Paper : Biomechanics

Biomechanical Differences Between Toe and Instep Kicking - Influence of Contact Area on the Coefficient of Restitution

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The coefficient of restitution (COR) was determined for toe and instep soccer kicks. Furthermore, experiments were performed with a pendulum that modeled the different impact areas in toe and instep kicking. Six sub-elite soccer players performed 20 toe and 20 instep kicks with no run-up at a range of velocities. The path of the foot and ball were recorded using a high-speed video camera (240 Hz) and manually digitized. The velocity of the pendulum and the velocity of the ball were determined using an opto-electrical system (500 Hz). The COR is the ratio between the foot/pendulum and ball velocity before and after impact. In the pendulum experiments the COR was larger for the small area (Toe) at all velocities, whereas this only was found at the lower velocities (< ~15 m s^{-1}) in the human experiments. In both experiments the COR dropped with increased impact velocity. The different impact areas in the two types of kicks might explain why it is advantageous to perform a toe kick if aiming at producing the highest possible ball velocity. However, this advantage is lost at higher velocities, possibly because, in toe kicks, it is not possible to keep the foot aligned.

Keywords: Kicking, Soccer, Toe, Instep, Coefficient of Restitution

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1. Introduction

In all soccer kicks, the velocity of the ball after impact is determined by the velocity of the foot before impact, the effective striking mass of the foot and the coefficient of restitution (COR) of the impact (Plagenhoef 1971; Bull Andersen, et al., 1999). The COR in soccer kicking describes the transfer of momentum from the foot to the ball during the impact phase. The factors determining the COR are the mechanical properties of the foot and ball, i.e. stiffness, contact area and contact point. Furthermore, the COR, when recording the motion with only one camera (i.e. two-dimensional analyses), is affected by the direction of the path of the foot before impact and the path of the ball after impact.

The most widely studied soccer kick is the instep kick (Lees and Nolan 1998, Dörge, et al., 1999, Nunome, et al., 2006, Apriantono, et al., 2006) while only one study has investigated the toe kick (Tsaousidis & Zatsiorsky 1996). The main difference between these types of kicking is the orientation of the foot during impact. This affects the moment of inertia of the shank-foot segment about the knee joint, but does not seem to affect the movement strategy of the whole leg. The different orientations of the foot cause the ball, i.e. when contacted by the toe, to apparently be contacted by a smaller area.

A few attempts have been made to quantify the COR in kicking (Plagenhoef 1971; Zernicke and Roberts 1978; Bull Andersen, et al., 1999); however, most studies on the COR, have been performed on smaller balls traveling at much lower velocities (Cross 1999; Cross 2000; Hubbard and Stronge 2001). No attempts have been made to investigate the effect of changing the impact area on the COR, and correspondingly relating the impact area to which part of the foot hit the ball in soccer kicking.

The aim of the present study was to investigate the

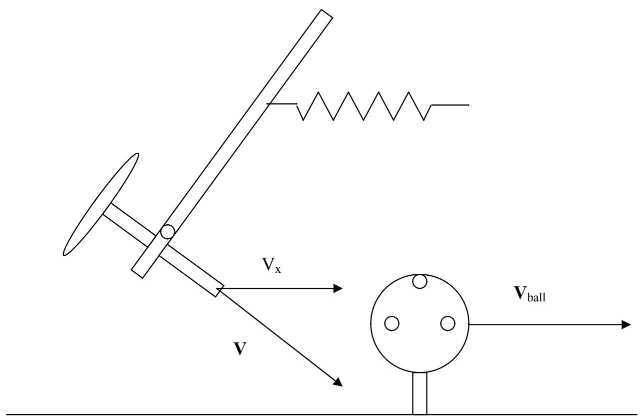

Figure 1 A model of the pendulum used in the experiments. The pendulum could be turned so that either a rod with a diameter of 0.03 m or a plate with a diameter of 0.25 m could impact the ball. Three spherical markers were glued to the surface of the ball. The vectors indicate the velocity of the pendulum and the velocity of the ball. The vectors V (velocity) and V_x (horizontal velocity) are equal at the time of impact.

mechanical differences of the impact in soccer kicks with the toe and the instep through two experiments: (A) a pendulum experiment designed to investigate the influence of different impact areas on the COR and (B) a kicking experiment where human subjects performed toe and instep kicks at different velocities.

2. Methods

2.1. Pendulum experiments (A)

A pendulum was constructed, that modelled toe and instep kicks (**Figure 1**). Two metal springs (spring constant = 2560 N m^{-1}) were attached to the pendulum 0.3 m from the axis of rotation. The springs were attached so that they reached slack length before the pendulum reached vertical position; accordingly, the springs applied no force on the pendulum just before and during the impact period. The end of the pendulum consisted of one piece of metal with a rod with a diameter of 0.03 m in one end and a plate with a diameter of 0.25 m in the other end. These two ends could be swapped so that either the rod (small area) or the plate (large area) could hit the ball (**Figure 1** shows the ball being hit by the rod). This ensured that the moment of inertia of the pendulum was equal in the two types of impacts. The mass of the pendulum was 15.5 kg and the center of mass was at a distance of 0.44 m from the axis of rotation. The distance between the impact points and the axis of rotation was 0.87 m. The moment of inertia of the pendulum was determined experimentally (I = 5.02 kg m^2) by letting the pendulum oscillate with small amplitude and then observing its frequency (Young and Freedman 1996).

One reflective spherical marker was placed on the end of the pendulum and three spherical markers were placed on the ball. The three-dimensional motion of the markers was recorded with a three camera opto-electronic system operating at a frame rate of 500 Hz (ProReflex, Qualisys Medical AB, Sweden). The geometrical centre of the ball was calculated from the positions of the three markers placed on the surface of the ball. Furthermore, the rotational velocity (spin) of the ball was calculated. A FIFA (Fédération Internationale de Football Association) approved ball (size 5, mass 0.44 kg, pressure 0.9 bar) was used in all experiments.

The beginning of the impact was determined as the first frame after the frame where the pendulum was vertical. It was ensured, that this frame corresponded to the last frame before the ball showed a clear positive acceleration. The velocity of the ball after impact was calculated as the average velocity of 10 frames starting 20 ms after the beginning of the impact. Displacement data from the pendulum from the instant at which its marker was visible to the cameras (approximately at an angle of 45 degrees) until the last frame before the beginning of the impact was filtered using a digital fourth-order Butterwoth low-pass filter (15 Hz, determined by residual analysis) with zero degrees phase lag (Winter 1990). The ends of the signal were extrapolated before filtering by reflection both for the horizontal and vertical direction, so that the slopes of the original and extrapolated sequence were matched at the end-point (Tanabe & Ito 2007). After filtering, the extrapolated sequences were removed. From the filtered displacement data, the linear velocity of the end of the pendulum was derived by finite difference computation. The velocity of the contact points on the pendulum at the last frame before impact was then calculated from the angular velocity of the marker about the axis of rotation of the pendulum.

The spin of the ball was below 6 rad s^{-1} (~2 revolutions per second) in all experiments, hence the rotational kinetic energy of the ball after impact could be neglected and the impact considered one-dimensional. The rotational kinetic energy of the ball was below 0.45% of the total kinetic energy of the ball in all trials. Furthermore, there was no significant difference in the magnitude of the spin between impacts with the large and the small area.

Accordingly, the coefficient of restitution was calculated from the following expression (Bull Andersen, et al., 1999):

$$V_{ball} = \frac{V_{pendulum} \cdot I_{pendulum} \cdot (1 + e)}{I_{pendulum} + m_{ball} \cdot r^2} \qquad (1)$$

where V_{ball} is the velocity of the ball after impact, $V_{pendulum}$ is the velocity of the pendulum before impact, $I_{pendulum}$ is the moment of inertia of the pendulum, e is the coefficient of restitution (COR), m_{ball} is the mass of the ball and r is the distance between the axis of rotation of the pendulum and the contact point on the pendulum.

A series of six experiments were conducted, ensuring a range of pendulum velocities from approximately 2 m s^{-1} to 11 m s^{-1}. Ten trials were recorded for each condition (small or large area) at each velocity.

2.2. Kicking experiments (B)

Six sub-elite soccer players (23-29 years, 1.73-1.87 m, 63-87 kg, practicing 4 times per week, belonging to the 4th and 5th Danish league) kicked 20 toe kicks and 20 instep kicks with no run-up in an indoor gym. The subjects were wearing indoor soccer shoes, basically corresponding to outdoor soccer shoes but with a rubber sole instead of cleats. Each subject was free to wear his own shoes; the mass of each shoe was measured to enable calculations of the moment of inertia of the lower leg and foot. The average mass of the shoes was 0.31 kg (SD=0.02). In accordance with the local ethics committee, the subjects provided informed consent before participating in the study.

The subjects were instructed to kick the ball as hard as possible for five times with either the toe or the instep. The order was randomised. Before the next five kicks the subject was instructed to shorten his execution time. In the third series of kicks, the execution time was further shortened and in the fourth series of kicks the subjects were instructed to kick the ball as quickly as possible (minimizing the execution time). The execution time was defined as the period from when the kicking foot was lifted off the ground until it hit the ball. The execution times in the four groups were 0.51 s (SD=0.07), 0.41 s (SD=0.06), 0.34 s (SD=0.07) and 0.25 s (SD=0.06). This lead to a range of ball velocities after impact from 11.5 m s^{-1} to 22.2 m s^{-1}, with five kicks in each series.

A high-speed camera operating at a frame rate of 240 Hz (JVC DV 9700, JVC, USA) was placed 11 m from and perpendicular to the sagittal plane of motion. Reflective markers were placed laterally on the kicking leg, corresponding to the estimated axis of rotation of the ankle joint and the fifth metatarsophalangael joints, i.e. the lateral malleolus and the distal head of the fifth metatarsus. The position of the markers and the centre of the ball were digitized using APAS (Ariel Performance Analysis System, Ariel Dynamics Inc, CA, USA).

To determine the foot velocity before impact, the same filtering procedure as in the pendulum experiments was performed on the markers on the toe and ankle. The velocity of the foot was calculated as the velocity of the centre of mass of the foot, at the mid-point between the two markers (Winter 1990). The velocity of the ball was calculated as the average of the velocity during 6 frames after impact. The COR was calculated based on the same standard formula adapted to soccer kicking experiments as is used for the pendulum experiments (Equation 1).

3. Statistics

In both pendulum and human kicking experiments, the COR date were divided into groups according to the pendulum and foot velocity before impact (six groups in the pendulum experiments and four groups in the kicking experiments). These data sets were compared in each experimental condition using two-way analysis of variance (ANOVA) and a Tukey’ s post hoc test at the 5% significance level

4. Results

(A) pendulum experiments: **Figure 2** shows the velocities of the pendulum and the resultant ball velocities for the two groups. For the impacts between the pendulum and the ball, the COR was significantly lower for velocities of the pendulum of ~6 m s^{-1} and above compared to the lowest velocity, ~2 m s^{-1} (p<0.01) (**Figure 3**). This was consistent for impact both with the small area and the large area. It was found that there was a significant (P<0.001) difference for the COR between the impact of the

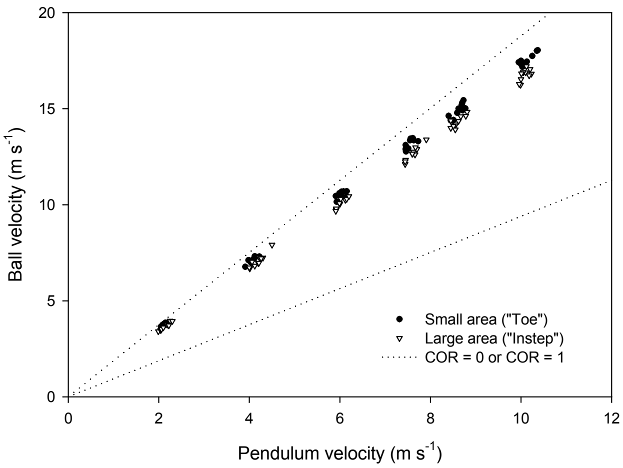

Figure 2 Graph of the velocities of the pendulum and the corresponding velocities of the ball. The dotted lines are plotted to illustrate how this relationship would look if the impact was completely inelastic (COR=0) or completely elastic (COR=1).

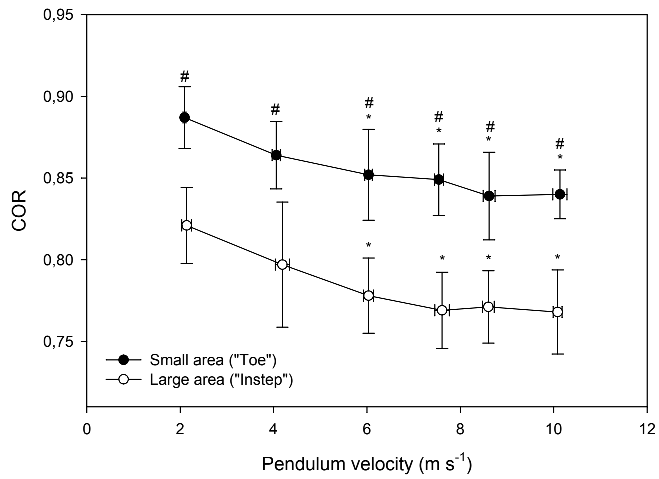

Figure 3 COR in the different groups in the pendulum experiments. The bars indicate the standard deviation. # indicate a significant difference between the small and large area conditions and * indicate significant difference from the trials with the lowest velocity in each condition.

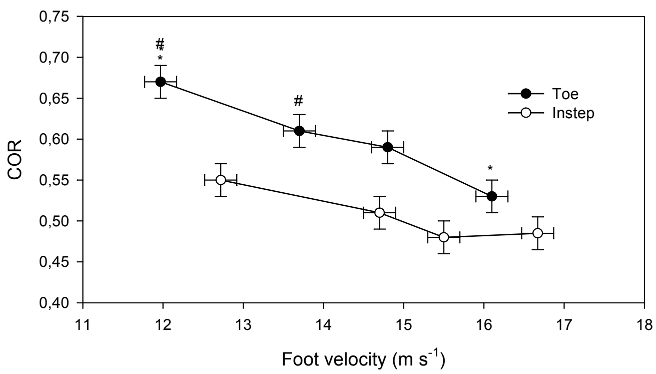

Figure 4 COR in the different groups in the kicking experiments. The bars indicate the standard error of the mean. # indicate a significant difference between toe and instep kicking and * indicate significant difference from the kicks with the lowest velocity in each condition.

small area and that of the large area for all velocity conditions (**Figure 3**).

(B) kicking experiments: The COR was significantly larger than that of the instep kicks in two conditions with shorter execution time (corresponding foot velocity < 15 m s^{-1}) (p<0.001, **Figure 4**). For the instep kicks no statistically significant influence of foot velocity on COR was found. However, for the toe kicks, the COR was found to be larger for the kicks with the lowest foot velocity (11.9 m s^{-1}) compared to the highest foot velocity (16.1 m s^{-1}) (p<0.01).

5. Discussion

A comparison of the COR in the pendulum experiments and the human kicking experiments revealed a considerable difference. This, however, is what would be expected when comparing impacts including a stiff metal rod and a ball to impacts involving a compliant foot and a ball.

A ball that meets the FIFA requirements should bounce to 1.35 m (+- 0.02 m) when dropped from 2 m onto a concrete floor. This corresponds to a COR of approximately 0.82, which is in agreement with the results obtained in the pendulum experiments. Previous measurements of the COR suggest that the COR is between 0.50 and 0.65 for human kicking motions (Reilly 1996; Enoka 1994), which is also in agreement with the present results. The difference between the pendulum experiments and the human kicking experiments can be explained by differences in stiffness of the foot and metal rod; the combined foot and ankle stiffness is lower than that of the metal pendulum.

In the present study, an attempt was made to determine the mechanical differences between the toe and instep kicks. There are two main differences between these two types of kicks corresponding to the different orientation of the foot during ball contact: (a) a different area of the foot is in contact with the ball and (b) the stiffness of the foot and ankle joint are not likely to be equal. Accordingly, the pendulum experiments were performed to investigate only a change of impact area, while keeping everything else equal. This experiment is, of course, not directly comparable to the human kicking experiments, but allows us to tell whether or not a difference in contact area has any influence on the human kicking mechanics.

The results from the pendulum experiments (A) showed that changing the impact area had a significant effect on the COR. The COR was higher for the smaller impact area at all velocities. Hence, everything else being equal, we suggest that ball velocity would be maximized by hitting the ball with a smaller area. A similar pattern was observed for the human kicking motions at low velocities. At high velocities, there was no difference in COR between the toe and the instep kicks. Accordingly, we suggest that for the human kicking motions at high velocities, a stiff pendulum cannot model the foot. In toe kicks, the line of action of the impact force on the foot is directed approximately towards the ankle joint. If there is a small misalignment to the left or to the right between the ankle joint and the contact point on the foot, then a torque about a vertical axis is created. At high impact velocities the contact force is large and, accordingly, a large torque is created. At some level of impact force, this torque would be larger than the stabilizing muscle torque and then the foot will rotate about its vertical axis. Hence, we speculate that the stiffness of the foot and ankle in the toe kicks were insufficient to keep the foot aligned during ball impact at higher velocity conditions. This may be a reason why the difference of the impact area does not cause a difference in the COR at these velocities. In contrast, in instep kicks, the ankle joint is fully plantar flexed and becomes more stable when more force is applied to the instep.

Accordingly, the results from the two types of kicks suggest that, when the foot velocity is below a certain critical velocity (approximately 15 m s^{-1}), it is advantageous to perform a toe kick if the aim is to produce the highest possible ball velocity. In game situations this could, for instance, occur when a strikers' run up and/or kick execution time is restricted by the opponents' defensive players.

A smaller impact area causes a higher COR. This occurs as a result of a changed ball-surface bending stiffness. Less energy would be lost when the surface of the ball is more compliant. In a previous investigation, a ball was dropped from the same height onto two different sized impact areas (Bull Andersen, et al., 2005). The contact force-time profiles showed that the ball-stiffness when impacting the smaller area was approximately half that of impacts between the ball and the larger area. (Bull Andersen, et al., 2003). Correspondingly, the collision period was about twice that of impacts on the large area. In general, the energy loss in collisions increases with larger bending stiffness of the surface of the ball (Cross 2000). The bending stiffness would be larger when impacts occur between a ball and a large area, and hence, corresponds to a lower COR.

6. Conclusions

It can be concluded that the size of the impact area plays a significant role in determining the coefficient of restitution (COR). In the pendulum experiment, conducted in the present study, showed that the COR would be higher when the ball was hit by a smaller area. In the human kicking experiment, the toe kicking was found to be more efficient to transfer the momentum to the ball at low velocities (<15 m s-1) than the instep kicking. However, there observed no differences for the COR between the toe kick and the instep kick at high velocity (>15 m s-1) in which lower stability of the foot during the toe kicking can be considered as a main reason for this phenomenon.

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