Influence of outsole design on centre of rotation during turning movements

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Abstract

A bespoke 3D measurement system was used to investigate the influence of the outsole configuration on the centre of rotation during a movement used by football players to change direction. Five outsole configurations were selected for analysis ranging from rounded studs to bladed designs. High-speed video information and force-plate data were collected and analysed to obtain the shoe kinematic and kinetic results. The centre of rotation was calculated during shoe-surface contact using the location of the stud positions on the outsole. Results indicated that significant differences occurred between outsole designs for the kinetic data, but all shoes impacted the ground at a similar orientation. The resulting centre of rotation varied between designs, but on average was located towards the toe of the shoe. This differs from the centre of rotation often used in traction testing and as a result, may influence the veracity of current assessment techniques.

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1. Introduction

Football shoe manufacturers aim to find the balance between an outsole that improves performance but also minimises the risk of injury. Improvement in performance is often achieved by increasing the translational traction, preventing the shoe from slipping on foot-strike or push-off. Increase in translational traction can be achieved by increasing the area of contact between the outsole and the surface either through increasing the number of studs or the depth of stud penetration. Translational

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traction is typically measured by moving a studded plate or shoe across the surface recording the horizontal resistance to movement (traction). Translational traction testing devices range from complex robotic legs [1] to motor driven studded plates or shoes [2] to simple pendulum swing tests [3].

Rotational traction is an important consideration and is more commonly associated with reducing injuries than improving performance. The influence of the shoe-surface interaction on lower limb injuries has been extensively investigated by Orchard et al. [4]; with the authors concluding that excessive traction may be one of the contributing factors to the cause of anterior cruciate ligament (ACL) injuries during turning movements. Cameron and Davis [5] developed one of the earliest design suggestions to minimise the potential problems of stud fixation during turning. The design was based on biomechanical analysis from laboratory based testing and observation of injuries to American Football players. The resulting design consisted of a studded swivel plate (capable of rotating 360° in either direction) attached to the forefoot of the shoe; this allowed the studs to remain fixated to the surface reducing translational movement (slip) but ensured the foot and leg were able to freely rotate. The authors noted a reduced injury rate and concluded that at the time, this was the most effective method to reduce injuries. Modern outsole designs aim to minimise weight to provide players with the perception of speed [6], additional moving parts such as swivel plates add weight to the shoe and as such are difficult to incorporate into the design. To reduce rotational resistance, recent designs instead orientate the studs or blade configuration about the centre of the forefoot; effectively reducing the swept area of the studs as the shoe rotates about this point.

Rotational resistance or traction of surfaces is often assessed by measuring the torque required to rotate a studded plate on a surface; the Fédération Internationale de Football Association (FIFA) use this technique as one of the standard tests for the quality assessment of football turfs [3]. Similar approaches are used to measure the rotational traction of outsole designs. Livesay et al. [7] replaced the studded plate with a full shoe and measured the peak torque and rotational stiffness of a range of different shoes and surfaces under varying vertical loads. The authors observed that although significant differences existed between different shoe and surface types, the optimum torque and rotational stiffness was still undetermined, and as such it was difficult to comment whether a shoe that offered a lower torque was preferential to one that displayed higher values. Motorised traction testing devices also exist, allowing modifications to the speed of rotation and more precise measurement of torque.

The main assumption in rotational traction measurements is that the centre of rotation is positioned near the mid forefoot. This allows the stud configuration to be orientated to reduce the rotational resistance of the forefoot rotating about its midpoint, but does not provide any evaluation of the stud configuration rotating about different loci. There is little reported literature to date that measures the centre of rotation of the foot during different movements or provide recommendation on where the ideal centre should be positioned to reduce lower limb injuries.

To develop a rotational traction test device that is representative of the motion of the shoe during realistic movements, the loci of the centre of rotation during shoe-surface interactions need to be obtained. This however raises further questions; namely, is the measured centre of rotation just an artefact of the outsole design and where is the natural centre of rotation? This paper aims to investigate the influence of stud configuration on the measured centre of rotation during turning movements.

2. Methodology

A controlled study using a single participant was undertaken in a laboratory environment with institutional ethics approval. Two high-speed cameras were used to capture a 1.5 x 1.5 x 1 m volume and calibrated using the checkerboard technique. The cameras recorded at 1000 frames per second for 0.6 s at a resolution of 512 x 382 pixels. A force-plate covered with artificial turf was positioned in the centre of
the filming zone. The force-plate sampled at 1000 Hz and was triggered by a falling edge signal on foot-strike. The trigger from the force-plate was used to activate the two synchronised high-speed cameras. This allowed timings of events to be matched from the force-plate and video data. The participant performed a 30° side-cut (left to right) and the motion of the left shoe was captured. The participant was made aware that the left foot needed to land on the force-plate but was given sufficient practice time to ensure minimal modification to their natural movement occurred. Five outsole configurations were tested (Figure 1) with five repeats made of each configuration. The outsoles selected covered a range of different stud heights, shapes and configurations (Table 1).

![Fig. 1. Schematic of stud configurations](image)

| Shoe | No. of studs | Stud profile | Stud height | Stud material | Intended use |
|------|--------------|--------------|-------------|---------------|--------------|
| A    | 8 FF, 4 H    | Round        | 8 mm FF, 11 mm H | Moulded, soft | FG           |
| B    | 4 FF, 2 H    | Round        | 12 mm FF, 15 mm H | Metal         | SG           |
| C    | 65           | Round        | 6 mm FF, 8 mm H | Moulded, soft | AT           |
| D    | 10 FF, 4 H   | Bladed       | 5 mm FF, 8 mm H | Moulded, hard | AT           |
| E    | 9 FF, 4 H    | Bladed       | 9 mm FF, 12 mm H | Moulded, hard | FG           |

Five markers were placed on each test shoe to define two rigid bodies; a rear-foot and forefoot section. The markers were tracked using a semi-automated image processing algorithm and stereo-triangulation was used to determine the 3D global coordinates of each marker (accuracy ± 0.5 mm) [8]. A transposition matrix was calculated for each outsole design to convert the marker coordinates to stud positions. This allowed the stud position to be determined during contact with the surface even though the studs may be obscured from view. The 2D centre of rotation of the shoe during contact with the surface was calculated using the Reuleaux method in which the displacement of any rigid body in 2D using two points (stud positions) from one time-step to the next can be carried out with a rotation of angle θ about the pole of displacement or centre of rotation [9]. The position of the mean centre of rotation for each shoe was calculated and the analysis of variance (ANOVA) statistical test used to identify significant differences between stud configurations. Additional information on shoe kinematics (orientation on impact and translation distance) and kinetics (maximum vertical and horizontal forces) were also analysed to assist in the understanding on the influence of outsole configuration.
3. Results and discussion

3.1. Force

Force data (normalised to body weight, BW) was recorded for each movement in order to assess the influence of stud configuration on the kinetic behaviour of the movement. Figure 2 shows an example force profile for shoe A; maximum vertical, lateral and posterior forces occurred during the latter stages of the movement rather than on initial foot-strike. This indicated the importance of the push-off phase of the movement. The maximum force in the lateral, vertical and posterior directions were selected for comparison (Table 2). The Scheffé’s confidence interval post hoc test was used to determine significant differences between the groups. Significant differences were observed for shoe B in both the lateral and vertical force components against all shoes \( (p < .01) \) and between shoe E and C, E and A, and B and C in the posterior direction \( (p < .05) \). Shoe B consisted of only two studs on the heel and four on the forefoot and had the longest stud profile out of the outsoles tested. During contact with the surface, lateral displacements up to 160 mm were observed during the transition from foot-strike to push-off for shoe B. This was potentially due to the limited traction available from the studs as the intended use of the shoe was for soft ground conditions, not artificial turf. The reduced traction caused the participant to hesitate in subsequent trials with shoe B, resulting in reduced loading in both the vertical and lateral directions. No significant differences in measured force were observed between shoe A, C and D; all shoes were designed for either artificial or firm ground conditions. Translation during shoe-surface contact was also not observed. Shoe E showed slightly reduced lateral and posterior forces but consisted of harder and longer studs than the other firm ground shoe tested (A) and was again, not being tested on its intended surface. Slip of approximately 170 mm was observed in the posterior-lateral direction during the push-off phase resulting in the lower than average posterior force.

| Shoe | Fx (BW)       | Fy (BW)       | Fz (BW)       |
|------|---------------|---------------|---------------|
| A    | 1.29 ± 0.15   | -0.36 ± 0.03  | 1.86 ± 0.15   |
| B    | 0.85 ± 0.11   | -0.26 ± 0.08  | 1.54 ± 0.08   |
| C    | 1.21 ± 0.08   | -0.37 ± 0.04  | 1.76 ± 0.04   |
| D    | 1.10 ± 0.09   | -0.30 ± 0.06  | 1.75 ± 0.11   |
| E    | 1.06 ± 0.07   | -0.25 ± 0.04  | 1.76 ± 0.03   |

3.2. Orientation at foot-strike

The orientation of the shoe (Table 3) was determined from the Euler angles using the direction cosine matrix of the stud positions. The angles are expressed in terms of pitch, yaw and roll and are non-commutative. The velocity was calculated using a five-point central differencing method. On initial foot-strike, all shoes landed in a level elevation with minimal pitch angle recorded. Notable roll angles were observed indicating that the first studs to contact the surface were on the medial side of the shoe, but due to the low pitch angles observed, both the forefoot and heel studs came into contact almost simultaneously. High yaw angles were also seen on foot-strike, suggesting that the participant was pre-empting the change in direction and was already positioning the shoe in order to achieve maximum
propulsion on push-off. Results indicated that there was no significant difference between the resultant velocities of the shoes at foot-strike. Significant differences were observed in the orientation of the shoe at foot-strike, most notably in the roll angle, with differences between shoe C and A, and C and B (p < .05), D and A, and D and B (p < .01) and E and C, and E and D (p < .01). Significant differences were also seen between shoe A and D in terms of pitch angle (p < .10). Although shoe B differed significantly in terms of maximum force recorded on push-off, the orientation of the shoe did not differ significantly from shoe A or E for pitch, yaw or roll angles. This could suggest that although slipping and the perception of limited traction may have influenced the loading the participant exerted during the movement, the initial positioning and kinematics of the shoe did not change. The highest roll angles were observed for shoe C and D. Both shoes were intended for use on artificial surface and had lower stud heights than the other shoes tested. This may have influenced the participant’s perception on how the shoe would perform during the movement, and subsequently was committed to loading the shoe at a greater roll angle as the reduced stud height effectively enabled more studs to be in contact with the surface than a shoe with a greater stud height, but smaller roll angle.

Table 3. Orientation and resultant velocity of the shoe at foot-strike. Note: mean ± standard deviation

| Shoe | Pitch     | Yaw     | Roll     | Resultant velocity |
|------|-----------|---------|----------|--------------------|
| A    | -3.1 ± 3.4° | -17.0 ± 4.8° | -19.9 ± 4.0° | 2.53 ± 0.45 ms⁻¹  |
| B    | -2.4 ± 1.8°   | -10.8 ± 3.4°  | -19.6 ± 6.0°  | 2.42 ± 0.77 ms⁻¹  |
| C    | -1.7 ± 1.1°    | -18.8 ± 5.3°  | -29.0 ± 2.3°  | 2.41 ± 0.48 ms⁻¹  |
| D    | 0.7 ± 1.9°     | -17.2 ± 3.4°  | -33.2 ± 4.7°  | 2.21 ± 0.37 ms⁻¹  |
| E    | -1.6 ± 1.2°    | -12.8 ± 2.1°  | -17.8 ± 1.9°  | 1.88 ± 0.29 ms⁻¹  |

3.3. Centre of rotation

The period of time during which the greatest change in yaw angle was observed was identified for each shoe. A change in yaw angle with little change in pitch or roll angles signified that the shoe was rotating in the horizontal surface plane. Not all shoes were observed to rotate during the movement (48% rotated). For the trials that did rotate, this rotation was observed to occur just prior to push-off when only the forefoot studs were in contact with the surface. The centre of rotation and angle of rotation was calculated using the Reuleaux method with the assumption that the dominant movement occurred in the horizontal plane (Table 4). The centre of rotation for all shoes occurred predominantly on the medial side of the forefoot, towards or in advance of the toe studs with the exception of shoe A where the centre of rotation was closer to the lateral side of the shoe (Figure 3). The mean centre of rotation was positioned near the centre of the shoe (medial/laterally) but towards the toe of the shoe in the anterior/posterior direction rather than the centre of the forefoot as currently tested in traction assessments. In the anterior/posterior direction, the maximum difference between measured centres of rotation was 58.7 mm (between shoe D and E). This was approximately 50% of the mean anterior/posterior centre of rotation. In the medial/lateral direction the maximum difference in centre of rotation was 36.4 mm (between shoe A and E). This difference was greater than the mean medial/lateral centre of rotation. The notable differences between the range of the centre of rotations recorded for each shoe and the overall mean of the centre of rotation suggests that the outsole may influence the location of the centre of rotation. During the time periods investigated, shoe A displayed the greatest degree of rotation (approximately 27°) and shoe E the least (7°) although the speed of rotation for shoe B was smallest (175° s⁻¹). The mean rotation angle was 15 ± 8°; this is typically less than the angle of rotation tested during traction assessments,
although the high standard deviation (53% of the mean) suggested that the outsole also influenced the amount of rotation. Shoe D and E consisted of bladed stud profiles, differing in stud height and location of the centre studs on the forefoot (Figure 1). Shoe E showed a reduced angle of rotation during the movement, potentially caused by the increased stud height. The bladed stud design of shoe D (designed for artificial turf) did not noticeably reduce the amount or rate of rotation compared to the rounded stud profile shoes. The multi-studded shoe C, similarly designed for artificial turf displayed a low rotation angle but the rate of rotation was the median result.

Table 4. Angle and speed of rotation during investigated time period. Note: mean ± standard deviation

| Shoe | Angle | Speed     |
|------|-------|-----------|
| A    | 27°   | 270 °s⁻¹ |
| B    | 14°   | 175 °s⁻¹ |
| C    | 9°    | 225 °s⁻¹ |
| D    | 19°   | 270 °s⁻¹ |
| E    | 7°    | 200 °s⁻¹ |
| Mean | 15 ± 8° | 228 ± 43 °s⁻¹ |

Fig. 3. Centre of rotation (x) for shoe A. • = forefoot stud positions at t = 0.195 s, o = at t = 0.295 s

4. Conclusion

The variability between the centre of rotation results (range 36.4, 58.7 mm) suggested that the outsole configuration influenced both the centre of rotation and the degree of rotation observed. However, despite the variability, all results indicated that the centre of rotation for the movement analysed was positioned towards the toe of the shoe and not the centre of the forefoot as often used in traction testing. Initial results from a single participant indicated that modifications to current test procedures may be required to improve the realism of the tests, but further work is necessary to collect a larger data set of rotation centres during different movements and on a wider range of surfaces.

References

[1] Grund, T., Senner, V. & Gruber, K., 2007. Development of a test device for testing soccer boots under game-relevant high-risk loading conditions. *Sports Eng*, 10, 55-63.
[2] Haake, S.J., Carré, M.J., Kirk, R.F. & Senior, T., 2004. Traction of studded boots on turf. *Sports Eng*, 544-551.
[3] FIFA, 2008. *FIFA Quality Concept for Football Turf: Handbook of test methods* [online]. Available from: http://www.uefa.com/MultimediaFiles/Download/uefa/UEFAMedia/74/52/07/745207_DOWNLOAD.pdf [28 October 2011].
[4] Orchard, J., Rodas, G., Til, L., Ardevol, J. & Chivers, I., 2008. A hypothesis: could portable natural grass be a risk factor for knee injuries? *J Sport Sci Med*, 7(1), 184-197.
[5] Cameron, B.M. & Davis, O.M.D., 1973. The swivel football shoe: A controlled study. *J Sport Med*, 1(2), 16-27.
[6] Torell, V.B., 2011. As fast as possible rather than well protected: experiences of football clothes. *J Cult Res*, 3, 83-99.
[7] Livesay, G.A., Reda, D.R. & Nauman, E.A., 2006. Peak torque and rotational stiffness developed at the shoe-surface interface. *Am J Sport Med*, 34(3), 415-421.
[8] Driscoll, H., Kirk, B., Holmes, C., Koerger, H. & Haake, S., 2011. Tracking of foot movement during sprinting in studded footwear. *Footwear Science*, 3(sup1), S51-S53.
[9] Eberharter, J.K. & Ravani, B., 2006. Kinematic registration in 3D using the 2D Reuleaux method. *J Mech Design*, 128, 349-355.