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A Study of Football Footwear Bending Stiffness

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Abstract

For the past century, football boots have constantly changed, with new designs and materials being developed by sporting goods manufacturers to meet player demands. Investigating the effect of such changes on performance was important to further develop football boots. Bending stiffness has been demonstrated as an important performance parameter in running footwear; a concept with potential to investigate football footwear. As football boots consisted of an upper and an outsole, with the latter being manufactured from a far stiffer material than the upper, it could be speculated that the outsole limits the boot's flexibility. The aim of this paper was to create a testing device to quantify whether the whole shoe needed to be considered when designing football boots. The test device consisted of a simplified foot based on biomechanical factors linked to an Instron machine to quantify the load during bending. The bending stiffness of the uppers and boots were found to be non-linear, highlighting the need to specify the angle at which the stiffness was recorded. The upper was shown to have a significant effect on the bending stiffness of the overall boot construction, whilst different upper constructions were shown to affect the bending stiffness. With regard to the findings in this paper, it was concluded that the upper was an important consideration in boot design.

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Upper; Boot; Football; Footwear; Bending Stiffness; Testing Device

1. Introduction

Football boots have evolved in the past century, transforming from ankle-high steel-toe capped boots to

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footwear weighing less than 200grams (Soar and Tyler, 1986). With a competitive market, manufacturers constantly change football boot design in order to meet player demands. As these designs change, it was important to quantify their effect on performance parameters. The modern day boots consist of two major components; the outsole and the upper, designed to protect the foot without inhibiting performance (Hilgers and Walther, 2011). Functionally, the outsole provides an intermediate surface between the foot and ground as well as allowing the foot to flex during movements. Generally the upper's main role is to encompass the foot, holding it against the outsole.

Examination of the football boot components during a game allowed a greater understanding of their function. The role of the boot can be split into two distinctive classifications; player movements and boot-ball contact. Player movements in football occur constantly during a game; the majority of movements tend to be low intensity actions, such as walking, with short bursts of high intensity movements types such as sprinting (Hennig and Sterzing, 2010). However, boot to ball contacts last for a shorter period of time when compared to player movements. Both these classifications have led to the development of football footwear. Research into football uppers has mainly focused on the boot to ball interaction. Pressure gradients have been researched, investigating its effect on ball accuracy and velocity when changing the upper's dorsal surface (Hennig *et al*, 2009). With advances in material selection and manufacturing processes, different outsole constructions have influenced boot flexibility (Lees, 1996). However, the influence of the upper during typical game related movements has remained relatively unknown. Park *et al* (2007) highlighted that, when looking at running shoes, the whole shoe construction needed to be considered during the measurement of bending stiffness, not just the stiffness of the midsole. Importantly, the influence of the upper needed to be considered when designing football footwear.

To investigate the influence of the upper on the whole boot, a parameter was required. Bending stiffness has been identified as an important performance parameter in running footwear (Park *et al*, 2007). In sprinting, Toon *et al* (2011) showed that performance improvements were possible by changing the mechanical properties of the shoe. During walking, it has been documented that a greater level of flexibility in the footwear allows a greater range of motion and power generation of the ankle joint during walking (Cikajlo and Matjačić, 2007). As a result, it was logical for bending stiffness to be applied to football footwear.

To quantify the bending stiffness, the approach was taken to develop an initial, laboratory based, simple mechanical device to test the footwear. The role of the device was to investigate whether the upper affected bending stiffness of the whole boot construction, highlighting whether the upper needs to be considered when designing football boots. Furthermore, it was of interest to examine whether different uppers constructions affected bending stiffness. This paper detailed the development of the testing device, based on the identification of factors during running. A methodology and testing protocol was documented, relating bending stiffness for upper and boot constructions.

2. Novel Testing Device Development

A testing device was required to quantify the bending stiffness of different upper and boot constructions. Measuring the bending force was an important factor in the test design, thus a bespoke frame of rigid structure was manufactured. The frame was assembled around an Instron 3365 machine - typically used to measure the force output during uniaxial tensile tests. The foot geometry was required to constrain the footwear, based on the deformation mechanism of the human foot during linear running.

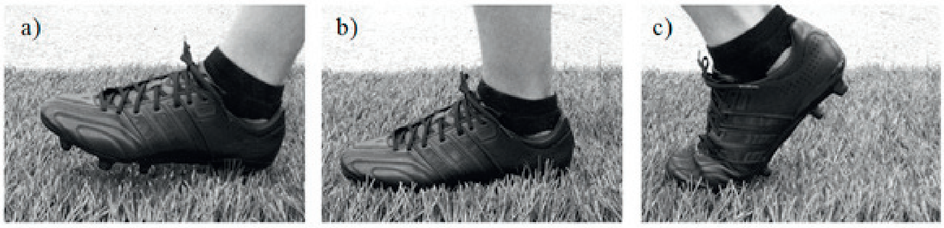

Figure 1: Three stages of the stance phase; a) Heel Strike, b) Midstance, c) Toe-off

To understand the deformation mechanics during linear running, high speed video analysis demonstrated that upper deformation in the forefoot region was prominent during toe-off phase of human gait (Figure 1). Rotation of the rear foot around the metatarsophalangeal joint (MPJ), occurs during toe–off. The MPJ is located between the metatarsal bones in the foot and the proximal bones in the toes. The toe-off phase itself can be split into two phases; digitigrade and unguligrade (Bosjen Moller and Lamoureux, 1979). The digitigrade phase involved rotation around the lateral metatarsophalangeal joint (MPJ) axis up to 60 degrees, with the toes remaining fixed to the floor whilst raising the heel. Unguligrade phase had 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). For high intensity movements, such as sprinting, the MPJ will rotate around the transverse axis, located between the first and second metatarsal heads (Bosjen Moller, 1978). During human gait, a passive function allowed the stiffening of the foot, known as the Windlass effect (Hicks, 1954). This phenomenon tensions the midfoot region.

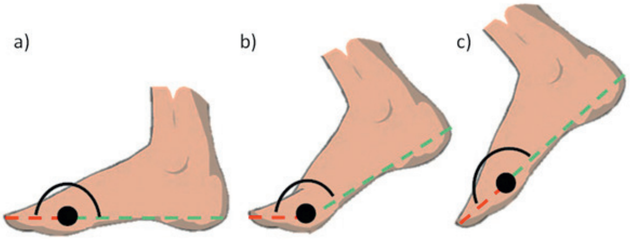

Figure 2: MPJ Extension during Toe-Off; a-b: Digitigrade Phase, b-c: Unguligrade Phase

Based on the foot deformation mechanism, a simplified foot for the testing device was created. The rearfoot was assumed to be rigid due to the Windlass effect (Hicks, 1954), which led to the foot being manufactured from a shoe last to ensure the geometry didn't change during operation. The main mechanism observed during the digitigrade phase involved the rearfoot being rotated about the MPJ axis. Only rotation around this joint was allowed, which meant that the MPJ axis was important when creating the foot. Krumm *et al* (2013) documented a study involving 6000 scans, locating the MPJ axis at 73% of the foot length from the heel at 20^0. Other studies have the MPJ axis at 12^0 (Hillstrom *et al*, 2005). In this paper, MPJ axis was assumed to be at approximately 12^0 located 73% of the foot length from the heel (Figure 3).

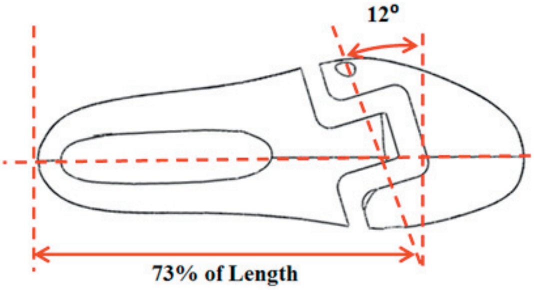

Figure 3: Outline of Foot Geometry for Testing Device

The bespoke frame attached to the Instron 3365 machine and used to quantify the loading profile during operation. Other devices used to test bending stiffness in footwear bend the toe and fix the heel [Krumm *et al* (2013), Hillstrom *et al* (2005)]. As shown in Figure 1, forefoot buckling in the upper was observed during toe-off, which led to the device raising the heel rather than flexing the toe. A cable and pulley system was used to integrate the foot's heel to the load cell, with the toe being held fixed. To ensure the forefoot remained fixed during operation, two screws attached the toe against a rigid plate, enabling different footwear types to be tested. The rigid plate was then constrained to the main frame. When testing uppers, holes were removed from the lasting board to allow attachment from the rigid plate into the toe. When testing the boot construction, holes were drilled through the studs in the first stud-row, and attached directly into the toe, clamping it against the rigid plate. Other testing devices for footwear bending stiffness allowed bending angles of 30^0 (Krumm *et al,* 2013) to 55^0 (Hillstrom *et al*, 2005). The device in this paper was allowed to flex to 50^0, which was within the angular change experienced in the digitigrade phase of toe-off.

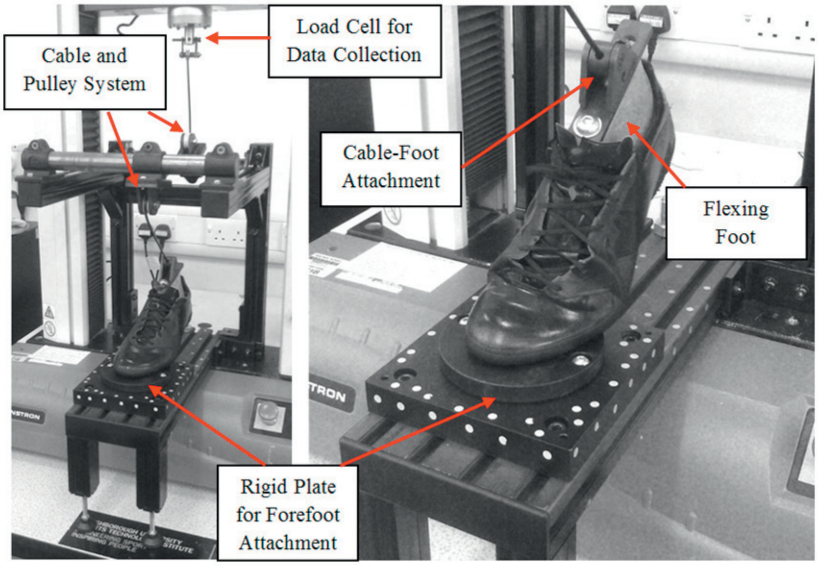

Figure 4: Testing Device Set-up for Upper/Boot Bending Stiffness Analysis

3. Methodology

3.1. Testing Procedure

The operating procedure started with fitting the foot within the boot/upper. The toe was positioned within the shoe to allow the attachment to the toe plate. Importantly, the lacing was kept consistent for all tests. The same lace was used for all the tests, with white marks placed on the lace at the point that it went through each eyelet. During the testing, the foot was aligned to ensure that the load was applied perpendicular to the MPJ axis. The initial foot position was kept consistent for all tests. The cable was then fed through the pulley system and attached to the load cell. The Instron load cell set-up involved a simple linear displacement profile. MPJ extension of the foot was observed as the load cell was vertically displaced, recording the force/displacement profile. No separation between the upper collar and rearfoot was observed during operation. Geometric calculations were required to determine the bending moment of the shoe during MPJ extension (Figure 5). The bending moment required to drive the foot when unshod was subtracted from the test data for boot and upper constructions. Three different upper constructions were tested (Upper A, B and C). Each of the upper types varied in material selection and design. The relationship between the bending stiffness of the full boot and upper construction was evaluated by testing Upper A and Boot A. Boot A consisted of Upper A glued to an outsole to allow the effect of the upper during bending to be evaluated. Three specimens of each upper/boot were tested.

3.2. Calculations

The purpose of the mechanical device was to quantify the bending stiffness of different football boot constructions. The load cell recorded a force displacement relationship between the force required to bend the shoe and the cable displacement. A series of calculations related the cable displacement to the MPJ angle, using measurements taken from the testing device (Figure 5). Assuming that the cable remained strain free and no frictional effects at the pulleys, the displacement of the Instron machine was equal to the cable displacement ***(h)***, which corresponds to a Load ***(L)*** calculated by the load cell. The load was applied perpendicular to the MPJ axis. As the rearfoot was rigid, the distance ***(d)*** remained constant throughout operation. The angle between the 1st pulley and the cable attachment ***(θ)*** changed as the heel was raised, meaning the subsequent moment was affected ***(Eqn. 1)***. For each value for MPJ rotation, the resulting θ was calculated. Therefore a relationship was developed to calculate the bending moment and angle of MPJ rotation. The bending stiffness was defined as the bending moment divided by the angle of MPJ rotation.

$$M = F.d = L.\cos\varphi .d \qquad \text{[Eqn. 1]}$$

a	Horizontal Distance between 1st Pulley and MPJ
b	Horizontal Distance between MPJ and Cable attachment
c	Horizontal Distance between Cable and 1st Pulley
d	Distance between MPJ and Cable
e	Vertical Distance between Cable and 1st Pulley
f	Vertical Distance between MPJ and Cable
g	Vertical Distance between MPJ and 1st Pulley
h	Cable Distance Between attachment and 1st Pulley
θ	Angle between horizontal and cable attachment
β	Angle between cable and the horizontal
φ	Angle between the cable and perpendicular to d
L	Load

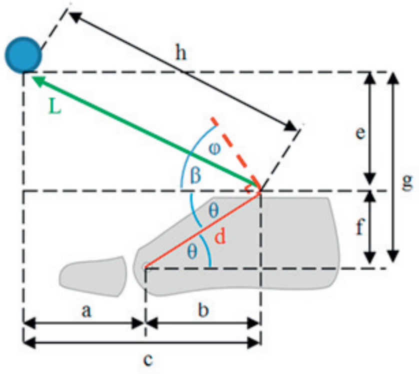

Figure 5: 2D Free Body Diagram for Foot Flex Calculations (Right) with nomenclature (Left)

4. Results and Discussion

Non-linear behaviour between the bending moment and MPJ extension highlighted that bending stiffness must be approached with caution in football footwear (Figure 6); the angle of flex must be specified when discussing the bending stiffness. From the test data, the upper was observed to have a significant effect on the bending moment when compared to the boot (Figure 6). Upper A was used as an example to generate the comparison (*Boot A* consisted of the same upper type as *Upper A*, with the boot including the outsole). These results would agree with the statement by Park *et al* (2007) that the whole shoe construction needs to be considered when measuring bending stiffness in footwear.

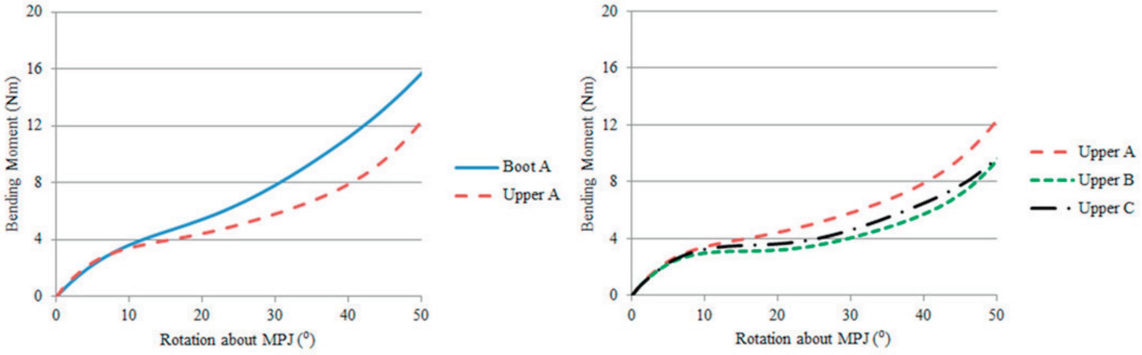

Figure 6: Upper Bending Stiffness Comparison (Left), Upper and Boot Constructions Bending Stiffness Comparison (Right)

As the upper had been shown to significantly affect bending stiffness with regard to the whole boot, it was important to examine this parameter for different upper constructions. The bending stiffness at two angles for all three uppers was shown in Table 1 and loading profile shown in Figure 6. It was apparent that the uppers had an effect on the footwear's bending stiffness. The differences between the bending stiffness of the uppers and non-linearity could be related to the material and design. However it cannot be concluded from this paper the effect each of these have. A further investigation to quantify the role material selection and design had on upper bending stiffness was required. Whilst it has been shown in other studies that bending stiffness was an important parameter in footwear (Park *et al*, 2007), there was a limited knowledge on how the parameter affects performance in football. However, the paper has shown the upper is an important consideration in boot design, proven by the variation in bending stiffness of different upper constructions, which has been shown to influence the entire boot's flexibility.

Table 1. Bending Stiffness of Uppers at 20⁰ and 40⁰.

	Bending Stiffness at 20⁰ (Nm/⁰)	Bending Stiffness at 40⁰ (Nm/⁰)
Upper A	0.215±0.012	0.198±0.002
Upper B	0.174±0.011	0.163±0.007
Upper C	0.153±0.008	0.143±0.004

5. Conclusions

The upper was found to be an important consideration in boot design. Non-linearity of the bending stiffness of both the boot and upper constructions during operation required the bending angle to be specified. In addition to the significant effect of the upper on the boot's bending stiffness, the upper constructions were shown to affect the bending stiffness.

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