface; Data projected on FEA Boot Surface
Discounting the regions with a tolerance greater than ± 4 mm (displayed in Figure 4-3), 93.4% of the surfaces for the physical and modelled boot were within ± 2.75 mm. To provide context, length scales for both the longitudinal length and the heel width at the base of the outsole were used. These equated to ± 0.97% difference with respect to the longitudinal length and ± 4.58% with respect to the heel width, further demonstrating the excellent agreement between the virtual and physical assembly process. Manufacturing tolerances could potentially change the surface deviation (only one physical boot was used), but with this research project focused towards generating a representative football boot model, the requirement was to evaluate the virtually assembled geometry. Analysis of the surface curvature of the model provided a 93.4% confidence that the model represented the physical boot’s geometry within ± 2.75 mm, exhibiting the potential of using FEA to virtually assembly boots from constituent parts.
4.3 Experimental Measurement of Load and Deformation Response of Physical Football Boots

In accordance with objective 3, a three point bend test was used to measure forefoot bending in boots based on the relative simplicity of the loading condition. Whilst the loading condition was different to the expected boot deformation during player motion, a simple testing protocol would enable methods to be developed and comparisons to be drawn to infer the applicability of the FEA boot model. With the overall goal to provide comparative data for model verification, the response in terms of both the bending force and deformation of the physical boot was measured.

4.3.1 Experimental Measurement Methodology

Common in measuring the footwear stiffness, studies have utilised mechanical tests to investigate the relationship between biomechanics of the foot during running and shoe stiffness (Kleindienst et al. 2005; Stefanyshyn and Fusco 2004; Roy and Stefanyshyn 2006; Willwacher et al. 2013). The tests generally comprise of two supports to hold the test specimen, with a load or displacement being applied equidistant from the supports, measuring the force deflection relationship.

In this study, the testing methodology was in accordance with the ASTM 790 standard for flexural properties of unreinforced and reinforced plastics (ASTM 790). With a horizontal distance of 70 mm between the two supports, the load was applied in the forefoot of the outsole, upper and boot constructions. An Instron 5569 screw-driven uni-axial testing machine was used to measure the force relative to the displacement. The test was initiated with a pre-load applied at the start, which ensured the same initial position between all test samples. A displacement driven loading of the specimen followed the pre-load with strain rate dependency analysed. Of each component type, three specimens were tested, with loading in the forefoot resulting in deflection of the specimen. A preload of 3 N was applied to both the upper and boot components before the end effector was displaced 40 mm, flexing the component in the forefoot. Beyond this value, slip was observed. Testing the outsole required a preload of 5N before the displacement of the end-effector to 10 mm.

The influence of strain dependency on the quasi-static test was investigated by testing a single specimen using three different displacement velocities; 25 mm/min, 100 mm/min and 400 mm/min (Figure 4-4). Strain rate sensitivity was observed when samples were tested at 400 mm/min, with close agreement measured at 25 mm/min and 100 mm/min. Greater material stiffness at higher strain rates would indicate viscoelasticity in the loading of the component, but
with hyperelastic material models used within the model and to develop simple material models, a velocity of 100mm/min was used to test the samples for comparison with the FE model.

![Force Displacement Graph](image)

**Figure 4-4: Influence of Strain Dependency during Upper testing at three different velocities**

Deformation response was quantified by measuring the vertical displacement of the specimen’s rearfoot. Images were captured perpendicular to the test specimen for the undeformed and peak deformation states, with the relative distance of a marker at the rear of the sample tracked using Image Pro Analyser®, calibrated by measuring the distance between two stud locations in the software and experimentally. Figure 4-5 demonstrated point selection of the undeformed and peak deformation response during loading. Vertical displacement all test specimens (outsole, upper and boots) were captured, with an overall mean and standard deviation quantified for comparison with modelling data.

![Experimental Measurement of Sample Deformation](image)

**Figure 4-5: Example of Experimental Measurement of Sample Deformation during Forefoot Bending; Undeformed (Left) and Peak Deformation (Right)**
4.4 Evaluation of Simulated Load and Deformation Response of Football Boot Model

With a plethora of modelling techniques available within the FEA software package, the aim was to further explore and detail the most applicable to represent load response of the physical boot. With regards to objectives 4 and 5, the focus was to compare the modelled loading scenario in terms of bending force and deformation response with physical boots. Whilst the loading condition was a simple test when compare with volumetric bending, the approach was a developmental step required to provide representative data, exported from the model prior to comparative analysis, with material models, element types and modelling constraints evaluated to investigate their significance.

4.4.1 Mechanical Test Modelling – Load and Deformation Response

Modelling the three point bend test involved the apparatus being created as discrete rigid parts, with reference points defining their relative motion. The supports were fixed in space, whilst the end effector was displaced vertically downwards to replicate the mechanical test. The outsole, upper and boot assemblies were tested. History outputs were calculated for the rigid end effector, providing a force displacement relationship to compare with the experimental test data.

The model was split into two steps to replicate the experimental test. The first step involved the pre-loading of the component, followed by the displacement of the end effector resulting in forefoot bending. The force required to bend the specimen was measured using history outputs, extracting the vertical displacement and reaction force of the reference point associated with the end-effector. This was exported into excel and compared directly with the experimental test data to determine the accuracy of the virtually formed boot model. Vertical displacement of the rear of the test sample was also quantified for comparison with experimental test data.

As described in Section 4.2.1, the upper and outsole components were imported into the model based on the geometry created during the boot assembly simulation. These were important as new parts without residual stresses, maintaining the 3D geometry.

4.4.2 Comparison of Experimental Measurement and Simulated Output – Outsole

The material used in the outsole’s construction was a Polyamide 11 glass fibre reinforced injected material. Due to the raw material sample data not being accessible to characterise the behaviour, material data supplied by the manufacturer was used to form an initial material model. An elastic
linear material model was prescribed to the elements, with the defined materials; Young’s Modulus (2.6 GPa), Poisson’s Ratio (0.35) and density (1070 kg/m³) (CAMPUSPlastics 2012).

Tetrahedral elements were applied to the outsole component due to the complexity of the geometry, resulting in the potential to use two different element types; C3D4 and C3D10M. Whilst C3D10M elements provide improved performance over C3D4 elements when modelling thin structures, additional nodes increase the computational cost (Abaqus 2014), as demonstrated in Figure 4-6. Artificial stiffening of the outsole using C3D4 could explain the large discrepancy in observed force between the two element types, with volumetric locking a modelling phenomenon experienced during bending, resulting in the increased stiffness of C3D4 element types (Abaqus 2014). C3D10M elements have hourglass control, improving accuracy of the analysis, thus providing a greater representation of the loading condition than C3D4 elements, as shown in Figure 4-6.

Figure 4-6: Force vs Displacement Relationship between Experimental Test Data and FE Model during Three Point Bend Test of the outsole component.

The relative deformation of the outsole for both elements types was shown in Figure 4-7 and quantified in Figure 4-8. Close agreement was measured for both element types during forefoot bending, with the vertical displacement 3% and 13% away from the experimental mean for C3D4
and C3D10M elements respectively. Whilst a more accurate representation of the deformation response was prominent when using C3D4 elements, the elements resulted in far stiffer force measurement. However, C3D10M elements provided close agreement in terms of force and deformation measurement. A negative to using quadratic element types was the additional computational time required to solve the loading scenario; 53 hours on a single CPU for C3D4 elements and 141 hours on a single CPU for C3D10M elements. Whilst the modelling approach to use C3D10M elements increased the computational cost by 266% when compared with C3D4 elements, the closer representation of forefoot bending suggested that the computation cost was acceptable.

**Figure 4-7:** Visual Comparison of Outsole Deformation at Peak Displacement during Bend Test; Experimental (Left) and FE Model - C3D4 Elements (Middle) and C3D10M Elements (Right).

**Figure 4-8:** Vertical displacement of Rearfoot of FE and Experimental Test Data.

Mesh refinement is a process used to ensure the computed results provide appropriate outputs without incurring unnecessary associated computational costs. With C3D10M elements used to model thin solid structures, their quadratic algorithm increases the computational cost, thus a mesh refinement was essential. The mesh density within the modelled component was changed, with the bending force at peak displacement (10 mm) used to infer the most applicable element number. Figure 4-9 displayed the associated force relative to the number of elements within the
modelled outsole component, with the chosen mesh density displayed in red. The trend plotted suggested convergence. The associated computational cost between an outsole component with 29446 elements (displayed red in Figure 4-9) and with 48858 elements was increased by 123% whilst the computed force was within 15% of the two mesh densities. The chosen mesh (29446 elements) was deemed acceptable as it provided appropriate outputs for the shortest computational costs.

The influence of friction between the test apparatus and outsole component had no significant effect on the modelled bending force. A penalty contact coefficient of friction, ranging between 0 and 0.3, was used to investigate the effect.

Modelling the outsole using C3D10M elements improved the accuracy of the model, but the force at 5 mm and 10 mm deflection was 45% and 35% greater than the experimental test data. With consideration to the injection moulding process, orientation of the glass fibre, moisture content and powder quality have been reported to influence material behaviour (Van Hooreweder et al. 2013). The material data used to define the physical attributes of the outsole component provided a starting point from which an iterative approach was developed to better represent the physical experimental test data, changing the outsole’s tensile modulus. The refined material model consisted of a Young’s Modulus (1.56 GPa) 60% of the original material data. A difference of 1% and 2% was measured at 5 mm and 10 mm deflection between experimental and the refined material model, with the data graphically represented in Figure 4-10. The three point bend test for forefoot bending of the outsole component demonstrated how physical test data can be used to provide an initial starting point from which a refined material model was generated. Evaluating the model of an entire component as demonstrated with the outsole

Figure 4-9: Mesh Refinement Study for Outsole at Peak Displacement (10 mm). Selected Mesh Density signified by Red Data Point (29446 Elements).
provided a representative material model accurate within 2% of experimental test data of the physical equivalent under simple loading conditions.

**Figure 4-10: Model correction of Young’s Modulus; Force vs Displacement Relationship between Experimental Test Data and FE Model with Original Material and Refined Material Models prescribed to C3D10M Elements**

### 4.4.3 Comparison of Experimental Measurement and Simulated Output – Upper

The upper component was aligned to the three point bend test visually, based on the experimental test alignment (Figure 4-11). Laces were removed from both the model and experimental testing, with the end-effector impacting the first row of eyelets. In the experimental test, the rear of the upper was rested on a platform to enable the upper’s forefoot to sit on the two supports. Three upper specimens were tested five times, with peak deflection of 40mm measured after a preload was applied.
Continuum shell elements used to represent the upper component could only be first order and have two types depending on the element shape; wedge (SC6R) and hexagonal (SC8R). It is worth noting that element types in the upper must be defined prior to boot assembly, as once formed, the shape of the elements cannot be changed in subsequent models. The element seeding within the components were kept consistent between the two models, with the visual difference in mesh structure of the formed upper displayed in Figure 4-12.

Graphical representations of the force displacement relationship of the two different element types were displayed in Figure 4-13. The magnitude was far greater for the modelled forefoot bend test than the experimental test results, with a difference between 284% and 333% at peak deflection for Wedge and Hexagonal elements respectively. With the wedge elements closer to the respective experimental test data, the SC6R elements were explored further with regards to material model and frictional effects on the modelled measured force.
A mesh refinement study was used for the upper component to determine the most applicable number of elements to simulate the loading condition. Figure 4-14 demonstrates the computed bending force at 40 mm displacement, with the chosen mesh density displayed in red. A trade-off between accuracy and computational cost led to the mesh being chosen; doubling the computational time resulted in a difference in the computed bending force of 15% (33106 elements and 61239 elements). It was accepted that the chosen mesh would provide representative results without leading to unnecessary computational costs.

Changing the global penalty friction coefficient had a small influence on the bending force; when the tangential friction coefficient ranged between 0.1 and 0.3, the bending force was increased by
5% and 7% at 20 mm and 40 mm displacement respectively. Whilst the contact conditions were shown to have a small effect of bending force, these results did not explain why such a large magnitude was measured in the FE model when compared with physical experimental test data.

With consideration of the Euler-Bernoulli bending theory (Eqn. 4.1), the relationship between the bending moment (in this scenario the force) and the vertical displacement is governed by the material property (Young’s Modulus – \( E \)) and the geometry (Second moment of area – \( I \)) (Clifford et al. 2009).

\[
M(x) = -EI \frac{d^2y}{dx^2}
\]  
Eqn 4.1

Geometrical analysis of the undeformed physical and modelled boot surface difference showed that 93.6% confidence that the modelled assembled geometry was between ± 2.75 mm of the physical boot. Therefore the material models used to represent the physical test data could influence the bending force, potentially explaining the significant differences between the experimental and modelled data.

![Material Model Behaviour Relative to Experimental Test Data Mean.](image)

Material behaviour was characterised as discussed in Section 3.3, with response curves fitted based on the most applicable material model. Once assembled, the material model prescribed to the relevant constituent can be changed, thus the influence of different material models could be investigated during upper deformation. With the upper constructed from primarily synthetic leather, two material models were created based on the characterised material data from uniaxial tests on the raw materials. The two materials chosen to explore the influence was a Neo-Hookean and a Yeoh material model, with their material behaviour displayed in Figure 4-15.
The increased bending force measured in the model was as a result of the different material models being fitted to the test data - a 19% and 12% difference in bending force measured at 20 mm 40 mm of deflection respectively (Figure 4-16). This demonstrated the sensitivity of the model during bending due to different material behaviour applied to the upper; caution must be taken during fitting of material models with regards to the measured outcomes.

![Figure 4-16: Force Displacement Relationship during forefoot bending of Upper component with different material models applied to the elements representing the synthetic leather.](image)

A refinement process was implemented to generate a material model that represented the experimental test data of physical uppers. An iterative approach using different material model stiffness’ based on the Neo-Hookeon material model demonstrated in Figure 4-15 were applied to the boot model with the resulting bending force measured. The bending force model with the optimised material model was displayed in Figure 4-17. Reducing the overall material stiffness of the synthetic leather by a factor of 9 (from the Neo-Hookeon model described in Figure 4-15), provided close agreement between the model and experimental test data mean; 8% and 1% at 20mm and 40mm respectively. Whilst such a large factor was required to reduce the material stiffness of synthetic leather within the model to provide representative load response to physical uppers, the model was able to measure the bending force of a mechanical test and provide sufficient data for a comparison with experiments.
Figure 4-17: Graphical Representation of Reversed Engineered Material Model with Experimental Test Data.

The modelled mechanical test using the optimised material model demonstrated a difference of 10.3% between the measured rearfoot vertical displacement of the mean physical upper response and the FE model (Figure 4-18).

Figure 4-18: Deformation of Upper at Peak Deflection during Forefoot Bending; Experimental Test (Left) and FE Optimised Model (Right).
4.4.4 Comparison of Experimental Measurement and Simulated Output – Boot

The upper and outsole components of the boot were evaluated separately, discussing the principles of the modelling techniques to verify the application of FEA techniques. The reported findings from the analysis were implemented to model the boot, with the most representative element type, material model and modelling constraints applied. The same three point bend loading condition was applied to the boot, with the initial alignment based on the physical test. Two approaches were trialled to join the components to form the boot; tie approach and contact approach (Figure 4-19).

The tie approach involved adjacent nodes of the two components being constrained together in all degrees of freedom, simulating the adhesion process used in physical manufacture. The contact approach implemented a rough contact interaction (coefficient of friction = 1), essentially fixing the contacting surfaces together with no separation between the contacting surfaces allowed. The influence of these two approaches on the bending force was displayed in Figure 4-20. Whilst the tie approach mimics the adhesion between upper and outsole, the response of the model was artificially stiffened; the contact approach reduced the load response significantly. The deformation response at peak displacement of the contact approach was within 16% of the measured rearfoot response during experimental testing, whereas the tie approach increased the stiffness of the response resulting in a 68% difference in rearfoot vertical displacement. The response of the contact and tie approach was shown in Figure 4-21.

The load response of the boot model through analysis of the individual components demonstrated the modelling factors when compared to experimental test data of physical boots. Whilst optimised material models were required, the use of a rough interaction between the
contacting surfaces provided a valid method to virtually evaluate boot load response during a simple loading condition.

![Graph showing force vs. displacement with labels for Experimental Test Data, Contact Approach, and Tie Approach.]

**Figure 4-20:** Plot to demonstrate the Modelling Approaches to Represent the Boot during Forefoot Bending when compared with Experimental Test Mean and Standard Deviation.

![Images of a boot showing deformation response at peak deflection: Experimental Test (Left), Contact Approach (Middle), and Tie Approach (Right).]

**Figure 4-21:** Deformation Response of Boot at Peak Deflection during Forefoot Bending; Experimental Test (Left), Contact Approach (Middle) and Tie Approach (Right).
4.5 Chapter Summary

The aim of the chapter was to evaluate whether the assembled FE boot model was representative of the physical equivalent. With respect to objective 1 and 2, a method was developed to compare the relative curvature of the model and physical boot. Geometric analysis used surface comparison software (GOM Inspect) to determine the relative perpendicular distance between the physical boot scan and assembled boot model. With respect to scanned data of a physical boot, 93.4% of the FE boot model was within ± 2.75 mm, providing confidence the assembled geometry of the model represented the physical boot.

Objectives 3, 4 and 5 were answered by using a three point bend mechanical test to compare both experimental and modelled data, evaluating the influence of different modelling techniques and approaches to measure their relative accuracy. Whilst the loading condition was different to the expected boot deformation during player motion, a simple testing protocol would enable methods to be developed and comparisons to be drawn to determine the level of confidence in the FEA boot model. Extraction of reaction forces and displacements from the model enabled both experimental and modelled data to be compared, with material models proving to have the greatest significance on the measured data.

The outsole and upper components were evaluated individually, with material model refinement necessary to accurately represent the load response of both outsole and upper components. A simple linear elastic material model (E=1.56 GPa) and C3D10M elements applied to the outsole provided a bending force within 2% of the experimental test mean. The upper was modelled with continuum shell elements with hyperelastic material modes. A refined material model was implemented for the synthetic leather, with the upper’s load response within 8% and deflection response within 16%. The boot was modelled using the results of the individual component analysis, with contact interaction between the adjoining surfaces providing the most appropriate representation of the boot relative to the load response and deflection of physical boots.

Modelled boot assembly demonstrated large surface deformation experienced by the pattern piece component. With discrepancies measured between the simulated and physical loading of the upper, the role of manufacture could explain the measured differences, thus further investigation of boot assembly was required.
Chapter 5:  
Influence of Manufacture on Material Behaviour in Football Boots

5.1 Introduction

Manufacturing of physical football boots involves the application of temperature, pressure and bonding agents to construct the three dimensional boot from two dimensional constituent parts. Observation of boot manufacture identified four key stages, stated in the literature review; Preparation of constituent parts, rearfoot and forefoot assembly followed by outsole attachment. Evaluation of the role manufacture has on these parts to create boots could indicate and explain differences identified between the load response of the model and physical boots detailed in Chapter 4.

5.1.1 Aims and Objectives

The study documented in this chapter looked to quantify material deformation and behavioural change of relevant constituent parts during boot manufacture. In the pursuit of this aim, the objectives listed below were followed:

1. Develop techniques to experimentally measure surface deformation of constituent parts during assembly
2. Compare the measured surface deformation with the FE boot assembly simulation
3. Quantify influence of manufacturing methods on material behaviour
4. Incorporate quantifiable results measured during boot manufacture into forefoot bend model to indicate influence on load response of the model
5.2 Measurement of Material Deformation during Boot Manufacture

Understanding the effect manufacturing processes had on constituent parts in boot design was important with regard to the global load response. Studying the manufacturing process indicated that the materials within the pattern piece underwent high temperatures and pressures during boot assembly (Section 2.1.2), potentially changing the material structure and its subsequent behaviour. This section documents the experimental measurement of the pattern piece constituent part during manufacturing, providing comparable data to determine the validity of the FE boot assembly techniques, addressing objectives 1 and 2.

5.2.1 Surface Deformation Measurement - GOM ARAMIS System

GOM Aramis is a non-contact optical 3D deformation measuring system (GOM ARAMIS 2014), able to calculate surface deformations of the measured object. Known as Digital Image Correlation (DIC), the system allocated coordinates to image pixels using two cameras fixed at an optical angle. A reference stage was used to represent the undeformed state, before subsequent images measured the deformation. Algorithms within the software calculated the deformation, comparing the digital images for displacement and deformation of the object characteristics. To track surface deformation, the provision of object characteristics was required if not present. Creating a stochastic pattern on the objects surface enabled the software to track how the surface deformed.

The purpose of the study was to quantify the levels of strain during boot manufacture. With the upper components being formed into a 3D geometry from flat 2D materials, the level of strain could have been significant when analysing boot performance. To measure the 3D shape change, two cameras were used. The positioning of the two cameras created a capture volume, in which the surface deviation was calculated. Both cameras were pointed towards the centre of the targeted volume, aligned with lasers. Specific distances were used, depending on the capture volume required (Figure 5-1).

Calibration of the system was required to create a capture volume within the software, relative to the camera positioning. Before the calibration processed began, the cameras were adjusted for their focus and contrast. It was imperative that both cameras had the similar monochrome contrast. Capture frame rate was important to reduce blur, thus adequate lighting was necessary during fast image capture. A calibration panel, which consisted of specific marker positions, enabled the capture volume to be created (Figure 5-1). Thirteen different images were taken, with the calibration panel moved and rotated within the volume, angled towards the two
cameras. The software used an algorithm to relate the positioning of the markers to the images captured by the two cameras. The manufacturer recommended a calibration deviation between 0.01 and 0.04 pixels.

**Figure 5-1: Aramis Capture Volume (Left) and Calibration Panel (Right) (GOM ARAMIS 2014).**

Image capture post calibration led to a series of frames, consisting of two images (from each camera). The software split the images up into rectangular or square image details, known as facets. The size of the facet was adjusted in the software, depending on the resolution required. An example of how facets were used by the software was displayed in Figure 5-2. Each facet tracked how the stochastic pattern changed between stages, calculating the surface deformation over capture time. Post-processing within the software detailed the level of strain and surface curvature for analysis and report generation.

**Figure 5-2: 15 x 15 facets with 2 pixels overlapping (GOM ARAMIS 2014).**

Facet computation required start points in all stages of analysis. Both automatic and manual settings of start points were possible. Manual start points were required when the software couldn’t find the same facet in subsequent images. From these start points, the software in principle knows the position of the surrounding facets, and computes the three dimensional position of the facet using both images. From the initial starting point, the software automatically identified the facet position and calculated how the stochastic pattern changed from one stage to the next, with the overall deformation related to the reference stage.

**5.2.2 Methodology to Capture Surface Deformation during Boot Manufacture**

During boot manufacture, the component which underwent the highest level of surface change was the pattern piece. To measure the surface deformation of the pattern piece during upper manufacture, a method was developed using GOM ARAMIS. To create the stochastic pattern, heat resistant white enamel, typically used to paint household radiators, was used. The white paint was applied to black pattern pieces with no logos present. All the components used in the shoe were used, but only the pattern piece had the stochastic pattern applied to it. The cameras were distanced 1160 mm from the capture zone centre, with an optical angle of 25°. 50 mm lenses were used creating a capture volume of 400 mm³. The system was calibrated using a CP20 panel.
Image Capture

Four phases were identified during boot manufacture and used to analyse the surface deformation; undeformed pattern piece with regions bonded, rearfoot assembly, forefoot assembly and outsole attachment. As the software’s algorithms cannot compute images which exceeded 40° out of plane, a series of images were taken with the upper rotated in ten different positions. At the end of each manufacturing stage, images were captured at all positions. Data from each position was stitched together, creating three dimensional shapes of the pattern piece throughout manufacturing. The test was conducted at a manufacturing facility in Germany. The cameras remained fixed throughout image capture, with the boot moved into each position. The test set-up was shown in Figure 5-3.

![Figure 5-3: GOM ARAMIS Experimental Set-Up for Surface Deformation Measurement.](image)

The first stage involved the image capture of the undeformed pattern piece. This was the reference stage used throughout the analysis. The medial and lateral sides of the pattern piece were pulled around the last during production, requiring four separate reference images (Figure 5-4). To help the software calculate the strain change, it was important to align each image set with that of the previous manufacturing stage. If the software couldn't find the start point or recognise its surrounding facets, the algorithm would not work. For the software to calculate the strain change between images, it was important to align the reference stages. Four different images were used to cover the entire pattern piece.
The next stages during upper manufacture were captured after the rearfoot assembly process was completed. The upper was moved into the ten different positions, pre-set for ease during post-processing. By keeping the same positions during the stages, software was able to track surface deformation. Due to the high curvature in the forefoot and rearfoot, a greater number of images were captured around these regions. Ten positions of the boot were captured with images taken when each of the green lines were aligned to the centre of the camera (red line) as displayed in Figure 5-5. The circular platform was rotated for the image capture.

**Figure 5-5: Boot Positioning for Image Capture (Green Lines aligned to Red Line for Capture).**

**Post-Processing Deformation Data**

The aim was to track surface deformation, known as major strain, from the undeformed geometry to the fully assembled shoe. From this data, the most influential manufacturing stage was highlighted, with the level or deformation calculated. Figure 5-6 displayed the four key stages captured during boot manufacture with the strain contour plot overlaid. The methodology aligned the regions of the boot during manufacture, ensuring the algorithm could track elongation of the stochastic pattern.
Figure 5-6: Surface Deformation of an Image sequence of a single position; Undeformed (Top Left), Rearfoot Assembly (Top Right), Forefoot Assembly (Bottom Left) and Outsole Attachment (Bottom Right).

Strain analysis at each position was calculated, creating a three dimensional contour plot. Within each position, a local reference system was used. Creating a cumulative strain plot, consisting of all ten positions, required each stage to be aligned to the same coordinate system. A different software, S-View, was used to create a 3D overlay of the complete upper. White elliptical markers were added to the boot before manufacture, creating reference points in GOM ARAMIS. These were added in clusters of three markers, creating a local coordinate system. All ten positions captured at least two sets of marker clusters. An example of a cluster of three markers was shown in Figure 5-7.
Each position was added in sequence, starting from the lateral side. The software, S-View, imported data from a GOM ARAMIS file. To progressively create three dimensional strain models at each manufacturing stage, both the imported data and the S-View file were aligned to the same coordinate system. Figure 5-8 outlined this procedure, displaying how two separate images were stitched together. The project was then transformed using a ‘3-2-1 Transformation’. The function created a reference axis from three reference points, with the order defining the X, Y and Z axis. A single strain surface was created (Figure 5-8).

The new deformation surface was then transformed to a different reference system which aligned with the next positional data which was to be imported. Once all the data for each position was overlaid, each manufacturing stage was analysed for surface deformation (major strain). The software was only able to capture the stochastic pattern change up to 40° of out of plane curvature, therefore with curvature greater than this angle at the heel, it was not possible to analyse this region.

5.2.3 Experimental Measurement of Surface Deformation

The three stages of manufacturing used to analyse the surface deformation involved rearfoot assembly, forefoot assembly (upper construction) and outsole attachment (boot construction). Low levels of deformation were measured in the pattern piece during rearfoot assembly (Figure 5-9).
It was difficult to determine the level of strain in the heel region, due to the high degree of surface curvature. A single layer of foam and lining was glued to the heel region, which increased the stiffness; quantifying this change was not possible. The low level of strain measured in the forefoot was expected, as no production processes were applied to the region other than the joining of edges. Small strains were measured due to the curvature created during this process.

Forefoot assembly manufacturing processes involved the forefoot region of the pattern piece being pulled around the last and attached to the lasting board. When compared to the rearfoot assembly process, the surface deformation experienced by the pattern piece was far greater. Peak strains were observed around the toe region, reaching values of up to 25% strain (Figure 5-10). The toe region experienced the highest level of deformation when compared to the rest of the upper. Greater curvature in the toe region was a reason for the high deformation. The strain gradient decreased from the toe towards the rear of the upper. The medial and lateral regions of the boot remained relatively low, with measured strains between 6 and 9%. Lower curvature in the midfoot of the last would suggest why the strain was relatively low.
The final stage of the boot assembly involved the attachment of the outsole. Adhesive applied to the adjoining regions ensured a permanent fixture after pressure was applied in a downward direction. The result of this process during boot manufacture was shown in Figure 5-11. No significant effect on surface deformation was recorded during the outsole attachment process.
(Figure 5-10 and Figure 5-11). This result was expected, as the manufacturing process only involved adhesion of the outsole to the upper. It was important to highlight that this process had no effect however.

5.2.4 Experimental Measurement and Simulated Surface Deformation Comparison

Construction of the Boot model within FEA software provides quantifiable data to understand material deformation during the virtual assembly process. Whilst beneficial in the design process to predict how the material will behave during manufacture, a validation process was required to compare surface deformations measured experimentally and virtually in their deformed state (Figure 5-12). Close agreement was observed between the model and experimental data, with similar strain gradients. Peak strain of 25% was recorded in the toe box region of the upper. Differences in the strain magnitude were observed between the midfoot region of the two data sets, potentially due to the simplification of the modelling approach to remove the bonding region. Whilst only a single boot was experimentally measured through the manufacturing processes, the comparison between the model and experimental test data showed close agreement, demonstrating the potential of simulated manufacturing process to assess the impact of shape change on the post-production product.

![Image of strain distribution](image_url)

Figure 5-12: Visual Comparison of Surface Deformation between Simulated Assembly and Experimental measurement of Upper Manufacture in Football Footwear
5.3 Anisotropy of Upper Material Behaviour during Preparation Stage of Boot Manufacture

The magnitude of surface deformation experienced by the pattern piece during manufacture demonstrated the potential influence these processes have on material behaviour – providing an explanation for the disparity between the modelled and physical boot load response during bending. Refinement of the synthetic leather material behaviour within the FE model was required to represent the load response measured from the physical equivalent.

The first stage in upper manufacture involved the preparation of the constituent parts, cutting the materials and applying stitching and bonding regions where necessary to form a single component. The orientation of the materials during the cutting process required investigation, with anisotropy of materials common. To address objective 3, anisotropy of the synthetic leather material was investigated, to understand the influence this material’s alignment could have on the upper’s load response.

5.3.1 Material Orientation on Material Stiffness

Reduction in waste material during production has the potential to orientate patterns as shown in Figure 5-13. The orientation would not be a problem for an isotropic material, but if anisotropic, the material would have different stress-strain behaviour depending on the respective loading angle.

**Figure 5-13: Football Upper Manufacture - Material Alignment (Pullover 2014).**

The synthetic leather material consisted of three layers; an outer and inner layer laminated to a middle layer as demonstrated in Figure 5-14. Images of the material’s micro structure were captured using a Leica DMLM transmitted/reflected light trinocular inspection microscope (Leica Microsystems Wetzlar GmbH 2001). The middle layer consisted of fibres orientated in a grid structure with filler material. The top layer comprised of a thin TPU structure providing a surface coating to the material, with a backing material laminated to the bottom surface. With a fibre grid structure within the middle layer, an investigation into the material orientation was conducted to examine the potential influence of constituent component alignment during the preparation phase in boot manufacture.
5.3.2 Material Behaviour Characterisation

To quantify the effect of manufacturing on material behaviour in the pattern piece, the same material characterisation protocols were used as documented in Section 3.3. An Instron 5569 Machine capable of recording the force required to displace materials in one direction was used to measure the material behaviour. Large tension clamps were attached to the base and to a 1kN load cell. Softening due to the deformation of a material was a phenomenon known as the Mullins Effect (Mullins 1969). An incremental cycling procedure was configured to account for this phenomenon, increasing the material by 1mm every 5 cycles.

The synthetic leather material had dog bone shaped samples cut out of raw material, orientated at three angles; vertical (A), diagonal (AB) and horizontal (B) as demonstrated in Figure 5-16. All three angles were tested using five specimens, with their average calculated to evaluate their material behaviour, as graphically represented in Figure 5-15.
Figure 5-15: Mean Experimental Test Data of Synthetic Leather to quantify load response at different material orientations (A, AB and B).

Whilst the vertical orientation was determined based on the supplied raw material sample, its relative orientation was used for the comparative purposes. The material stiffness was calculated between 5 - 10% strain, using linear regression, based on the qualitative results captured during upper manufacture. This provided a comparison to analyse material anisotropy and manufacturing processes. The stiffest orientation was the vertical direction (A), with a reduction in stiffness of 45% and 33% for diagonal (AB) and horizontal (B) orientations respectively. Examination of the middle layer within the synthetic leather showed evidence of this anisotropic behaviour, demonstrated in Figure 5-16. With an increased fibre orientation in direction A relative to direction B, a greater force was required to strain the material, resulting in the different material behaviour shown in Figure 5-15.

Figure 5-16: Micro-structure of 3 Different Specimens of the Middle Layer taken from Raw Material

Material behaviour of the synthetic leather suggested that the orientation of the yarns within the material created a greater resistance in specific orientations. This was an important consideration in manufacturing of football boots using this material. If the pattern pieces were cut out of the
synthetic leather material at different orientations as shown in Figure 5-13, the effect on upper stiffness during bending and torsion could be significant.

5.3.3 Simulation of Upper Load Response – Influence of Material Anisotropy

To answer objective 4, the upper forefoot bend model described in Section 4.4.3 was implemented to quantify the influence of material anisotropy of synthetic leather. Material models were generated based on the mean test data at the different orientations displayed in Figure 5-15. The influence of the different material models were demonstrated in Figure 5-17. Whilst the orientation direction of AB and B resulted in significantly lower reaction forces at peak deflection, they were still far greater than the experimental test data. Assuming linearity of the material behaviour of the three orientations, the difference in material stiffness equated to 55% and 67% for direction AB and B relative to direction A. With regards to the virtual test, the peak force at 40mm between AB and B orientations relative to the A orientation resulted in a difference of 60% and 63%. This suggested that within the model, the influence of the synthetic leather was integral to the upper in bending. Whilst the element type used to model the upper could not model anisotropy of the material, consideration of its orientation was important to accurately model the upper.

![Graph showing force vs. displacement for different orientations.](image)

Figure 5-17: Implementation of Anisotropic Material Models into Virtual Upper Three Point Bend Test.
5.4 Effect of Manufacturing Processes on Upper Material Behaviour

With materials within the upper subjected to heat, pressure and bonding procedures in addition to up to 25% strain measured experimentally during boot manufacture, the impact on material behaviour required further investigation to answer objective 3. Detailed in the literature review, preparation of the pattern piece into a single component involved the bonding of reinforcement materials to the synthetic leather. Once prepared, the boot underwent rearfoot assembly, forefoot assembly and outsole attachment to complete the boot. Identified from the manufacturing processes, three key stages were used to provide quantitative data to evaluate material behaviour change; raw materials, bonded pattern piece and completed upper (Figure 5-18).

![Figure 5-18: Three key stages analysed for material behaviour.](image)

Five sections were cut out of the pattern piece as shown in Figure 5-19. The toe cap region consisted of a layer of synthetic leather and toe lining material. The medial and lateral regions consisted of synthetic leather and TPU material. The loch region was constructed from synthetic leather material with a different TPU material.

![Figure 5-19: Regions of Pattern Piece used for material testing; Toe Cap (Left), Medial and Lateral Region (Middle) and Loch Region (Right).](image)
Dog bone samples, commonly used in material testing, were used to ensure consistency between specimens. These were cut out from the raw material, pattern piece and formed upper depending on the construction of the respective region. Three specimens were taken at each stage in each location. The material behaviour data was measured as outlined in Section 3.3, compared together and the differences between the three stages were obtained. Material stiffness was calculated using linear regression between 5-10% strain, with the mean data computed from the experimental test data to act as a comparison between the three stages.

5.4.1 Raw Material to Bonded Pattern Piece

It was evident from Figure 5-20, Figure 5-21 and Figure 5-22 that the forming of the pattern piece had a significant effect on material behaviour. Whilst the orientation of the material was important consideration with regards to boot load response (outlined in Section 5.2.3), the bonding processes to form the packaged component also influenced how it subsequently behaved. A reduction in material stiffness was observed, with the greatest reduction between the raw material stiffness and the bonded pattern piece measured at the toe cap; reduced to 22%, 29% and 25% in material stiffness at the toe cap, medial and lateral region and the loch regions when compared to orientation A respectively. Simply adding the raw material, characterised by uni-axial tension extension tests, was not an accurate representation of the material behaviour for the pattern piece. The upper had a significant influence on the whole boot during bending and torsion. A change in material stiffness of the upper would lead to different shoe stiffness’s, affecting the range of motion of the foot during bending and torsion. This was an important consideration in football boot design.

![Figure 5-20: Difference between Raw Material and Bonded Pattern Piece at Toe Cap.](image-url)
Figure 5-21: Difference between Raw Material and Bonded Pattern Piece at Medial and Lateral Regions.

Figure 5-22: Difference between Raw Material and Bonded Pattern Piece at Medial and Lateral Lochs.

5.4.2 Bonded Pattern Piece to Assembled Upper

During the bonding processes to form the pattern piece, a significant effect on material behaviour had been reported. Creation of the upper resulted in the forefoot being strained in excess of 25%. It was important to quantify whether manufacturing processes, which led to the deformation of the pattern piece, resulted in any material behaviour changes. No significant change was documented during the forefoot assembly process in the medial and lateral regions or in the loch regions (Figure 5-23 and Figure 5-24). These regions were shown to have low levels of strain in comparison to the toe box region. However, a difference in loading profile was shown in the toe box region (Figure 5-25). The forefoot assembly process involved heat and pressure applied to the pattern piece surface, in which the lower edges were pulled over the lasting board and fixed in place using an adhesive.
Figure 5-23: Difference between Bonded Pattern Piece and Formed Upper at Medial and Lateral Regions.

Figure 5-24: Difference between Bonded Pattern Piece and Formed Upper at Medial and Lateral Lochs.

Figure 5-25: Difference between Bonded Pattern Piece and Formed Upper at Toe Cap.
Manufacturing processes resulted in a significant influence on the material behaviour of those used in upper construction. A reduction in material stiffness was measured from the raw materials to the finished boot; stiffness was reduced to 22%, 29% and 25% in the toe cap, medial and lateral regions and loch regions respectively. Further reduction in material stiffness of the toe cap by 7% during the forefoot assembly was recorded. Testing pre-assembled materials have been shown to not replicate the material behaviour of boot materials post-manufacture. The greatest material changed occurred as a result of the pattern piece being bonded together, which suggested that when using material characterisation tests, specimens must be cut out of the formed pattern piece, rather than the raw materials supplied to the manufacturer.

5.4.3 Simulation of Upper Load Response – Influence of Manufacturing Processes

Manufacturing processes have been reported to have a significant influence on material behaviour, reducing the stiffness to 22% when compared with the corresponding region of raw material with synthetic leather orientated at A (Figure 5-26). A new material model was created based on the reduction in material stiffness due to manufacturing and prescribed to the synthetic leather in the virtual test. The force displacement relationship of material anisotropy and manufacturing effects were displayed in Figure 5-26. The influence of manufacture was shown to reduce the force at peak displacement by 45%. However the influence of manufacturing processes resulted in a peak force twice that of the highest force of the three specimens calculated by the experimental test.

![Figure 5-26: Implementation of Manufacturing Effects on Material Model during Virtual Testing.](image-url)
5.5 Chapter Summary

To meet the aim of the chapter, two stages in boot manufacture were identified to influence material behaviour; bonding of the pattern piece into a single component and the forefoot forming process. Surface deformation of the synthetic leather upper was measured using GOM ARAMIS, which tracked the displacement of a stochastic pattern (Objective 1). During forefoot assembly, surface deformation reached a peak stain of 25% in the toe box, with low levels measured in the medial and lateral regions of the upper. Excellent agreement between the FE assembly simulation and the experimental measurement of surface deformation was demonstrated, meeting objective 2.

With regards to objective 3, material anisotropy and manufacturing processes were both shown to influence the material properties of the synthetic leather. Manufacturing processes were found to significantly change material behaviour, with preparation of the pattern piece the most influential. When compared to the raw materials in that region, material stiffness was reduced to 22%, 29% and 25% in the toe cap, side and loch regions respectively.

Quantifying the influence both material anisotropy and preparation of the pattern piece on the synthetic leather material model involved applying relative material models based on the quantified differences, answering objective 4. The non-woven structure of the synthetic leather was anisotropic, resulting in the reduction of the reaction force during the virtual three point bend test. Whilst the element type used to model the upper did not allow the assignment of anisotropic material models, nevertheless an understanding of the influence material orientation was demonstrated in Figure 5-17. The influence of manufacturing was implemented into the synthetic leather material model and displayed in Figure 5-26. Virtual testing of the material model demonstrated that the reduction in material stiffness led to lower bending force measurements but were still twice the magnitude of the average experimental data captured through physical boot testing.

The modelling principle demonstrated thus far in the thesis provides representative data in terms of load response and deformation of a representative boot model. With materials models refined and appropriate element types defined, application of more representative loading conditions to measure boot function were required.
Chapter 6: Experimental Measurement of Boot Function using Mechanical Test Devices

6.1 Introduction

With an established modelling principle to simulate the assembly of a football boot and the subsequent load and deformation response during a simple bend test, evaluating the predictive capabilities through more complex loading conditions was necessary to meet the research aim. As detailed in the literature review, bending and torsional stiffness have been reported to be important characteristics in assessing the performance or injury risk carried by athletic footwear (Stacoff and Reinschmidt 2001; Stacoff et al. 1996; Stuessi et al. 1989; Reinschmidt and Nigg 2000; Hintermann and Nigg 1998; Sandrey et al. 2001; Stefanyshyn and Nigg 1998; Stefanyshyn and Fusco 2004). Mechanical test devices were used to quantify load and deformation response of physical boots, providing comparable data to verify the applicability of the boot model.

6.1.1 Aims and Objectives

The aim of the study reported in this chapter was to quantify bending and torsional stiffness of physical boots using experimental laboratory test devices. Existing and, where necessary, new test devices were developed to measure these boot properties, providing comparable data for model verification. To meet this aim, the following objectives were pursued:

1. Use existing and where necessary develop mechanical test devices based on knowledge acquired through literature review
2. Development of testing standards to measure boot bending and torsional stiffness
3. Experimental measurement of physical boots to provide comparable data for model verification
4. Calculate bending and torsional stiffness for two additional boot types to provide an accepted range to further determine the applicability of the assembled FEA boot model
6.2 Experimental Measurement of Boot Function - Bending

In the pursuit of the chapter aim, the structure of this section was divided into three subsections, each answering the chapter objectives for bending stiffness measurement of physical boots.

6.2.1 Experimental Test Device Development

Measuring bending stiffness experimentally involved selecting the appropriate level of complexity to represent boot loading whilst providing relevant and meaningful results to compare with the FE model. Player movements involve the foot deforming the boot based on the necessary motion required. However existing mechanical tests typically involve bend tests without the presence of a volume within the shoe, potentially limiting the suitability of the test to replicate match-play related loading conditions (Kleindienst et al. 2005; Stefanyshyn and Fusco 2004; Roy and Stefanyshyn 2006; Willwacher et al. 2013). A test device was developed to encompass a volume within the shoe, based on biomechanical data outlined in the literature review (Chapter 2) during typical game related movements.

Experimental measurement of boots during bending requires three factors; means to measure the force and displacement of the boot, a mechanism to provide a volume within the shoe whilst enabling the boot to bend, and to an infrastructure to hold the mechanism during operation. An Instron 3365 uni-axial tension test machine, commonly used in material testing, was selected to measure the bending force (Instron 2014), with a bespoke frame built to anchor the boot forefoot whilst facilitating bending moment measurement. To represent the foot, a bending mechanism was developed based on key boundary conditions identified from human biomechanics, whilst abstracting factors that unnecessarily increased the complexity of the test.

The bending mechanism provided a physical constraint and required abstractions where necessary to represent the human foot, providing a volume within the boot whilst facilitating the required bending motion. With a complex structure and variation in human feet, a simple foot geometry was used. The mechanism was split into two parts to define the rearfoot and forefoot – a concept supported by Stefanyshyn & Nigg (1997). A pin joint connected the two parts to replicate the Metatarsophalangeal Joint (MPJ), defined as the angle between the 1st and 5th metatarsal head, measured from a perpendicular axis relative to a line between the heel and 2nd metatarsal head, as demonstrated in Figure 6-1.
Figure 6-1: Approximated Angle of MPJ Axis for Pin Joint in Bending Mechanical Foot.

Existing literature reported the approximate position of the MPJ in the human foot located 73% along the length (Krumm et al. 2012), with an approximated MPJ axis defined at 12° (Hillstrom et al. 2005). The rearfoot and forefoot parts were pinned together at this axis location and angle by a 6 mm diameter metal rod. A region was milled from the foot to enable the two parts to rotate around the pin joint without contact during rearfoot rotation. Metal inserts were added to the forefoot, ensuring that it remained fixed during operation. The bending mechanism, based on appropriate boundary conditions identified in human locomotion, is displayed in Figure 6-2. The foot was constructed from a shoe-last, made from a high density polyethylene providing a far stiffer material than those used in the football boot.

Figure 6-2: Outline of Bending Mechanical Foot for Testing Device.

A bespoke frame was manufactured to facilitate the load measurement, with two main factors considered to hold the forefoot stationary and enable rotation of the rearfoot in the sagittal plane. To hold the foot during operation, three components were produced; the base plate, slider and toe plate (Figure 6-3).
Figure 6-3: Assembly of Toe Clamp Components: Base Plate (Left), to which the Slider is placed on top (Middle) with the and Toe Plate aligned using a pivot located on the Slider’s top (Right).

Essentially these three components formed a clamp. The slider’s position was adjusted depending on shoe length and sat on the base component. The toe plate and base were clamped together, with two screws fed through the slots in the slider into threaded holes in the base plate. Recessed slots within the toe plate allowed the foot to be fixed for both uppers and boots. The difference between both the boot and upper was the presence of the outsole. Holes were drilled into the forefoot of all the specimens, which enabled screws to clamp the shoe to the toe plate (Figure 6-4).

Figure 6-4: Toe Plate attachment to Outsole (Left), Upper (Middle) and Boot (Right).

To quantify the force required to rotate the heel, a cable and pulley system acted as a link between the rear foot and the load cell. Two pulleys constrained the cable to allow the rearfoot to be pulled forward, raising the heel as it rotated around the MPJ. Vertical displacement of the
load cell facilitated this action. Ball bearings within the pulleys reduced the losses during operation. The cable, 4 mm diameter, consisted of a 2 mm diameter steel cable covered with a plastic coating. The attachment between the rearfoot and cable was constructed from mild steel and bolted to the top of the rearfoot. To allow the cable to freely rotate at the attachment point during operation, the cable end was fed through a hole in a circular steel component. The component’s frame enabled rotation perpendicular to the angle of rearfoot rotation. Two balls within the component were tightened once the cable was inserted into the hole, clamping it together. A weight (2kg) was added behind the rearfoot, ensuring the foot returned to its initial starting position during operation.

Peak MPJ dorsiflexion has been reported to range between 27° - 60° during walking (Leardini et al. 1999; Carson et al. 2001; Bojsen-Møller and Lamoreux 1979) and 35° during running (Leardini et al. 2007). However, footwear was reported to reduce peak dorsiflexion; 45-50° when walking with flexible footwear, and 25-30° when walking in a stiff shoe (Bojsen-Møller and Lamoreux 1979). Based on this literature, the range of travel to measure bending stiffness up to a peak angle of 45° was used.

![Figure 6-5: Schematic Diagram (2D) of Bending Mechanical Foot due to the Displacement of Cable through Pulley System to Result in Rotation of the Rearfoot around the Pin Joint.](image)

The frame was constructed from RK Rose+Krieger® components, in addition to the manufactured toe clamp and fixed to the Instron machine by an M16 bolt. Two pulleys enabled a cable to be fed between them, facilitating the heel to be raised during vertical displacement of the load cell (Figure 6-5). By virtue of this principle, the frame remained rigid during operation, holding the pulleys in position. The cable was attached to the load cell via a locking fixture. A stop was
constructed underneath the rearfoot to match the height of the toe plate. This acted as a platform resulting in the same initial position for each footwear type. The completed testing rig is shown in Figure 6-6.

Figure 6-6: Mechanical Bending Test Rig (a); Toe Clamp (b), Cable-Load Cell Connection (c), and Lateral Side of Boot at Initial Position prior to Operation (d).
6.2.2 Experimental Test Device Methodology – Load Measurement

Measuring bending stiffness of the boot required a series of stages, starting with quantifying the force displacement relationship during bending. Positive vertical displacement of the load cell led to rearfoot rotation (MPJ angle ($\theta$)), providing measurements in terms of force, extension and time. Two-dimensional geometrical analysis of the experimental test rig enabled a relationship to be derived between the measured extension and MPJ angle, permitting this angle to be calculated at each instantaneous extension.

The fundamental principles used to derive the relationships were outlined in Figure 6-7 and Equations 6.1 - 6.6. During operation, the frame was assumed to be infinitely stiff (it would not deflect during operation), the toe would remain fixed in position and the cable would remain strain free (the load acting on the cable was insignificant compared to the cable’s stiffness). Based on these assumptions, the following statements enabled bending stiffness to be calculated:

- Dimension A, B, C and D did not change throughout the analysis, thus $\alpha$ was constant
- Dimension H was related to the measured extension

With the initial dimension H calculated prior to MPJ extension, the resulting load cell displacement was subtracted at each measurement step from the original length of H. MPJ angle ($\theta$) was calculated in equation 6.4 based on finding $\alpha$ in equation 6.2 and $\theta$ in equation 6.3 using the cosine rule. Moment around the pin joint at MPJ angle ($\theta$) was computed by finding phi ($\phi$) from equation 6.5. As phi changed relative to the MPJ angle, the moment at that instantaneous MPJ angle of flex was calculated using equation 6.6. The moment ($M$) was calculated based on the measured force ($F$), MPJ angle ($\theta$), and perpendicular distance ($d$).

![Figure 6-7: 2D Geometric Analysis of Experimental Testing Rig; Relationship of dimensions based on rig geometry (Left) and displaying of relevant angles and dimensions for equations 6.1-6.6 (Right).](image-url)
Test specimens were fitted to the experimental testing rig by securing them to the toe plate before fastening the plate to the slider and fixed in position. A cable tie was used to ensure no slip at the heel during operation. The added mass and cable attachment were fixed to the top of the rearfoot with the cable fastened to the load cell. The mass ensured that the footwear type sat on the stop, giving the same initial angle of flex for the boot, upper and outsole. Consistency was ensured by using the same initial position of the load cell. Preloading the specimens ensured any cable slack was removed from the system, lifting the rearfoot to the point at which the specimen was to be raised off the stop (Figure 6-8). A different preload was used for the outsole, upper and boots to ensure the same initial position. The reaction moment due to the system (the moment required to bend the mechanism with no test specimen) was removed from each of the test specimen data sets. Spacers were used to replicate the same gap between the toe plate and bending mechanism when a boot was tested.

![Figure 6-8: Schematic Diagram (2D) demonstrating the cable extension required to remove the slack in the cable prior to MPJ angle rotation.](image-url)
Driven by vertical displacement of the load cell, geometric analysis was used to achieve an MPJ angle of 45°, with the presence of studs in the outsole forefoot leading to different displacements being required; 140 mm displacement for boot and outsole specimens, and 134 mm for upper specimens. Data acquisition involved the use of a 1 kN load cell with a displacement rate of 600 mm/min and a sampling rate of 10 Hz. Each test involved 4 pre-cycles, followed by the measurement of the 5th cycle. Five tests were conducted for each boot, upper and outsole with three different specimens used for each type. The resulting boot flex at 0°, 15°, 30° and 45° was shown in Figure 6-9.

![Operational Boot Bending during MPJ Extension](image)

**Figure 6-9: Operational Boot Bending during MPJ Extension; 0° (Top Left), 15° (Top Right), 30° (Bottom Left), and 45° (Bottom Right).**

Within MS Excel, MPJ angle and the associated bending moment were calculated based on the method described above. Bending stiffness was calculated by differentiating this relationship. Noise during operation was amplified during differentiation of the measured bending moment, leading to difficulty determining the signal, as demonstrated in Figure 6-10. Linear regression was performed to quantify the bending stiffness in walking, working and combat boots (Hillstrom *et al.* 2005; Krumm *et al.* 2012). However bending of the components exhibited a non-linear relationship between the bending moment and MPJ angle, thus an approach was taken to split
the data into different segments, performing linear regression within each. Analysis of the appropriate segment size using least squares fitting of the data suggested segments of 5° would be the most applicable when determining the relevant stiffness. Each segment was colour coded to indicate the bending stiffness of that region based on the bending moment and differentiated data for comparable analysis between experimental measurement and simulated results, as demonstrated in Figure 6-10. Error bars displayed on the bar chart demonstrate the standard deviation of the data within the segment. Higher deviation was correlated with the non-linear regions between bending moment and angle of rotation. Reducing the range of the segments would lower the deviation, but with the purpose of the data to provide comparative analysis with the model, the approach to use 5° segments was implemented. For comparable analysis with the FE model, the data in the bar chart was used to display bending stiffness of the experimental test and model data.

Figure 6-10: Example of the Analysis of Bending Stiffness with Colour coded segments to show the linear stiffness measurement with standard deviation.
6.2.3 Experimental Test Device Methodology – Deformation Measurement

Observation of the boot during bending demonstrated buckling of the upper material shown in Figure 6-9. Measuring the deformation response of the upper material would provide comparable data with the model, identifying the validity of FEA techniques. Buckling of the forefoot observed during mechanical testing limited the use of GOM Aramis DIC software, as it would not provide sufficient coverage of the deformed region due to regions of the upper being out of plane by greater than 40°. An alternative method involved the implementation of a REVscan 10189 handheld scanner, enabling the capture of three-dimensional data of the physical boot surface. The scanner functioned with two cameras identifying laser lines projected onto a surface, creating three dimensional data points based on the relative position of the scanner.

Data points captured by the two cameras based on the projected laser across the object are aligned based on reference points, enabling the position of the scanner relative to the object to be obtained. It was important to have enough reflective markers such that the software could overlay the data relative to a co-ordinate system. Insufficient markers during the scan resulted in that region not being added to the existing data. An algorithm within the VxScan 4.0 SR2 software used a line of best fit process to generate a single surface from the 3D data points acquired during the scanning process.

Figure 6-11 demonstrates the stages required to represent the surface curvature of the measured object. Reference points were placed onto the test rig, to which surface scans of the boot during bending were captured, with their relative position captured as features. Scanning the object created surfaces based on the captured three dimensional data points. Facets were created based on this surface data, constructing a mesh and exported as an STL file. To reduce scanning errors, the boot surface was captured statically at two bending angles (22.5° and 45°) with only the upper surface measured due to the inability to capture the surface of the outsole due to its colour.
Figure 6-11: Surface Deformation Measurement Process; Test Rig with Object (a), Reference Points within Software (b), Surfaces created through capture (c) and Facets created to represent Object (d).

Quantifying the curvature of the deformed boot involved the use of GEOMAGIC software. The surface scan data was imported into the software, to which geometric surfaces were assigned to the mesh (Figure 6-12). Curvature analysis algorithm provided a contour plot across the measured surfaces, highlighting the regions of high and low curvature. Visual comparison will be used to detail the deformation across the boot forefoot of the three physical samples as well as the FE boot model.

Figure 6-12: Surface Curvature Analysis using GEOMAGIC Software; Import Scan Data (Left) and Surface Curvature Analysis (Right).
6.2.4 Experimental Test Device Results

The mean bending stiffness measured for the outsole, upper and boot are displayed graphically in Figure 6-13, with error bars displaying the experimental standard deviation of the three specimens. The general trend involved the stiffness of all three components reducing between 0° and 20° before increasing beyond 20°. The results displayed in Figure 6-13 suggested that the contribution of the upper during first 15° of MPJ extension was important in defining the overall boot’s stiffness, with an average contribution of 80% measured between 0° and 5° (Table 6-1). This is an important finding regarding bending stiffness analysis of footwear, where studies comparing athletic performance to shoe bending stiffness have used mechanical tests which do not account for a volume throughout the shoe and generally only consider the outsole of the shoe (Kleindienst et al. 2005; Stefanyshyn and Fusco 2004; Roy and Stefanyshyn 2006; Willwacher et al. 2013). Contrary to the existing tests, results captured from this bending test demonstrates the effect of a volume within the shoe, with a significant proportion of the bending stiffness contributed by the upper, highlighting the need to consider this component with regards to shoe bending stiffness, rather than just the outsole that existing mechanical tests measure. Beyond 15°, the contribution decreased, dropping below 50%. The outsole bending stiffness was less significant throughout MPJ extension, with the relative contribution of the component exerting less than 18% relative to the boot’s stiffness.

![Figure 6-13: Mean Experimental Measurement of Bending Stiffness of Outsole, Upper and Boot with error bars demonstrating standard deviation.](image)

To provide context of the experimentally measured bending stiffness of football boots, Krumm et al. (2012) used linear regression analysis to quantify the bending stiffness of walking, working and combat boots up to 30° with stiffness varying between 0.61 ± 0.03 to 2.38 ± 0.08 Nm/°. From this
study, bending stiffness measured in football boots up to 30° (between 0.23 ± 0.02° and 0.69 ± 0.05°) was lower than the data reported by Krumm et al. (2012). The results measured were of a similar magnitude, providing a level of confidence. The construction of walking, working and combat boots was the most probable explanation for the higher measured stiffness.

<table>
<thead>
<tr>
<th>Bending Stiffness</th>
<th>Contribution of Upper Relative to Boot Stiffness</th>
<th>Contribution of Outsole Relative to Boot Stiffness</th>
<th>Combination of Upper and Outsole Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°-5°</td>
<td>80%</td>
<td>8%</td>
<td>88%</td>
</tr>
<tr>
<td>5°-10°</td>
<td>65%</td>
<td>3%</td>
<td>68%</td>
</tr>
<tr>
<td>10°-15°</td>
<td>50%</td>
<td>10%</td>
<td>60%</td>
</tr>
<tr>
<td>15°-20°</td>
<td>43%</td>
<td>11%</td>
<td>54%</td>
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<tr>
<td>20°-25°</td>
<td>38%</td>
<td>9%</td>
<td>47%</td>
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<td>25°-30°</td>
<td>36%</td>
<td>16%</td>
<td>52%</td>
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</tr>
<tr>
<td>40°-45°</td>
<td>29%</td>
<td>18%</td>
<td>47%</td>
</tr>
</tbody>
</table>

Table 6-1: Contribution of the Outsole and Upper components Bending Stiffness relative to the Boot, with the combination of their relative contribution to demonstrate the difference to the boot during Bending.

With reference to beam bending theory, the neutral axis defines whether the material will be subjected to compressive or tensile stresses (Clifford et al. 2009). In this scenario, the neutral axis was orientated parallel with the floor, running through the pin joint of the deformation mechanism, as demonstrated in Figure 6-14. With the rearfoot being raised during operation, the material above the neutral axis will be subjected to negative stresses, whilst below the axis will experience tensile stress.

Figure 6-14: 2D Analysis of Neutral Axis of Boot during Bending.

The relative contribution of the upper on the overall boot’s bending stiffness was reduced below 40% once the mechanism rotated beyond 20°. Surface deformation measurement at 22.5° and 45° highlighted the significance of the defined buckling lines in Figure 6-16. Whilst the magnitude of curvature was shown to increase, the location of these lines remained consistent between the
two measured angles with small variation observed between the physical boots. The bending stiffness of the upper was shown to increase between 20° and 45° (Figure 6-13) as a result of the increased compressive load deforming the material around the established buckling lines, but their relative contribution with the overall boot stiffness reduced.

As the mechanism rotates about the pin joint, compressive loading of the upper material results in the material buckling, as demonstrated in Figure 6-15. The buckling effect exerts a resistive moment opposing the rotation of the mechanism due to additional force being required to deform the material, explaining the large contribution the upper has on the overall boots bending stiffness. Buckling phenomenon within shells structures is a highly complex scenario, observed during compressive strains, with their structure generally sensitive to geometric imperfections induced during the fabrication process (Teng 1996).

![Establishment of Buckling Lines](image)

*Figure 6-15: Example of Upper Deformation with the establishment of buckling lines during MPJ Rotation; 10° (Left) and 15° (Right)*

Experimental capture of the upper deformation enabled the angle of curvature to be quantified, highlighting the position and magnitude of deformation. Evident from the curvature experienced by the upper material during bending, slight differences in the location of the buckling lines were observed demonstrating this phenomenon (Figure 6-16). Manufacturing of the pattern piece from raw materials into the packaged component could explain the slight difference between the buckling locations displayed in Figure 6-16.
Beyond 20°, the increase in bending stiffness could have been due to deformation of the outsole component. At low angles of rotation (<20°), the outsole component rotated around the bending mechanism. However at angles greater than 20°, the outsole surface contacts the mechanism, straining the material, thus exerting a reaction moment. The magnitude of outsole deformation observed between the 2nd and 3rd stud row was evident through visual comparisons demonstrated in Figure 6-17.

The data presented in Table 3-2 indicated that the full shoe assembly must be evaluated rather than combining the individual component’s bending stiffness. Combining the two components had a greater relative contribution of the measured boot stiffness between 0° to 15° (88%, 68% and 60% for 0° to 5° 5° to 10° and 10° to 15° respectively), than angles greater than 15°. In the
creation of the boot, the upper and outsole components are adhered together, essentially creating a composite material along the joined regions. A stiffer bond will result in the transfer of stress faster between the elements, therefore result in superior component stiffness properties (Le and Nairn 2014), thus the creation of the boot combined from the upper and outsole components results in a greater bending stiffness when compared with the summed stiffnesses of the individual components. This is an important consideration in the development of computer simulation techniques for the analysis of mechanical function. Furthermore, in a review of existing computational modelling techniques to predict footwear function, Cheung et al. (2009) stated that to further improve computational modelling prediction, there was a need to create techniques to evaluate the full shoe assembly. The data compiled from the physical testing of the upper, outsole and full boot construction supports this statement, hence the requirement to create computational modelling techniques to quantify mechanical function requires simulation of the full boot during loading.
6.3 Experimental Measurement of Boot Function - Torsion

In the pursuit of the chapter aim, the structure of this section was divided into three subsections, each answering the chapter objectives for torsional stiffness measurement of physical boots.

6.3.1 Experimental Test Device Development

Torsion of the foot is common during linear running, with the torsional angle defined as the rotation of the forefoot relative to the rearfoot. Torsional stiffness of the boot dictates how much rotation is possible during this angular rotation. The literature review highlighted the role of torsional stiffness in athletic footwear, with multiple studies relating shoe construction with potential over-use and over-pronation injuries during both linear running and cutting movements (Stacoff and Reinschmidt 2001; Stacoff et al. 1996; Stuessi et al. 1989; Reinschmidt and Nigg 2000; Hintermann and Nigg 1998; Sandrey et al. 2001). This section details the measurement of torsional stiffness in physical football boot, providing comparable data to verify the FE boot model.

An existing mechanical test device was used to experimentally measure the torsional stiffness of athletic footwear (Figure 6-18). Access to the test device was possible whilst on placement at the industrial collaborator. The testing device consisted of a forefoot and rearfoot plate, in which hydraulic actuators clamp the forefoot and rearfoot regions, functioning by fixing the rearfoot whilst rotating the forefoot, measuring the resistive torque through a load cell.

Figure 6-18: Mechanical Testing Device to measure torsional stiffness of athletic footwear.

Representative foot geometry provided a volume within the boot during operation, with a last, commonly used in footwear manufacture, shortened to an equivalent length of a human foot
based on the size of boot tested (UK size 8½). Two ball and socket joints connected the forefoot and rearfoot via a metal beam, which allowed the two segments to rotate independently of each other but remain a fixed distance apart. A midfoot region, constructed from rubber material, was able to rotate around the metal beam. The representative foot geometry was displayed in Figure 6-19. The load cell recorded data at a frequency of 80Hz, with an inbuilt software measuring the torsional moment (torque) for a known rotational displacement. The testing device was displacement driven.

![Torsion Mechanical Test Device](image)

Figure 6-19: Torsion Mechanical Test Device (Left) and Mechanical Foot with and without midfoot region (Right).

### 6.3.2 Experimental Test Device Methodology – Load Measurement

Identifying the typical range of torsional rotation during linear and multi-directional movements required analysis of published biomechanical data. Footwear construction has been reported to limit the range of motion; between 13° eversion and up to 20° inversion was documented in a study involving barefoot running (Stacoff et al. 1989). When shod, the rotation was significantly reduced to 7° eversion and up to 6° inversion, thus the construction of the footwear type required consideration. Without a measure of torsional rotation this specific boot type would experience during human running, an accepted rotational range of ± 10° about the longitudinal axis was chosen as a compromise between barefoot (20° to -13°) and shod rotation (6° to -7°). Three specimens for the outsole, upper and boot type were tested with the 5th cycle measured following 4 pre-cycles. After each test, pressure was released on the clamps and the foot removed from the specimen before reversing the process, evaluating the repeatability of the method and test samples. Five trials for each specimen were recorded. The rate of displacement was 10°/s, with the data recorded when the forefoot reaches its peak inversion (10°) before completing a full cycle (from 10° to -10° and back to 10°). Torsional stiffness was calculated by taking the
differential of the torsional moment and angle relationship. To provide consistency between the tested samples, the distance between eyelets was marked onto the lace, ensuring the same initial lace tension was applied through displacement of the lace.

Figure 6-20: Example of the Analysis of Torsional Stiffness with Colour coded segments to show the linear stiffness measurement with standard deviation.

With the objective of the experimental testing of physical boots to provide comparative data with the FE model, a similar approach was taken as described when quantifying the bending stiffness. A non-linear relationship was recorded during loading of the boot from inversion to eversion, with difficulty establishing the signal from the raw test data due to the differentiation process to capture torsional stiffness. The torsional stiffness was calculated for eight segments, each spanning 2.5°, through linear regression analysis. Non-linearity in the bending moment led to the
large deviation between the data and the representative stiffness for the 7.5° - 10°. Whilst this was the most appropriate means to represent the data for model comparison, the levels of deviation were considered when verifying the model. Figure 6-20 demonstrated how the torsional stiffness was established for each segment, with the format used to analyse samples represented in the bar chart.

6.3.3 Experimental Test Device Methodology – Deformation Measurement

The purpose of quantifying the level of strain during torsional rotation was to provide comparable measurements with the FE model. GOM Aramis was used to measure the surface deformation, as documented in the measurement of upper deformation during manufacture (Section 5.2.1). A black boot with a white stochastic pattern was applied to the upper surface, with cameras distanced 1160 mm from the capture zone centre, at an optical angle of 25°. 50 mm lenses were used to create a capture volume of 400 mm³. The system was calibrated using a CP20 panel. With the aim of the thesis to determine the predictive capability of an FE constructed boot, only a single boot was analysed with regards to strain measurement. A black boot was introduced to improve strain capture – coverage issues were experienced when measuring a black pattern on the white boot. The test set up used to quantify the surface strain was displayed in Figure 6-21. Data was collected for three different trials, with capture of the medial and lateral side.
6.3.4 Experimental Test Device Results

Measurement of torsional stiffness using the experimental test device enabled the boot, upper and outsole components to be quantified (Figure 6-22). The component was rotated to 10° before the loading of the boot between 10° to -10° was measured. Hysteresis was observed in the boot, upper and outsole, with the boot exerting a far greater stiffness when inverted during the loading phase. All the components were shown to follow similar trends, with an initial increase in stiffness before reducing to a more linear profile between 5° to -10°. The results displayed in Figure 6-22 further emphasise the requirement to evaluate footwear with a volume present within the shoe.

The evidence provided by this study demonstrates that the outsole is not the only component which defines the bending stiffness, with the upper contributing a significant proportion to the overall torsional stiffness; between 10° and 2.5° inversion, the upper has a greater contribution to the overall stiffness of the boot than the outsole. These findings support those discussed when measuring bending stiffness in football boots. Deformation response of the outsole, upper and boot is displayed in Figure 6-23 at peak inversion and eversion.

![Figure 6-22: Mean Experimental Measurement of Torsional Stiffness for Outsole, Upper and Boot with error bars demonstrating standard deviation.](image)

The data presented in Table 6-2 supports the concept of full boot testing when evaluating the mechanical function, rather than simply combining the properties of the upper and outsole. Assessment of the relative contribution of the individual components’ torsional stiffness with respect to the boot demonstrated that, like during bending, the combined components led to a higher stiffness. The components represented a maximum of 71% of the torsional stiffness when compared to the measurement of the full boot, providing further evidence that the evaluation of the individual components does not correlate to the finished product.
Contribution of Outsole Relative to Boot Stiffness
Contribution of Upper Relative to Boot Stiffness
Combination of Upper and Outsole Stiffness

<table>
<thead>
<tr>
<th>Angle</th>
<th>Outsole</th>
<th>Upper</th>
<th>Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5° - 10°</td>
<td>27%</td>
<td>42%</td>
<td>67%</td>
</tr>
<tr>
<td>5° - 7.5°</td>
<td>17%</td>
<td>34%</td>
<td>51%</td>
</tr>
<tr>
<td>2.5° - 5°</td>
<td>23%</td>
<td>27%</td>
<td>50%</td>
</tr>
<tr>
<td>0° - 2.5°</td>
<td>22%</td>
<td>18%</td>
<td>40%</td>
</tr>
<tr>
<td>-2.5° - 0°</td>
<td>21%</td>
<td>19%</td>
<td>40%</td>
</tr>
<tr>
<td>-5° - 2.5°</td>
<td>24%</td>
<td>25%</td>
<td>49%</td>
</tr>
<tr>
<td>-7.5° - 5°</td>
<td>27%</td>
<td>28%</td>
<td>55%</td>
</tr>
<tr>
<td>-10° - 7.5°</td>
<td>35%</td>
<td>36%</td>
<td>71%</td>
</tr>
</tbody>
</table>

Table 6-2: Contribution of the Outsole and Upper components Torsional Stiffness relative to the Boot, with the combination of their relative contribution to demonstrate the difference to the boot during Bending.

Figure 6-23: Images of Peak Inversion (Top) and Eversion (Bottom) of Boot Components; Outsole (Left), Upper (Middle) and Boot (Right).

Stacoff et al. (1991) reported rotational angles of 9.4° ± 3.2 in eversion and 8.7° ± 3.0 in inversion for running shoes and 39.9° ± 3.9 in eversion and 38.7° ± 4.0 in inversion for sprint spikes when a moment of 2 Nm was applied to the forefoot. Experimental measurement of football boots were reported to be stiffer in torsion than both running shoes and sprint spikes, with mean rotation of 6.53° ± 0.14° in eversion and 6.08° ± 0.11° in inversion at 2Nm of torque. These results further demonstrate how construction influences mechanical properties of football boots. Foamed copolymer of ethylene and vinyl acetate (EVA) is widely used in running shoe midsoles (Verdejo and Mills 2002), whereas the boot outsole was constructed from a polyamide material. Whilst the
elastic moduli of EVA foams increases with density (Verdejo and Mills 2002), an established range between 0.002 GPa to 0.28 GPa has been characterised (Bashford 1996). The boot outsole material elastic modulus was characterised at 2.6 GPa (CAMPUSPlastics 2012), thus the difference in material stiffness suggested a greater torsional stiffness, reducing the boot’s rotation relative to the running shoe. The geometry of the shoe will also influence the reaction moment of the shoe, thus the thickness of the shoe design is important when consideration of torsional beam theory (Clifford et al. 2009).

Material deformation at peak inversion and eversion were captured to provide comparative data for the model. Visual inspection of the contour plots displayed in Figure 6-24 and Figure 6-25 demonstrates the repeatable response of the same boot specimen through three different tests. The results exhibited the change in deformation magnitude across the upper material with between 0.5% and 2.5% strain measured at both peak inversion and eversion in torsion (Figure 6-24 and Figure 6-25). Consistencies between the captured strain gradient represented by contour plots across the midfoot region suggest repeatable data to compare with the model’s deformation output.

![Contour plots](image)

*Figure 6-24: Maximum Principal Strain Measurement of Boot at Peak Inversion (10°); Lateral (Top) and Medial (Bottom) displaying consistency between three different tests of the same specimen.*
Figure 6-25: Maximum Principal Strain Measurement of Boot at Peak Eversion (-10°); Lateral (Top) and Medial (Bottom) displaying consistency between three different tests of the same specimen.
6.4 Experimental Measurement of Additional Football Boots to Determine Stiffness Range

When assessing the simulated bending and torsional stiffness, it is important to factor in whether the model can be considered to be good. With limited published data with regards to boot properties, general public acceptance was considered to generate an accepted range of bending and torsional stiffness. A means to provide comparable data involved experimental measurement of two additional boots, calculating both bending and torsional stiffness as reported previously in this chapter. It was assumed that these boots were accepted by the market, produced by a major sporting brand, thus experimental results would provide a range of stiffnesses acceptable to players.

The exact testing protocols were followed, with only the full boot evaluated; three specimens for each boot were measured. For the purpose of analysis, the physical equivalent of the boot model reported in this thesis will be denoted Boot 1, with the additional boots termed Boot 2 and Boot 3. Only load response of the additional boots was reported.

Boot 2 consisted of an upper constructed primarily from Taurus leather, with stitching across the forefoot for surface detailing. The midfoot region of the upper consisted of a synthetic leather for brand detailing with a heel counter built into the upper. The outsole was created from the same material as Boot 1, with subtle differences in its geometry.

Boot 3 consisted of an upper constructed from synthetic leather, with regions bonded on to the outer surface, a large foam pad in the instep and a heel counter incorporated into the upper. Again the outsole was created from the same material as Boot 1, with subtle differences in geometry.
6.4.1 Evaluation of Acceptable Range of Boot Bending Stiffness

Figure 6-26 demonstrates the bending stiffness of three boots experimentally measured to determine an accepted range. General trends were reported, with a reduction in bending stiffness between 5° to 20° prior to an increase beyond 20°. Error bars displayed in the plot indicated one standard deviation from the mean. The variation demonstrated in the error bars were used to create an accepted range, factoring in the three specimens of each boot type. The maximum and minimum values of the error bars at each stiffness were used to form the accepted range as specified in Table 6-3. These values will be referred to in Chapter 7 when evaluating the modelling approach to simulate bending stiffness.

![Figure 6-26: Mean Bending Stiffness' of Three Market Accepted Boots to Determine an Accepted Range with error bars displaying one standard deviation from the mean.](image)

<table>
<thead>
<tr>
<th>Angle Range (°)</th>
<th>Lower Limit of Accepted Range (Nm/°)</th>
<th>Upper Limit of Accepted Range (Nm/°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° - 5°</td>
<td>0.551</td>
<td>1.017</td>
</tr>
<tr>
<td>5° - 10°</td>
<td>0.226</td>
<td>0.376</td>
</tr>
<tr>
<td>10° - 15°</td>
<td>0.110</td>
<td>0.284</td>
</tr>
<tr>
<td>15° - 20°</td>
<td>0.144</td>
<td>0.257</td>
</tr>
<tr>
<td>20° - 25°</td>
<td>0.220</td>
<td>0.500</td>
</tr>
<tr>
<td>25° - 30°</td>
<td>0.333</td>
<td>0.854</td>
</tr>
<tr>
<td>30° - 35°</td>
<td>0.443</td>
<td>1.236</td>
</tr>
<tr>
<td>35° - 40°</td>
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<tr>
<td>40° - 45°</td>
<td>0.858</td>
<td>1.538</td>
</tr>
</tbody>
</table>

Table 6-3: Accepted Range of Bending Stiffness measured from Boot 1, 2 and 3 based on the maximum and minimum of 1 Standard Deviation from their respected mean.
6.4.2 Evaluation of Acceptable Range of Boot Torsional Stiffness

Figure 6-27 demonstrates the torsional stiffness of the three boots experimentally measured to determine an accepted range. The variation demonstrated in the error bars (1 standard deviation from the mean) was used to create an accepted range, factoring in the three specimens of each boot type. The maximum and minimum values of the error bars at each torsional stiffness were used to form the accepted range as specified in Table 6-4. These values will be discussed in chapter 7 when determining the simulated stiffness of the FEA boot model.

![Figure 6-27: Mean Torsional Stiffness of Three Market Accepted Boots to Determine an Accepted Range with error bars displaying one standard deviation from the mean.](image)

<table>
<thead>
<tr>
<th>Angle (°)</th>
<th>Lower Limit of Accepted Range (Nm/°)</th>
<th>Upper Limit of Accepted Range (Nm/°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5° - 10°</td>
<td>1.067</td>
<td>1.688</td>
</tr>
<tr>
<td>5° - 7.5°</td>
<td>0.406</td>
<td>0.943</td>
</tr>
<tr>
<td>2.5° - 5°</td>
<td>0.357</td>
<td>0.697</td>
</tr>
<tr>
<td>0° - 2.5°</td>
<td>0.289</td>
<td>0.510</td>
</tr>
<tr>
<td>-2.5° - 0°</td>
<td>0.163</td>
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</tr>
<tr>
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</tr>
<tr>
<td>-7.5° - -5°</td>
<td>0.074</td>
<td>0.422</td>
</tr>
<tr>
<td>-10° - -7.5°</td>
<td>0.064</td>
<td>0.337</td>
</tr>
</tbody>
</table>

Table 6-4: Accepted Range of Torsional Stiffness measured from Boot 1, 2 and 3 based on the maximum and minimum of 1 Standard Deviation from their respected mean.
6.5 Chapter Summary

With regards to objectives 1 and 2 stated in the introduction, simplified laboratory based mechanical tests were used to quantify both load and deformation response of physical boots, with a bespoke testing device developed to quantify bending stiffness. Torsional stiffness was quantified through the use of an existing mechanical testing device, with surface strain measurements captured using GOM Aramis to provide comparable results for verification of the modelled deformation response. Testing methodology was developed to provide measurement of the bending and torsional stiffness, with biomechanical data cited in literature used to inform the range of motion; 0°- 45° during bending and ±10° inversion and eversion in torsion.

To address objective 3, experimental measurement of physical boots were quantified for both bending and torsional stiffness. Non-linear bending stiffness was reported, with the upper having a large influence on the boot’s bending stiffness during low angles of MPJ rotation (80%, 65% and 50% between 0° - 5°, 5° - 10° and 10° - 15° respectively). The establishment of buckling lines was observed at low angles of MPJ rotation, thus a higher reaction moment was measured. It was suggested that beyond 15°, deformation of the outsole defined the boot stiffness. A method to compare the complex deformed 3D geometry was developed and proven, with the surface curvature captured using a hand held scanner (REVscan 10189) providing comparable data between physical boot and potentially with the model. Bending and torsional stiffness ranges were reported through the experimental measurement of two additional market accepted boots to meet objective 4. The existing testing devices reported in this chapter were used.

In torsion, non-linear stiffness was measured, with hysteresis observed during loading. Boot stiffness was shown to be greater than running shoe midsoles, demonstrating how the construction of footwear influences the mechanical properties. Surface deformation was captured across the midfoot during torsion, with consistent measurements between 0.5% and 2.5% maximum principle strain reported.

Experimental measurement of the individual components and full boot reported no correlation in terms of the mechanical response, suggesting the requirement of computational modelling techniques to evaluate the full shoe construction. This supports the review by Cheung et al. (2009) into existing virtual methods to evaluate footwear, stating that the full shoe assembly must be modelled to improve predictive capabilities of computational modelling. Representative models will be based on the test conditions detailed within this chapter, enabling the applicability of using FEA techniques to predict boot function to be investigated.
Chapter 7:
Simulation of Boot Function using Finite Element Analysis Techniques

7.1 Introduction

The FEA techniques reported thus far in this thesis detail the application of simple boundary conditions to the constructed boot model which has provided measurable outputs that can be compared to experimental data captured from the mechanical loading of physical boots. To better represent common loading conditions of the boot through volumetric bending and torsion, more intricate mechanical tests were developed, thus increasing the complexity of the equivalent models and simulations. Further development of FEA techniques to model the deformation mechanisms with appropriate boundary conditions could determine the applicability and predictability of the model. This chapter details the modelling process developed to represent the mechanical test devices, as presented in Chapter 6, comparing outputs of the model and physical equivalent, discussing the applicability of the FEA approach.

7.1.1 Aims and Objectives

The aim of the study reported in this chapter was to evaluate the suitability of the boot model to predict boot stiffness in bending and torsion. Modelling approaches were required to quantify the relative stiffness, determining the predictive capability of the model when compared with experimental measurement of the physical equivalent. This aim was achieved by addressing several objectives, as listed below:

1. Represent deformation mechanisms in FEA model
2. Develop modelling methods to fit representative deformation mechanisms to the FEA boot model
3. Apply appropriate boundary conditions to simulate loading conditions of mechanical test
4. Compare bending and torsional stiffness outputs from FEA model with Experimental measurements to determine the predictability of the modelling approach
5. Discuss the applicability of FEA boot model to predict bending and torsional stiffness
7.2 Simulation to Fit Mechanical Foot within FEA Boot Model

This section documents how the two mechanisms were represented within FEA, followed by a fitting process to enable subsequent load response analysis meeting objectives 1 and 2.

7.2.1 FEA Representation of Mechanical Foot - Bending

A REVscan 10189 handheld scanner enabled the capture of a three-dimensional scan of the physical mechanical foot. The principles of the software were detailed in Section 6.2.3. Reflective markers were placed onto the bending mechanical foot’s surface, with more markers placed in regions where the surface curvature changed sharply. To capture the 3D surface, the toe was fixed to the heel to avoid any rotation around the pin joint. Once captured, the scanned data was exported as an STL file and imported into HYPERMESH. Surfaces were created within the software based on the imported 2D mesh, with the region around the pin joint edited to account for scanning discrepancies. Figure 7-1 demonstrated the three dimensional representation of the bending mechanical foot, with visual comparison to the physical geometry.

![Figure 7-1: Bending Mechanical Foot (Left) and Representative FEA Model (Right).](image)

7.2.2 FEA Representation of Mechanical Foot - Torsion

The torsion mechanical foot used in the mechanical test to measure torsional stiffness was modelled using CAD geometries provided by the industrial collaborator. Imported into HYPERMESH, a surface mesh was created based on the three components, with solid continuum elements were prescribed to the 3D mesh built based on the surface mesh of each component. All three components within the mechanical foot were exported as input files, which were subsequently imported into ABAUQS CAE. A visual comparison between the torsion mechanical foot and the FEA representation was demonstrated in Figure 7-2. Whilst a bar was present in the
torsion mechanical foot, linking the rearfoot and forefoot, the representative model used a link constraint to reduce computational cost.

Figure 7-2: Torsion Mechanical Foot (Left) and Representative FEA Model (Right).

7.2.3 Simulation of Mechanical Foot Fitting Procedure

In practice, fitting the mechanical foot into the physical boot would involve releasing the tension from the lace structure prior to placing it within the boot, followed by the re-tensioning of the laces. A modelling approach was required to simulate the physical process to enable subsequent load response analysis of the modelled boot stiffness. As detailed in Section 4.4.3, the assembled boot was imported as two parts, with tie constraints applied to edge pairings within the upper, lace structure and eyelet position and interacting nodes located along the adjoining surfaces of the outsole and upper. These constraints simulated the permanent attachment of the constituent parts observed during physical boot manufacture.

A procedure was developed to fit both the bending and torsion mechanical feet within the boot virtually. For the purpose of demonstrating the method, the bending mechanical foot fitting process was documented.
The bending mechanical foot was brought into the model assembly, with the geometry positioned directly above the outsole through visual alignment (Figure 7-3). During the fitting process, the mechanical foot remained rigid with a single reference point used to define its relative motion. Material thickness and behaviour of the modelled boot were consistent with those prescribed to the assembly model. Incompressible materials (v=0.5) were used throughout the simulation, avoiding element distortion during the fitting process.

The simulation was divided up into 3 different steps, in which different boundary conditions and contact surfaces were prescribed. The first step involved the displacement of the mechanical foot, initiating contact between the outer surface and the base of the upper. Specific contact pairs were set up to allow the elements within the mechanical foot to pass through the top of the upper, only allowing contact between the deformation mechanism and the top of the lasting board and heel pad. Contact was also allowed between the lace structure, pattern piece and tongue regions, with pressure applied to the inner surface of the outsole heel region. Once positioned, the deformation mechanism remained fixed in all degrees of freedom throughout the remainder of the simulation. The next step involved the expansion of the upper through a pressure load, displacing the elements away from the outer surface of the mechanical foot. With the pressure applied to the upper and outsole elements, penetration of the deformation mechanism was avoided, thus the final stage involved the removal of boundary conditions and loads from the boot. An extended step time facilitated material relaxation after the application and removal of pressure. The fitting process for the bending mechanical foot was displayed in Figure 7-3.

Fitting of the torsion mechanical foot to the boot followed the same procedure as documented for the bending mechanical foot. The resulting boot model and torsion mechanical foot was displayed in Figure 7-4.
Figure 7-3: Bending Mechanical Foot Fitting Process; Initial Alignment (a), Vertical Displacement (b) and Final boot geometry after Material Expansion and Relaxation, fitting around the Mechanical Foot (c).

Figure 7-4: Final Boot Geometry of Torsion Mechanical Foot Fitted using Modelling Approach.
7.3 Bending Stiffness Simulation – FEA Approach

7.3.1 FEA Representation of Mechanical Test

Evaluation of boot bending stiffness required the creation of a representative model based on the boundary conditions applied to the experimental test device. As outlined from experimental testing, measuring the stiffness of the outsole and upper individually did not correlate with the overall boot’s load response. Modelling the individual components prior to the full boot would be computationally expensive, thus only the boot was modelled.

With regard to objective 3, an initial model was generated by importing the bending deformation mechanism, upper and outsole to which relevant constraints and boundary conditions were applied. The constraints prescribed to the model were listed below:

- The axis of rotation was defined by a co-ordinate system (CYS) with the X axis aligned to the centre line of the pin joint within the mechanism, as demonstrated in Figure 7-5.

![Figure 7-5: Position and Angle of MPJ Axis for Pin Joint.](image)

- A kinematic coupling constrained the inner nodes within the pin joint to a reference point at the origin of the axis of rotation CYS. Rotation of the reference point resulted in rearfoot rotation (Figure 7-6).

![Figure 7-6: Kinematic Coupling at Pin Joint; Highlighted Nodes (Pink) coupled with Reference Point to drive MPJ rotation about pin joint (Red).](image)
• The cable tie was represented through a MPC link constraint, implemented to provide a rigid link to ensure a fixed distance between the deformation mechanism and the associated nodes on the outsole. The nodes associated with the link constraint were free to rotate during analysis (Figure 7-7).

Figure 7-7: Link Constraint to represent the cable tie used in experimental testing.

• Rigid constraint was applied to the elements within the toe geometry, fixed in all degrees of freedom during operation to reduce the computational cost. An infinitely stiff material model was applied to the rearfoot region based on the assumption that it did not deform during operation.

• Tie Constraints were applied along the upper edge pairs and eyelets with rough contact between the interacting surfaces of outsole and upper (Figure 7-8)

Figure 7-8: Tie Constraints within Upper (Left) and contact surface between Outsole and Upper (Right).
Documented in both Chapter 4 and 5, material models and appropriate element types were developed for the outsole and synthetic leather based on load response analysis, providing comparable data between the FE and physical boot. Implementation of the FEA knowledge acquired through simple loading of the boot was used as an initial starting point to model volumetric bending. The outsole was modelled using C3D10M elements with an elastic material model (\( E = 1.56 \) GPa, \( v = 0.35 \), \( \rho = 1070 \) kg/m\(^3\)), whilst the upper was modelled using SC6R elements with a synthetic leather based on the quantified difference between the raw and packaged material due to manufacture as detailed in Section 5.4.1.

Boundary conditions applied to the deformation mechanism included the forefoot part being fixed in all degrees of freedom. The simulation was driven by applying a rotational displacement of 45° to the pin joint reference point, resulting in rearfoot rotation around the X axis (Figure 7-9). The first stud row of the outsole was held fixed throughout the analysis. Field and history outputs were requested from the simulation, capturing the rotational displacement and the reaction moment of the pin joint reference point about the X axis, providing quantifiable measurements of the bending moment and angular displacement. Bending stiffness was evaluated using the same approach detailed in Section 6.2.2, providing comparative data between the model and the experimental test.

![Deformation of Boot Model using Appropriate Boundary Conditions and Constraints; 0° and 45° MPJ rotation](image_url)
7.3.2 FEA Modelling of Bending Stiffness

Measurement of both bending stiffness and the resulting deformation were possible within the model. This section provides a comparative study between the FEA model and experimental measurement to meet objective 4. Figure 7-10 and Figure 7-11 demonstrates the computed data extracted from both history and field output requests. When compared with the experimental test data measured in Chapter 6, the modelled load response demonstrated close agreement up to 20° of MPJ extension; the model was within 20.1% of the experimental test mean of the physical boot bending stiffness, but within 13.8% of one standard deviation. However, beyond 20° the model failed to represent the bending stiffness, as shown by the disparity between the FE model and mean experimental test data displayed in Figure 7-10.

![Graph showing comparison of experimental and modelled bending stiffness](image)

Figure 7-10: Measured Load Response of Model and Experimental Data; Bending Moment and Stiffness displaying standard deviation of experimental measurement.
Visual comparison between the physical deformation of the boot and the predictive FE model demonstrated similarities, with the buckling of the material between the first and second eyelet row observed (Figure 7-11). Deformation was common along the MPJ axis, with high strains (20%) measured within the model along the buckled regions.

Figure 7-11: Visual Comparison between FE Model and Experimental Measurement of Bending Stiffness at 45°; FE Model displaying Maximum Principal Material Strain.

A published report concluded that the foot is compromised by footwear, with the peak dorsiflexion reduced from 45°-50° to 25°-30° due to the shoe stiffness (Bojsen-Møller and Lamoreux 1979). Running shoes constructed from EVA (70 Shore C) (deemed to be stiff in forefoot flexibility and torsion (Kleindienst and Bruggemann 2003)), were found to reduce the MPJ dorsiflexion to 28° ± 5.7° (Lin et al. 2013). The presence of a thin carbon fibre plate further reduced the peak dorsiflexion to 24.1° ± 5.7°, demonstrating the role the footwear has on MPJ rotation. In running at 4.5 m/s, typical mean MPJ peak angles ranged between 23.3° to 24.9° in females and 24.8° to 26.9° in males, when EVA midsole running shoes were worn (Kleindienst et al. 2005). Studies into
sprinting performance reported a higher peak dorsiflexion in sprint spikes 42.3° ± 5.7°, 36.3° ± 5.1° and 31° ± 3° (Smith et al. (2014), Smith et al. (2012) and Toon et al. (2009) respectively). With limited published data on the direct influence of boot construction on MPJ dorsi-flexion, inferring results captured from athletic footwear demonstrated that approximate values of 25° of MPJ rotation is common in walking and running, but a greater range was reported during sprinting, thus further analysis of the model was conducted to investigate potential reasons between physical and simulated boot loading.

Close agreement between the simulated bending stiffness and experimental measurement was reported up to 20°. With peak MPJ rotation of up to 25° reported in literature, the model was able to predict the bending stiffness within 20.1% up to 20° - 80% of the mean range reported in walking and running. Statistical analysis of match play reported low intensity movements, classed as walking and jogging, consisted of between 83.6% to 90.9% (Withers et al. 1982; Ali and Farrally 1991; Mayhew and Wenger 1985), thus the model was deemed acceptable in reporting data for up 90% of match play. The impact of only predicting bending stiffness up to 20° means that the high intensity sprint movements could not be simulated reliably. Whilst infrequent, these fast movements are importing in football match play.

Within the first 20° of MPJ rotation, the FE model was within 20.1% of the experimental mean of the physical boot specimens. As detailed in Section 6.4.1, a bending stiffness range based on three market accepted boots was compiled due to limited published data. The accepted range and FE model data displayed in terms of bending stiffness was demonstrated in Table 7-1. The model was within 5.6% of the accepted range.

<table>
<thead>
<tr>
<th>Lower Limit of Accepted Range (Nm/°)</th>
<th>Upper Limit of Accepted Range (Nm/°)</th>
<th>FE Model - Initial Model Bending Stiffness (Nm/°)</th>
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<tr>
<td>0°- 5°</td>
<td>0.551</td>
<td>0.680</td>
</tr>
<tr>
<td>5°- 10°</td>
<td>0.226</td>
<td>0.376</td>
</tr>
<tr>
<td>10°- 15°</td>
<td>0.110</td>
<td>0.284</td>
</tr>
<tr>
<td>15°- 20°</td>
<td>0.144</td>
<td>0.257</td>
</tr>
</tbody>
</table>

*Table 7-1: Comparison between the FE Model and Accepted Range of Bending Stiffness measured from Boot 1, 2 and 3 based on the maximum and minimum of 1 Standard Deviation from their respected mean.*

As detailed in Chapter 6, the level of deformation observed within the forefoot region during bending restricted the potential of using DIC software to measure surface deformation, providing quantifiable analysis for the modelled deformation. An alternative measurement system was introduced, providing surface scan data of physical boots at 22.5° and 45°. Figure 7-12 and
Figure 7-13 demonstrates the angle of curvature of the surfaces scan data using GEOMAGIC software. An algorithm determined the relative angle between the data points, displaying the results as a contour plot within the software. Qualitative analysis of the results identified common deformation modes experienced in the upper, with the material buckling due to compressive strain caused by forefoot bending around the MPJ. Consistency during buckling was observed on the lateral forefoot region during bending of physical boots, whilst different deformation patterns were represented on the medial forefoot region of the model. Large angles of curvature were quantified through experimental measurements of physical boots reporting curvature to exceed 100°. A potential reason for differences between the physical boot and modelled deformation could be due to the element type and mesh density. With such large changes in curvature angle, computational analysis of the deformation may not be possible, shown in Figure 7-12. Mesh density may be a factor, but increasing the number of nodes increased the computation cost by 243% (22 CPUs), with a mesh refinement study demonstrating the increased angle of curvature between the FE initial model and refined mesh model. However with the computed strain energy a function of the element, increasing the number of elements defined by the mesh density can influence the accuracy and convergence of the simulation, leading to modelling issues such as volumetric locking, reducing the predictive applicability of the model; the computed stiffness obtained by the finer meshed FE model increased by a mean stiffness of 10.3% ± 3.1% between 0° to 20°.

Figure 7-12: Comparison Between FE Model and Physical Boots in terms of Surface Curvature at 22.5°; Lateral Images (Top) and Medial Images (Bottom).
As demonstrated in Chapter 4, rough contact and tie constraints were two methods used to model the adhesive bond between the upper and outsole. When tie constraints were applied to the nodes along the interacting regions of the upper and outsole, the simulated bending stiffness was increased with respect to the rough contact approach (31%, 116%, 187% and 225% for 0° to 5°, 5° to 10°, 10° to 15° and 15° to 20° respectively) as displayed in Figure 7-14. With the associated nodes in the upper tied to the outsole nodes in all degrees of freedom, the far stiffer outsole material (1.56 GPa) compared to the synthetic leather (0.048 GPa) governed the deformation response, leading to the stiffer response in the model.

Figure 7-14: Demonstration of Bending Stiffness when Modelling the Adhesive Bond between Upper and Outsole; Rough Contact and Tie Constraints applied adjoining surfaces of Upper and Outsole.
The initial FE model demonstrated the approximation of mechanical bending of the boot in terms of its stiffness and deformation response. Close agreement between the experimental measurement and modelled bending stiffness up to 20° was shown, in addition to the deformation mode in the material. To determine the predictive capabilities of the FEA approach to modelling football boots (Objective 4), variables within the model were investigated to determine the sensitivity to provide a level of confidence in the approach developed to simulate bending stiffness of a football boot.

During simple loading of the boot, material behaviour was shown to influence the load response of the model. Investigating the impact this had on the modelled bending stiffness involved the relative stiffness of the material behaviour within the outsole and upper. With the upper primarily constructed from synthetic leather, only this material was investigated within the upper. As detailed in Section 4.4.3, Figure 4-15 demonstrated how hyperelastic response curves can lead to inaccuracies in the model. Analysis of the material model used to represent the synthetic leather incorporating the effects of manufacture reported -19% and 11% difference between the Neo-Hookeon Material model and test data. To investigate this impact the synthetic leather material stiffness was increased by 20%, with the same percentage increase attributed to the outsole material. Simulating the increased stiffness of the material model found that the outsole material had the greatest influence on bending stiffness through boot loading, with an average increase in computed stiffness of 9.2% ± 5.0% compared with 6.7% ± 3.7% of the synthetic leather (Figure 7-15).

![Figure 7-15: Computed Bending Stiffness from Model based on Relative Material Stiffness Increase of Outsole and Synthetic Leather Material Models.](image)

Experimental measurement of the upper’s contribution showcased the importance the component has during the first 20° of MPJ rotation. However the model calculated that an
increase of 20% of the synthetic leather would only result in a 3% increase in bending stiffness between 0° - 10° whereas as the outsole would lead to a 4% increase. With the model unable to measure the deformation measured at 22.5° (displayed in Figure 7-12) the significance of the upper during bending at low angles of rotation may not be represented.

Observations of the both the experimental and modelled bending involved buckling of the dorsal region of the forefoot, primarily between the first and second eyelet rows. Consideration of the lace structure during bending and the potential influence it could have on the stiffness and deformation was a necessary step in determining the applicability of the model. Beam elements used to represent the lace structure could only have linear elastic material behaviour assigned to them, thus the linear regression from non-linear data was important, displayed in Figure 7-16. It was assumed that the lace structure was tensioned prior to loading of the boot, thus three different material stiffnesses were calculated based on the experimental data for the lace structure during uni-axial loading (Figure 7-16).

![Figure 7-16: Material Behaviour of a lace structure; Stress Strain plot of mean experimental behaviour of the boot lace during uni-axial loading, with relative material stiffness quantified for 3 scenarios.](image)

Application of the alternative lace material models had little impact on the overall bending stiffness of the model (Figure 7-17) or the material deformation in the forefoot (Figure 7-18). Despite a large change in material stiffness from lace 1 to lace 3, only a 6% ± 5% increase in the computed bending stiffness was reported.
The model consisted of many interacting surfaces with friction potentially influencing the load response of the model. A general contact algorithm involves stating the relative interaction properties within the model; penalty friction coefficient of 0.2 was applied to the initial model with a ‘hard’ normal contact. This value was used as an initial starting point with a specific coefficient not known. With validation of the model as detailed previously, the evaluating the impact of this coefficient was important. Whilst the contact conditions have been reported to influence the measured frictional properties (Lewis et al. 2014), examples of the coefficient has been reported. Skin and sock interaction has been reported to have a mean coefficient of 0.51 ± 0.11 (Zhang and Mak 1999), whilst a coefficient of 0.4 between the upper and ball was used when simulating football kicking using FEA (Ishii et al. 2014). The friction coefficient was increased to 0.4 to reflect these typical values, with reference to the contact condition playing an important part in defining the interaction property. This effect was simulated in Figure 7-19 and Figure 7-20 for bending stiffness and deformation respectively. Friction between the surfaces resulted in the stiffness varying throughout the 45° of rotation, essentially changing the load response of the model. Deformation response of the model, detailed in Figure 7-20, was influenced by the friction
coefficient, with higher strain magnitudes observed in the higher frictional model. Cross-sectional analysis of the interaction along the MPJ axis demonstrated that increasing the tangential friction coefficient would result in the tongue material being force into the recess between the toe and rearfoot components.

![Graph showing effect of friction on bending stiffness measured from model.](image)

**Figure 7-19:** Effect of Friction on Bending Stiffness measured from model.

![Deformation of Model during bending with different friction coefficients assigned to the tangential interaction to simulate the contact; μ=0.2 (left) and μ=0.4 (right).](image)

**Figure 7-20:** Deformation of Model during bending with different friction coefficients assigned to the tangential interaction to simulate the contact; μ=0.2 (left) and μ=0.4 (right).

Boundary conditions within the model were defined by the relative motion of the deformation mechanism. Both the axis and location of bending could impact the stiffness of the boot, thus both were investigated. Visual alignment of the initial model was used, positioning the mechanism within the modelled boot as demonstrated in Figure 7-21. Alternative positions were determined based on the initial position, with position 1 and position 2 varied by moving the mechanism 2mm and 4mm towards to the toe respectively. The positions were chosen based on the maximum distance the mechanical foot could reach relative to the toe of the physical boot.
This defined the maximum value (4mm), with an intermediate value (2mm) to provide comparative data.

![Figure 7-21: Bending Mechanical Foot Relative Alignment within the Undeformed Boot Model.](image)

Modelling the different bending location had a small influence on the load response of the model as displayed in Figure 7-22; moving the bending mechanism towards the toe did increase the stiffness, with mean values computed of $10.4\% \pm 5.7\%$ and $12.6\% \pm 6.3\%$ for Position 1 and Position 2 relative to the initial position.

![Figure 7-22: Load Response of Boot at Different Mechanical Foot Positions.](image)

Evaluating the strain distribution of the outsole with different bend axes suggested that changing the axis transfers the bend location towards the second stud, away from the flex line between the second and third stud row; higher strain was measured behind the lateral stud in the second row.
for the initial position when compared to the other two (Figure 7-23). The resistance due to the stud may explain the small increase in the bending stiffness measured from the model.

Figure 7-23: Maximum Principal Strain Measured in Outsole during Different Bending Locations.

With the original MPJ axis defined at 12° as defined in the creation of the bending mechanism detailed in Figure 6-2, to emphasise the potential influence of the bending axis, two alternative axes were introduced, with co-ordinate systems (CYS) defined by rotating their position ± 3° around the Y axis denoted in Figure 7-5. Corresponding constraints, boundary conditions and history outputs were defined for the respective CYS, depending on the axis of rotation. Deviation from the initial axis of MPJ led to mean differences of 10.4% ± 6.9% and 4.6% ± 2.1% in bending stiffness at 3° and -3° respectively (displayed in Figure 7-24). The effect of this variation in bending stiffness has on movement performance has not been quantified in football, thus it is difficult to determine the potential significance change in MPJ axis has. However the model suggests that variation in the human foot structure and bending axis could influence the bending properties of the boot.

Figure 7-24: Influence of Rotation Axis on Bending Stiffness Measurement of Model.
As discussed in Chapter 3, investigation into the most appropriate element type suggested continuum shells was the most accurate when comparing simulated outputs to theoretical calculations. However the element type cannot compute anisotropic material behaviour, a property observed during material model characterisation in Chapter 4. Volumetric bending and torsional mechanical tests provide a fixed constraint to the boot under loading, resulting in the material being strained in three dimensions. With the upper elements in the model only programmed to compute isotropic behaviour, the mechanical response is the same in all directions, a discrepancy with the physical boot potentially explaining the differences between physical and simulated volumetric bending. Further development of continuum shells to incorporate anisotropic behaviour has the potential to improve the model accuracy, with published research by Salahouelhadj et al. (2012) demonstrating the importance of material anisotropy when using continuum shells to model sheet material during steel forming. Strain hardening is another material property that was not incorporated into the material model but could be a potential source of error between the measured bending stiffness of physical boots and the representative model. Due to the large deformation across the forefoot, the stiffer response of the physical boot at high strains which were not defined within the model could also explain the differences. However, increasing the complexity of the material model by adding these properties requires associate time costs, with further material characterisation testing necessary. Another factor could be due to the adhesive bond between the components. With adhesive used to bond the upper and outsole components during manufacture, the adjoining regions form a composite structure, with the bond demonstrated to change mechanical properties if the adhesive had a thickness (Le and Nairn 2014). Whilst this phenomenon may have contributed to the differences, it was not expected to have led to the large disparity between the simulated and physical bend tests. The thickness of the adhesive would have to be greater than cavity between the outsole and upper components as a result of manufacturing to have an effect on the bending properties.

The modelling variables discussed in this section have been shown to influence the computed bending stiffness, with isolation of specific parameters enabling the level of confidence to be predicted. Analysis of each of these independent factors were not normalised within this study, thus they cannot be compared together. Rather they indicate the constraints of the modelling approach and express the potential influence they have on the computed bending stiffness.
7.4 Torsional Stiffness Simulation – FEA Approach

7.4.1 FEA Representation of Mechanical Test

Demonstrated through the approach developed to model boot bending stiffness, measurement of torsional stiffness required the appropriate application of boundary conditions to the deformation mechanism when creating representative models. With regard to objective 3, the constraints and boundary conditions applied within the model were described below:

- The toe and heel parts were constrained as rigid bodies due to the shoe-last being constructed from a far stiffer material than those used in the boot. Relative motions of the constrained nodes within the part were based on the associated reference points, with their location demonstrated in Figure 7-25.

![Figure 7-25: Associated Reference point locations for Toe (Red) and Heel (Purple) Parts of Torsion Mechanism Foot.](image)

- Tie Constraints were applied along the upper edge pairs and eyelets with rough contact between the interacting surfaces of outsole and upper, as demonstrated when modelling bending stiffness of the boot (Figure 7-8).
- Abstraction of the metal bar from the model reduced computational cost, with boundary conditions applied to the toe and heel reference points to ensure a fixed distance remained. A kinematic couple constraint was assigned to the inner nodes, only allowing rotation around an axis created to represent the centre line of the torsion axis in the foot as displayed in Figure 7-26.
Figure 7-26: Coupling constraint assigned to midfoot region (Blue) with specified rotation axis (Green).

- To represent the mechanical test, the heel was kept fixed in all degrees of freedom throughout the analysis, with the toe only allowed to rotate about the rotation axis as shown in Figure 7-27.

Figure 7-27: Rotation Axis based on Load Cell Position Measured from Mechanical Test (Black) Relative to Torsion Mechanism

The model was driven by rotating the outsole forefoot using a kinematic coupling constraint relative to a reference point located on the toe part reference point (displayed in Figure 7-25). Only the loading phase was analysed to provide comparable data to the experimental
measurement of the physical boots, thus the reference point was rotated to 10° about the defined axis shown in Figure 7-27, before rotating from 10° to -10°.

The position of the load cell was measured relative to the torsion mechanism when testing the physical boots. With the heel fixed in all degrees of freedom, no vertical displacement was allowed at the rear studs. Both these boundary conditions were displayed in Figure 7-28.

Figure 7-28: Torsional Stiffness Model with Rotation of Outsole Forefoot nodes (Pink) and no vertical displacement of the rear studs (Red)

Determining the applicability of the constructed FE boot model required the same initial material models and element types implemented into the torsional model as used to measure bending stiffness. History and field outputs were requested to quantify the reaction moment and angular displacement of the reference point associated with boot rotation, with the forefoot rotating relative to the rearfoot as shown in Figure 7-29. The load and deformation response extracted from the model was then compared with experimental measurement data of physical boots to determine the relative representation of the approach.

Figure 7-29: Deformation of Boot Model using Appropriate Boundary Conditions and Constraints; Peak Inversion (Left) and Peak Eversion (Right)
7.4.2 FEA Modelling of Torsional Stiffness

The application of boundary conditions to the representative boot and deformation mechanism resulted in the computed torsional moment and stiffness values graphically displayed in Figure 7-30 and deformation response in Figure 7-31, meeting objective 4. Close agreement was observed between the moment and stiffness magnitudes of experimental and modelled measurements throughout the loading phase. The model followed the general trend exhibited by the experimental test data. However, discrepancies between the model and physical load response between -7.5° to -10° were computed. The torsional stiffness computed between 10° and -7.5° was within 17% of the experimental mean, with larger differences experienced between -7.5° to -10° (43%).

![Graph showing torsional moment and stiffness](image)

**Figure 7-30**: Measured Load Response of Model and Experimental Data; Torsional Moment and Stiffness displaying standard deviation of experimental measurement.
Without measuring the torsional angle of players when shod in the boot used to create the FEA model, the torsion angle reported during running ranged between 6° - 7° when shod (Stacoff et al. 1989). As documented previously in the analysis of the bending simulation, statistical analysis of match play reported low intensity movements, classed as walking and jogging, consisted of between 83.6% to 90.9% (Withers et al. 1982; Ali and Farrally 1991; Mayhew and Wenger 1985), thus the simulation was able to compute the stiffness between 10° and -7.5° within 17% of the experimental mean model; deeming the model to represent typical torsional rotation from published research studies for up to 90% of match play.

![Figure 7-31: Visual Comparison between Experimental (Top) and Modelled (Bottom) Boot Deformation during Torsional Rotation; Inversion (10°) and Eversion (-10°).](image)

Due to limited published data regarding playing performance and football boot stiffness, a range was created from the standard deviation limits of three different boots, with the accepted range and FE model data displayed in Table 7-2. Between 10° and -7.5° the model was within the accepted range, with inaccuracies observed between -7.5° and -10°. However these were within 27.1% of the upper limit, demonstrating the applicability of the model within market accepted boots.
### Table 7-2: Comparison between the FE Model and accepted Range of Torsional Stiffness measured from Boot 1, 2 and 3 based on the maximum and minimum of 1 Standard Deviation from their respected mean.

<table>
<thead>
<tr>
<th>Lower Limit of Accepted Range (Nm/°)</th>
<th>Upper Limit of Accepted Range (Nm/°)</th>
<th>FE Model - Initial Model Torsional Stiffness (Nm/°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5° - 10°</td>
<td>1.067</td>
<td>1.688</td>
</tr>
<tr>
<td>5° - 7.5°</td>
<td>0.406</td>
<td>0.943</td>
</tr>
<tr>
<td>2.5° - 5°</td>
<td>0.357</td>
<td>0.697</td>
</tr>
<tr>
<td>0° - 2.5°</td>
<td>0.289</td>
<td>0.510</td>
</tr>
<tr>
<td>-2.5° - 0°</td>
<td>0.163</td>
<td>0.498</td>
</tr>
<tr>
<td>-5° - 2.5°</td>
<td>0.186</td>
<td>0.457</td>
</tr>
<tr>
<td>-7.5° - 5°</td>
<td>0.074</td>
<td>0.422</td>
</tr>
<tr>
<td>-10° - 7.5°</td>
<td>0.064</td>
<td>0.337</td>
</tr>
</tbody>
</table>

Deformation response of the model was compared with the experimental measurement of physical boots using GOM Aramis system. The principle and associated steps required to quantify surface deformation was documented in Chapter 5 and Chapter 6. Digital image correlation software enabled the change of a stochastic pattern to be measured, quantifying the material strain at peak inversion and eversion. Qualitative analysis of the model and experimental data were displayed in Figure 7-32 and Figure 7-33. Agreement was demonstrated in the corresponding strain magnitudes except at peak inversion on the lateral side of the boot. Strain distribution between 0.5% and 3% were observed in both the experimental measurement and simulation of the torsional rotation. Discrepancy between the surface strains on the lateral side at peak inversion (10°) was explained by the midfoot region deforming differently within the simulation, leading to isolated pressure distribution on the upper material, resulting in the 5% peak strain computed in the simulation. Despite the differences, surface deformation of the upper during torsional rotation showed general agreement between the simulated and experimental measurements.
Figure 7-32: Surface Deformation of Boot at Peak Inversion (10°); Max Principal Strain Measurement of Experimental (Left) and FE Model (Right).

Figure 7-33: Surface Deformation of Boot at Peak Eversion (-10°); Max Principal Strain Measurement of Experimental (Left) and FE Model (Right).

The initial FE model demonstrated the model's approximation of mechanical torsion of the boot in terms of its stiffness and deformation response. The torsional stiffness measured between 10° and -7.5° was within 17% of the experimental mean, with larger differences experienced between -7.5° to -10° (43%). Deformation response of the boot during torsion displayed agreement in terms of the strain gradient (between 0.5% and 3%), but higher levels of strain were measured in the lateral side at peak inversion.
Whilst the initial FE model suggested close agreement of the measured load and deformation response, with an intricate loading condition, potential sources of error were analysed, such that the sensitivity of the model could be investigated. A similar process to determine the model’s sensitivity was introduced to the torsion model to investigate material stiffness as used in the bending stiffness analysis, providing a confidence level between the two simulations.

Both the outsole and synthetic leather material model stiffness were increased by 20%, implementing them within the model and evaluating their influence on the torsional stiffness (Figure 7-34). In general, increasing outsole material stiffness resulted in a greater torsional stiffness than synthetic leather. In fact changing the synthetic leather material only resulted in an increase in stiffness between -7.5° and -5°. However the outsole increased the stiffness when compared to the initial model in inversion but was less effective in eversion. The mean increase in torsional stiffness was 9.8% and 6.3% when the outsole and upper material stiffness was increased by 20%.

![Graph](image)

**Figure 7-34: Influence of Material Stiffness of Outsole and Synthetic Leather on Torsional Stiffness measured from FE Model.**

As discussed when verifying the sensitivity of the model to quantify boot bending stiffness, lace stiffness measured during experimental uni-axial tests detailed the change in the material behaviour based on the tension applied to the laces prior to movements (Figure 7-16). Mean increase in bending stiffness was measured, with 2.3% ± 1.6% and 4.5% ± 2.5% of lace stiffness 2 and 3 relative to lace stiffness 1, as shown in Figure 7-35.
The boot construction model involved a number of interacting surfaces across the constituent parts, with their tangential behaviour potentially influencing the result. As detailed in the bending stiffness model, penalty friction coefficient of 0.2 was introduced as a starting point. To evaluate the effect of friction on torsional stiffness, a friction coefficient of 0.4 was used to investigate this variable, with the results displayed in Figure 7-36. In general, torsional stiffness increased with friction coefficient of 0.4, except 0° - 2.5°. However the measured difference was relatively low (between 2% to 18%).

The FE model was driven by a reference point located at an approximate position based on the mechanical test. Both the position and rotation axis could be a potential source of error, thus the influence of these factors required further analysis. With rotation about the Z axis which defines the axis of rotation, both the X and Y co-ordinates of the rotation point were isolated and evaluated by changing their position by ± 5 mm, as demonstrated in Figure 7-37. The values were chosen to demonstrate the extent of a change by ± 5 mm through inaccurate measurement.
The results were shown in Figure 7-38. Y direction (vertical) had the greatest impact on the measured torsional stiffness, when compared with the X direction. The general trend of the stiffness and angle relationship was common, with variation in magnitude observed. With an increase in vertical height (Y + 5mm), the resulting torsional stiffness was increased by an average of 14.4 ± 4.9%, whereas lowering the rotation point led to an average reduction of 14.1 ± 3.5% when compared to the initial model. In the X direction, the impact of changing the rotation point was less influential on the deviation from the initial model (increase of 6.7 ± 2.5% and decrease of 5.4 ± 3.3% for X + 5mm and X - 5mm respectively).
The torsional stiffness was shown to vary depending on the rotation axis between ±10°, with an average reduction in stiffness measured 16.3 ± 6.4% and 15.3 ± 5.7% for the Axis +10° and -10° respectively (Figure 7-39).

Isolation of specific parameters within the model highlighted their influence on the computed torsional stiffness. As demonstrated when establishing the predictive reliability of the model to measure bending stiffness, analysis of each of these independent factors were not normalised within this study, thus they cannot be compared together.
7.5 Applicability of Boot Stiffness Simulation Techniques

Consideration to the levels of agreement necessary for the simulated bending and torsional stiffness models to be deemed useful was required.

The FEA techniques reported in this chapter enabled both bending and torsion simulations to use the same material models, element types and surface interactions, demonstrating good agreement between the simulated outputs and experimental measurements; bending stiffness was predicted within 20.1% of the calculated experimental mean up to 20° of rotation, whilst the computed torsional stiffness was within 17% of the experiment mean from 10° inversion to 7.5° eversion. Experimental Measurement of two additional boots to quantify an accepted range was necessary due to limited published data to provide relationships between bending and torsional stiffness in football boots. The range created an upper and lower limit based on the standard deviation of the three boots, with the first 20° of MPJ rotation considered in bending and ± 10° in torsion. The model was within 5.6% of the accepted range for bending stiffness and within the torsional stiffness range between 10° and -7.5°.

With limited published data on the bending and torsional range of football boots, other athletic footwear types had to be considered to provide context to the experimental and simulated stiffnesses. Studies have reported that the natural foot is compromised by footwear (Bojsen-Møller and Lamoreux 1979; Lin et al. 2013; Kleindienst et al. 2005; Toon et al. 2009; Smith et al. 2012; Smith et al. 2014), with an approximated MPJ rotation of 25° based on the analysis of peak dorsi-flexion during walking and running in footwear (Bojsen-Møller and Lamoreux 1979; Lin et al. 2013; Kleindienst et al. 2005). During running, the torsion angle was reported to range between 6° inversion and 7° eversion when shod (Stacoff et al. 1989). Statistical analysis of elite match play in football reported up to 90.9% of activity involved walking and jogging (Withers et al. 1982; Ali and Farrally 1991; Mayhew and Wenger 1985), thus the ability of the models to simulate up to 80% of the approximated peak MPJ rotation and 100% of the torsional rotation range for a large proportion of boot loading, showcased the successful application of FEA techniques to predict boot mechanical function.

Limitations of the models were found, with bending stiffness representation accepted up to 20°, with a torsional range of 10° and -7.5°. Studies into sprinting performance reported a higher peak dorsiflexion in sprint spikes 42.3° ± 5.7°, 36.3° ± 5.1° and 31° ± 3° (Smith et al. (2014), Smith et al. (2012) and Toon et al. (2009) respectively). The impact of only predicting bending stiffness up to 20° meant that the high intensity sprint movements could not be simulated reliably. Whilst
infrequent, these fast movements are important in football match play, thus limiting the model when simulating bending stiffness. Factors such as material anisotropy, bond stiffness and strain hardening could further improve the accuracy of the modelling techniques.

The fundamental techniques developed to construct and predict mechanical properties of football boots involved the application of uni-axial tensile test data to generate adequate material models. The same material behaviour can be applied to both bending and torsional stiffness measurement models, thus reducing pre-processing time. However, limitations of this approach may be experienced when more dynamic movements are modelled, with quasi-static mechanical tests used in this research project to provide experimental measurement of physical boots.

The potential of using the FEA techniques reported thus far in this thesis could enable the evaluation of new concepts based on their predicted performance through models and simulations. With bending and torsional stiffness two properties associated with boot function, the models could be implemented into the design process as outline by Cheung et al. (2009). For the FEA techniques to be used within the design process, they must reliably predict boot function as well as reducing the costs associated with the iterative process necessary to manufacture physical prototypes. As detailed above, the models are able to predict bending and torsional stiffness for typical foot deformations for up to 90% of match-play, requiring approximately two days to prepare, with the simulated virtual assembly of constituent parts requiring 0.5 hours and simulating bending and torsion requiring 4 hours each using 10 CPUs. Therefore once the models have been set up after an initial preparation time, each iteration takes approximately 8.5 hours, demonstrating the potential time reductions associated with the design process. Whilst the implementation of FEA techniques into the design process would still require physical prototypes to be created and tested prior to the finalised product, a reduction in the number of iterations can be achieved. However from the initial concept design through to boot function simulations, user interaction is necessary, adding associated costs to the process. The potential of automating the modelling methods denoted in this thesis could add significant attraction to utilising FEA techniques within the design process.
7.6 Chapter Summary

This chapter has documented the successful application of mechanical testing devices to evaluate the predictive capabilities of the FEA boot model when measuring bending and torsional stiffness. With regards to objectives 1, 2 and 3, representative FEA models were created from the deformation mechanisms, fitted to the FEA boot model and assigned constraints and boundary conditions to simulate bending and torsional stiffness.

To address objective 4 and 5, bending and torsional stiffness FEA models were compared with experimental test measurement. Good agreement between the simulated outputs and experimental measurement were observed; bending stiffness was predicted within 20.1% of the calculated experimental mean up to 20° of rotation, whilst the computed torsional stiffness was within 17% of the experiment mean from 10° inversion to 7.5° eversion. Experimental measurement of two additional boots provided a range necessary to provide relationships between bending and torsional stiffness in football boots. The range created an upper and lower limit based on the standard deviation of the three boots, with the first 20° of MPJ rotation considered in bending and ±10° in torsion. The model was within 5.6% of the accepted range for bending stiffness and within the torsional stiffness range between 10° and -7.5°. Based on literature, approximate values for MPJ rotation of 25° and torsion ranging between 6° inversion and 7° eversion when shod were compiled and combined with statistical analysis of elite match play in football to suggest the applicability of the models. The models were able to simulate up to 80% of the approximated peak MPJ rotation and 100% of the torsional rotation range for a large proportion of boot loading, showcasing the successful application of FEA techniques to simulate boot mechanical function. However, MPJ rotation experienced during sprinting was beyond 20°, thus the modelling of sprint performance could not be achieved.

The FEA techniques demonstrated in this thesis have exhibited a valid principle to create a representative model to predict boot function through the measurement of bending and torsional stiffness. With these methods defined, consideration of how these techniques could be automated was necessary to demonstrate the potential of them being implemented within the design process.
Chapter 8:
Application of FEA Techniques to Simulate Boot Assembly and Mechanical Function

8.1 Introduction

With the context of this research project focused on exploring the potential of implementing FEA capabilities within the football boot design process, the development of techniques to automate the modelling workflow was necessary. Changing specific aspects of constituent parts prior to assembly and evaluating their impact on mechanical functionality of the boot has the potential to reduce development time and provide financial benefits. Automation of FEA techniques would require a modelling workflow to be established, in conjunction with developing methods to relate input parameters to simulated outcomes. Two case studies will provide insight into how constituent parts can be analysed when investigating boot function, demonstrating how the approach could be applied in football boot development.

8.1.1 Aims and Objectives

The aim of this study reported in the chapter was to develop a method to automate the modelling workflow from the assembly of constituent parts through to the evaluation of mechanical functionality. Relevant case studies will provide examples of the workflow framework applicability. To meet the aim, the following objectives were followed:

1. Establish a framework for modelling approaches developed within the thesis
2. Based on created the framework, develop techniques to facilitate the model workflow
3. Demonstrate applicability of framework through two case studies
8.2 Modelling Workflow Framework

Identical modelling constituents, such as material models and element types, applied to representative FEA models facilitated good prediction of both boot bending and torsional stiffness. The opportunity to automate the modelling processes to assemble and evaluate mechanical properties of boots could enable factors within boot design to be directly related to function. Furthermore, the potential to change specific parameters within the constituent parts and perform functional analysis on the assembled boot would provide quantifiable data to evaluate their impact on boot properties without needing to build physical prototypes. Thus, to address objectives 1 and 2 stated in the chapter aims, a workflow framework and relevant techniques to facilitate the automation of the modelling approaches developed throughout this thesis was required.

An approach was developed to combine python scripts and batch commands to automate the model generation, enabling parameters within the constituent components to be changed. Batch commands were used to execute both python scripts and the ABAQUS solver, thus a sequential execution would automate a single iteration. Consideration of both techniques was necessary in order to fashion a relevant framework.

Python scripts enable individual functions to be processed within ABAQUS CAE automatically, performing a series of tasks dependant on the modelling requirements. The script consisted of codes, each performing a specific task, to carry out the desired changes within a model, before writing an input file for execution by the solver. The initial script was created by performing the required tasks manually within the software, which writes a replay file (.rpy) consisting of python code to update the model file in the event that the software crashes. ABAQUS CAE then runs this script and performs the functions outlined. To facilitate this process, the configuration of the model file was necessary, with the individual components parameterised depending on the analytical objective. Whilst the replay file provided the core content of the script, amendments to the code were required. Within the script, individual parameters within the model could be changed, before the subsequent execution of the ABAQUS solver. Scripting techniques were used to export simulated outputs, such as bending moment.

Batch files permitted the sequential execution of commands, automating the process. Python scripts were executed without the graphical user interface (GUI), carrying out the required parametric changes before generating the input file. Execution of the input file using ABAQUS
Explicit solver would provide data through output database files (odb) with python scripting used to interrogate the file and export the relevant data based on the desired objectives.

With the combination of python scripts and batch commands demonstrating the potential to change inputs and quantify mechanical response of the boot, a workflow framework was established, displayed in Figure 8-1. The framework demonstrates a single iteration, with input parameters specified within the python script to prepare the constituent parts within the FE boot construction model. The process demonstrates the complexity of the workflow process, with analysis requiring three modelling stages to evaluate the constructed boot, but the expansion to five models is necessary when evaluating both bending and torsional stiffness. Whilst high initial user time associated to prepare the models and scripts for the framework, the level of analysis as a result of the automation capabilities would offset the initial cost.

Figure 8-1: Workflow Framework to automate a single iteration, linking input parameters applied to constituent parts with simulation outcomes from Boot Function Analysis Models.
8.3 Case Study: Changing an Internal Region within a Constituent Part

This case study aims to detail necessary modelling methods to facilitate the automated approach to simulated boot assembly followed by functional loading of the 3D boot model, providing quantitative results when applying the framework denoted in Figure 8-1, to answer the third chapter objective.

8.3.1 Introduction

Large upper deformation was observed during experimental measurement of bending stiffness in football boots, with buckling common across the forefoot region as reported in Chapter 7. Relative contribution of the upper to the entire boot at low angles of MPJ rotation suggested the potential influence pattern piece design could have on the simulated bending stiffness. With regard to the framework detailed in Figure 8-1, a method was developed to parameterise the pattern piece forefoot, changing the geometry of regions on the medial and lateral side of the forefoot, termed bands. Material applied to these banded regions remained constant throughout the iterations. Whilst the method specifically details the necessary steps required to change the band regions within the forefoot, the principle could be applied to any internal region of the constituent part.

Python scripts were utilised to change parameters within an existing model file, followed by constructing the model based on a sequential, predefined set of tasks. The process which the python scripts followed would be detailed, but the generation of an existing model in which the forefoot of the pattern piece could be changed was required first.

8.3.2 Methodology

Model Generation – Virtual Assembly

Band regions were generated by only applying partitioning techniques to the pattern piece forefoot, thus the rearfoot remained identical throughout the analysis. Figure 8-2 depicts the two regions to which bands were generated, with four lines aligned based on the relative orientation to two construction lines. Parameterising these four angles enabled them to be changed automatically using python scripts, enclosing the banded regions. For this analysis the pattern piece was split into two parts, the toe and rearfoot, as the latter would not change.
As detailed in the FE boot construction methodology (Chapter 3), superficial geometrical parts were included within the model from which attachment points were offset. This enabled the generation of wire features to which connector elements were applied. The benefit of such a process meant that wires were independent of the pattern piece components, thus for each iterative change in band geometry, wire creation was not necessary. This reduced the complexity of the script greatly. Figure 8-3 demonstrates the model with and without the pattern piece, thus showcasing how python scripts can easily import the constituent part and position it within the model space, aligning it with the wires for assembly.

An additional benefit of using attachment points involved the application of boundary conditions. FE boot assembly required a sequential application of loads and boundary conditions, essentially wrapping the constituent parts around the shoe-last by joining edge pairs. By prescribing
boundary conditions to the attachment points, and utilising tie constraints with the adjacent node in the pattern piece, any displacement of the attachment point would result in the pattern piece being moved. Loads were assigned to the connector elements, thus only importing the pattern piece to the assembly was required.

**Automation of Parametric Changes – Virtual Assembly**

With the band geometries governed by two lines with an associated angle, a python script was used to change the parameters once the model was opened through a batch command. The script was written to open the sketch module for the toe part and change parameters within the code. The specific angles were defined within apostrophes as highlighted in Figure 8-4, with these changed manually prior to script execution. These values were changed depending on the desired geometry of the bands. Once complete, the script included a function to regenerate the part, with the new band geometries defined within the part.

![Figure 8-4: Python Code (Right) generated when changing Band Angle.](image)

Validation of the FE constructed boot through bending and torsional loading highlighted the applicability of continuum shells within the upper. A method was developed within the thesis to create the multiple layering of elements, as described in Section 3.4, with this process involving a high level of user interaction; python scripts offered the opportunity to automate this process.

The two dimensional geometry of the toe part was used to build the continuum shell layers, with the mesh parts created based on a 2D surface mesh, extruding the layers dependant on the material thickness. Within ABAQUS CAE, elements are numbered individually within a part based on the total number. With the purpose of the case study to change the band geometry, fluctuation in the number of elements within the region would cause problems when extruding element layers and assigning sectional properties. Specific codes were used within the script to
account for the change in number of elements. Interrogation of the part using the code described in Figure 8-5 enabled to the number of elements within the part to be calculated.

```python
elemArr = mdb.models[modelName].parts[PartName_6].elements;
len(elemArr);
```

**Figure 8-5: Code required to calculate the number of elements within a part**

Replacing the number generated within the script with the variable “len(elemArr)” enabled the code to mesh all the elements within the part, even when the number changed between different band orientations. With layers extracted from an original 2D mesh, the element number varied by a factor related to the number calculated in “len(elemArr)” – the second layer of elements consisted of elements between len(elemArr) and 2*len(elemArr). As each layer was extruded, they were given sets, with each material type denoted by a specific name. Once all the components were created into a single part, the code was written to assign sections to set names. For example all synthetic leather material element layers were assigned the set name “SYN”, assigning the corresponding section to this set name.

**Figure 8-6: Model Assembly Without (Left) and With (Right) Pattern Piece Imported and Aligned.**

The completed pattern piece was imported and aligned with the other components within the model assembly (Figure 8-6). As the new pattern piece had the same number of nodes along the perimeter edges, attachment points were tied to these nodes. Sets were used to automate the process, with all the nodes within the pattern piece used within the tie constraint. A small search tolerance was used (0.001mm). Boundary conditions and loads required to virtually manufacture the components were assigned to elements within the model prior to the inclusion of the pattern piece. This modelling approach meant that only the generation of the pattern piece component
was required before the simulation was executed. The virtual assembly method resulted in the formed boot, shown in Figure 8-7. The method described how internal regions within constituent parts can be changed by partitioning the sketched geometries as two-dimensional components using specific parameters.

![Figure 8-7: Virtually Manufactured Boot; Different Band Orientations for Formed Boots.](image)

**Model Generation and Automation – Bending Stiffness Simulation**

As described when simulating bending and torsion, mechanical feet were fitted to the FE boot model. Python scripts were used to automate these stages, described in Section 7.2. Two models were configured, one to fit the deformation mechanism, and a subsequent model to simulate bending stiffness. Whilst these models applied different boundary conditions, they both involved importing deformed geometries as parts, thus a generic script was written. Model generation ensured that the only necessary changes to the model involved importing the deformed boot geometry and assignment of materials. Boundary conditions, loads and constraints were applied to sets created in the virtual assembly model.

**8.3.3 Application**

Batch file commands were used to sequentially execute commands to automate the necessary stages to change the four angle parameters which define the band geometry, through to computing bending and torsional stiffness. This example denotes three different scenarios, with the respective band geometries defined in Figure 8-8.
Figure 8-8: Angle Dimensions for Band Geometries.

The automated approach led to the three sets of angles added to python scripts, generating the different band geometries as displayed in Figure 8-9. TPU material was applied to the top layer of the band region, with a synthetic leather layer beneath.

Figure 8-9: Band Geometry within Pattern Piece; Band Geometry 1 (a), 2 (b) and 3 (c).

Execution of the virtual manufacturing model created the formed boots shown in Figure 8-10. The automated process to create these geometries resulted in three different upper geometries, demonstrating how the principle was applied to investigate specific parameters within the upper.
8.3.4 Results

History and field outputs were extracted from the model using python scripts, providing the bending stiffness outputs as text files for subsequent graphical analysis, as displayed in Figure 8-11. Images at two angles were exported, with the deformation plotted as both the deformed state and with maximum principal strain (Figure 8-12 and Figure 8-13 respectively).

Figure 8-11: Computed Bending Stiffness for the first 20° of MPJ Rotation with 3 Band Geometries.
The model predicted that changing the banded regions of the three iterations detailed in this case study would only result in less than 5% difference in bending stiffness up to 20° of rotation. Whilst the results were small in magnitude, the significance of stiffness on player performance would be necessary to state their impact. Differences were observed in the magnitude of surface deformation (less than 2% strain), as a result of the banded regions as demonstrated in Figure 8-13, but general gradients were common. The results suggest that whilst these banded regions can influence the levels of material deformation experienced across the forefoot, the mode of deformation remained consistent. With the bands all located within the buckling zone observed through both modelling and experimental measured of physical boots, the impact on bending stiffness was low.
Figure 8-13: Maximum Principal Strain at 20° of MPJ Rotation for 3 different band geometries.

8.3.5 Summary

The aim of this case study was to demonstrate how the framework can utilise a workflow framework, applying bespoke scripting techniques to change parameters within the constituent parts, simulate assembly and perform functional analysis to provide quantifiable results. Whilst the forefoot region was highlighted to potentially impact the deformation of the boot during bending, of the three geometries used to demonstrate the methodology, only small differences were measured in terms of boot stiffness and surface deformation.
8.4 Case Study: Functional Analysis of Changing Last Geometry

This case study will look to utilise the automated framework to change an alternative constituent part (the last), to provide quantitative results to showcase a different application of the methodology detailed and demonstrated in Section 8.2 and 8.3 to answer objective 3.

8.4.1 Introduction

Generally constructed from high-density polyethylene, shoe-lasts can influence the fit and comfort as well as the finished design of footwear (Luximon and Luximon 2009); essentially, the last acts as mould, defining the overall shape of the shoe. It has been stated that the shoe-last is a limiting factor in the mass-customisation of footwear, with experienced shoe last designers creating new master shoe-lasts by modifying existing lasts based on the desired fit and style of the shoe (Luximon and Luximon 2009). Comfort of footwear is an important shoe property; boot comfort was reported to be the most desired property by players (Hennig and Sterzing 2010). Mass customisation of footwear is a concept aimed at providing consumers with bespoke shoes fitted to their foot, avoiding potential discomfort that a mass produced shoe may result in. Digitising the master shoe-last, commercial software is used to enable size changes and grading but adjusting the overall geometry within the software is limited (Luximon and Luximon 2009).

Figure 8-14: Last geometry change based on static foot scan - Taken from Luximon and Luximon (2009).

Studies have detailed algorithms to build lasts from static foot scans (Hwang et al. 2005; Luximon and Luximon 2009; Wang 2010), splitting the foot into multiple segments to which a virtual shoe-last geometry is generated. Software developed through scientific research into virtual simulation of footwear comfort has demonstrated fitting virtual representations of footwear to representative scan data of human feet (Rupérez et al. 2010). The principle to construct and functionally analyse boots through FEA models could be applied to this scenario, by creating the FEA boot model based on different last geometries and exploring its respective influence on boot function.

8.4.2 Methodology

Generally mass produced footwear is grouped into arbitrary sizes, based on the length of the foot. With this in mind, the last width was varied by ± 10% along its length within SOLIDWORKS CAD software, creating two geometries to emphasise a potential influence; termed narrow (-10%) and
wide (+10%). Height and length of the last was kept constant with respect to the original. The three lasts were displayed in Figure 8-15. These lasts were exported from SOLIDWORKS as IGES surface files, before being meshed in HYPERMESH. Tetrahedral rigid elements were assigned to the representative lasts.

![Figure 8-15: Width Adjustment of Last; Narrow (Left) Original (Middle) and Wide Last (Right).](image)

Virtual assembly involved the same modelling approach detailed in Chapter 3. The alternative lasts were imported into ABAQUS and aligned with the original. The existing modelling constituents remained the same. The magnitude of surface deformation was displayed in Figure 8-16. As expected, the width of the last affected the level of deformation experienced in the pattern piece as a result of boot assembly. With consideration to the results displayed in Figure 8-16, the ability to simply replace the last with an alternative demonstrated the versatility of the model, as well as the potential to use the FEA techniques to investigate the impact of customisable lasts on material behaviour during manufacture.
Figure 8-16: Maximum principal strain measured through FEA Construction Model; Narrow (Top), Original (Middle) and Wide Last (Bottom).

8.4.3 Results

With the FE boot model constructed from narrow and wide lasts, the framework was followed to quantify the bending and torsional stiffness of the boots, indicating the potential impact the last width has on boot function. Bending stiffness was only analysed across the first 20°, whereas torsional stiffness was analysis between -10° and 10°.

The model predicted mechanical properties of football boots would be influenced by the width of the last, with greater differences measured in torsional stiffness (Figure 8-17 and Figure 8-18).
The width of the boot was defined by the last geometry, which was shown to affect the mechanical properties of the boot. In bending, changing the width both positively and negatively resulted in increases in bending stiffness; mean increase of $35\% \pm 6.6\%$ and $8.2\% \pm 3.1\%$ during the first 15° of rotation for the narrow and wide lasts respectively. However in torsion, the effect was far greater, with the boot geometry changing the level of stiffness in eversion than in inversion (Table 8-1).

<table>
<thead>
<tr>
<th></th>
<th>Narrow Last</th>
<th>Wide Last</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inversion</strong></td>
<td>22% $\pm$ 5%</td>
<td>-21% $\pm$ 13%</td>
</tr>
<tr>
<td><strong>Eversion</strong></td>
<td>61% $\pm$ 15%</td>
<td>-57% $\pm$ 5%</td>
</tr>
</tbody>
</table>

*Table 8-1: Percentage difference between Narrow and Wide Last in Torsion with respect to Normal Last.*

These predicted results demonstrated that the shape of the boot relative to the mechanical foot would influence the stiffness. Therefore the fit of the boot (relationship between the respective
geometry of the boot and foot) could influence the way the boot performance during bending and torsion.

8.4.4 Summary

The width of the last constituent part was changed to investigate the potential of customising lasts to improve fit between the foot and boot. The framework established in this chapter again facilitated the simulation of assembly and boot stiffness. The predicted results extracted from the simulations suggested that changing the width of the boot would change the boot properties with respect to the original last. Whilst the stiffnesses measured in this analysis cannot be related to player performance due to limited published data, the magnitude of these differences suggests the consideration on the overall geometry of the boot must be considered, especially with regards to customisation of footwear.
8.5 Application within the Design Process

The methods described in this thesis document a novel approach to use FEA techniques to evaluate mechanical properties of a virtual prototype, directly relating input parameters with measurable outputs. With athletic footwear construction reported to influence performance and injury risk (Stacoff and Reinschmidt 2001; Stacoff et al. 1996; Stuessi et al. 1989; Reinschmidt and Nigg 2000; Hintermann and Nigg 1998; Sandrey et al. 2001; Stefanyshyn and Nigg 1998; Stefanyshyn and Fusco 2004), evaluation of mechanical properties during the conception of new products offers feedback earlier in the product development cycle, potentially reducing development costs and lead times. Furthermore, integration of the framework detailed in Section 8.2 within the design process could potentially change the traditional paradigm associated with product creation, using computer simulation to drive the design process. As opposed to existing product development processes which create physical prototypes prior to functional testing, modelling techniques such as Design of Experiments would predict the influence of input parameters on mechanical performance, informing and identifying targets which footwear developers can use, such as sourcing materials with specific properties. With mechanical properties of the shoe defined, this approach could redefine the design process, using virtual prototyping to reduce lead times associated with the iterative approach currently used.

Whilst precise mechanical properties of the boot have not been defined in published literature, the significance of athletic performance variation due to the shoe construction is an important consideration. Investigation into sprint performance and the bending stiffness of sprint spikes demonstrated that whilst an average increased in sprint time was observed, performance varied across the athletes, suggesting that personalising the mechanical properties of individual’s footwear could have further improved athletic performance (Stefanyshyn and Fusco 2004). Incorporating the developed automated techniques, the constituent parts can be parameterised, creating a template in which specific features within the design could be adjusted, changing the mechanical properties of the full shoe, enabling the stiffness to be tuned to the athletic requirement of the individual. With constituent parts modelled using manufacturing patterns, geometries and materials, the specific parameters can be extracted from the model and directly fed into manufacture, enabling sporting goods manufacturers to offer individuals personalised footwear to meet their functional requirement; a feature that could provide a competitive advantage in a highly competitive market.
8.6 Chapter Summary

A workflow framework was reported in this chapter, combining python scripting techniques and batch commands to automate the construction and subsequent testing of FEA boot models, addressing objectives 1 and 2. Two case studies demonstrated the benefits of using the framework, with internal regions of the pattern piece and width parameter of the last highlighting how input parameters can be related to measured outputs. Banded regions within the forefoot were predicted to have a 5% difference in bending stiffness up to 20°. Changing the last width by ± 10% resulted in a predicted mean increase of 35% ± 6.6% and 8.2% ± 3.1% during the first 15° of rotation for the narrow and wide lasts respectively, with torsional stiffness increasing due to a narrow last and reducing due to a wider last. These results suggested that the fit of the boot could influence the mechanical properties during player movements.

The established framework details the extent to which predictive simulation techniques can be used to inform product development decisions during initial creation of new concepts, offering an alternative to the traditional paradigm associated with athletic footwear creation. Furthermore, the predictive techniques can provide target metrics for factors associated in footwear manufacture such as material properties to ensure the required mechanical response is met. With athletic performance reported to vary in humans due to the mechanical properties of the shoe (Stefanyshyn and Fusco 2004), computer simulation techniques can be used to adjust parameters within the constituent parts to enable the mechanical properties of the shoe to be tuned to the individual, potentially improving athletic performance. The modelling approach reported within this thesis provides a potential alternative to the current design process associated with athletic footwear development.
Chapter 9: Conclusions

The FEA techniques documented in this thesis have facilitated the construction of a representative three dimensional football boot model from constituent parts associated with physical manufacture. Virtual representation of manufacturing patterns, geometries and materials were integrated into the model, with isotropic hyperelastic and elastic material models generated by capturing their physical properties through experimental testing. Analytical processes enabled the most applicable element type to be applied to the constituent parts; continuum shell elements were used to model the upper parts, whilst tetrahedral continuum solid elements were applied to the outsole part.

Simulated assembly of these constituent parts required the development of FEA methods, involving the creation of edge pairs through partitioning techniques. Wire features provided links between the respective node pairings, to which axial connector elements were assigned, joining the associated nodes. Sequential application of boundary conditions and loads simulated the assembly process, forming the three dimensional geometry around the shoe-last. Excellent geometrical agreement was exhibited between the assembled FEA boot model and the physical equivalent, with 93.4% of their outer surface within ± 2.75 mm.

New methods were developed to assess physical boot manufacture, with digital image correlation hardware and software used to experimentally measure surface deformation of the pattern piece constituent part throughout production. Substantial surface deformation during forefoot assembly of the upper component was demonstrated, with up to 25% strain reported in the toe box region. Good correlation between the simulated and physical manufacturing of football boots verified the predictive capabilities of the FEA assembly methods. Contrary to the surface deformation reported during forefoot assembly, the preparation stage during boot manufacture (where raw materials were formed into the constituent parts) had the greatest influence on material behaviour, with experimental measurements reporting material stiffness reduction to 22% of the raw material behaviour. This demonstrated the need to capture material behaviour once the constituent parts had been formed and was incorporated into subsequent models.

Bending and torsion were identified as two boot functions, with their respective stiffness reported to be important regarding performance and injury reduction in athletic footwear design. Mechanical test devices were used to provide comparable experimental measurements of the physical equivalent, with the development of a bending stiffness experimental testing rig, whilst
torsional stiffness was measured using an existing test rig. Digital Image Correlation hardware and software was used to quantify surface deformation during torsion, whilst a novel method was created to capture the buckled deformation during forefoot bending. With large deformation observed, a handheld scanner was introduced to capture three dimensional point cloud data of the upper during bending, with an algorithm used to quantify the angle of curvature to provide comparative data with the simulated output.

FEA modelling of boot bending and torsion based on the mechanical test devices enabled predictive simulations to capture both the respective stiffness and deformation response, with general trends between experimental measurements and simulated outputs reported. Bending stiffness simulation was within 20.1% of the experimental mean measurement of the physical equivalent up to 20°, with good agreement reported between the deformation locations. Torsional stiffness simulation was within 17% of the experiment mean from 10° inversion to 7.5° eversion, with good correlation between surface deformations except at 10° inversion. The model was unable to represent bending stiffness beyond 20° and torsional stiffness between 7.5° and 10° eversion.

Limited published data regarding football boot stiffness resulted in the capture of two additional boot types, creating an accepted range to determine the significance of the developed models and simulations. An accepted range was created by taking the top and bottom value of the standard deviation captured from experimental measurement of the three boots for each stiffness segment. In bending up to 20° the simulated stiffness was within 5.6% of the accepted range, whilst in torsion the simulated stiffness was within the accepted range between 10° inversion to 7.5° eversion. During match play, up to 90.9% of player activity has been reported to be low intensity movements, with kinematic studies of running footwear used to compile levels of bending and torsional rotation; an approximated peak MPJ rotation of 25° and torsion angle ranging between 6° inversion and 7° eversion. Based on these values, the model was able to represent 80% of bending and 100% of torsion during a large proportion of match play. However sprint performance, an important factor in a game for the player to find space to dictate play, was reported to require a greater MPJ rotation (up to 42.3°) a factor the model could not represent.

The development of valid FEA techniques to represent the physical equivalent within a specified tolerance related to functional performance demonstrated the potential of the modelling and simulation techniques within the design process. Case studies demonstrated the automation of the modelling process, with the overall goal to relate input parameters with simulated outputs. In accordance with a workflow framework, python scripts and batch commands facilitated the
application of the novel modelling techniques reported throughout the thesis, changing specific parameters, followed by the simulated assembly process prior to load and deformation response of the model automatically. The two case studies demonstrated the potential of using the technique within the design process, providing a predictive insight into the impact concepts may have on the finalised product. The application of the developed techniques has demonstrated the potential to provide target metrics associated in footwear manufacture directly with athletic performance through the mechanical response of the shoe. With variation in the mechanical function of shoes in humans, the techniques can predict necessary adjustments to the constituent parts to change the properties of the shoe to meet an individual’s needs, with the potential to improve athletic performance.

This thesis is the first to report the assembly of a representative FEA football boot model, constructed from constituent parts based on manufacturing patterns, geometries and materials. Documentation of a novel method to capture and quantify the surface deformation through manufacture of a football boot provided comparable data with the modelling assembly process as well as insight into the influence production has on material behaviour. A bespoke experimental testing device to measure bending stiffness was developed and built, with a novel method used to capture deformation of the upper during buckling to provide comparable data with the FEA simulations. Modelling methods were developed to import the assembled boot, apply relevant constraints and simulate boundary conditions for outputs to be extracted and compared with experimental measurements for model verification. Automation techniques were developed to link the multiple modelling stages to investigate the impact input parameters within constituent parts have on simulated outputs to assess mechanical performance of football boots.
Chapter 10
Further Work

The FEA methods reported within the thesis have been successful at predicting boot stiffness up to 80% of the MPJ rotation in bending and 100% rotation in torsion, for typical loading up to 90.9% of game related activity for a single boot. However the model was not able to predict bending stiffness beyond 20°, thus sprint performance could not be evaluated. To explore this and further strengthen the techniques developed in this research project, the following future work was suggested.

10.1 Additional Validation of Techniques

The modelling approaches documented within the thesis only considered a specific boot type in order to investigate the potential of using FEA techniques to predict mechanical function. With an established technique, application of the developed methodology to other boots would provide further verification of the usefulness of the approach.

10.2 Further Development of Modelling Techniques

Encompassing sprint performance within the model by representing bending stiffness beyond 20° would require further FEA technique development. Expanding on the developed FEA techniques could provide a modelling methodology to account for this. Improving material model definitions by including such as strain hardening and anisotropy properties (where modelling element permits), are factors that require further investigation.

10.3 Influence of Bending and Torsional Stiffness on Playing Performance

Both experimental tests and modelling techniques reported in this thesis facilitated the measurement of bending and torsional stiffness. However, with limited published data on boot stiffness and player performance, the results computed in this work could not be calibrated. Capturing the influence these properties have on performance with quantifiable results would provide context to the experimental measurements and simulated outputs further evaluating the potential of the FEA techniques developed within this research project. With identified boot stiffness properties, the methods described in this these could be used to virtually optimise design parameters based on athletic performance requirements, which can be fed directly into the manufacturing process to create bespoke footwear for individuals.
10.4 Representative Loading Conditions

Predictions of bending and torsional stiffness were based on quasi-static experimental tests within this research project. To further investigate the potential of FEA techniques, quantifying the model with respect to more representative loading conditions such as the dynamic foot strike could be beneficial. Incorporating techniques demonstrated by Hannah et al. (2012) to model the footstrike using biomechanical human test data, representing the full shoe construction to evaluate its mechanical properties under dynamic loading.

10.5 Evaluation of Boot Geometry on Human Foot Anatomy

Further development of modelling approaches combined with the ability to capture three dimensional data points of human feet would enable virtual evaluation of static fit, as detailed in Figure 10-1. With boot comfort an important property of a boot demanded by athletes (Hennig 2011), this concept has the potential to identify regions of the boot that could cause discomfort. In conjunction with the modelling framework developed in this thesis, there is a potential to use the predictive computer simulations techniques to define parameters within manufacture to personalise the shoe to an individual’s foot.

Figure 10-1: Concept to Evaluate Contact between the representative boot model and human foot; Contact pressure map identifies potential sources of discomfort due to boot fit (Right)
Chapter 11:
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