The biomechanics of kicking in soccer: A review

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Abstract

Kicking is the defining action of soccer, so it is appropriate to review the scientific work that provides a basis of our understanding of this skill. The focus of this review is biomechanical in nature and builds on and extends previous reviews and overviews. While much is known about the biomechanics of the kicking leg, there are several other aspects of the kick that have been the subject of recent exploration. Researchers have widened their interest to consider the kick beginning from the way a player approaches the ball to the end of ball flight, the point that determines the success of the kick. This interest has encapsulated characteristics of overall technique and the influences of the upper body, support leg and pelvis on the kicking action, foot–ball impact and the influences of footwear and soccer balls, ball launch characteristics and corresponding flight of the ball. This review evaluates these and attempts to provide direction for future research.

Keywords: *Kicking, biomechanics, technique, soccer*

Introduction

Kicking is the defining action of soccer (also known as association football or simply football in many countries), so it is appropriate to review the scientific work that provides the basis of our understanding of this skill. The focus of this review is biomechanical in nature, as it is advances in biomechanical methods in recent years that have made an impact on our understanding of the kicking skill. This review focuses on soccer but more specifically it focuses on the kicking of a stationary ball, as most of the published research emanates from this variant of football and type of kick.

Previous reviews and overviews (Barfield, 1998; Kellis & Katis, 2007; Lees & Nolan, 1998) have considered mainly the kicking leg, and the kinematic, kinetic, and electromyographic characteristics of its segments, joints, and muscles. While much is known about the biomechanics of the kicking leg, there are a number of other aspects that have been the subject of recent exploration. Researchers have widened their interest to consider the characteristics of overall technique and the influences of the upper body, support leg and pelvis on the kicking action. In addition, there is now more information available concerning foot–ball impact, the influences of footwear on foot–ball impact and the corresponding launch and flight characteristics of the ball. This review considers the kick in its entirety beginning from the way a player approaches the ball to the end of ball flight, the point that determines the success of the kick.

The intention of this review is not only to evaluate recent research as it impacts on our understanding of factors that affect performance, but also to provide directions for future research.

Kicking technique

The approach

Skilled players performing an instep kick approach the stationary soccer ball from an angle to the direction of ball flight, at a distance of a few steps, and make a curved approach to the ball. An angled approach is favoured by players and self-selected approach angles around 43° have been reported by Egan and colleagues (Egan, Vwerheul, & Savelsbergh, 2007), supporting previous research that

found an approach angle of around 45° generated maximum ball speed (Isokawa & Lees, 1988). Players also prefer to use an approach distance that requires them to take a small number (2–4) of steps. An approach of this type generates a modest approach speed of around 3–4 m · s^{-1} (Kellis & Katis, 2007; Lees, Kershaw, & Moura, 2005). Thus the nature of the approach appears to be important for performance.

The length of the last stride or step is important in maximal kicking. Stoner and Ben-Sira (1981) reported a longer last stride length when professional players performed a long-range kick (1.69 m) compared with a medium-range kick (1.50 m). Lees and Nolan (2002) reported a larger last step length for two professional players performing a maximal instep kick (0.72 and 0.81 m) compared with a sub-maximal kick (0.53 and 0.55 m). They associated the greater length of the last step with a greater degree of pelvic retraction, which in turn allowed a greater range for pelvic protraction (i.e. forward rotation of the kicking side).

The approach path made by skilled players is curved (Marqués-Bruna, Lees , & Grimshaw, 2007) and as a consequence the body is inclined towards the centre of rotation. It is likely that the purpose of the curved run is to ensure the body produces and maintains a lateral inclination as the kick is performed. One reason is that the inclined kicking leg foot is more able to get under the ball to make better contact with it (Plagenhoef, 1971). A second reason is that a more inclined lower body would allow a more extended kicking leg knee at impact and thus a higher foot velocity. A third reason is that a curved approach provides a stable position for executing the kick, thus contributing to the accuracy and consistency of kick performance (Lees, Steward, Rahnama, & Barton, 2009).

The support leg and pelvis

Lees and Nolan (1998) reported that the placement of the support foot had received little interest in the research literature and this issue has not been addressed subsequently. The authors of this review have identified no recent research that has reported data on this issue, even though it is known to be important to the type of kick produced.

The ground reaction forces made as the support foot contacts the ground have been reported for a maximal instep kick as 15–20, 4–6, and 5–6 N · kg^{-1} in the vertical, posterior (braking), and lateral (towards the non-kicking side) direction respectively (Kellis, Katis, & Gissis, 2004; Lees et al., 2009) but slightly higher values have been reported by Orloff et al. (2008). In particular, all three studies showed that the horizontal forces are directed solely in the

posterior and lateral (to non-kicking side) directions. These force data, together with the reduced velocity of the hip after support foot contact, suggest that the motion of the body is slowed during the kicking action. This slowing may have benefits for stabilizing the action, enabling greater muscle forces to be produced, or to influence the kicking leg action. To date, there has been no adequate investigation of these possibilities.

The support leg knee is flexed to 26° at foot contact and remains flexed throughout the duration of the kick, being flexed to 42° at ball contact (Lees et al., 2009). The flexion of the knee continues for longer than necessary to absorb the impact of landing and is a cause of the slowing forward motion. It begins to extend just before ball contact (Lees et al., 2009) stabilizing the action, as the slow contraction velocity of the muscles around the support leg knee enables these muscles to generate their highest forces.

Kinetic data for the joints of the support leg during kicking are sparse. Lees et al. (2009) reported flexion/extension joint moments during a maximal instep kick performed by skilled players of 4.0, 3.2, and 2.2 N · m · kg^{-1} for the hip, knee, and ankle joint respectively. The values for the knee and ankle are considerably larger than those for the kicking leg (reviewed by Kellis & Katis, 2007) and may be the cause of bilateral strength differences noted in players (Rahnama, Reilly, Lees, & Graham-Smith, 2003).

The body is inclined backwards to the vertical and laterally to the non-kicking side at ball contact, although researchers have reported only on the angulation of the trunk and shank segments. With regard to the trunk, Prassas and colleagues (Prassas, Terauds, & Nathan, 1990) reported a backward lean of 13° and 17° in skilled players performing a low and high trajectory kick respectively. Lees and Nolan (2002) reported a backward lean of 12° and 0° and lateral inclinations to the non-kicking side of 10° and 16° at ball contact for two professional players performing a maximal instep kick. In collegiate level players, Orloff et al. (2008) reported trunk backward lean of 3° and 13° and a lateral lean of 3° and –8° in males and females respectively, the negative sign indicating that the males were leaning to the kicking side. With regard to the support leg shank, a lateral angle to the vertical of 25° was reported by Orloff et al. (2008), which did not differ between the sexes. It appears that the support leg is inclined further to the non-kicking side than the trunk, leading to lateral flexion between the two segments.

The pelvis is retracted before support foot contact and protracts through a significant range of motion to ball impact. Mean ranges of rotation for pelvic retraction to protraction at ball contact in skilled

players have been reported as 30° and 36° (Lees & Nolan, 2002; Lees et al., 2009; Levanon & Dapena, 1998). Although none of these studies established maximal ranges of motion at the joints, it is likely, given the good agreement in these data, that skilled kickers use a maximal or close to maximal pelvic range of motion. Levanon and Dapena (1998) and Lees et al. (2009) have also reported on pelvic tilt and obliquity. Regarding tilt, the pelvis at kicking foot take-off was orientated forwards (17° and 25° respectively) and then moved backwards to have a backward orientation (10° and 20° respectively) at ball contact. Regarding obliquity, the pelvis at kicking foot take-off was lowered on the kicking side (2° and 3° respectively) and then elevated on the kicking side (15° and 10° respectively) at ball contact. This raising of the pelvis on the kicking leg side, together with the inclination of the lower body, would allow greater kicking leg knee extension and hence foot speed at contact. The data of Lees et al. (2009) indicate two further things. First, the obliquity of the pelvis changed little between support foot contact and ball contact, suggesting a stable pelvis in the medio-lateral direction, which would be beneficial to the precision of foot impact position on the ball. Second, a rapid change in pelvic tilt and rotation was found just (around 50 ms) before ball contact, suggesting that muscles are acting to increase the rotational speed of the pelvis in these two directions. This in turn would influence the dynamics of the kicking leg but to date this interaction not been investigated.

The kicking leg

The kicking leg has been studied widely and recent reviews (Barfield, 1998; Kellis & Katis, 2007; Lees & Nolan, 1998) have provided a good account of the kinematic and kinetic data associated with this limb. It is worth noting that despite a wide acknowledgement that the kick is three dimensional (3D) in nature, relatively few 3D studies have been conducted and relatively limited kinematic data in the abduction/adduction and internal/external axes are available. There is no normative data and little statistical information available for these important descriptive variables.

Many studies have reported a reduction in angular and/or linear velocity of the kicking leg immediately before ball impact (Barfield, 1995; Dörge, Andersen, Sorensen, & Simonsen, 2002; Lees, 1996, Lees & Nolan, 1998; Teixeira, 1999). A robust relationship exists between the foot swing velocity and the resultant ball velocity (Asami & Nolte, 1983; Barfield, 1995; Levanon & Dapena, 1998; Nunome, Ikegami, Kozakai, Apriantono, & Sano, 2006a). This implies that to achieve maximal performance, the

energy generated before ball contact should not be reduced. The nature of the leg swing observed by many in the final phase of kicking has left an enigma that has been interpreted by some as a motor control strategy to "enhance accuracy" (Teixeira, 1999). In contrast, coaches often advise players to "kick through the ball". In an attempt to address this conflict, Nunome and colleagues (Nunome, Lake, Georgakis, & Stergioulas, 2006b) reported representative kinematics of the soccer instep kick using advanced technology, which included high sampling rates (1000 Hz) and a new filtering procedure (time-frequency filtering). They found that the shank was still accelerating until ball impact (Figure 1), which was very different than that reported previously. They also succeeded in reproducing the typical reduction in shank angular velocity before impact by down-sampling of the data (to 250 Hz) and applying a conventional filter with low cut-off frequency (10 Hz). These results provided new evidence supporting the above practical instruction from a biomechanical perspective, thereby helping to fill the gap between coaching practice and biomechanical research.

Kinetic data, represented by joint moments, have been of interest for some time with two-dimensional (2D) flexion/extension moments widely reported (for a summary, see Kellis & Katis, 2007). Nunome and colleagues (Nunome, Asai, Ikegami, & Sakurai, 2002) were the first to report full 3D joint moments (i.e. for the abduction/adduction and internal/external axes) for the kicking leg. Further 3D joint
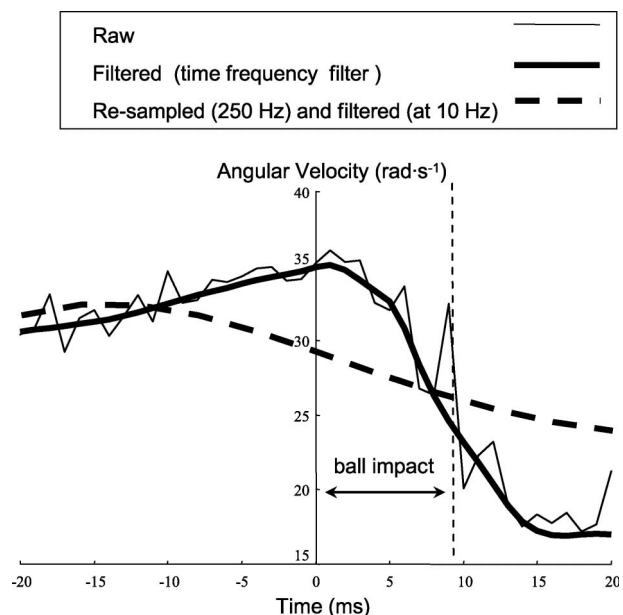

Figure 1. Comparison of changes in angular velocity of the shank through ball impact computed from three different filtering and sampling techniques: (1) raw, (2) applied time-frequency filter, and (3) re-sampled (250 Hz) and applied conventional filter at 10 Hz. Reprinted with permission from Nunome et al. (2006b).

moment data for the kicking leg have been reported recently by Kawamoto and colleagues (Kawamoto, Miyagi, Ohashi, & Fukashiro, 2007), who attributed the better performance of experienced players to their greater hip joint moments (hip flexion, adduction, and external rotation were 168, 100, and 41 N · m respectively) compared with inexperienced players (94, 115, and 26 N · m respectively).

Inconsistencies between the joint moment and the segmental motion (e.g. a flexor moment at the knee joint while the knee extends) have been reported (Luhtanen, 1988; Nunome et al., 2002; Robertson & Mosher, 1985). Barfield and colleagues (Barfield, Kirkendall, & Yu, 2002) referred to this unique phenomenon as the ''soccer paradox'', associated with ''Lombard's paradox'' (Gregor, Cavanagh, & LaFortune, 1985) found in the early years of the last century for a standing movement from a chair. However, from another point of view, this paradox implies that kinetic sources other than muscle moments are partially responsible for the distinctive pattern of segment motion during kicking. Putnam (1991) was the first to reveal the substantial influence of the ''motion-dependent'' moment on soccer kicking. Dörge et al. (2002) applied Putnam's procedure to soccer instep kicking and quantified the amount of work done by the motion-dependent moment due to the thigh angular velocity. This corresponded to 20% of the work done by the knee extension moment.

These studies markedly improved our understanding of the effectiveness of segmental interaction in kicking. However, they did not acknowledge the interference of ball impact on the change of moments just before ball impact. As mentioned earlier, the change of joint moments near ball impact are very sensitive to data treatments. To date, the study by Nunome et al. (2006a) is the only one to have addressed such issues using reasonable data treatments and clearly demonstrated the detailed time-series changes of both joint and motion-dependent moments simultaneously. In their study, the knee extension moment rapidly decreased during the final phase of kicking and finally began to exhibit a reverse (flexion) moment immediately before ball impact, while the motion-dependent moment rapidly increased to exhibit an extension moment at ball impact (Figure 2). It is possible that the motion-dependent moment helps to compensate for the inhibition of the muscle moment, thereby serving to increase the angular velocity during the final phase of kicking. From these changes, Nunome et al. (2006a) speculated that as the shank angular velocity exceeded the inherent force–velocity limitation of muscles immediately before ball impact, the muscular system becomes incapable of generating any concentric force. It would seem that the coaching advice to ''kick through the ball'' should be focused on muscle groups other than the knee, with the hip and trunk muscles most likely contributing.

Efficient action of the motion-dependent moment can be considered as an index of better segmental coordination. This index has been used to clarify the inter-segmental coordination influences of limb preference (Dörge et al., 2002) and fatigue (Apriantono, Nunome, Ikegami, & Sano, 2006). It seems
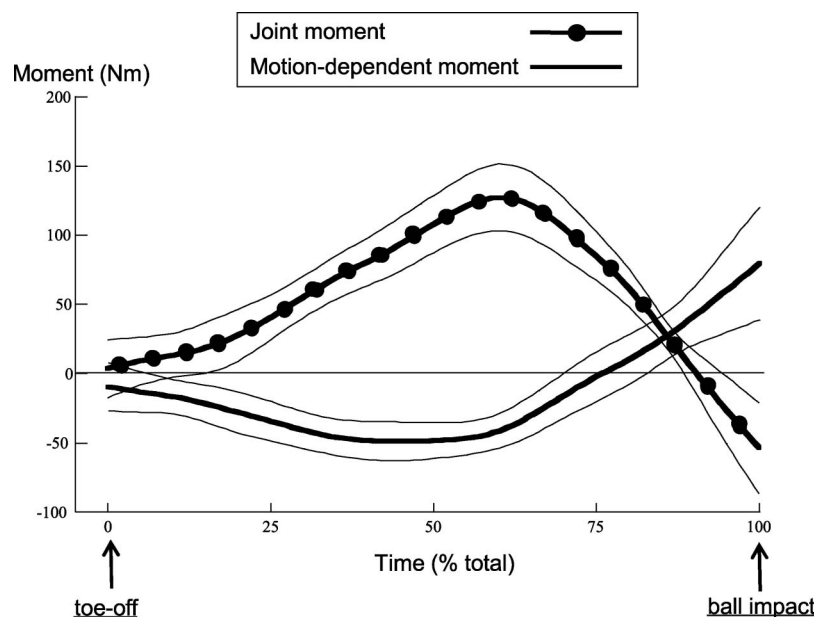

Figure 2. Average (s) changes in joint and motion-dependent moment at the knee joint during leg swing of soccer instep kicking. Reprinted with permission from Nunome et al. (2006a).

that the motion-dependent moment is independent from the joint moment and depends greatly on the action of joint moments generated at other joints, mainly the proximal joints. This implies that adjacent or even distant joints are effectively coupled to each other through the action of the motion-dependent moments. Putnam's (1991) equation allows the effect of the hip linear motion (acceleration) on the motion-dependent moment acting at the knee to be extracted. To date, conflicting results have been reported for the effect of the hip motion on the motion-dependent moment. Dörge et al. (2002) showed no positive work done by the hip motion, while Putnam (1991) showed a small but positive contribution (16% of the averaged magnitude of the net moment) and Nunome and Ikegami (2005) demonstrated a more dominant contribution of the hip upward motion. In these cases, the interference of ball impact and its treatment would not account for these discrepancies because the shock of ball impact is not thought to transmit to the hip (Nunome et al., 2006a). It is clear that further investigation of this issue is necessary, and such attempts have the potential to reveal the concealed kinetic link between the support and kicking legs.

Of interest, but infrequently reported, is the power produced at the joints during kicking. Robertson and Mosher (1985) computed the hip and knee power produced by the kicking leg. In both joints there was power absorption during the early phase of the kick (before support foot contact) that served to slow the retraction of the kicking leg followed by a power generation (from support foot contact to ball contact) representing the kicking effort. This reached around 2000 W for the hip, although no more than 100 W for the knee. The mean positive work done by the hip was 113 J, while that for the knee was only 5 J. These data suggest that the hip is the prime mover for the kick and the work done by the knee contributes little to the angular acceleration of the shank. Nunome et al. (2002) reported power profiles for the kicking leg hip, knee, and ankle during an instep kick similar to that of Robertson and Mosher (1985) but the positive power values for the knee were much higher at over 1000 W. Furthermore, Nunome et al. (2002) are the only authors to present internal/external rotation power profiles, reporting a positive rotational power at the hip close to 1000 W for the side foot kick. It would appear that considerable effort is expended at the hip joint to orientate the foot so that a suitable side foot kick may be made. Lees et al. (2009) also reported flexion/extension power values for the kicking leg ankle, knee, and hip that had similar profiles and values to Robertson and Mosher (1985).

A more detailed understanding of the action and power source of the kicking motion has been gained recently and might serve as an aid to bridge the gap between the training field and scientific research. The concept of segmental interaction may provide an alternative view for describing kicking mechanics. This has great potential to explain efficient human movement, in which adjacent or distant joints couple together to achieve higher resultant end-point velocity.

The upper body

The upper body demonstrates some important characteristics of technique. The non-kicking side arm is abducted and horizontally extended before support foot contact and then adducts and horizontally flexes to ball contact (Shan & Westerhoff, 2005). In addition, the shoulders are rotated such that they move out of phase with the rotation of the pelvis. This leads to a trunk twist during the preparation phase of the kick and untwist during the execution phase.

Shan and Westerhoff (2005) reported shoulder joint angle data during the kick stride in skilled male performers. The non-kicking side shoulder went through a range of horizontal extension of 158° and a range of abduction of 36°, compared with 63° and 20° respectively during the previous running strides. These results have been confirmed for maximal instep kicking by female participants (Shan, Daniels, Wang, Wutzke, & Lemire, 2005). The greater range of motion suggests that the non-kicking side arm has a role to play in the kick. The horizontal elevation of the arm is frequently attributed to the maintenance of balance, but Shan and Westerhoff (2005) provide a more convincing explanation. They identified a "tension arc" that goes across the body from the kicking leg as it is withdrawn to the non-kicking side arm as it is extended and abducted (Figure 3). The forward motion of both limbs yields a release of this tension arc (a shorten arc) and is an expression of the stretch–shorten cycle. Shan and Westerhoff (2005) also reported greater ranges of motion in the hip, knee, and ankle for skilled players compared with novice players, suggesting more prominent use of the stretch–shorten cycle.

The retraction of the kicking leg and non-kicking side arm leads to a twist in the torso that is indicated by the "hip–shoulder" separation angle. This is measured by the difference in orientation angles of a line representing the hip joints and a line representing the shoulder joints projected onto the transverse plane. This variable may also be considered to represent the "tension arc" (Shan & Westerhoff, 2005). Lees and Nolan (2002) reported that range of motion for hip–shoulder separation reached 38° and 42° for maximal instep kicks in two professional players, but was lower in sub-maximal kicks (6° and
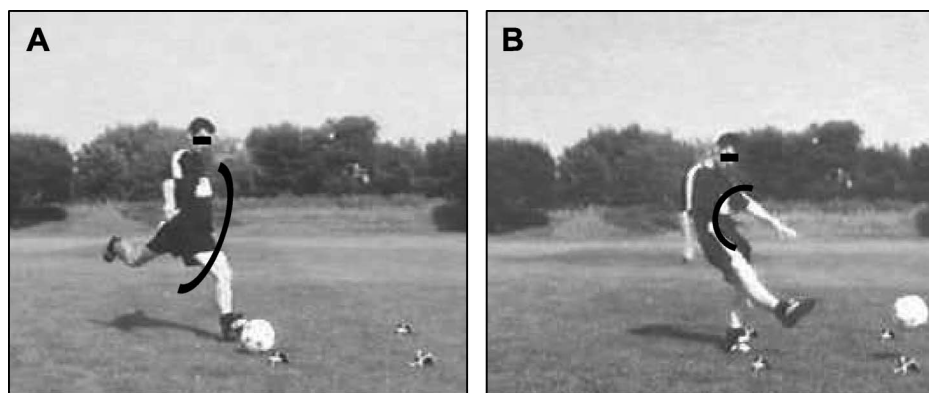
Figure 3. An illustration of (A) the tension arc and (B) the shorten arc.

12° respectively). The higher values for the maximal kick suggests that hip–shoulder separation is an important performance variable.

Foot–ball interaction

Foot–ball contact lasts for less than 10 ms (Nunome et al., 2006b), so high-speed imaging has proved to be invaluable for determining the precise nature of impact. Asami and Nolte (1983) used high-speed cameras (500 Hz) during a maximal instep kick to show that ball impact on the foot was located towards the distal end of the foot causing forced plantar flexion of the ankle joint. Their results revealed not only that increased plantar flexion resulted in reduced ball speed, but provided an explanatory mechanism for the medical condition of anterior ankle impingement syndrome or ''footballer's ankle''. This was later confirmed by Tol and colleagues (Tol, Slim, Soest, & Dijk, 2002), who analysed impact location and impact force using high-speed video (1000 Hz) and supported the hypothesis that spur formation in the anterior ankle impingement syndrome was related to recurrent ball impacts producing repetitive microtrauma to the antero-medial aspect of the ankle. Using higher-speed video (2500 Hz), Ishii and Maruyama (2007) found that the ball speed was maximized when the area of impact was near the centre of gravity of the foot and estimated the peak impact force to be approximately 1200 N for a ball speed of 16.3 m $\cdot$ s^{-1}. Shinkai and colleagues (Shinkai, Nunome, Ikegami, & Isokawa, 2008) used ultra high-speed video (5000 Hz) to observe that the foot was passively abducted, everted, and plantar flexed (following slight dorsal flexion) during ball impact, and estimated that the peak impact force could exceed 2800 N in a maximal speed kick.

Soccer footwear has been shown to influence foot–ground and foot–ball interaction and modify both the support leg and kicking leg actions that affect kicking success (Sterzing & Hennig, 2008). Regarding the support leg, traction properties of the shoe affect the run-up and the critical final foot plant prior to kicking. Suitable traction characteristics would increase the horizontal ground reaction forces acting on the support leg and provide a superior start to the kinetic chain sequence (Sterzing & Hennig, 2007a). Regarding the kicking foot, one benefit of footwear is that it reduces impact pain compared with unshod kicking. Astonishingly, the use of soccer footwear reduces ball velocity by up to 1.5% compared with barefoot kicking for players that are able to disregard pain during barefoot kicking (Sterzing, Kroiher, & Hennig, 2008), confirming an early observation of a football player kicking faster and further without shoes (Plagenhoef, 1971). The suggested mechanism underlying this phenomenon is passive forced plantar flexion of the foot during the impact phase (Lees, 1993; Shinkai, Nunome, Ikegami, Sano, & Isokawa, 2007). The shoe does not allow players to voluntarily fully plantar flex the ankle joint immediately before impact leading to further forced plantar flexion during impact. The absence of this mechanism during barefoot kicking was detected by high-speed video analysis (Sterzing & Hennig, 2008). When kicking barefoot, the foot is already fully plantar flexed at the beginning of impact, providing a more rigid surface and therefore superior collision mechanics.

The specific soccer shoe features that reduce ball velocity have been examined in isolation (Sterzing & Hennig, 2008). An increased toe box height can reduce ball velocity by up to 2.0%. As the toe box deforms during contact, the initial stiffness of the shoe is reduced, increasing the range of forced plantar flexion, as described above. The shoe upper material friction can reduce ball velocity by up to 1.2%. Moderate friction appears to be superior to low or high friction between shoe and ball (Sterzing

& Hennig, 2007b), which may be due to the amount of spin imparted to the ball.

Two other important characteristics of soccer shoes were shown to have no influence on ball velocity. First, shoe weight does not affect ball velocity. While an increase of weight has been shown to reduce foot velocity (Amos & Morag, 2002), it has not been found to influence ball velocity (Amos & Morag, 2002; Sterzing & Hennig, 2008). An explanation for this is that the heavier shoe produces a more effective strike providing a compensatory mechanism leading to an unaltered ball velocity. Second, outsole stiffness does not affect ball velocity. A small degree of outsole stiffness appears to be sufficient to resist the full voluntary plantar flexion of the ankle joint. Furthermore, high outsole stiffness does not increase ball velocity (Sterzing & Hennig, 2008), contradicting the idea that this would support the foot and enhance the transfer of momentum.

The soccer shoe can improve ball accuracy, as barefoot kicking has been shown to decrease accuracy compared with shod kicking by up to 20%. Furthermore, various types of soccer footwear evoked different ball accuracies for instep kicks. Differences in accuracy of up to 13% between different shoes have been reported (Hennig, Althoff, & Hömme, 2009).

Soccer ball construction also influences foot–ball interaction. The soccer ball deforms during impact by as much as 68 mm after initial ball contact (Shinkai et al., 2007). Robotic kicking leg testing has shown no effect of different ball pressures (0.6, 0.9, 1.2 bar) on ball velocity (Neilson & Jones, 2005). However, the authors suggested that ball launch elevation was approximately $2°$ higher with lower ball pressure (0.6 vs. 1.2 bar). In addition, ball launch elevation was lower when placing the valve at the bottom versus the top. These data illustrate the need to control for ball characteristics when performing kicking studies in soccer.

Rigid body modelling has been widely used to understand foot–ball impact (Bull-Andersen, Dorge, & Thomsen, 1999; Plagenhoef, 1971; Tsaousidis & Zatsiorsky, 1996). More recently, finite element analysis modelling has been undertaken to systematically investigate the factors that influence foot–ball interaction. Asai and colleagues (Asai, Akatsuka, & Kaga, 1995) constructed a three-dimensional finite element model of the leg and foot and ball and studied the ball speed and the deformations in the ball and ankle joint during ball impact. They showed that deformations of the ankle joint reduce ball speed, confirming earlier findings on the effect of forced plantar flexion. Asai and colleagues (Asai, Carré, Akatsuka, & Haake, 2002) employed finite element analysis to quantify the influence of the horizontal offset distance (i.e. the distance between

the centre of the area of impact and the centre of the ball) on ball speed and spin. The maximum ball velocity was achieved for a zero offset, but this was also associated with a small spin, which was thought to be due to the asymmetries of the foot. As the offset distance increased, ball velocity decreased and spin increased . Maximum ball spin of 101 rad · s^{-1} was generated but this caused the ball velocity to fall from 26 to 11 m · s^{-1}. It was also found that for very large offset distances, both spin and velocity decreased as the energy of impact failed to be transferred to the ball. In addition, Asai et al. (2002) showed that ball spin increased as the coefficient of friction between foot and ball increased, although variation in the coefficient of friction had less effect than the horizontal offset distance. Their model was also able to predict the impact force during an instep kick (Figure 4) with the maximum forces for an ankle velocity of 25 m · s^{-1} being approximately 2500 N. Such high values were later confirmed by Shinkai et al. (2008).

Asai and colleagues (Asai, Nunome, Maeda, Matsubara, & Lake, 2005) expanded their earlier work to include a finite element skeletal leg–foot model (Figure 5) and used this to evaluate the effect of vertical offset distance on ball speed and release angle for an instep kick. They demonstrated that the maximum ball velocity was obtained for an offset distance below the ball's centre of mass of between – 20 to –40 mm. The greatest angle of projection of $16°$ was achieved for an offset of –20 mm. Both velocity and projection angles reduced as the offset distance moved below or above these optimal positions.

In the above studies, the foot was constrained to approach the ball along its line of impact (attacking angle $= 0°$). Kicks are typically made with the foot
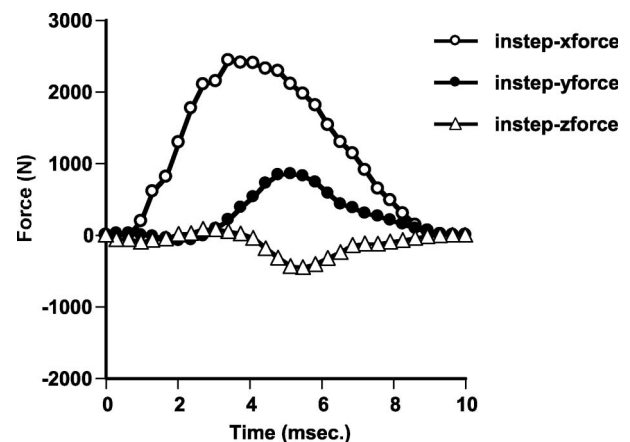

Figure 4. The impact force of an instep kick based on finite element analysis. The x-axis indicates horizontal direction, the y-axis indicates vertical direction, and the z-axis indicates lateral direction.
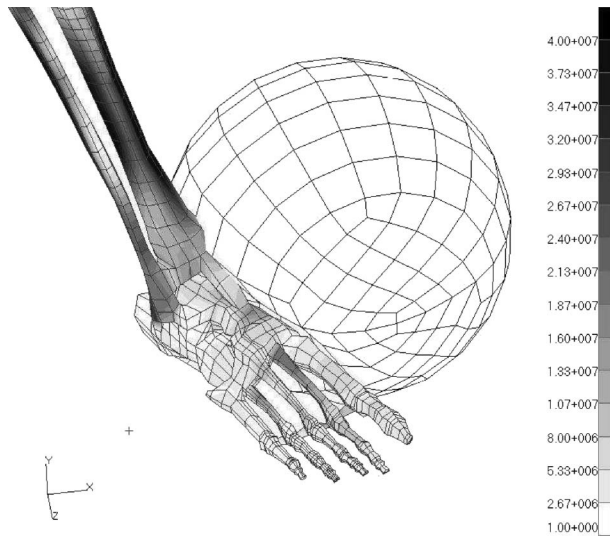
Figure 5. An example of stress contour on deformed shape at impact using the finite element skeletal leg–foot model. Units of stress are Pa.

moving at an angle to the line of impact where the attacking angle is the angle made between the velocity vector of the foot and to the normal at the point of impact. Using their finite element skeletal leg–foot model, Asai and colleagues (Asai, Takano, Carré, & Haake, 2004) investigated the effect of attacking angle on ball speed and spin for curve kicks. They showed that ball spin increased with the attacking angle, but decreased sharply at attacking angles greater than approximately 55° as the foot slipped across the ball. Ozaki and Aoki (2008) conducted an experimental investigation of the values for attacking angles of the standard curve kick (which was found to have an attacking angle of 46°) and the angle curve kick (attacking angle of 36°). The ball spin of the standard curve kick was greater than that of the angle curve, confirming the predictions of Asai et al. (2004).

Foot–ball interaction during impact is a complex phenomenon that occurs over an extremely short time. It is therefore necessary to investigate it using a variety of experimental and modelling methods. Foot placement on the ball must be quite precise to achieve maximum or desired speeds and spin. Small modifications in technique will lead to sub-optimal performance. Footwear and soccer balls also influence this interaction, and industrial aims are to develop equipment that allows kicking to be as fast and accurately controlled as possible.

Ball flight

The consequence of kicking technique and foot–ball interaction is that the ball will be projected with linear and angular velocity. These will determine the

flight of the ball and the success of a kick. In recent years, there has been increased interest in understanding the aerodynamics of a soccer ball. The trajectory of a soccer ball that is kicked or thrown is influenced not only by the initial condition of release, but also by the flow of air caused by a rotation of the ball during its flight. Consequently, an analysis of the ball's in-flight trajectory is indispensable for an analysis of its aerodynamic characteristics.

The forces acting on a soccer ball in flight are specified by the drag and lift forces and are determined by the drag (C_D) and lift (C_L) coefficient respectively. Asai and colleagues (Asai, Akatsuka, & Haake, 1998) speculated that the soccer ball would behave like a rough sphere where at low ball velocities the drag coefficient would be high (around 0.5), reduce rapidly to around 0.1 at the critical Reynolds number (the point at which the air flow in the boundary layer becomes turbulent), and then gradually increase again as ball speed increased. Carré and colleagues (Carré, Goodwill, Asai, & Haake, 2005) confirmed this general pattern in wind tunnel experiments, where the drag coefficient decreased from 0.5 to 0.2 over the transition phase (corresponding to a Reynolds number from 90,000 to 130,000). The increase in drag coefficient with Reynolds number (from 130,000 to 500,000, equivalent to ball speeds of 9 to 32 m · s^{-1}) was gradual and linear, reaching no higher than 0.25 at the highest speed.

Average drag and lift coefficients over the whole of the period of ball flight have been estimated by comparing simulated flight paths with actual flight paths. Carré and colleagues (Carré, Asai, Akatsuka, & Haake, 2002) were able to estimate average drag and lift coefficients from the trajectory of soccer balls in flight, employing ball launching equipment and high-speed video cameras. The average drag coefficient increased from 0.05 to 0.35 as launch velocity increased from 17 to 30 m · s^{-1}. The increase in the drag coefficient suggests that the critical Reynolds number had been surpassed and the data lay on the ascending part of the drag coefficient curve (Asai et al., 1998; Carré et al., 2002). However, this range is in excess of that reported from wind tunnel tests. Bray and Kerwin (2003) found an average drag coefficient of between 0.25 and 0.3 for kicks whose speeds ranged from 23 to 28 m · s^{-1} using a similar comparative approach. They assumed these had all surpassed the critical Reynolds number, which was taken to be 210,000.

It is clear that there is a discrepancy between wind tunnel and comparative flight path tests both in terms of actual drag coefficients and how they change as ball speed increases. This discrepancy has not been resolved but it is worth noting that the drag force acting on the ball (around 3.25 N for a typical

ball speed of 25 m · s^{-1}) would cause the ball to slow by around 6 m · s^{-1} over an 18-m free kick, in turn reducing the drag force further. Thus, the average drag force would represent a mean as it changed from a higher to lower value during flight. Clarification of this issue would be helpful to understand the influence of drag on ball flight and would be especially important for penalty and short free kicks.

The curve kick has become strategically important for free kicks close to the goal. The curve of the ball in flight is due to the Magnus or lift force induced by the spin of the ball and is determined by the lift coefficient. Carré et al. (2002) were able to add spin to their ball-launching experiments and reported that the average lift coefficient increased rapidly from zero as spin was applied, but reached its maximum value of 0.26 with spins of around 100 rad · s^{-1}. This did not increase further as spin increased to 240 rad · s^{-1}. Interestingly, they also found the average drag coefficint was influenced by spin, increasing from 0.2 at zero spin to 0.5 at 240 rad · s^{-1}. Bray and Kerwin (2003) reported average lift coefficients in the range 0.23–0.29. Griffiths and colleagues (Griffiths, Evans, & Griffiths, 2005) used a motion-capture system to track the trajectory and rotation of a soccer ball kicked within the range 15–18 m · s^{-1}. They obtained lift coefficients within the range 0.15 to 0.36, which also showed an increase with spin rate. The data reported by these authors using in-flight methods are generally in agreement. In wind tunnel tests, Carré et al. (2005) reported a gradual increase in the lift coefficient as a function of spin from zero to a value of 0.2, which then remained constant. However, they did not find that spin influenced the drag coefficient. In contrast, Spampinato and colleagues (Spampinato, Felten, Ostafichuk, & Brownlie, 2004) used a full-scale soccer ball in a wind-tunnel test to study rotating and non-rotating soccer balls. In the case of a rotating ball, an increase in speed from 13 to 32 m · s^{-1} resulted in a corresponding increase in the lift coefficient from 0.31 to 0.39. While there appears to be general agreement between researchers on lift coefficients, there is still uncertainty regarding the influence of spin on the drag coefficient.

The data reported above have enabled researchers to speculate on flight paths and free kick strategies. Carré et al. (2002) computed the flight path taken by two hypothetical free kicks over 18 m: one, a maximal kick of 26 m · s^{-1} with no spin, and a second, a curved kick, with the same foot speed but an impact position on the ball 8 cm off-centre. Based on their earlier data (Asai et al., 2002), this off-centre impact reduced the speed of the ball to 18.5 m · s^{-1} and induced a spin of 64 rad · s^{-1} around a vertical axis. This changed the flight path considerably by introducing a curve, with the ball deviating from its

original direction of motion by over 3 m but requiring a greater angle of projection and a 78% longer flight time. For a similar free kick at 25 m · s^{-1} over a distance of 18 m, Bray and Kerwin (2003) estimated that to successfully curve over and around a defensive wall and enter the goal, the ball would have to be kicked with a vertical angle within the narrow range of 16.5–17.5°. Clearly, successful free kicks of this type require exceptional precision by the player.

The methods described above have enabled researchers to investigate specific characteristics of ball design and construction on flight characteristics. Asai and colleagues (Asai, Seo, Kobayashi, & Sakashita, 2006) examined a full-scale soccer ball of the type used in the 2002 Football World Cup (Fevernova and Roteiro; 32-panel type) and the 2006 Football World Cup (Teamgeist; 14-panel type) in wind-tunnel tests (Figure 6). In the case of a non-rotating ball, the critical Reynolds number was found to be 220,000 (approximately 15 m · s^{-1}), considerably higher than that reported previously by Carré et al. (2002). Barber and colleagues (Barber, Haake, & Carré, 2006) examined the effect of the seam shape on the drag coefficient in non-rotating soccer balls and found the width of the seam to have a greater influence on the drag coefficient than its depth. The differences between the two studies noted above could be due to the influence of the seams associated with the balls used. Furthermore, Asai and colleagues (Asai, Seo, Kobayashi, & Sakashita, 2007), also using wind-tunnel tests, examined the Teamgeist ball when both rotating and non-rotating. Their results indicated that for a rotating ball the critical Reynolds number was 300,000 (approximately 20 m · s^{-1}) and was closer in value to that of a smooth ball.

Existing research has shown that non-rotating soccer balls show a reduction in the drag coefficient
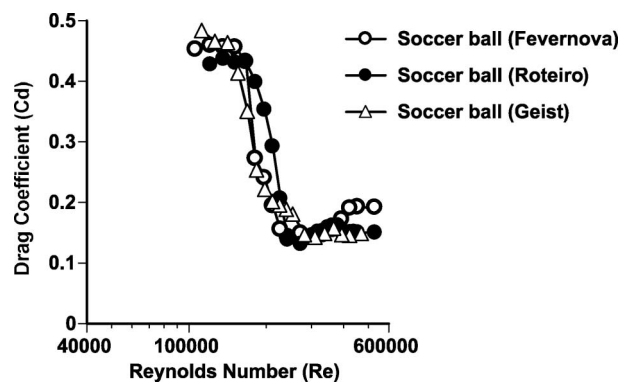

Figure 6. Graph of drag coefficients (C_{D}) for a non-spinning soccer ball. For comparison, the drag coefficients for a smooth sphere during non-spinning flight were ∼0.5 in the sub-critical region and ∼0.1 in the super-critical region. The critical Reynolds number for the soccer ball reached 2.2–3.0 × 10^5, which was between that of a golf ball and a smooth sphere.

corresponding to a critical Reynolds number in the range of 200,000 to 300,000 depending on the type of ball. However, in the case of a rotating ball, changes in drag and lift coefficients do not involve a sudden change in their aerodynamic coefficients and it is speculated that this is due to increased airflow around the rotating ball.

In recent years, irregular movements or "knuckling effects" have been observed and are caused by zero or low rotation. The knuckling effect makes the ball travel unpredictably with haphazard changes in the direction of the trajectory or even "zigzagging". The causes of this are the shape and arrangement of the ball panels and the materials used to make the soccer ball, the speed required to reach the critical Reynolds number, and large-scale undulations of the vortex trail following the ball (Asai, Kazuya, Kobayashi, & Nunome, 2008a). Although several other reasons are also believed to cause the knuckling effect, their details are unknown (Asai et al., 2008b).

Other aspects

General aspects

Kicking technique has been associated with underlying principles of movement. Principles of movement are qualitative statements about a movement that are based on mechanical or biological principles. Lees (2007) identified five such principles that are applicable to kicking: range of motion, stretch–shorten cycle, end-point speed, action and reaction, and proximal-to-distal sequence. These principles are not necessarily exclusive (for example, a proximal-to-distal segmental sequence also results in a high end-point speed), and they are not necessarily applicable to only one aspect of the technique (for example, the stretch–shorten cycle is applicable to kicking leg knee flexion and extension, as well as stretch of the torso produced by the elevation and horizontal extension and flexion of the non-kicking side arm). One of these principles (proximal-to-distal sequence) has been the subject of intense biomechanical investigation (for an overview, see Kellis & Katis, 2007), but the others have received little attention in the literature. The value of representing the kick in these terms is that it encourages a mechanical understanding of the skill and enables practitioners to make qualitative evaluations of performance, enhancing their own effectiveness, without recourse to complex and detailed biomechanical data. To date, there has been no attempt to evaluate the efficacy of this approach within a coaching and training context.

The idea of "technical level" was introduced by Marqués-Bruna et al. (2007) to rank the way in which a child performed selected key parts of the kick. For example, in the mature kick the approach is angled and a curved run is used. Less skilled players approach at an angle but use a straight run. Players who are even less skilled use a straight approach. These define three "technical levels" of performance. Marqués-Bruna, et al. (2007) identified technical levels associated with five key aspects of the kicking skill, all based on principles of movement, and evaluated them for 187 children in three age groups (5–6, 7–8, and 9–10 years) and 31 adults who were recreationally active but not soccer players. The authors showed how technical level improved as age increased, but found that not all adults were able to demonstrate the highest technical level associated with a mature form of the skill. Furthermore, they were able to show how gender influenced technical level, with girls performing at a lower technical level and with a slower technical development with age. The use of technical level is a novel approach for the analysis of skill. It capitalizes on the descriptive characteristics of the kicking skill and qualitative observation, which provides the means for investigations involving large numbers of participants.

One area of developing interest is the application of kinematic analysis to investigate issues related to coordination (Davids, Lees, & Burwitz, 2000). In a series of studies, Chow and colleagues (Chow, Davids, Button, & Koh, 2005, 2007, 2008) investigated lofted chip tasks to establish characteristics of coordination patterns. They used a range of kinematic data but focused primarily on the kicking leg knee angles and angular velocities. They used angle–angle plots to demonstrate coordination and the timing of peak flexion or extension velocities to quantify coordination. They were able to show the presence of a global pattern of coordination in skilled kickers but with subtle individual differences (Chow et al., 2005), important coordination differences between skilled and unskilled (Chow et al., 2007), and the positive influences of practice on coordination (Chow et al., 2008). These studies have demonstrated that kicking can be used as a vehicle to successfully investigate skilled performance.

Methodological issues

Advances in the technology of measurement systems have meant that it is possible for researchers to undertake 3D analyses. Some studies that have used 3D analyses have reported angular orientations and angular velocities along the abduction/adduction and internal/external axes as well as the more conventional flexion/extension axis. However, angular orientations (but not angular velocities; Zatsiorsky, 1998) reconstructed from 3D data are influenced by the Cardan sequence used. The most common sequence used in kicking research is the X–Y–Z

sequence representing rotations about the flexion/extension (X), abduction/adduction (Y), and internal/external (Z) axes. Lees and colleagues (Lees, Barton, & Robinson, 2010) compared estimates of orientation angles for the ankle, knee, and hip of the kicking leg using all six of the possible Cardan sequences. They showed that for all sequences (except the Y–Z–X sequence) the flexion/extension orientations were quite similar but that serious deviations occurred between sequences for the abduction/adduction and internal/external orientations. Although no "gold standard" for the choice of Cardan sequence exists for kicking, from their experience they suggested the most suitable choice was the X–Y–Z sequence. As most of the literature has coincidentally used an X–Y–Z sequence, this should be regarded as a *de facto* standard and used by all future studies to allow comparison between studies.

The methods used for 3D reconstruction have varied between studies. Levanon and Dapena (1998) and Nunome et al. (2002) used that proposed by Feltner and Dapena (1986). This method uses markers placed only on the major joint centres. The consequence of this is that the internal/external rotation of a segment is determined by the plane made from markers attached to other joints. The plane is well defined when there is substantial flexion at a joint but becomes less well defined as the joint extends to become straighter. The kicking leg knee joint has only a small degree of flexion during the main phase of kicking, so the internal/external rotation data during this period will be more susceptible to errors. A second popular method is based on a 6 degrees-of-freedom reconstruction in which sufficient markers (at least 3 per segment) are placed on the segment to define all of its degrees of freedom. Kellis et al. (2004) used markers placed at the joints and at the mid-segment. This method is used widely in gait analysis but is susceptible to soft tissue movement, particularly at the mid-segment locations. Kawamoto et al. (2007) also used markers placed at the end of the segments, while Lees et al. (2009) used marker clusters attached to a rigid shell placed close to the middle of the segment. The use of clusters enables the location of one marker relative to the other to be maintained and is less susceptible to soft tissue movement. No study has attempted to compare and contrast these different methods of reconstruction for the kick, thus it is not possible to identify how these methods influence the data reported.

Concluding remarks

It is evident that advanced measurement systems and analytical techniques have been used widely to extend our understanding of the kicking skill and the factors that influence its performance. At the broad level, attention has gone beyond the interest of the kicking leg to encompass influences of other parts of the body and other parts of the action. There is a growing acceptance that kicking foot velocity is the result of actions of the whole body. While these have generally been investigated in isolation, a holistic view has been developed using qualitative analysis methods, specifically the use of principles of movement and technical levels. These can be used at the practical level of coaching, and this is one area that will benefit from further study to establish their efficacy.

At the specific level, more is known now about the 3D kinematic and kinetic characteristics of the kicking action. These data are predominantly related to the kicking leg, but data from other body joints, segments, and limbs are beginning to appear in the literature. Currently, there is no normative data for kicking. Advances in our understanding of the general mechanisms underpinning performance have been made with specific regard to the influence of motion-dependent moments. There is a recognition that these are due to body segments in addition to the kicking leg thigh, which to date has been the sole segment used to quantify this aspect. The mechanics involved in quantifying these are complex but it is likely that this will soon be solved for kicking.

There are some methodological issues that require further development. Suitable 3D models, data processing methods, and angular conventions all need to become more widely established to enable comparison of data between studies. The difficulty of comparing even ball speeds between studies is indicative of how a lack of progress in these important methodological areas can impact considerably on the development of our understanding.

Foot–ball–ground interactions have received much attention through the use of high-speed video and advanced modelling procedures. Not only has this considerably developed our knowledge but has enabled rather complex issues such as the influence of foot structure and footwear characteristics on performance to be elucidated. Kicking performance is traditionally evaluated through ball flight characteristics (e.g. speed, spin, direction, accuracy) and it is clear that these are understood better with knowledge of the factors that influence ball flight. Application to a wider selection of kicks, footwear, and ball types will enable future researchers to be more explicit about equipment design, performance, and injury.

This review has attempted to address both the wider interests related to the skill of kicking and to bring to the reader the range of contemporary topics currently of interest to researchers in the field. We hope we have provided a timely evaluation of current literature to inform and direct future studies.

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