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The effects of midsole bending stiffness on ball speed during maximum effort soccer kicks

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The soccer kick is the most prominent movement in soccer. Kicking performance depends on two major factors: kicking accuracy and ball speed. During the soccer kick, momentum is transferred from the foot/cleat to the ball. This interplay between the foot/cleat and the ball can be modelled as a mixture of ‘impulse-like’ and ‘throwing-like’ components. While kicking the ball, the metatarsophalangeal (MTP) joint and the cleat experience deformation. This deformation can be reduced by increasing the bending stiffness of the cleat’s midsole. Therefore, the purpose of this study was to investigate experimentally the influence of midsole bending stiffness on ball speed during maximum effort soccer kicks.

Twenty male subjects (mean ± SD; age: 29.5 ± 5.6 years, height: 175.5 ± 6.4 cm, mass: 74.3 ± 8.4 kg) performed six maximum effort soccer kicks in five stiffness conditions. Kinematic data were collected using an optical motion capture system consisting of eight high-speed cameras, and ball speed was recorded using a radar gun. There was no significant difference in the average ball speed between the five stiffness conditions when all subjects were pooled. Further, there was no significant difference in the change of the MTP joint angle from before ball contact to after ball contact between the stiffness configurations. Thirteen (of the 20) subjects showed the highest ball speed in the two stiffest cleats. The differences between the best and the worst performing stiffness configurations across all subjects ranged from 2.2 km/h to 9.2 km/h. The optimal stiffness condition that resulted in highest ball speed was subject specific, and therefore soccer cleats need to be tuned to individual players.

Keywords: footwear; biomechanics; performance; soccer; cleats

Introduction

The soccer kick is the most relevant and most prominent movement in soccer (Tsaousidis & Zatsiorsky, 2007). Nearly 80% of all goals scored at the 2016 UEFA European Championship were achieved by playing the ball with the foot (MacKenzie & Sprigings, 2016). Due to its importance for the sport, the soccer kick has received a lot of attention in previous biomechanical research (Barfield, 1998; Hennig & Sterzing, 2010; Hennig & Zulbeck, 1999; Lees & Nolan, 1998; Sterzing, Kroiher, & Hennig, 2008; Tsaousidis & Zatsiorsky, 1996). The performance of a soccer kick depends on two major factors: kicking accuracy and ball speed (Sterzing et al., 2007). Both factors are influenced by six components of kicking: the approach angle, plant foot forces, swing limb loading, kinematics of the hip and knee, foot contact with the ball, and the follow-through after ball contact (Barfield, 1998). An optimised interplay of these components allows for the most effective transfer of momentum from the foot/cleat to the ball, which ultimately results in a higher ball speed (Hennig & Sterzing, 2010). Previous research has shown that the soccer kick cannot be modelled as an elastic impact only, but rather as a mixture of ‘impact-like’ and ‘throwing-like’ components due to the relatively long contact time between the foot and the ball (Tsaousidis & Zatsiorsky 1996). The interaction between two bodies can be regarded as an elastic impact if: 1) the duration of the interaction and the displacement of the bodies during the collision is small and can be neglected, 2) the external forces are small and can be neglected, and 3) the total momentum and kinetic energy of the system are conserved. According to the findings by Tsaousidis & Zatsiorsky (1996), none of the above-mentioned assumptions is valid for the cleat – ball interaction during a soccer kick. The authors demonstrated three reasons why the soccer kick cannot be modelled solely as an elastic impact: (1) During the contact period, the cleat and ball undergo substantial displacement together (26.0 ± 2.3 cm). (2) More than 50% of the ball’s speed and at least 30% of its kinetic energy is imparted to the ball without any contribution of the potential energy of the ball deformation. (3) The foot does not decelerate during the contact phase with the ball, despite the fact that forces act from the...
decompressing ball on the foot. This is only possible due to contracting muscles during this phase, which generates force and produces mechanical work (Tsaoisidis & Zatsiorsky, 1996). This led to the author’s conclusion that the soccer kick must be considered a movement that consists of ‘impact-like’ and ‘throwing-like’ components. Similar movements that consist of ‘impact-like’ and ‘throwing-like’ components are the golf swing and the ice hockey slap shot. Both of these examples also consist of elongated contact times, where momentum is transferred between the equipment (club/stick) and the ball/puck. In contrast to golf and hockey, soccer equipment (the cleat) does not bend and store elastic energy prior to contacting the ball. However, the midsole of the cleat does deform during the soccer kick (Hennig & Zulbeck, 1999), which could result in energy storage or dissipation. For clarification, the entire soccer boot or soccer shoe is referred to as the ‘cleat’ throughout this manuscript. The midsole describes the part of the cleat that connects the studs or spikes with the upper material.

In golf, the shaft of the club is bent at the early part of the downswing and then recovers just before impact (Milne & Davis, 1992). Depending on the deflection of the shaft, more or less elastic energy is stored, and can later be released to accelerate the ball (MacKenzie & Spriggins, 2009). The authors showed that clubhead speed was higher in the flexible shaft compared to the stiffer shaft. Greater amount of elastic energy can then be stored in the shaft during the downswing and released at ball contact. This phenomenon follows the principle of energy return, where sports equipment stores elastic energy during deformation, and then can be used to enhance athletic performance when released at the right time, location, and frequency (Nigg, Stefanyshyn & Denoth 2000).

In hockey, the blade of the stick makes contact with the ice prior to the impact with the puck, which initiates stick bending. The stick then recoils when in contact with the puck, which propels the puck forward (Pearsall, Montgomery, Rothsching, & Turcotte, 1999). As with golf clubs, the authors showed that the most compliant hockey stick resulted in the highest shaft deflection during the contact phase, and highest puck speed at release. Again, more elastic energy is stored in the more compliant sticks, and therefore results in greater puck speed upon puck contact, which also follows the principle of energy return (Nigg et al., 2000).

Based on these findings for golf and hockey, it can be speculated that the soccer cleat during a kick can be modelled similarly, where energy is stored in the midsole due to deformation, which could affect ball speed. Previous research has shown that midsoles of soccer cleats experience deformation during maximum effort kicks (Hennig & Zulbeck, 1999). This deformation of the midsole results in greater metatarsophalangeal (MTP) plantarflexion. One way of decreasing the MTP joint deformation is by increasing the midsole bending stiffness of sports shoes (Madden, Sakaguchi, Wannop, & Stefanyshyn, 2015; Oh & Park, 2017; Roy & Stefanyshyn, 2006; Stefanyshyn & Nigg, 2000; Stefanyshyn & Wannop, 2016). A study conducted by Hennig and Zulbeck, (1999) investigated the influence of different midsole stiffness on ball speed. The authors reported differences in specific footwear features, such as peak midsole deformation and peak midsole deformation velocity when performing maximum effort soccer kicks in different soccer cleats. However, no systematic relationship was found between these features and ball speed. The authors reported that this might be due to the fact that the cleats differed in multiple footwear features, and concluded that future studies should use identical shoes, only differing in a single footwear feature (e.g. bending stiffness) to better understand the influence of a specific cleat characteristic on ball speed.

Stefanyshyn and Fusco (2004) introduced the concept of an individualised optimal midsole bending stiffness for sprinting spikes that must be tuned to a given athlete for maximising performance. They found that most sprinters showed the best sprint performance in shoes with increased stiffness, however, if the stiffness was increased beyond a certain threshold the benefits were reversed and resulted in slower sprint times. Similar results were found in distance running (Oh & Park, 2017; Roy & Stefanyshyn, 2006) and a 25-minute continuous field-based soccer protocol (Vienneau, Nigg, Tomaras, Enders, & Nigg, 2016). Mean oxygen consumption rates changed as a function of bending stiffness. Oh and Park (2017) suggested that the optimal bending stiffness for a given athlete would be close to the individual’s MTP joint stiffness at maximum deformation of the joint during the stance phase. Further, they proposed that an increased bending stiffness is beneficial for maximising performance, provided it does not restrict the movement of the MTP joint. These four studies all concluded that midsole bending stiffness can be tuned or optimised to an athlete in order to maximise performance. However, the mechanism for increased ball speed as a function of shoe construction is not well understood.

Therefore, the purpose of this study was to investigate the influence of cleat midsole bending stiffness on the ball speed during maximum effort soccer kicks, and to investigate whether the change in ball speed is related to the amount of deformation of the MTP joint. It was hypothesised that ball speed would be higher in more compliant cleats as more elastic energy can be stored in the midsole of the cleat upon ball contact compared to the stiff cleats. Further, it was hypothesised that the
optimal bending stiffness, i.e. the stiffness in which subjects achieve highest ball speed, would be subject-specific.

Materials and methods

Twenty male subjects (mean ± SD; age: 29.5 ± 5.6 years, height: 175.5 ± 6.4 cm, body mass: 74.3 ± 8.4 kg) participated in this study. Biomechanical testing was performed at the Human Performance Laboratory at the University of Calgary. The study was approved by the University of Calgary Conjoint Health Research Ethics Board: REB16-2046. A commercially available soccer cleat was modified to five different levels of bending stiffness (Figure 1). The bending stiffness was altered by injecting different amounts of plastic material into the midsole during the production process (Table 1).

The kicking foot of each subject was equipped with nine spherical light-reflecting markers with a diameter of 12 mm to capture MTP joint kinematics (Figure 2). The markers were applied by the same researcher throughout the study, and were mounted on the following anatomical landmarks: (1): distal phalanx of the great toe, (2): lateral forefoot, (3): distal head of the 1st MTP, (4): distal head of the 5th MTP, (5): lateral heel, (6): lower heel, (7): upper heel, (8): medial malleolus, (9): lateral malleolus. The measurement setup (Figure 3) consisted of eight high-speed video cameras (Motion Analysis Corporation, Santa Rosa, USA) version 3.6.1.1315, which collected kinematic data at a sampling rate of 240 Hz. Ball speed was measured using a Stalker® Sports radar gun (Applied Concepts Inc., Richardson, USA). Kinematic data were smoothed using a lowpass filter with a cut-off frequency of 8 Hz. The power spectrum for marker trajectories of the forefoot (locations 2, 3 and 4; Figure 2) for 10 randomly selected trials were determined. The cut-off frequency for each trial was determined using the residual analysis (Winter, 2009). The highest frequency of the 10 trials was selected for all kicking trials to reduce the risk of losing information due to a low cut-off frequency. This allowed for an objective method of determining the cut-off frequency.

Subjects were instructed to perform six maximum effort instep kicks in each stiffness condition. The number of trials per cleat was determined using pilot data where subjects performed ten maximum effort soccer kicks. After six trials the mean ball speed did not change more than approximately 2% of the overall mean. The cleat order was randomised to mitigate the risk of fatigue influencing ball speed. The investigators and the subjects were blinded to the stiffness condition. Reflective tape was affixed to the ball, and ball contact was determined as the point in time when the reflection changed position in the anterior direction for the first time during the kick.

For each kick, the change in MTP dorsi-/plantarflexion angle from before ball contact to after ball contact was computed using a custom-made MATLAB script (The MathWorks, Inc., Natick, USA; Version: R2018a). The change in MTP joint angle in the sagittal plane was determined as the difference between the joint angle from one frame before ball contact and the maximum
plantarflexion angle within the first 10 frames (approximately 40 ms) after ball contact. This 40 ms period included the whole contact phase between foot and ball, which has been shown to be approximately 9 ms long (Shinkai, Nunome, Isokawa, & Ikegami, 2009).

Friedman’s test for non-parametric data was used to investigate differences in (1) the change in MTP joint angle and (2) the ball speed between stiffness conditions. The Spearman rank correlation coefficient was determined for each subject individually in order to investigate the relationship between the MTP joint deformation and ball speed. The significance level \( \alpha \) was set to 0.05.

Results
There was no significant difference \( (p = .57) \) in the change in MTP joint angle in the sagittal plane between

![Image](image-url)
the five stiffness conditions (Figure 4). On average, the highest deformation of the MTP joint during the soccer kick was found in the moderately stiff cleat (C3).

Thirteen (out of 20) subjects had the highest ball speed in the two stiffest cleats, C4 and C5 (Figure 5). Four subjects performed best in the second most compliant cleat (C2) and no subject performed best in the most compliant cleat (C1).

When all subjects were pooled, the ball speed did not change significantly ($p = .14$) between stiffness conditions (Figure 6). However, individual differences in ball speed were observed with some individuals performing better in more compliant cleats and others in stiffer cleats (Figure 7).

The correlation coefficients between the change in MTP joint dorsi-/plantarflexion angle from before ball contact to after ball contact and ball speed for each individual ranged from $-0.8$ to $0.4$, indicating no systematic relationship across all subjects. Ten subjects showed a negative relationship, six showed a positive relationship, and four showed no relationship between change in MTP joint dorsi-/plantarflexion angle and ball speed.

Discussion
In golf and hockey, more compliant golf shafts and hockey sticks experience greater deformation when swings or shots are performed (MacKenzie & Sprigings, 2009; Pearsall et al., 1999). Further, the compliant shafts and sticks result in higher shooting speeds compared to the stiffer equipment. A possible explanation is that more elastic energy can be stored in the compliant equipment when bent and then released upon contact with the ball or puck, thus resulting in higher shooting speeds. Similarly, it was speculated that more compliant cleats would deform more, and therefore store and release more elastic energy when performing maximum effort soccer kicks. This would in return, transfer greater energy to the ball, resulting in higher ball speeds, compared to kicks in stiffer cleats. However, this hypothesis was not confirmed because first, the MTP deformation in the compliant cleats was not significantly larger than in stiff cleats, and second, average ball speed did not differ between stiffness conditions. A possible explanation is that the elastic energy stored in the bent midsole cannot be used to propel the ball because ball release is hypothesised to occur prior to the recoil of the midsole.
Figure 8 shows the MTP joint angle in the sagittal plane of one subject during one maximum effort soccer kick. In preparation for ball contact, the subject plantarflexed the MTP joint. Elastic energy was stored in the cleat during phase I because of midsole deformation resulting from contact with the ball. However, this energy cannot be used to accelerate the ball because ball release occurred before the midsole recoiled and had the potential to transfer the stored energy to the ball. Ball release was estimated to occur approximately 10 ms after ball contact, which has been determined by previous researchers measuring foot/ball interaction during the ball impact phase using two ultrahigh-speed cameras (Shinkai et al., 2009). It is speculated that optimal ball release would occur when the MTP joint angle reaches the angle at ball contact (end of phase II), which would allow the midsole to recoil and return the stored elastic energy to the ball. In golf and hockey, the principle of energy return is applied, where elastic energy is stored in the sports equipment due to bending prior to contact with the ball/puck. In soccer, however, the rationale is not the same as the midsole of the cleat is not bent substantially prior to ball contact, but rather during and after ball contact (Figure 8). Therefore, the principle of energy return cannot be applied to the soccer kick. Instead, the principle of minimising energy loss (Nigg et al., 2000) could be more applicable to the soccer kick. Due to the fact that the recoil of the midsole occurred after ball release, the elastic energy stored in the cleat dissipated and was not beneficial to performance. Instead, greater cleat deformation (i.e. C1) was disadvantageous and resulted in lower ball speed. Therefore, the deformation of the MTP joint should be restricted by the footwear, e.g. with increased midsole bending stiffness, in order to achieve higher ball speeds. This was partially supported by the findings. Thirteen out of 20 subjects performed best in the two stiffest cleats, although there was no significant decrease in MTP joint deformation compared to the compliant cleats.

As stated by Barfield (1998), the soccer kick and its performance are influenced by many different factors. This study tried to isolate one of these factors, the midsole bending stiffness, and investigate its direct effect on ball speed. However, there are multiple other variables, e.g. swing limb loading or plant foot forces, which could have affected the outcomes of this study. Those factors have been controlled for as good as possible but it cannot be ruled out that they have played a major role in why no systematic relationship was identified between midsole bending stiffness of soccer cleats and ball speed during maximum effort soccer kicks.

Previous research showed that different individuals perform best in different levels of midsole bending stiffness of sports shoes (Oh & Park, 2017; Roy & Stefanyshyn, 2006; Stefanyshyn & Fusco, 2004; Vienneau et al., 2016). This study showed that optimal midsole bending stiffness, i.e. the bending stiffness that resulted in the highest ball speed, was subject specific (Figure 9). However, MTP joint deformation was not systematically associated with midsole bending stiffness or ball speed. Therefore, future studies should investigate the individual characteristics (e.g. anthropometric or neuromuscular) that relate to improved performance in specific stiffness conditions in order to better understand how to optimise footwear bending stiffness across athletes.

Hennig and Zulbeck (1999) have shown that different shoe models influence ball speed. However, because the soccer cleats used in their study were different on-the-market shoe model brands, they differed in several footwear features, such as midsole stiffness or upper material. Therefore, it is difficult to conclude whether the changes in ball speed occurred due to differences in a specific footwear feature or a combination of multiple footwear characteristics. The current study was the first...
to systematically change one property of a soccer cleat, the midsole bending stiffness, and investigate its effects on ball speed, thereby isolating the effects of a single independent variable on ball speed.

The differences in ball speed between best and worst performing cleats ranged from 2.2 km/h to 9.2 km/h. Only three out of 20 subjects showed statistically significant differences in ball speed between stiffness conditions. Although the number of significant differences was low, an increased ball speed of 2.2 km/h could be a determining factor for whether a goalkeeper is able to reach the ball before it crosses the line (Hennig & Sterzing, 2010). The individuals that showed a significant difference in ball speed between stiffness conditions had lower within-cleat variability.

A major limitation of this study was the low sampling frequency of 240 Hz of the motion capture system resulting in a resolution of 4.2 ms. Shinkai et al. (2009) showed that contact times between foot/cleat and ball are approximately 9 ms using ultrahigh-speed cameras with a sampling frequency of 5000 Hz. This means that the system used in this study would record two data points during the contact phase between foot/cleat and ball. Therefore, it cannot be guaranteed that maximum MTP joint deformation or the points in time where peak ball reaction forces occur during the contact phase were observed.

Another limitation is the use of a radar gun to determine ball speed. All radar guns need to clock objects moving directly at or away from the gun. Clocking at an angle results in erroneous measurements of ball speed. According to the manufacturer of the radar gun that has been used in this study, the measurement error ranges between 0.4% and 29.3% when clocking at an angle of 5 degrees to 45 degrees, respectively. In the current study, the radar gun was placed directly behind the ball, minimising the error. Furthermore, the reflective tape on the ball that was used to determine ball contact was tracked for ten frames after ball contact to calculate ball speed using the motion capture system. The correlation coefficient was determined for 561 kicks (20 subjects × 5 conditions × 6 kicks; 39 trials had to be excluded due to erroneous ball speed measurements using the motion capture system) using ball speeds measured with the radar gun and the motion capture system. The ball speeds were significantly correlated ($R^2$-value = 0.79, $p$-value < .001), which leads to the conclusion that the radar gun can be used to measure ball speed during maximum effort soccer kicks.

According to Shinkai et al. (2009), the foot/cleat deforms the ball without actually displacing it anteriorly during the first 2 ms of ball contact. Due to the low sampling frequency of the motion capture system used in this study, it was not possible to determine this exact point in time. For this reason, MTP joint deformations were determined starting from one frame before ball contact (i.e. 4.2 ms before the ball moves for the first time). This allowed to measure MTP joint angles one frame before ball contact, approximately two frames during ball contact (assuming contact times of 9 ms), and eight frames after ball contact.

Further, impact position was not accounted for. A kick closer to the toes could result in greater deformation of the MTP joint due to impact forces acting further distally to the joint centre. Future studies should try to control for impact position using ultrahigh-speed video analysis.

Conclusion

The midsole bending stiffness of soccer cleats influenced ball speed. Some individuals achieved higher kicking velocities in stiffer cleats while others benefited most from more compliant cleats. This indicates the existence of an optimal midsole bending stiffness that results in higher ball speeds, and therefore needs to be tuned for each individual. The concept of increased energy storage/release in compliant sports equipment (e.g. golf clubs and hockey sticks) was not supported by the findings of this study, which could be due to the complex interaction of the foot/cleat with the ball.

Disclosure statement

No potential conflict of interest was reported by the authors.

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