Forefoot bending stiffness of cleated American football shoes

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Forefoot bending stiffness of cleated American football shoes

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In American football, hyper-dorsiflexion of the first metatarsophalangeal (1 MTP) joint is the predominant mechanism of 1 MTP sprains (turf toe). The risk of acute 1 MTP sprain has been found to increase as 1 MTP angle increases. The bending resistance of the shoe dictates the proportion of an externally applied load that can be passed into the shoe (i.e., not through the 1 MTP joint) and thus influences the magnitude of flexion imparted to the 1 MTP joint. This study quantified the forefoot bending resistance of a range of cleated American football shoes. A total of 21 pairs of size 12 shoes were dynamically tested over flexion angles from 30° to 90°. Bending stiffness ranged from 0.10 to 0.35 Nm/deg, while peak torque ranged from 5.1 to 16.6 Nm. The relationship between torque and flexion angle was nearly linear for all of the shoes tested and the peak torque values were substantially lower than 1 MTP joint moments that have been measured in the human foot during athletic activities. These results suggest that an opportunity exists to better balance athletic performance and acute 1 MTP joint injury risk by incorporating non-linearity into the torque-angle characteristic of football cleats, such that the proportion of external load borne by the shoe increases at flexion angles above 60°.

Keywords: bending; stiffness; longitudinal; cleated shoe; forefoot (foot); football

Introduction

Sprain of the first metatarsophalangeal (1 MTP) joint, or ‘turf toe’ (Bowers & Martin, 1976), accounts for a substantial amount of lost playing time in American football (Clanton, Butler, & Eggert, 1986; Coker, Arnold, & Weber, 1978) because these injuries are both frequent (Kaplan et al., 2011) and potentially debilitating. Rodeo et al. (1990) found that 45% of professional players sustain a 1 MTP joint sprain at some point in their career. The injury is potentially debilitating because the halluc is crucial to an athlete’s ability to run and cut. While 1 MTP joint sprains have been attributed to several different and specific mechanisms, hyperextension (or hyper-dorsiflexion) (Figure 1) appears to be the most frequent mechanism of acute injury in American football (Coker, Arnold, & Weber, 1978), accounting for up to 85% of turf toe injuries (Rodeo et al., 1990).

Bojsen-Moller (1979) observed that human forefoot rotation can occur about either of two alternative axes (Figure 2). The first axis being a transverse axis through the first and second metatarsal heads (1–2 MH axis), and the second axis being an oblique axis extending from the second to the fifth metatarsal heads (2–5 MH axis). Bojsen-Moller (1979) referred to these first and second axes as the ‘high gear’ and ‘low gear’, respectively. For the high gear axis, the functional anatomy allows the foot to become a rigid lever for propulsion (Bojsen-Moller, 1979). During high intensity movements associated with athletic manoeuvres, it is this high gear, or 1–2 MH axis, that is the rotational axis of interest. Importantly, this is also the axis that is associated with the hyper-dorsiflexion of the 1 MTP joint that can result in a turf toe injury.

Regarding rotations of the 1 MTP joint around the 1–2 MH axis, there is a performance regime that appears to be largely distinct from an injury regime. Riley et al. (2013) showed that the peak dorsiflexion angle of the 1 MTP joint was less than 60° during an array of football-specific tasks performed by nine elite athletes, with running generating the highest 1 MTP angles. By comparison, Frimenko et al. (2013) demonstrated that the risk of turf toe injuries, due to hyper-dorsiflexion, increases non-linearly as the 1 MTP angle increases. The bending resistance of the shoe, particularly at flexion angles beyond the performance regime, dictates the proportion of a potentially injurious external load that can be passed into the shoe (i.e., not through the 1 MTP joint) and thus may be a factor in limiting potentially injurious hyper-dorsiflexion. Furthermore, the bending resistance of the shoe during performance could, presumably, be essentially unaffected by the bending resistance at angles above 60°.

In the performance regime, bending stiffness of various sports shoes has been the topic of both study and
debate (ASTM F911-85, 1994; Frederick 1989; Oleson, Adler, & Goldsmith, 2005; Roy & Stefanyshyn, 2006; Stefanyshyn & Nigg, 2000; Sterner 2011; Tinoco, Bourgit, & Morin, 2010). While the traditional concept in shoe design has been that the shoe should be flexible (Frederick, 1989), some research has demonstrated that performance may in fact increase with increasing bending stiffness of the shoe (Stefanyshyn & Nigg, 2000). Furthermore, loads passed through the foot to the rest of the lower extremity are affected by shoe stiffness in ways that are not fully understood with regard to either performance, chronic injury, or acute injury. Currently, while no

![Hyperextension (hyper-dorsiflexion) injury mechanism to the 1 MTP joint.](image)

Figure 1. Hyperextension (hyper-dorsiflexion) injury mechanism to the 1 MTP joint.

![Flexion axes in the human forefoot.](image)

Figure 2. Flexion axes in the human forefoot.

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<table>
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<th>Shoe identifier</th>
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<th>Stiffness rank</th>
<th>Torque rank</th>
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$^1$ Stiffness values measured over the 60° – 75° flexion interval.
specific design target or industry standards exist for the bending stiffness of football cleats in the performance regime, there are accepted test methods for measuring the stiffness of shoes at bending angles well below the transition to the injury regime (ASTM F911-85, 1994). In the injury regime, however, there is neither consensus on the desired bending stiffness of shoes, nor an accepted method for measuring it. The objective of this study is to present a method for testing cleated footwear at angles into the injury regime and to quantify the forefoot bending stiffness of a range of contemporary football shoes.

Method
For this study, 21 different types of cleated American football shoes were selected for dynamic testing to measure forefoot bending stiffness (Table 1). The shoes were provided by three manufactures and represented shoe types worn by all player positions and included ‘moulded’, ‘detachable’, and ‘lineman’ type cleat patterns. All shoes were right aspect and size 12. Shoes are identified by manufacturer, model, and by a unique identifier for each test sample (Table 1).

Test setup
The test methodology, adapted from ASTM-F911-85 (1994), was designed to flex each shoe dynamically while measuring the torque required to flex the shoe about an axis located directly beneath the 1 MTP joint. A dynamic shoe flexion device was used (Flexer 2.0, Exeter Research, Inc., Brentwood, NH) (Figures 3 and 4). This device is typically used in commercial applications to evaluate the
flexibility of running shoes in the performance regime (i.e., below 60°). To accommodate testing into the injury regime, a 30° wooden wedge was secured beneath the heel of the shoe during the tests. This allowed for the bending resistance of the shoe to be evaluated over a range of shoe flexion angles from 30° to approximately 90°. Prior to the test a rigid aluminium forefoot plate was fitted into the forefoot of the shoe (Figure 3), such that the posterior edge of the forefoot plate aligned with the 1–2 MH axis. A compression spring applied a vertical load of 756 N to the top surface of the forefoot plate. This vertical load secured the shoe forefoot in place during the test and also simulated the distributed load applied to the shoe by the planted forefoot during high-intensity athletic movements. Beneath the forefoot cleats was a rigid support plate that incorporated a thin layer of commercial grade neoprene, which further secured the shoe forefoot and specifically prevented translation or slipping of the forefoot during the tests. Figure 3 shows perspective and lateral views of the test device and setup as well as multiple views of the shoe forefoot boundary condition used during the tests. Figure 4 provides a schematic diagram of the test device.

**Shoe preparation and flexion axis**

Prior to the test the upper portion of the shoe, or ‘upper’, was removed to prevent mechanical interaction with the test device at angles greater than 60°. Following the removal of the upper, the total inside length of the shoe was measured, and a mark was placed on the inside surface of the shoe sole, at a distance that was 70% of the distance from the heel to the toe of the

![Figure 4. Schematic diagram of the test device.](image-url)
shoe. This measurement is referred to as 70% of inside shoe length (Figure 5) and was presumed to closely approximate the longitudinal location of the 1.5\textsuperscript{C}H axis. Thus, the posterior edge of the forefoot plate (Figure 3) was specifically aligned with the mark at 70% of inside shoe length. This established the shoe flexion axis for each test and is consistent with that described in ASTM F911-85 (1994). Figure 5 illustrates the consistency among the flexion axis tested, the anatomical location of the 1.5\textsuperscript{C}H axis, and the flexion axis of the shoe during running. Additional information regarding the determination of the 70% flexion axis is provided in Appendix 1.

**Dynamic test details**

Prior to testing, the shoe was flexed through 500 dynamic preconditioning cycles to achieve a steady-state response of the shoe. No data were collected during the shoe preconditioning. At the completion of the 500 preconditioning cycles, the test device was stopped to allow the data collection link to be established for the actual dynamic test. The dynamic test consisted of 75 continuous cycles of flexion from 30° to approximately 90° and back to 30°. Starting from a stop, 75 cycles were found to be sufficient to bring the testing device up to a steady-state condition for the torque-angle measurement. Tests were performed dynamically at 3 Hz, which corresponded to an average flexion rate of approximately 360°/sec at the shoe. Torque was measured using a load cell (AL311BR, Honeywell International, Inc., Morristown, NJ, USA) mounted at known distance from the flexion axis and flexion angle was measured using a potentiometer (CP-2FCB(M)5K, Midori Precisions Co. Ltd., Tokyo, Japan). Data were sampled at 1000 Hz and were collected and post-processed using an A/D computer link and custom software (Flexer 2.0 Software, Exeter Research, Inc., Brentwood, NH).

**Data processing**

For each shoe, the torque as a function of flexion angle, \( \theta \), was calculated as the average response measured over cycles 51–55 (\( N = 5 \) cycles) (Equation (1)). This interval was confirmed to be a stable, steady-state portion of the 75 cycle test. Equation (1) is defined for flexion angles of 30°–90°. At each flexion angle, \( \theta \), only the loading portion of the flexion cycle was considered (i.e., unloading and hysteresis were measured but are not considered here). Using the torque response obtained in Equation (1), the average stiffness over a desired flexion interval, \( k \), is defined in Equation (2). The shoe stiffness was determined for the flexion intervals of 30°–45°, 45°–60°, 60°–75°, and 75°–85°. Additionally, each torque curve was debiased, such that the torque value was zero at 30° of flexion. This debiased torque value was small and was approximately 1 Nm on average across the 21 tested shoes.

\[
\text{Torque}(\theta) = \frac{1}{N} \sum_{i=1}^{N} \text{Torque}_i(\theta)
\]  

\( \text{Torque}_i(\theta) \) is the torque at angle \( \theta \) for cycle \( i \), and \( N \) is the number of cycles in the interval.

\[
\text{Stiffness}_k = \frac{\Delta \text{Torque}_k}{\Delta \theta_k}
\]

\( \theta \) is the flexion angle, \( \text{Torque}_k \) is the torque at angle \( \theta_k \), and \( \Delta \theta_k \) is the flexion angle interval.

**Repeatability and reproducibility**

To assess repeatability and reproducibility, a limited number of additional tests were conducted. These tests included (1) repeated tests on previously tested shoes and (2) tests on additional, but identical, shoes of the same make and model as previously tested shoes.

**Results**

Forefoot flexion tests were successfully conducted on the right aspect of 21 size 12 shoes (Table 1). Figure 6 shows
stiffness values measured over the flexion intervals from $30^\circ - 45^\circ$, $45^\circ - 60^\circ$, $60^\circ - 75^\circ$, and $75^\circ - 85^\circ$. For a given shoe, the greatest stiffness was typically observed over the $60^\circ - 75^\circ$ flexion interval, where stiffness values across the tested shoes ranged from 0.10 to 0.35 Nm/deg (Table 1). Overall peak torque ranged from 5.1 to 16.6 Nm (Table 1). Figures 7 and 8 illustrate torque curves sorted by manufacturer and shoe type. Figure 9 provides a box plot summary of stiffness and peak torque across manufacturers and shoe types. Figure 10 provides a box plot summary of stiffness of the 21 tested shoes by flexion interval. Figures 11 and 12 provide torque curves for tests of repeatability and reproducibility.

Discussion

The primary objective of this study was to quantify the forefoot bending resistance of American football shoes into an injurious regime of 1 MTP dorsiflexion.

The 21 dynamic tests produced torque-angle loading curves having a smooth monotonically increasing response (Figures 7 and 8). Peak torque was typically achieved at the end of the tested range, at approximately 90°, while the greatest stiffness was observed to occur over the $60^\circ - 75^\circ$ flexion interval in 18 of the 21 tested shoes (Figure 6). This is also the interval with the greatest applied angular rate. All stiffness comparisons across shoes were made using the stiffness measured over the
Shoe stiffness and peak torque were found to be linearly correlated ($R^2 = 0.91$) in these tests. The range of peak torque and stiffness measured in these tests varied by more than a factor of 3 (3.25 for peak torque and 3.5 for stiffness). Figure 9 compares manufacturers and shoe types in terms of the mean, standard deviation (SD), maximum, and minimum values across a selected group. For the conducted tests, the average peak torque and stiffness were observed to be varied across manufacturers. Some of this variation in average peak torque and stiffness may be explained by the differences in the distribution of shoes that were tested since there were differences in both the number (e.g., $n = 12$, $n = 6$, and $n = 3$) and types of shoes available for testing (e.g., no lineman shoes were tested for one manufacturer). Regardless of manufacturer, moulded cleats had, on average, the highest average stiffness and peak torque with the three stiffest shoes being moulded cleats. Lineman shoes exhibited an essentially linear torque-angle response that was often observed to be stiffer than other shoe types at smaller flexion angles (Figure 8). Some moulded cleats exhibited a slightly non-linear (concave up) response (Figure 8). The moulded cleats that generated the greatest torque were typically associated with this concave-up response. Torque-angle response was observed to be both repeatable and reproducible as indicated by Figures 11 and 12. Repeated tests on the same shoe (conducted weeks apart in time) were found to differ by 0.64% and 1.6% on average for stiffness and peak torque values, respectively.
Similarly, tests on a different, but identical, shoe were found to differ by 2.6% and 0.9% on average for stiffness and peak torque values, respectively.

The test method described here necessarily includes some simplifications of the actual loading environment on an American football player’s foot. For example, forefoot bending is represented by a single axis and bending around other axes is not considered explicitly. Additionally, the posterior edge of the insert employed for testing possesses a sharper radius than that of the metatarsal heads. Also, the bending axis of the test device is located below the plantar surface of the foot, while the human foot’s flexion axis is within the laterally projected area of the metatarsal heads. Furthermore, as described in detail above and shown in Figures 3 and 4, the shoe upper was modified to facilitate gripping and loading in the tests reported here. The degree to which this influences shoe response is unknown. A second-generation loading device is under development and will address key limitations of the current device.

The greatest torque generated by any shoe in this study was 16.6 Nm. This value is substantially lower than the peak 1 MTP joint moment generated by elite athletes during performance. For example, 1 MTP joint moments as high as 112.4 Nm have been measured in the human foot during running and sprinting (Stefanyshyn & Nigg, 1997) and values greater than this are likely to occur in elite American football players during blocking or tackling activities. While there are clear performance and injury (particularly chronic) risk tradeoffs associated with increased bending stiffness of a shoe in the performance regime below 60° of dorsiflexion, it seems that there is an opportunity for injury mitigation by increasing the torque-generating capacity of football cleats at dorsiflexion angles above 60°. That regime is not typically involved in athletic performance tasks, but is a regime associated with increased risk of acute turf toe. A football cleat that stiffens dramatically into this injurious regime could generate a torque of magnitude sufficient to provide a meaningful load path (alternative to the 1 MTP itself) for an externally applied torque. By providing this alternative load path, the shoe could reduce the torque imparted to the 1 MTP and thus the degree of dorsiflexion experienced by the toe. Future research and development efforts should explore the feasibility of such a concept.

Figure 11. Tests of repeatability.
Conclusion
This is the first study to quantify the forefoot bending resistance of American football shoes at dorsiflexion angles above 60°. A total of 21 pairs of football shoes exhibited bending stiffness from 0.10 to 0.35 Nm/deg, and peak torque from 5.1 to 16.6 Nm. The peak torques generated by the shoes are approximately one order of magnitude lower than 1 MTP joint moments generated during athletic activities. These results suggest that an opportunity exists to better balance athletic performance and acute 1 MTP joint injury risk by incorporating non-linearity into the torque-angle characteristic of football cleats, such that the proportion of external load borne by the shoe increases at flexion angles above 60°.

Disclosure statement
No potential conflict of interest was reported by the authors.

References


Appendix 1.

Establishing the 70% flexion axis

Using data extracted from Parham, Gordon, and Bensel, (1992) for 24 individuals who would wear size 12 US-Men’s shoes, it was observed that the medial ball of foot length (BOFL-M) is located, on average, 21.29 cm (averaging both left and right feet) from the heel-most aspect of the foot. The BOFL-M corresponds with the widest part of the medial aspect of the foot adjacent to the first metatarsal head. The first MH location corresponds with the approximate location of the axis of the first and second metatarsal heads. Total foot length for this group of subjects was 29.02 cm. It is standard practice to add 1.5 cm to foot length as measured by the Brannock method to estimate total shoe length-inside (TSL-I). Therefore, the TSL-I for this size 12 grouping would have equated to 30.52 cm. This corresponds to \((21.29/30.52 = 0.698)\) an estimated 70% of TSL-I for the best location of the flex axis. In addition, 70% of TSL-I also corresponds to the recommended location of the flex axis in the ASTM method for the flexibility of running shoes (ASTM F911-85, 1994).

Citation: