Development of an end-effector to simulate the foot to ball interaction of an instep kick in soccer

Samuel Fraser*a, Andy Harlanda, Patrick Donovana, Laura O’Sheaa

“Sports Technology Institute, Loughborough University, Loughborough, LE11 3QF, UK

Accepted 02 March 2012

Abstract

Mechanical simulators are used to simplify the human kicking motion to provide repeatable contact between the end-effector and ball. The aim of the study was to examine the feasibility of using an ankle joint capable of simulating the plantar flexion deformation mechanism experienced by the human foot during the interaction with the soccer ball. A foot geometry was used to allow soccer boots to be fitted to the end-effector with a semi-bonded bush bearing to act as the ankle joint. The bearing provides a torsional resistance to radial loading, returning the foot to its starting position after the foot and ball impact. High speed video analysis using the GOM PONTOS system created three dimensional data points from markers placed on the end-effector, resulting in the relative rotations being quantified. Similarities between the plantar flexion mechanism in human kicking and the end-effector were observed, with a greater magnitude experienced by the end-effector. The end-effector provided repeatable foot rotations when struck with different initial foot velocities. The study concluded that a semi-bonded bush bearing can be used as an ankle joint to create repeatable contact between a foot geometry and a soccer ball. By increasing the bearing stiffness, the plantar flexion angular displacement can be reduced to levels experienced in human kicking.

1. Introduction

During a soccer game, the foot is used to strike the ball with varying speeds and techniques to achieve different ball velocities and spin rates, altering the resulting soccer ball trajectory. The instep kick is a complex technique, evaluated by a number of studies to quantify the relative displacements and velocities...
of the lower leg during the kick [1-6]. The contact between the foot and ball is influenced by a range of variables. Lees [1] developed a relationship between the ball velocity ($V_{ball}$) after contact and the initial foot velocity ($V_{foot}$) before contact based on work by Plagenhoef [2]. In the equation, $M$ is the effective striking mass of the leg, $m$ is the mass of the ball and $e$ is the coefficient of restitution.

$$V_{ball} = V_{foot} \left( \frac{M + m}{M} \right) (1 + e)$$

The foot velocity is altered by the player before contact, with research proving powerful kicking at impact results in differing ball velocities [3]. The term $(M+m)/M$ relates to the muscles involved in the kick, and their strength at impact [1]. The $(1+e)$ term relates to the rigidity of the foot at impact [1]. At impact, the dorsal region of the foot contacts the ball, resulting in forceful rotation around the ankle joint, leading to a loss of energy from the foot to the ball [1]. Once the ankle joint reaches its maximum angle of rotation, the metatarsophalangeal joint deforms [1]. Earlier studies described the dominant deformation mechanism of the ankle joint as forced plantar flexion of the foot [4,5]. Shinkai et al. [6] investigated the multi-axial rotation of the foot around the ankle joint during an instep kick using two cameras with an optical angle focused at the point of interest, to create a three dimensional capture volume. This study found that the foot passively rotated around the ankle joint in all three dimensions; plantar flexion (7.1±5.8°), abduction (14.9±5.5°) and eversion (3.1±1.5°) during an instep soccer kick. The study suggested that higher plantar flexion found in earlier research could have been due to the plantar flexion accounting for abduction the foot experienced during an instep kick. By analysing the passive rotation of the end-effector in three dimensions, the results can be compared to the study of Shinkai et al. [6].

Fig. 1. Kicking Robot Simulator (Left), and Current End-Effectors (Right)

Holmes et al. [7] developed a kicking simulator at Loughborough University to create a reliable kicking process (Figure 1). A motor drives the mechanical leg a total of 1080° for each kick, accelerating 270° followed by 90° of constant velocity when the end-effector strikes the ball. The deceleration phase involves two complete revolutions of the leg, reducing stresses as it returns to its starting position [7]. By changing the velocity profile, the initial contact velocity of the end-effector can be set. This has led to the department being able to test different ball constructions under the same initial conditions, providing a platform to compare ball spin rate and velocities after contact. The current end-effectors are simple, rigid structures created to provide a repeatable contact between the kicking robot leg and the ball (Figure 1).

From player studies and literature [4-6], the foot to ball interaction of an instep kick is a complex process, resulting in multi-axial rotations around the ankle joint. The current end-effectors do not allow for boots to be tested using the kicking robot, limiting the potential to impact different upper constructions with a variety of soccer balls. During ball contact, the foot is forced to rotate around the ankle joint, followed by deformation at the metatarsophalangeal joint [1]. The use of a rigid foot, attached to a device which enables plantar flexion, will isolate the rotations only to the ankle joint.
2. End-Effector Design

The aim was to create an end-effector capable of allowing the foot to plantar flex around an ankle joint (Figure 2). A last, used in shoe construction, provided a foot geometry for boots to be fitted to the end-effector. The rigid geometry isolated rotation only around the ankle as it contacted the ball. A semi-bonded bush bearing was chosen to act as the ankle joint. The bearing consisted of rubber pressed between an inner and outer bushing, as well as being bonded to the inner bush. By fixing the inner bushing whilst turning the outer bushing, the rubber provides a torsional resistance. When loading ceases, the inner bushing returns to its original position, provided that it did not exceed its loading limits. The design consisted of a shaft fixed to the kicking robot leg by two end plates. The shaft was freeze fitted to the inner bush, preventing any rotation or translation. A clamp surrounded the outer bushing to which the foot geometry was attached. The housing consisted of a steel base with four screws used to tighten the lid of the housing to the outer bush. Bolts provided a secure fixture between the circular plate and the last. The circular plate had pairs of holes drilled around the edges to allow the initial position of the foot to be changed when analysing the contact.

![Fig. 2. End-Effector Design: a) Complete Assembly; b) Foot Geometry; and c) Bearing Housing Assembly Without Clamp](image)

3. Method

To quantify the rotation about the joint at contact, reflective markers were placed on the mechanical foot. The marker positions were used to create a reference axes, allowing the resulting angular displacement of the foot around the ankle joint at contact to be assessed (Figure 3). GOM PONTOS, a passive marker tracking software, capable of high accuracy at high frame rate capture, was used to create 3D data points. Once calibrated, the software can track points within a capture volume. Two Photron SA1.1 high speed cameras with 50mm lenses were aligned with an optical angle of 25°. A 400mm³ capture volume was created by placing the cameras 1160mm from the contact zone between the end-effector and ball. The system was calibrated using a CP20 calibration panel. A frame rate of 5000fps with a shutter speed of 1/25000s was used to avoid the images becoming blurred during the kick. The system used images from two camera sets at each time frame during the foot to ball interaction, tracking the markers and generating three dimensional data points.

The next phase of data analysis involved the marker sets in each time frame of contact to be aligned with the reference axes shown in Figure 3. With the ankle joint marker point being the origin, the X axis was the direction of motion, the Y axis aligned with the centre of the ankle shaft, and the Z axis was normal to the XY plane. A MATLAB script was constructed to orientate each frames marker points with
the reference axes, from which the rotation of the foot about the ankle joint during ball contact could be obtained. Eversion/inversion rotation occurred around the X axis, plantar/dorsal flexion occurred around the Y axis and abduction/adduction occurred around the Z axis. Three different initial foot velocities were analysed (9.76, 13.15 and 16.72 m/s) with five kicks for each speed evaluated. A 32 panel, hexagonal pentagonal ball with a pressure of 12Psi was used for all kicks. Each kick involved the ball being placed in the same position to reduce the effects of impact location at contact.

![Fig. 3. Reference Axes Used to Analyse Foot Rotation (Left), and Testing Set-up Before End-Effector Contact (Right)](image)

### 4. Results

As the end-effector impacted the ball, the foot is forced to predominantly plantar flex around the ankle joint. Small levels of eversion and abduction were experienced by the foot, displayed in Table 1. The impact velocity had an effect on each of the rotation’s magnitude, with a linear relationship between the plantar flexion angular displacement and initial foot velocity. During the five trials at each initial foot velocity, the angular displacements remained very consistent. Small standard deviations were experienced, proving the repeatability of the end-effector; one of the fundamental aims of the project. The kicking robot foot velocity at impact was very consistent in these trials. As outlined in equation 1 [1], the foot velocity has an influence on the instep soccer kick, so it is important this remains consistent.

<table>
<thead>
<tr>
<th>Initial Foot Velocity (m/s)</th>
<th>Plantar Flexion (°)</th>
<th>Eversion (°)</th>
<th>Abduction (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.76±0.008</td>
<td>6.30±0.42</td>
<td>1.14±0.09</td>
<td>1.14±0.26</td>
</tr>
<tr>
<td>13.15±0.02</td>
<td>10.49±0.97</td>
<td>2.01±0.17</td>
<td>1.71±1.84</td>
</tr>
<tr>
<td>16.72±0.05</td>
<td>15.07±0.16</td>
<td>2.74±0.16</td>
<td>3.25±0.58</td>
</tr>
</tbody>
</table>

With an initial velocity of 16.72±0.05m/s the end-effector was forced into plantar flexion (15.1°±0.5°), abduction (3.25°±0.58°) and eversion (2.74°±0.16). However, the plantar flexion angular displacement was greater than the human kick testing calculated in the study by Shinkai et al. [6] (mean peak value of 7.1°±5.8° when struck at 20.5±1m/s). Small levels of eversion and abduction were experienced by the end-effector, but the focus was to simulate the plantar flexion mechanism. Figure 4 displays the components of rotation during the contact phase when struck with an initial velocity of 16.72±0.05m/s. Similarities between human kicking documented by Shinkai et al. [6] and the end-effector were observed, with the foot plantar flexing exponentially until the ball reached its peak deformation at 4ms. The plantar flexion...
then acts linearly until the ball leaves the foot. In human kicking [6], the foot is dorsally flexed as the ball deforms. The end-effector failed to replicate this motion.

![Graph](image)

**Fig. 4.** Angular Displacement of End-Effector During Ball Contact with An Impact Velocity of 16.72±0.05 m/s

![Images](image)

**Fig. 5.** Images of End-Effector Contacting Ball: a) Before Contact, b) Maximum Ball Deformation, and c) End of Contact

5. Discussion

As the end-effector impacted the ball, a moment around the ankle joint was created. The semi-bonded bush bearing was chosen to allow the foot to rotate, but provide a resistance to the loading and allow the foot to return to its original starting position. This loading caused the outer bushing of the bearing to rotate, highlighted in Figure 5. Once the loading on the foot exceeded the rubber’s ability to resist the torsion exerted on the bearing, the outer bush rotated around its central axis, in this case termed plantar flexion. A greater impact foot velocity resulted in the reaction force from the ball to increase the loading on the foot, resulting in greater torsion on the outer bushing; the result was a greater angular displacement (Table 1). When compared to human kicking, the study by Shinkai et al. [6], the mean peak plantar flexion experienced by the end-effector was greater. However, the plantar flexion for the end-effector remained within the standard deviation of human kicks due to high variability [6]. A reason for the higher plantar flexion could be a result of how the kicking robot leg is driven. The motor operates using a displacement profile, resulting in the foot being driven with a constant velocity during the contact phase. In human kicking, the foot velocity slows down during the contact phase [6]. The rubber stiffness will have also had an effect on the range of plantar flexion experienced by the foot. A solution to the high plantar flexion would be to increase the rubber stiffness. By providing a greater resistance to the torsion exerted on the outer bushing, the levels of plantar flexion can be reduced. The aim was to allow a
repeatable end-effector to simulate the plantar flexion mechanism experienced in soccer kicking. When comparing the biomechanics of the foot during ball contact, the end-effector allowed the foot to primarily plantar flex. By increasing the rubber stiffness, the plantar flexion can be reduced to a value similar to those experienced by the foot in human kicking. The objective was to allow plantar flexion, but small levels of abduction and eversion were experienced. As the foot impacted the ball, the rubber between the inner and outer bushing became compressed by radial loading at the proximal and distal ends, explaining the small levels of abduction and eversion recorded during testing. Importantly these rotations were consistent during all tests. Repeatability was an important factor with the development of the end-effector. When compared to the human foot to ball interaction, the end-effector provided greater repeatability for both the impact velocity and range of plantar flexion during contact (7.1±5.8° of plantar flexion after a foot impact velocity of 20.5±1m/s in human kicking [6] and 15.1±0.5° after an impact velocity of 16.72±0.05m/s for the end-effector).

The development of the end-effector resulted in a repeatable contact between a foot geometry and ball, allowing the foot to plantar flex around the ankle joint. The potential for the end-effector is to evaluate the role of different boot constructions on the resulting ball spin rate and velocity after contact. Impact position and initial foot velocity can remain consistent, allowing the important contact characteristics between the dorsal region of the boot and ball during contact to be isolated and investigated further.

Conclusion

The end-effector replicated the plantar flexion mechanism associated with human instep soccer kicks, providing repeatable levels of impact velocity and plantar flexion during contact. Similarities between the plantar flexion mechanism in human kicking and the end-effector were observed, with a greater magnitude experienced by the end-effector. Increased rubber stiffness in the semi-bonded bush bearing and an evaluation of the kicking robot’s displacement driven operation are two processes needed to reduce the level of plantar flexion of the end-effector to realistic angular displacements experienced in human kicking of an instep kick.

Acknowledgements

The author would like to thank adidas AG for their support in the project

References