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ADDING MASS TO THE SHOE DOES NOT AFFECT BALL VELOCITY IN A SOCCER PENALTY KICK

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The aim of this study was to identify the optimum shoe mass that maximizes ball velocity in a soccer instep penalty kick. Two players performed 20–30 maximum-effort penalty kicks while wearing football shoes with lead weights attached to the base of the shoe (total mass: 0.26 – 0.81 kg). The kicks were recorded by a video camera at 100 Hz and a biomechanical analysis was conducted to obtain measures of ball projection velocity and kinematics of the kicking leg. We found that ball velocity was insensitive to shoe mass (at least for the range of shoe mass tested). An important contributing factor to the observed relationship was that the velocity of the kicking foot at ball impact decreased as the mass of the shoe increased. Our result indicates that players should not change their shoes before taking a penalty kick.

KEYWORDS: collision, football, kinematics.

INTRODUCTION: Attaining a high ball velocity is very important in a penalty kick. The faster the player can kick the ball, the less time the goalkeeper has to react to the shot and so the better the chance of scoring a goal. Most players prefer lightweight shoes for field play so as to perform more rapid acceleration runs and to minimize the aerobic demands of running. However, calculations using a collision model of kicking (Daish, 1972) led us to believe that a player might increase ball projection velocity in a penalty kick by changing to a heavier shoe. Our calculations suggest that there might be an optimum shoe mass that is determined by the interplay between the advantage of increased striking mass in the foot-ball collision and the disadvantage of decreased foot velocity when swinging a heavier kicking leg.

The effect of shoe mass on ball velocity in a maximal instep kick was previously investigated by Moschini and Smith (2012). They used video analysis to examine 10 experienced male players who performed kicks while wearing shoes of mass 0.18, 0.26, and 0.36 kg. A heavier shoe reduced foot velocity at impact, but ball velocity was the same for all three shoe conditions. Moschini and Smith used inferential statistics (t-tests) to identify statistically significant differences in group mean values between shoe conditions. However, a single-subject intervention analysis is also an appropriate methodology, especially when studying relatively complex systems such as human movement (Bates, 1996). We suggest that a study of the responses of an individual participant, using a greater range of shoe masses, should lead to a precise knowledge of the form and magnitude of the relationship between shoe mass and ball velocity.

The aim of the present study was to quantify the relationship between shoe mass and the projection ball velocity of the ball in a simulated full-instep penalty kick. Our hypothesis was that there would be an inverted-u relationship, with a clear optimum shoe mass that produces the greatest ball projection velocity.

METHODS: This study used an experimental research design in which the mass of the shoe was systematically varied. Two experienced intercollegiate soccer players volunteered to participate in the study (female participant: 21 years, 1.65 m, 78 kg; male participant: 23 years, 1.91 m, 86 kg). The study adhered to the tenets of the Declaration of Helsinki and was conducted in accordance with procedures approved by our institutional ethics committee. The participants were informed of the protocol and procedures prior to their involvement, and written consent to participate was obtained.

The participants performed 20–30 simulated penalty kicks in still air conditions in an outdoor football facility. The kicks were performed on a 3G artificial grass surface using a FIFA-approved size 5 match ball that was inflated to the regulation pressure. The participants wore tight-fitting clothes and their own football shoes (female participant, Adidas Predator II X;

male participant, Nike CTR360 Trequartista III FG). Colour-contrasted markers were placed on the participant's skin or clothing directly over the joint centres of the shoulder (glenohumeral joint), hip (major trochanter), knee (lateral epicondyle of femur), ankle (lateral malleolus of fibula), and toe (lateral aspect of distal head of fifth metatarsus). Lead weights were attached to the base of the kicking shoe, giving a total shoe mass of between 0.29 and 0.81 kg for the female participant, and between 0.26 and 0.76 kg for the male participant. The participants used a constant run-up length of three steps (about 3 m), and the run-up and kicking action of the kicking leg were in the plane of the flight of the ball. The participants performed maximum-effort kicks while attempting to achieve maximum ball speed. The order of shoe mass was randomized and an unlimited rest interval was given between kicks to minimize the effects of fatigue on performance.

A JVC GR-DVL9600 video camera (Victor Company of Japan, Yokahama, Japan) operating at 100 Hz was used to record the movement of the ball and the participant during the kicks. The video camera was mounted at right angles to the kick direction and the movement space was calibrated with three vertical poles that were placed along the line of the kicking plane. An Ariel Performance Analysis System (Arial Dynamics, Trabuco Canyon, CA, USA) was used to digitize the motion of the participant's kicking leg and the centre of the ball in the video images. Each trial was digitized from one step before the kick to at least 10 frames after the ball broke contact with the foot. The coordinates of the participant and ball were calculated from the digitized data using the two-dimensional direct linear transform (2D-DLT) algorithm. Joint coordinate data were smoothed using a second-order Butterworth digital filter with a cut-off frequency of 10 Hz for the horizontal direction and 12 Hz for the vertical direction, and the velocities of the joint markers were calculated by numerical differentiation of the coordinate data.

The projection velocity of the ball was calculated using unfiltered ball displacement data from images immediately after the ball broke contact with the foot. The horizontal component of the ball velocity was calculated as the first derivative of a linear regression line fitted to the ball displacement data, and the vertical component of the ball velocity was calculated as the first derivative of a quadratic regression line (with the second derivative set equal to –9.81 m/s^2) fitted to the ball displacement data (Nunome, Ikegami, Kozakai, Apriantono, & Sano, 2006). The uncertainties arising from the fitted curves indicated that the uncertainty in ball velocity was about 0.3 m/s (±95% CI).

The participant's kicking technique was quantified with measures of foot velocity at impact, rotational range of motion of the thigh, knee angle at maximum knee flexion, maximum angular velocity of the thigh, and angular velocities of the thigh and shank at impact (Ball, 2009; Linthorne & Patel, 2011; Moschini & Smith, 2012). We also measured the angles of the knee and hip joints and the angle to the horizontal of the shank and thigh segments at the instant of impact. The horizontal velocity of the hip at touchdown of the support leg was taken as a measure of the participant's run-up velocity. In this study the greatest source of uncertainty in the kick technique variables arose from the sampling frequency of the video camera (Hay & Nohara, 1990). The uncertainties were: foot velocity, 1.5 m/s; run-up velocity, 0.3 m/s; segment angle or joint angle, 7 deg; and segment angular velocity or joint angular velocity, 60 deg/s.

The ball velocity and kicking technique variables (y) were plotted as a function of the mass of the shoe (m). A straight line, $y = bm + c$, and an inverted-u function, $y = y_{opt} – a(m – m_{opt})^2$, were fitted to the data (Linthorne & Patel, 2011). The most appropriate curve for the data was decided by examining the distribution of the residuals and with calculations of Akaike's Information Criterion (Motulsky & Christopoulos, 2004).

RESULTS: For ball velocity, we could not reliably distinguish between a linear relationship and an inverted-u relationship as the best fit to the data. Neither participant exhibited a clear optimum shoe mass (Figure 1a). The curvature of the inverted-u fit was zero (female, a = 8 ± 11 m/s per kg^2; male, a = 10 ± 13 m/s per kg^2; ±95% CI), and the gradient of the linear fit was zero (female, b = –0.7 ± 1.7 m/s per kg; male, b = –1.6 ± 3.3 m/s per kg). For the inverted-u fit, the difference in ball velocity between the calculated optimum shoe mass (female, m_{opt} =

0.50 ± 0.12 kg; male, m_{opt} = 0.44 ± 0.14 kg; ±95% CI) and the participant's normal shoe mass was not substantially different from zero (female, 0.5 ± 2.2 m/s; male, 0.3 ± 1.3 m/s; ±95% CI). Across all kicks the average ball velocity was 20.5 ± 0.5 m/s (mean ± SD) for the female participant and 21.6 ± 0.5 m/s for the male participant.

The participants displayed the characteristic whip action of the kicking leg, where the thigh angular velocity at impact was close to zero and the shank angular velocity reached a maximum at close to the instant of impact (Figure 1b). Most of the kick technique variables (run-up velocity, maximum thigh angular velocity, thigh angular velocity at impact, thigh and shank angle at impact) were independent of shoe mass. However, as shoe mass increased, the participants had a reduced range of motion in the knee joint during the swing of the kicking leg (because the minimum knee angle increased), and showed a linear decrease in shank angular velocity at impact. The decrease in shank angular velocity was reflected by a decrease in foot velocity (Figure 1a).

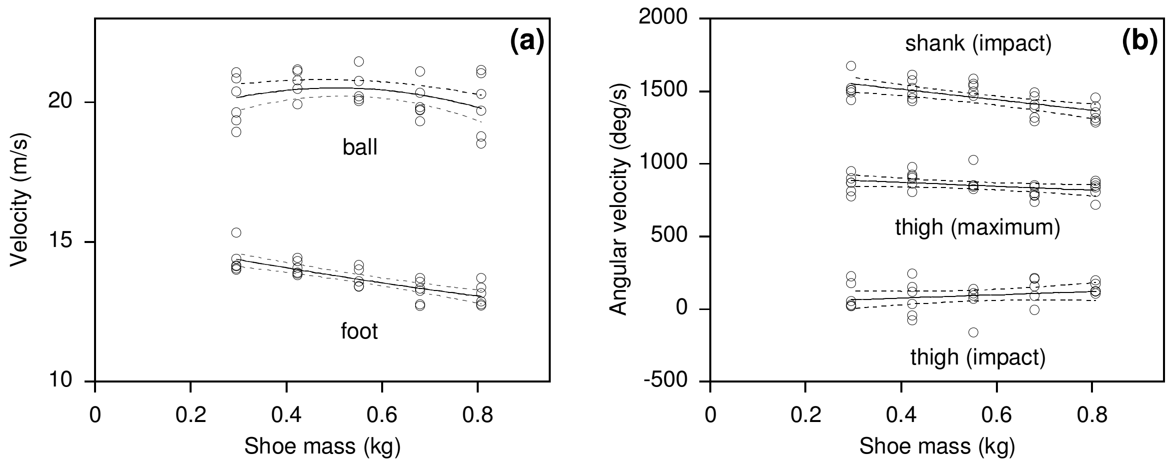

Figure 1: Plot (a) shows that the projection velocity of the ball was insensitive to shoe mass (female participant). Plot (b) shows that the maximum thigh angular velocity and the thigh angular velocity at impact were not affected by the mass of the shoe, but shank angular velocity at impact decreased with increasing shoe mass. The decrease in shank angular velocity was reflected by a decrease in foot velocity. The solid lines are the regression fits and the dashed lines show the 95% CI of the regression curve.

DISCUSSION: Kicking involves the transfer of momentum from the player to the ball. According to the collision model proposed by Daish (1972), the projection velocity of the ball is determined by the impact velocity of the player's foot, the effective mass of the player's foot, and the amount of energy that is dissipated during the collision. Our calculations with this model indicate that shoe mass should increase ball velocity at a rate of 0.5 – 5.5 m/s per 1 kg increase in shoe mass, depending on the strength of the mechanical coupling of the foot to the lower leg. However, these calculations are for a constant foot velocity at impact. Increasing the mass of the shoe reduces the foot velocity the player is able to generate in the swing. Several studies have found that ball velocity decreases at a rate of about 1.3 m/s per 1 m/s decrease in foot velocity (Bull Anderson, Dörge, & Thomsen, 1999). Overall, there should be an optimum shoe mass that is determined by the interplay between the advantage of increased striking mass in the foot-ball collision, and the disadvantage of decreased foot velocity when the swinging a heavier kicking leg.

The rate of decrease in foot velocity observed in the present study (2.6 m/s per 1 kg increase in shoe mass) should have produced a rate of decrease in ball velocity of about 3.4 m/s per kg. However, in the present study we found that ball velocity was independent of shoe mass. This result indicates that increasing the effective striking mass in the foot-ball collision produces an increase in ball velocity of about 3.4 m/s per kg. A rate of increase in ball velocity of this magnitude indicates that the mechanical coupling of the foot to the leg is relatively weak. The effective striking mass (1.4 kg) calculated from the collision model is similar to the actual combined mass of the foot and the shoe (1.5 kg), and thus indicates there is little or no contribution to the effective striking mass from the shank or thigh segments.

In this study we did not monitor the location of the impact point of the ball on the foot. However, changes in ball velocity are expected to be small (less than about 1.5 m/s) for changes in impact position of less than 5 cm (Ishii, Yanagiya, Naito, Katamoto, & Maruyama, 2012). In this study we did not monitor the position of the support leg, movements of the upper body, or 3D motions of the kicking leg out of the plane of the flight of the ball. Therefore, we cannot exclude the possibility that the observed relationship between shoe mass and ball velocity was affected by systematic changes in these factors.

A limitation of our study is the use of only two participants, and so the results we obtained might be idiosyncratic. However, we observed measures of kicking technique that were similar to those obtained in other studies of male and female players (Ishii et al., 2012; Nunome et al., 2006; Sakamoto & Asai, 2013; Shinkai, Nunome, Isokawa, & Ikegami, 2009). Therefore, it appears likely that the results from the present study would apply to other adult male and female players of similar standard.

CONCLUSION: We found that ball velocity in an instep penalty kick is insensitive to the mass of the shoe (at least for shoes with mass between 0.26 and 0.81 kg). This result suggests that players should not change their shoes before taking a penalty kick.

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