Biomechanical characteristics and determinants of instep soccer kick

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Abstract

Good kicking technique is an important aspect of a soccer player. Therefore, understanding the biomechanics of soccer kicking is particularly important for guiding and monitoring the training process. The purpose of this review was to examine latest research findings on biomechanics of soccer kick performance and identify weaknesses of present research which deserve further attention in the future. Being a multiarticular movement, soccer kick is characterised by a proximal-to-distal motion of the lower limb segments of the kicking leg. Angular velocity is maximized first by the thigh, then by the shank and finally by the foot. This is accomplished by segmental and joint movements in multiple planes. During backswing, the thigh decelerates mainly due to a motion-dependent moment from the shank and, to a lesser extent, by activation of hip muscles. In turn, forward acceleration of the shank is accomplished through knee extensor moment as well as a motion-dependent moment from the thigh. The final speed, path and spin of the ball largely depend on the quality of foot-ball contact. Powerful kicks are achieved through a high foot velocity and coefficient of restitution. Preliminary data indicate that accurate kicks are achieved through slower kicking motion and ball speed values.

Key words: Soccer, biomechanics, kicking, football, sports, technique analysis.

Introduction

The game of soccer is one of the most popular team sports worldwide. Soccer kick is the main offensive action during the game and the team with more kicks on target has better chances to score and win a game. For this reason, improvement of soccer instep kick technique is one of the most important aims of training programs in young players (Weineck, 1997).

Success of an instep soccer kick depends on various factors including the distance of the kick from the goal, the type of kick used, the air resistance and the technique of the main kick which is best described using biomechanical analysis. Previous reviews have examined biomechanics of soccer movements in-detail (Lees, 1996; Lees and Nolan, 1998). However, it becomes apparent that more research studies into biomechanics of soccer kick have been published within the last decade. Therefore, new aspects of soccer kick performance are being identified, including more details regarding the three-dimensional kinematics of the movement, joint-moments that drive the movement, mechanisms of soccer performance as well as various factors which affect soccer kick biomechanics such as age, gender, limb dominance and fatigue. The aim of the present study was to examine

recent findings on soccer kicking biomechanics and to identify new aspects that may be decisive for soccer kick performance.

Research articles were obtained by searching the Medline, Sport Discus and Institute of Scientific Information (ISI) catalogues. The keywords used were combinations of "soccer", "football", "biomechanics", "kinematics", "kinetics", "technique", "kick" and "performance". Articles were accepted when adequate information regarding the methodology and statistical findings were included.

Kinematics of instep soccer kick

The basic (two-dimensional) kinematics of the lower limb segments during instep soccer kicks have been previously reviewed (Lees, 1996; Lees and Nolan, 1998). These include examination of angular position – time and angular velocity curves during the kick as well as the linear kinematics of the joints involved (Figure 1). In this review, two characteristics of this movement will be described a) that the soccer kick is characterized by segmental and joint rotations in multiple planes b) the proximal-to-distal pattern of segmental angular velocities.

Soccer kick is characterized by segmental and joint rotations in multiple planes

Segmental rotations in multiple planes are observed throughout the kick. During the backswing phase, the kicking leg moves backwards, with the hip extending up to 29° (0° is defined as the neutral orientation with respect to hip flexion / extension, Levanon and Dapena, 1998) with a velocity of 171.9-286.5 deg·s⁻¹ (Nunome et al., 2002; Levanon and Dapena, 1998). The hip is also slowly adducted and externally rotated (Levanon and Dapena, 1998). The knee flexes (at an angular velocity of 745-860 deg·s⁻¹) and internally rotates (Nunome *et al.*, 2002). Given that the neutral position of the ankle is 0°, the ankle is plantarflexed (10°), abducted (20°) and slightly pronated (Levanon and Dapena, 1998) reaching maximum plantarflexion velocities of 860 deg·s⁻¹ (Nunome *et al.*, 2002). The back swing motion of the kicking leg is completed just after ground contact with the hip extended and the knee flexed (Levanon and Dapena, 1998).

Forward motion is initiated by rotating the pelvis around the supporting leg and by bringing the thigh of the kicking leg forwards while the knee continues to flex (Weineck, 1997). The hip starts to flex (reaching values of 20° (Levanon and Dapena, 1998) at speeds up to 745 deg·s⁻¹ (Nunome *et al.*, 2002; Levanon and Dapena, 1998) and abducts while it remains externally rotated
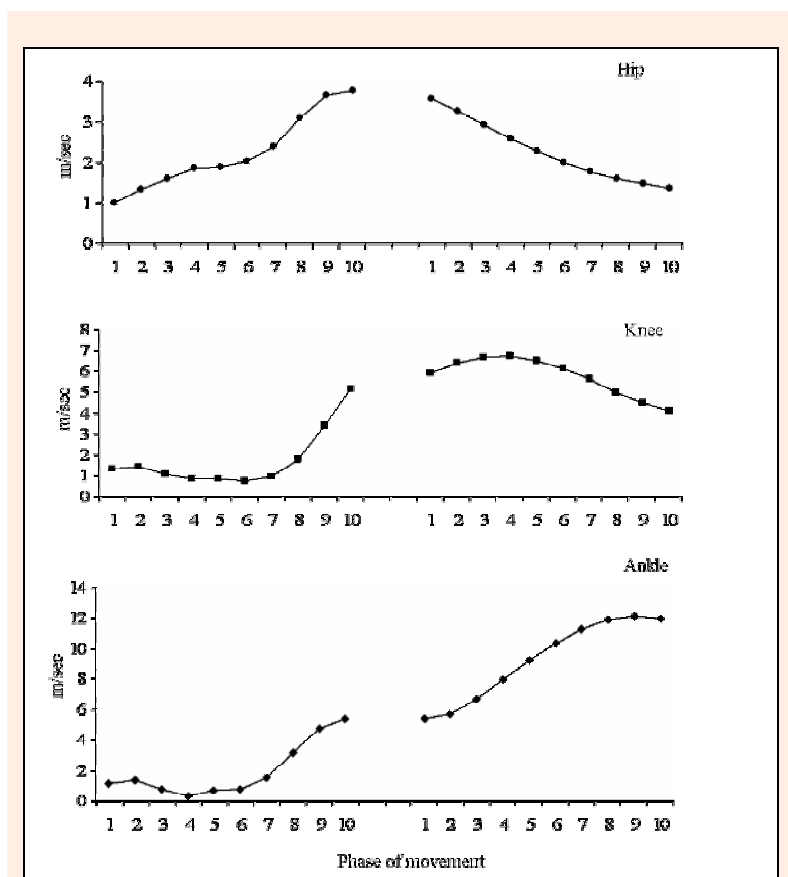
Figure 1. Ankle, knee and hip linear velocity during a soccer kick from the beginning of the motion to ground contact (left diagrams) and from ground contact to ball impact (right diagrams) separated to 10% for each phase.

(Levanon and Dapena, 1998). In the same period, the ankle is adducted and plantarflexed whereas supination – pronation motion is minimal (Levanon and Dapena, 1998). Simultaneously, knee extension velocity is maximized (860–1720 deg·s⁻¹) while external / internal tibial rotation values are generally low and less than 57.3deg·s⁻¹ (Nunome et al., 2002). Upon impact, the hip is flexed, abducted and externally rotated and the ankle plantar-flexed and adducted (approximately 12°) (Levanon and Dapena, 1998).

Proximal-to-distal pattern of segmental angular velocities
The majority of studies on soccer kick biomechanics have identified the importance of proximal-to-distal sequence of segmental angular velocities for kick performance (Dorge et al., 2002; Dorge et al., 1999; Huang et al., 1982; Levanon and Dapena, 1998; Nunome et al., 2002).
During the backswing phase, the thigh angular velocity is nearly minimal while the shank velocity is negative, due to the backward movement of the shank. During the initial part of the forward swing phase, the thigh angular velocity is positive ~286-401 deg·s⁻¹ (Huang et al., 1982; Lees and Nolan, 1998) whereas a negative shank angular velocity ~286-401 deg·s⁻¹ (Huang et al., 1982; Lees and Nolan, 1998) is observed. This is due to the instantaneous forward movement of the thigh while the shank moves backwards (until maximal knee flexion is achieved).

As the leg continues its forward movement, both thigh and shank move forward. The angular velocity of the thigh continues to increase and reaches its peak value (~516-573 deg·s⁻¹) just before the knee starts to extend. At this point, the thigh angular velocity equals the shank angular velocity and, thus, knee joint velocity is zero. As the knee starts to extend, the angular velocity of the thigh declines and the shank velocity increases linearly until ball impact reaching values of 1891 deg·s⁻¹ (Dorge et al., 1999). At ball impact, the thigh angular velocity is almost zero while the shank and the foot reach peak angular velocity and zero acceleration (Huang et al., 1982).

Joint and motion-dependent moments

Joint and segmental movements are the result of moments produced during the kick. Two types of analysis have been reported in the literature: estimation of the net moments exerted around joints (Dorge et al., 1999; Nunome et al., 2002; Roberts et al., 1974) and analysis of motion-dependent moments acting on specific segments (Kellis et al., 2006; Putnam, 1991; Putnam, 1983; Sorensen et al., 1996; Dorge et al. 2002).
Research on joint kinetics during the kick has mainly focused on two issues: first, the magnitude of the moments exerted around lower limb joints and, second, the time-sequence of moment generation during the kick. With respect to the first factor, research has shown that

Table 1. Hip flexion, knee extension and ankle plantarflexion moments (N·m) during soccer kicking in adult males as reported in the literature. Data are means (±SD).

Research Study	N	Parameter	Hip flexion	Knee extension	Ankle plantarflexion
Nunome et al. (2002)	5	Average	249 (31)	98 (27)	N/A
		Maximal	283 (30)	111 (39)	
Nunome et al. (2006a)	5	Maximal	309.2 (28.9)	129.9 (25.5)	N/A
Putnam (1991)	18	Average	229 (34)	85 (12)	N/A
Dorge et al. (1999)	7	Maximal	271.3	161.0	N/A
Zernicke & Roberts (1978)	N/A	Maximal	274 (36)	122 (23)	N/A
Robertson (1985)	N/A	Maximal	220	90	N/A
Luhtanen (1988)	29	Maximal	194 (33)	83 (21)	20 (4)
Roberts et al. (1974)	1	Maximal	~269	~68	~10
Huang et al. (1982)	1	Maximal	~250	~80	~20

hip flexion moments are almost twice the corresponding knee extension moments (Dorge et al., 1999; Luhtanen, 1988; Nunome et al., 2002; Putnam, 1991; Roberts et al., 1974; Zernicke and Roberts, 1978) during the kick (Table 1). Further, ankle plantarflexion moments are even smaller, reaching 20-30 Nm (Nunome et al., 2002) (Table 1).

The joint moment – time curve patterns during the kick differ between studies (Dorge et al., 1999; Nunome et al., 2002; Roberts et al., 1974). Particularly, during the initial backswing phase, some studies reported very low hip extension values (Roberts et al., 1974) whereas others reported high hip flexion moments (Dorge et al., 1999; Nunome et al., 2002). Further, some studies (Luhtanen, 1988; Nunome et al., 2002; Roberts et al., 1974) reported hip and knee moment – curves with one peak. Hip flexion moments reached maximal value at the end of the backswing whereas maximal knee extension values were observed immediately after, approximately at the end of the leg-cocking phase (Nunome et al., 2002). In contrast, Dorge et al. (1999) reported that the hip and knee moment – time curves demonstrate two peaks during the kick. Particularly, peak hip flexion moment was achieved approximately at 25-30% of kick duration, it then declined and increased again reaching an almost similar peak value just before impact. A curve with two peaks was also observed for the knee moment, with peak moments occurring immediately after the corresponding hip moment peaks. Both hip flexion and knee extension moments significantly decline immediately before impact (Dorge et al., 1999; Huang et al., 1982; Nunome et al., 2002; Roberts et al., 1974) while a recent study (Nunome et al., 2006b) reported an almost minimal hip moment at ball impact. Finally, ankle moments are generally very low during the first half of the kick duration and then increase, reaching maximal values at 70-80% of kick duration (Nunome et al., 2002; Zernicke and Roberts, 1978).

Comparison of previous findings shows a wide range of values for hip and knee joint moments mainly due to methodological differences (Table 1). For example, some studies (Nunome et al., 2002; Putnam, 1991) reported average values during the kick as opposed to instantaneous values reported by others (Dorge et al., 1999; Luhtanen, 1988; Zernicke and Roberts, 1978). Further, three-dimensional models yield higher knee extension moments compared with moments derived using two-dimensional analysis (Nunome et al., 2002; Rodano and Tavana, 1993).

Inverse dynamics models demonstrate several limitations which should also be taken into consideration when explaining soccer kick kinetics (Dorge et al., 1999; Levanon and Dapena, 1998; Nunome et al., 2002). Data processing has a significant impact on the magnitude and the patterns of estimated moments. The most important problem is data smoothing. From the start of the movement until ball impact, joint displacement data could be smoothed using an ordinary filter (i.e. Butterworth filter). However, upon impact there is a sudden change in segmental displacement and velocity values which requires further attention. Application of some filtering techniques may significantly alter the displacement signal by cutting high frequency components leading to an underestimation of the true displacement, velocity and acceleration patterns upon foot – ball impact. For example, Nunome et al. (2002) illustrated that the use of one direction smoothing shifted the time of hip peak moment towards ball impact compared with bi-directional smoothing, thus altering interpretation of the moment-time curves during the kick. Others have shown that the smoothing routines (polynomial curve fitting) applied to the hip and knee moment data may affect the predicted hip and knee joint moment curves (Huang et al., 1982). Recent data suggest that the use of a modified time-frequency algorithm achieves better capture of segmental motion upon impact compared with traditional filtering techniques, thus improving prediction of segmental moment – time curves during the kick (Nunome et al., 2006b).

Examination of moments exerted in other than the sagital plane also provides additional insight regarding kick performance. For example, prior to ball impact a considerable (~115 Nm) hip adduction moment has been reported (Nunome et al., 2002). This emphasizes the importance of hip adductor and abductors in controlling the orientation of the whole leg (Nunome et al., 2002). Rotation moments around the knee are rather minimal whereas ankle inversion moments (15-20 Nm) are almost equal to plantarflexion moments (Nunome et al., 2002). Despite their small magnitude, ankle moments are important as they may affect the final position of the foot at ball contact which determines not only the "power" of the shot but also the path and direction of the ball after impact.

Being a swing motion, soccer kick is characterised by proximal-to-distal sequence of segment motions. For kicking, this is the action of the thigh which slows down or reverses its motion prior to full knee extension is reached. Such motion is accomplished through exertion of moments generated through the joints at the proximal end

of the segment, exertion of several motion-dependent moments generated through segmental interactions as well as the moment of inertia of the segment about a transverse axis passing through its proximal end (Putnam, 1993; Nunome et al., 2006a; Dorge et al., 2002). Putnam (1991) first quantified both joint and motion-dependent moments acting on the thigh and the shank during the kick by modelling body segments as a series of rigid links rotating about points fixed in a system. It was found that initiation of the thigh movement is achieved through a hip flexor moment. This is followed by increased angular acceleration of the thigh while the knee flexes and the whole leg is being accelerated in the forward direction. As knee extension motion is initiated, the thigh starts to decelerate due to exertion of motion-dependent moments from the shank (Putnam, 1991) as well as a hip flexion moment (Nunome et al., 2002; Putnam, 1991; Dorge et al., 2002). This contradicts previous studies (Luhtanen, 1988; Zernicke and Roberts, 1978) which attributed the backward acceleration of the thigh to exertion of hip extension moment. In a recent study, Nunome et al. (Nunome et al., 2006a) confirmed the findings by Putnam (1991) regarding the role of the reactive moments from the shank for thigh deceleration; however, in contrast to all previous studies, Nunome et al. (2006a) found that the hip flexion moment had minimal influence on thigh deceleration.

The shank angular velocity increases as the knee extends towards the ball. Shank angular velocity is the result of the moments exerted by the knee joint muscles, the moment due to angular velocity and linear acceleration of the thigh, the moment due to gravitational acceleration of the shank and the moments due to hip acceleration (Putnam, 1991). Of these, the most influential are the muscle (extensor) moment and the moment due to the angular velocity of the thigh (Kellis et al., 2006; Dorge et al., 2002; Nunome et al., 2006a). Particularly, a high knee extensor moment is observed when the forward rotation of the lower leg is initiated (Nunome et al., 2006a). After this, the knee muscle moment declines which coincides with the increase of shank angular velocity. From this point onwards and until ball impact, an interaction moment is developed which increases gradually until just prior to ball impact (Nunome et al., 2006a). Nunome et al. (2006a) noticed that at the final stages prior to ball impact, the interactive (forward) moment accelerates the shank while the knee muscle moment acts in the opposite direction (backwards) as the muscular system is forced to be stretched due to the rapid segmental action of the shank. This is an important finding as it may assist us to better understand not only the kinetics of soccer kick but the associated activity of the involved musculature. The reader, however, should be aware that a limitation of the above studies is the assumption that motion-dependent moments are independent of joint moments which, in reality, is not the case (Putnam, 1991). Further, estimation is based on kinematic variables and therefore it is particularly sensitive to errors in kinematic data.

To summarize, it becomes apparent that the soccer kick is a complex movement which is driven by two types of moments: those exerted by the muscles around the joints and those exerted by the interaction of adjacent segments. To date, we have found only one study (Nunome et al., 2006a) which presents a global description of soccer kick movement based on both moments exerted. Since the initiation of human movement is normally due to forces exerted by the muscles, one may suggest that joint moment exertion should be linked to motion-dependent moments. However, based on previous simulations Mochan and McMahon (1980) and Putnam (1991) commented that this might not be the case. Due to movement complexity, the relationship between joint and interactive moments is non-linear thus making difficult to explain the precise role of joint moments during the movement (Putnam, 1991), although recent evidence is very promising (Nunome et al., 2006a). It is almost certain that further research is necessary to investigate the kinetics of soccer kick motion, taking into consideration moments exerted outside the sagital plane. For example, the role of hip adductors during the initial part of the movement should be explored in relation to the backward movement of the thigh, the exertion of hip extension – flexion moment and perhaps the effects of a motion-dependent moment by the shank whereas a similar type of analysis could be performed for the shank movement. This would allow a better understanding of the "optimal" soccer technique, identification of the major mechanisms that contribute to a fast or an accurate kick as well as the role of specific muscles in various phases of the kick.

Electromyographic characteristics

Electromyography (EMG) has been used to examine muscle activation patterns to explain the role and level of muscle activation during the kick (Bollens et al., 1987; De Proft et al., 1988; Dorge et al., 1999; Kellis et al., 2004; McCrudden and Reilly, 1993; McDonald, 2002; Orchard et al., 2002). To allow comparisons between different findings, all EMG values are frequently expressed as percentage of the EMG recorded during a maximum isometric effort (MVC).

Examination of EMG activity levels reported in the literature (Table 2) indicates large variations in EMG magnitude and temporal patterns, which prevents extraction of safe conclusions regarding the role of various muscles during the kick.

It appears that joint and segmental movements during the kick are driven by simultaneous activation of a relatively large number of muscles. From an anatomical point of view, some of these muscles or muscle groups produce moments around a joint in opposite directions (antagonists). Early studies in these area have called this observation as «soccer paradox» (Bollens et al., 1987; De Proft et al., 1988) because the higher the simultaneous activity of antagonist musculature, the lower the net moment produced around the joint and less powerful the resulting segmental action. In other words if both agonist and antagonist muscles co-contract, they produce opposing forces around a joint. The result of this action is a low net joint moment. This may enhance the stability of the joint but the movement becomes inefficient. However, examination of muscle function should take into consideration several factors such as the function of each skeletal muscle (bi-articular vs uniarticular), the type of action

Table 2. Characteristic EMG activity values during back swing and forward swing phases as reported in the literature.

Iliopsoas	60-80% [2]	65.1 – 100.9% [2]	
Rectus femoris	25-60% [2]	32.5 – 68.7% [2]	59.1 – 63.8% [3]
	47.8 – 51% [3]	78.6 – 85.5% [3]	
Vastus lateralis	0 – 40% [2]	~64 – 102% [2]	~80% [1]
	70% [1]	~80% [1]	
Vastus medialis	90% [1]	~80% [1]	~80% [1]
	33.1 – 40.8% [3]	66.9 – 70.4% [3]	55.4 – 70.8% [3]
Biceps femoris	15-25% [2]	5.2 - 30% [2]	~40% [1]
	70% [1]	<30% [1]	53.6 – 54.1% [3]
	38.9 – 50% [3]	39.8 – 40.1% [3]	
Gluteus maximus	5-15% [2]	2.1 – 32.1% [2]	~80% [1]
	65-70% [1]	<30% [1]	
Semitendinosus	70% [1]	30% [1]	~40% [1]
Tibialis anterior	40% [1]	30% [1]	~80% [1]

[1] De Proft et al. 1988, [2] Dorge et al, 1999, [3] Manolopoulos et al. 2006.

(eccentric vs concentric), the simultaneous movement of adjacent joints and segments and the time where each muscle is activated during the movement.

Some studies examined joint kinematics and kinetics in combination with activation patterns of specific muscles with somewhat different views regarding kick kinematics (Dorge et al., 1999; Sorensen et al., 1996). Although the study by Sorensen et al. (1996) refers to martial arts kick, two observations on muscle activity are worth mentioning. First, that the thigh acceleration was accompanied by considerable levels of rectus femoris (hip flexors) and hamstring (hip extensors) EMG as well as a high motion-dependent moment from the shank (Sorensen et al., 1996). Second, that shank acceleration was accompanied by a high muscular activity of the knee extensors whereas when the shank starts to decelerate this activity decreased whereas the hamstring and gastrocnemius (antagonistic) activation increased. Based on these observations, Sorensen et al. (1996) suggested that the hip muscles play a compensatory role during the backswing phase and an active role during the forward swing phase. Furthermore, it was proposed that thigh deceleration is mainly caused by interactive moment exerted by the shank rather than a hip extension or flexion moment. The recorded rectus femoris and hamstring activation were considered as indicative of their compensatory role for thigh deceleration. Due to the position of the hip and the knee (Hoy et al., 1990) during the backswing, it was also considered that the hamstrings exerted more torque around the knee rather than the hip.

Dorge et al. (1999) supported the active role of muscles throughout the kick which is partly in contrast to Sorensen et al. (1996). Using needle electrodes, these authors (Dorge et al., 1999) suggested that the EMG activity levels correspond to the proximal-to-distal segmental movement observed during the kick. Particularly, there was a high activation of the iliopsoas during the start of the kick which was followed by a high activation of the rectus femoris during backswing. In turn, the main forward swing phase was characterized by high activation of vastus lateralis. The biceps femoris and gluteus maximus demonstrated their peaks just prior to ball impact. In terms of EMG magnitude, a high activation of m. iliopsoas was observed during the backswing phase, which is indicative of the important role of the hip flexor muscles for kick performance.

Using surface EMG electrodes, De Proft et al. (1988) found maximal activity of hip and knee muscles during the terminal stage of the backswing phase which increased again prior to ball impact. Compared with needle measurements, surface EMG activity levels were higher for all muscles throughout the kick whereas a proximal-to-distal sequence of muscle activation was not evident.

From the above descriptions, it becomes clear that the rapid knee flexion and extension is an important aspect of soccer kick performance. This movement is accompanied by a stretch of the knee extensor musculature during backswing followed by immediate shortening during forward shank movement. It has been shown that kicking speed is significantly higher when the knee extensor musculature is stretched and then shorten compared with kicks involving only concentric actions (Bober et al., 1987). For this reason, the role of stretch-shortening cycle of the knee extensors for a successful kick has been particularly emphasized (Lees and Nolan, 1998). Muscle activity of both agonist and antagonist musculature is high at ball impact, mainly around the knee (De Proft et al., 1988; Dorge et al., 1999; Sorensen et al., 1996) (Table 2). If it is assumed that the main aim of the kicking action is to produce the highest ball speed possible, then one would suggest that antagonist (knee flexor) activity at the final stages of the kick is a limiting factor for performance. This seems to be supported by the observation that skilled players showed higher agonist and less antagonist muscle activity in the swinging phase than less skilled players (Bollens et al., 1987; De Proft et al., 1988). For example, research has shown that temporal EMG characteristics do not differ between expert and novice subjects' kicking patterns (Smith et al., 2002), thus suggesting that it is the magnitude rather than the sequence of muscle activity that characterizes soccer kicks by more skillful players.

From the above literature, it appears that only a few studies examined activation patterns during the kick with conflicting findings. This leaves many questions regarding the role of various muscles unanswered. For example, what is the activity of other muscles of the hip

and the ankle? What is the role of stretch-shortening cycle of knee extensor musculature for the shank acceleration? What is the link between muscle activation patterns and sequential joint moment development until impact?

Another important issue is that the above observations mostly apply to maximal instep kicks. However, one should consider that a powerful kick is not necessarily a successful (accurate) kick. In the latter case, muscle activation patterns around different joints may be more complex in order to achieve a fine control of lower limb movement. For example, what are the differences in muscle activity when a player has to kick the ball against a high or a low target? What are the necessary adjustments in muscle activity when the player uses an almost diagonal approach relative to the target?

Mechanics of foot-to-ball contact

Ball speed depends on the velocity of the foot (distal segment) upon impact as well as the quality of ball – foot impact (Asai et al., 2002; Bull-Andersen et al., 1999; Lees and Nolan, 1998; Levanon and Dapena, 1998). Correlation coefficients between ball and foot speed reported in the literature are high (r > 0.74) (Asami and Nolte, 1983; Levanon and Dapena, 1998; Nunome et al., 2006a). The higher the speed of the foot before impact, the shorter the foot-ball contact and the highest the ball speed. For this reason, the ball-to-foot speed ratio has been considered as an index of a successful kick (Asami and Nolte, 1983; Kellis et al., 2004; Lees and Nolan, 1998; Nunome et al., 2006a; Plagenhoef, 1971). For instep kicks, ball-to-foot speed ratios reported in the literature range from 1.06 to 1.65 (Asami and Nolte, 1983; Isokawa and Lees, 1988; Kellis et al., 2004; Kellis et al., 2006; Nunome et al., 2006a) depending on the foot area used to examine foot speed.

The mechanism of collision between the foot and the ball could be described by the following equation (Lees and Nolan, 1998):

$$V_{ball} = V_{foot} \cdot \frac{M \cdot (1 + \ell)}{(M + m)} \qquad (1)$$

where V_{ball} = velocity of the ball, V_{foot} = velocity of the foot, M = effective striking mass of the leg, m = mass of the ball and ℓ = the coefficient of restitution. The term $(1 + \ell)$ is related to the firmness of the foot at impact and the ratio M/ (M +m) provides an indication of the rigidity of the foot and leg at impact.

A different equation to describe the velocity of the ball after foot impact was developed by Bull-Andersen et al. (Bull-Andersen et al., 1999):

$$V_{ball} = \frac{I \cdot V_{f,before} \cdot (1 + \ell)}{I + m_{ball} \cdot r^2)} \qquad (2)$$

where V_{ball} = velocity of the ball, I = the moment of inertia of the shank-foot segment about the knee joint, $V_{f,before}$ = velocity of the foot before impact, ℓ = the coefficient of restitution, m_{ball} = the mass of the ball and r^2 = the distance between the knee joint and the centre of the ball as well as

the distance between the knee joint and the point of contact on the foot (the length r is the same between these points).

The coefficient of restitution was defined as:

$$\ell \cdot (V_{f,before} - V_{ball,before}) = -(V_{f,after} - V_{ball}) \qquad (3)$$

where $V_{f,before}$, the velocity of the foot before impact, $V_{f,after}$, the velocity of the foot after impact and V_{ball} the velocity of the ball.

The coefficient of restitution quantifies the extent to which a perfect collision is modified by the material properties of the colliding objects. A perfect elastic collision demonstrates an ℓ = 1 (Bull-Andersen et al., 1999). The coefficient of restitution ranges from 0.463 to 0.681 (Bull-Andersen et al., 1999; Dorge et al., 2002). It has been suggested that a change in the coefficient of restitution from 0.5 to 0.65 would lead to a 10% rise in ball speed (Bull-Andersen et al., 1999). The coefficient depends on the mechanical properties of the ball, the shoe, the ankle and the foot upon impact (Asami and Nolte, 1983; Bull-Andersen et al., 1999).

Upon ball contact the foot moves simultaneously with the ball for a distance equal to approximately the 2/3 of the diameter of the ball (Asai et al., 2002). Moreover, large deformation appears during ball impact which causes increased forces (Asai et al., 2002) and releases energy (Tsaousidis and Zatsiorsky, 1996). Consequently, apart from the phenomena observed during the pre-impact phase, it is necessary to understand the importance and the mechanisms during the collision phase.

Particularly, the coefficient of restitution would depend on the amount of deformation of the foot and the ball at impact. The less deformation by the foot, the higher the coefficient of restitution. The amount of deformation depends on the effective striking mass which is the equivalent of the striking object (in this case, the foot and shank). The effective striking mass increases as the limb becomes more rigid by muscle activation (Lees and Nolan, 1998). This takes place when the contact point is located closer to the ankle rather than the metatarsals (Asami and Nolte, 1983).

Based on equation (2), ball velocity can also be affected by the moment of inertia of the shank-foot segment. Bull-Andersen et al. (1999) showed that alterations in moment of inertia did not affect the velocity of the ball. It appears, therefore, that rotating the whole leg at the time of impact would lead to lower velocity of the foot and the ball. If the aim of the kick is to maximize ball velocity, then this technique is not recommended.

The above studies suggest that execution of a kick which aims to maximize ball velocity largely depends on the high velocity of the foot prior to impact and a small foot deformation at impact. Using a different methodological approach, Tsaousidis and Zatsiorsky (1996) estimated that more than 50% of the ball's speed is imparted to the ball without any contribution of the potential energy of the ball deformation. It was suggested (Tsaousidis and Zatsiorsky, 1996) that ball speed is affected by two factors. First, the energy or momentum which is a result of the co-ordinated movement and mechanical behaviour of the foot before impact and second, energy which is due

to muscle work produced during the collision phase. In general, this agrees with previous studies (Asami and Nolte, 1983; Bull-Andersen et al., 1999). However, Tsaousidis and Zatsiorsky's (1996) work emphasizes more the contribution by ankle muscle work at impact compared with other studies (Asami and Nolte, 1983; Bull-Andersen et al., 1999). This difference might be due to a different perspective used: Tsaousidis and Zatsiorski (1996) examined the quality of foot-ball interaction during a soccer kick whereas Bull-Andersen et al. (1999) and Asami et al. (1983) examined the necessary conditions for maximizing ball speed after impact.

The offset distance between the impact point and the centre of the ball seems to play an important role for path and direction of the ball after impact. An increase in the offset distance decreases ball speed but it increases ball spin until the offset distance exceeds the radius of the ball (Asai et al., 2002). Spin can also be imparted to the ball even when the coefficient of friction is zero. This is because there is a local deformation of the ball during impact which allows forces to be transmitted to the ball (Asai et al., 2002). Therefore, it seems that the offset distance from the ball's axis has a much larger effect on ball spin than a variation in the coefficient of friction (Asai et al., 2002). Moreover, if friction between boot and ball is reduced, possibly caused by wet conditions, less spin and less flying time of the ball will be observed (Carre et al., 2002).

From the available literature, it can be suggested that a soccer player should maximize the velocity of the foot (the angular velocity of the lower leg) and hit the ball with the upper part of the foot (closer to the ankle) in order to maximize ball velocity. The role of ankle muscles during impact is not clear; we could only speculate that muscle work would be produced when the player aims to kick the ball maximally but towards a specific direction or with a certain spin.

Ball speed

The speed of the ball is the main biomechanical indicator of kicking success and it is the result of various factors, including technique (Lees and Nolan, 1998), optimum transfer of energy between segments (Plagenhoef, 1971), approach speed and angle (Isokawa and Lees, 1988; Kellis et al., 2004), skill level (Commetti et al., 2001; Luhtanen, 1988), gender (Barfield et al., 2002), age (Ekblom, 1986; Narici et al., 1988), limb dominance (Barfield, 1995; Barfield et al., 2002; Dorge et al., 2002; Narici et al., 1988; Nunome et al., 2006a), maturity (Lees and Nolan, 1998), the characteristics of foot-ball impact (Asai et al., 2002; Bull-Andersen et al., 1999; Tsaousidis and Zatsiorsky, 1996), muscle strength and power of the players (Cabri et al., 1988; De Proft et al., 1988; Dutta and Subramanium, 2002; Manolopoulos et al., 2006; Taina et al., 1993; Trolle et al., 1993) and type of kick (Kermond and Konz, 1978; Nunome et al., 2002; Wang and Griffin, 1997). This explains the wide range of ball speed values reported in the literature (Table 3).

Ball speed values reported during competition are higher compared with those found under laboratory conditions. For example, ball speed values during the 1990 World Cup tournament reached 32-35 $m·s^{-1}$ (Ekblom, 1994) which are much higher compared with those reported in the literature (Table 3). Whether this is due to the training level of players or the nature of competition is unclear. Research findings are conflicting as some (Asami and Nolte, 1983) reported differences between professional and amateur soccer players whereas others (Commetti et al., 2001) found the opposite. It is evident, however, that current published data do not allow safe conclusions on the effects of training level on ball speed. This could be attributed partly to the difficulties in performing research during competitive games or on elite athletes.

Accuracy

The analysis of accurate kicks have received fewer attention compared with powerful kick biomechanics. The accuracy of the kick can be examined by recording the angle between the direction of the kick and the desired direction (Wesson, 2002). As a result, error margins of this angle can be determined for any given shooting distance. Alternatively, studies have compared the biomechanical characteristics of accurate versus non-accurate kicks (Lees and Nolan, 1998; Teixeira, 1999).

Kicking accuracy depends on how fast the player approaches the ball (Godik et al., 1993). It has been found that when players are instructed to perform instep kicks at their own speed of approach, then the faster kicks are the most accurate ones. In contrast, if players are instructed to kick the ball as maximally as possible, then the higher the run-up speed the less accurate the kick. This seems to indicate that there is an optimal approach speed in order to achieve an accurate kick (Godik et al., 1993).

When the player is instructed to perform an accurate kick, there is a reduction in ball speed, linear and angular joint velocities compared with a powerful kick (Lees and Nolan, 1998). This decline is associated with decreases in range of motion of the pelvis, hip and knee joints (Lees and Nolan, 1998). This seems to be supported by Teixeira et al. (1999) who found that soccer kicks towards a defined target have longer duration and smaller ankle displacement and velocity compared with kicks performed towards an undefined target. The above suggest that the target determines the actual constraints on accuracy; its manipulation leads to a trade-off between speed and accuracy of the kick. In other words, when the player is instructed to perform an accurate kick, then the approach as well as the joint rotations and velocities are also lower compared those recorded during a powerful kick.

Another interesting observation is related to the point of contact between the ball and the foot. It has been suggested that sources of inaccuracy arise from the error in the force applied by the foot (Asai et al., 2002; Carre et al., 2002; Wesson, 2002). The first arises from the error in the direction of the applied force and the second is due the misplacement of the force. If the ball is being hit at the center, it would follow a near straight trajectory and gain the maximum possible velocity with minimal spin (Asai et al., 2002; Carre et al., 2002). The ball demonstrates a higher forward velocity compared with the foot velocity, depending on the coefficient of restitution (Wesson 2002).

Table 3. Ball speeds (m·sec^{-1}) as reported in the literature (M = Males; F = females). Data are means (±SD).

Research Study	Subject characteristics			Kick	Approach (steps – angle)	Ball speed (m·s^{-1})
	N	Age (Years)	Training status			
Asami and Nolte (1983)	4	N/A	Professional	Instep	N/A	29.9 (2.9)
Narici et al. (1988)	11	25.1 (5.0)	Amateurs	Powerful	N/A	20.0 (3.6)
Opavsky (1988)	6	N/A	N/A	Instep	6-8 steps	23.48 – 30.78
Luhtanen (1988)	29	10.3-17.1	Trained	Instep	2 step	14.9 – 22.2
Kermond & Konz (1978)	1	22	Trained	Punt	2 step	25.8 (2.2)
Isokawa and Lees (1988)	6	20 – 26	Trained	Instep	1 step, 0°	18.73 (.95)
					1 step, 45°	20.14 (1.58)
					1 step, 90°	19.13 (1.64)
Poulmedis et al. (1988)	11	25.5 (3.0)	Trained	Instep	N/A	27.08 (1.32)
Rodano and Tavana (1993)	10	17.6 (.5)	Professional	Instep	2 step	22.3 – 30.0
Dorge et al. (2002)	7	26.4	Skilled	Instep	3 m, 0°	24.7 (2.5)
Ekblom (1994)	N/A	N/A	Professional	Instep	N/A	32-35
Levanon & Dapena(1998)	6	Inter- collegiate	Experienced	Instep	N/A	28.6 (2.2)
Barfield et al. (2002)	2 M 6 F	19-22	Elite players	Instep	2 step, 45-60°	25.3 (1.51) (M) 21.5 (2.44) (F)
Barfield (1995)	18	20.7 (1.7)	Amateurs	Instep	2 step, 45-60°	26.4 (2.09)
Nunome et al. (2002)	5	High – school	Experienced	Instep	N/A	28.0 (2.1)
Nunome et al. (2006a)	5	16.8 (.4)	Skilled	Instep	N/A	32.1 (1.7)
Nunome et al. (2006b)	9	27.6 (5.6)	Experienced	Instep	N/A	26.3 (3.4)
Apriantono et al. (2006)	7	20.0 (2.1)	Amateurs	Instep	N/A	28.4 (1.6)
Tol et al. (2002)	15	27.4	Amateurs	Instep	N/A	18.9 – 29.8
Roberts et al. (1974)	1	25	Experienced	Toe	2 step	24.09
Tsaousidis & Zatsiorsky (1996)	2	College	Amateurs	Toe	N/A	24.9 (1.1)
Taina et al. (1993)	15	18.1 (.3)	4th Division	Instep	N/A	96.02 (9.06)Km/h
Trolle et al. (1993)	24	N/A	Elite players	Instep	N/A	99.3-103.6 Km/h
Cometti et al. (1988)	95	25.0 (4.6)	Professional Amateurs	Instep	Free run	106.37 (12.89) Km/h 106.94 (7.52) Km/h
Asai et al. (2002)	6	N/A	Univ. Players	Curve	N/A	25.44 (.76)
Manolopoulos et al. (2006)	10	19.9 (.4)	Amateurs	Instep	2 step	27.9 (1.8)
Kellis et al. (2004)	10	21.3 (1.4)	Trained	Instep	1 step, 0°	19.79 (1.49)
					1 step, 45°	20.41 (2.44)
					1 step, 90°	18.51 (3.09)
Kellis et al. (2006)	10	22.6 (2.0)	Amateurs	Instep	2step, pre- fatigue	24.69 (1.8)
					2step, post fatigue	21.78 (2.2)

In contrast, if the force applied to the ball is directed at an angle relative to the desired direction, then the ball will demonstrate a lower speed, a higher spin, and a longer and more curved path with a possible change in the final direction of the ball (Asai et al., 2002; Carre et al., 2002; Wesson, 2002). Each of the above techniques can lead to accurate kick. This depends on the position of the ball relative to the goal and the external conditions (opponents, air resistance). Current practice shows that long-distance kicks (free kicks, for example) are generally characterized by a curved and longer ball path and spin. In contrast, kicks performed within the penalty area (short distance kicks) are generally faster as the player should hit the ball as fast as possible in order to surprise the goalkeeper. This suggests that the point of contact between the foot and the ball depends on the aim and the external conditions that define the kick.

In summary, it is apparent that only a few studies examined the biomechanics of accurate soccer kicks. It appears that accurate kicks are generally performed at slower speeds compared with powerful kicks. However, there are several issues that need to be addressed prior to making definite conclusions regarding kicking accuracy. This relates also to a deeper understanding of kinetics, kinetics and muscle activation patterns of accurate kicks as well as examination of ball speed characteristics in relation to external conditions under which the kick is being performed.

Effects of approach angle and distance

A soccer kick may be performed either from a stationary position or at a certain distance from the ball. The approach consists of several steps and can be performed at an angle relative to the ball. The length, speed and angle of approach are the most important aspects of this preparatory movement which has a significant effect on soccer kick success (Isokawa and Lees, 1988; Kellis et al., 2004; Opavsky, 1988; Roberts et al., 1974).

Kicking from an angled approach up to 45º may increase ball speed, although this increase may not be statistically significant (Isokawa and Lees, 1988). Further, kicking with running approach demonstrates higher ball speed values compared with static approach kicks (Opavsky, 1988). To our knowledge, the difference between one-step and multi-step approach on ball speed values is not clear. However, practice shows that soccer players prefer a multi-step approach, most often 2 or 3 steps prior to the main kicking action. Furthermore, in most cases, a soccer kick is not performed against a stationary ball. Instead, the ball is rolling towards the player. Research (Tol et al., 2002) has indicated insignificant

differences in ball speed between kicks performed against a stationary ball and kicks performed against a ball rolling at 2.2 m·s^{-1}.

Another important aspect of kicking success is the placement of the support foot behind and beside the ball. There is no general consensus regarding the placement of ball beside the foot. It has been suggested that the foot should land 5-10 cm behind and 5 – 28 cm beside the ball (Hay, 1993). However, this information has not been confirmed experimentally. Further investigation is necessary to examine the optimum distance for the placement of the supporting leg which could be proved a useful tool for trainers and coaches in guiding the kicking performance of soccer players.

Age and gender effects

The effects of age and gender on soccer kick technique and biomechanics received a little attention in the literature. In general, it appears that soccer kick indicators differ with age and gender. Particularly, previous studies reported that maximum ball speed and knee angular velocity increase with age (Capranica et al., 1992; Luhtanen, 1988). Ball speed values reach 32.1 m·s^{-1} for 15-18 year players (Table 3). Ball speed increases with age probably due to the increased muscle mass and technique improvements (Poulmedis et al., 1988; Rodano and Tavana, 1993; Taina et al., 1993; Tol et al., 2002; Trolle et al., 1993).

Maximum knee angular velocities during the kick range from 1014 deg·s^{-1} for 4.6 year-old children (Capranica et al., 1992) to 1204 deg·s^{-1} for 14 year-old players (Table 4). Improvement in kicking performance is partly because of the higher levels of muscle strength of the players (due to growth and maturation). Furthermore, improvements in muscle co-ordination are also important, although no experimental data exist to support this suggestion.

Research has shown females have the ability to instep kick on dominant and non-dominant sides with similar kinematic characteristics as men (Barfield et al., 2002). However, females generally demonstrated less ball velocity than their male counterparts (Barfield et al., 2002). This was attributed to lower foot and ankle speed in females compared with males. Further, an interesting finding was that knee extension velocity when kicking

with the dominant leg was higher in females compared with males. Barfield et al. (2002) suggested that this may be indicative of male ability to generate greater momentum of the distal segment prior to ball contact. This might also provide time for the hamstrings to initiate a reduction in knee angular velocity as the foot approaches the ball in order to reduce injury potential. Although this suggestion is reasonable, further research is required to examine the role of bi-articular muscles (such as the gastrocnemius) in males and females as these muscles play a very important role in energy transfer from knee to the ankle (Hof, 2001). Another issue which deserves further investigation is whether there are gender differences regarding the role of activated musculature in protecting the musculoskeletal system from injury during the kick (Barfield et al., 2002).

Limb preference

Research has shown higher ball speed values when the players kick the ball with the dominant limb as opposed to kicks with the non-dominant leg (Barfield, 1995; Narici et al., 1988; Nunome et al., 2006a). This was attributed to the higher moment produced by the dominant limb compared with the non-dominant limb (Narici et al., 1988) and a better inter-segmental pattern and a transfer of velocity from the foot to the ball when kicking with the preferred leg (Dorge et al., 2002). However, studies have failed to find significant difference in isokinetic strength between dominant and non-dominant legs (Capranica et al., 1992; Narici et al., 1988; Barfield, 1995). This is mainly because isokinetic movements cannot replicate the way muscles and joints work during actual soccer kick-conditions. Using kinetic analysis, Dorge et al. (2002) found non-significant differences in muscle moment exertion between the two limbs; however, there was a higher amount of work performed in the preferred leg compared with the non-preferred leg. In contrast, Nunome et al. (2006a) found that the faster swing of the preferred leg was not accompanied by a higher interaction moment and angular impulse. Since the players examined in the study by Nunome et al. (2006a) achieved higher foot speed values compared with those examined by Dorge et al. (2002), it was suggested that differences in kick biomechanics between the two limbs depend on the skill level of the players (Nunome et al. 2006a). The higher the skill level, the better the co-ordination for both limbs

Table 4. Characteristic values for maximum extension angular velocity of the knee joint reported in the literature. Data are means (±SD).

Research study	Subject characteristics	Knee angular velocity (deg·s^{-1})
Elliott et al. (1980)	4.4 years	1014
	9.9 years	1604
Rodano and Tavana(1993)	Males, Trained	1206 (218)
Barfield et al.(2002)	Males, Trained	1134 (257)
	Females, Trained	1113 (107)
Lees and Nolan (2002)	Males, Trained, high-speed kick	1364 (80)
	Males, Trained, accurate kick	1175 (75)
Levanon and Dapena (1998)	Intercollegiate male players	1805 (289)
Nunome et al. (2002)	High-school male players	1364 (298)
Barfield (1995)	College male players	1587 (280)
Manolopoulos et al.(2006)	Males, Amateur	1874 (155)
Kellis et al.(2006)	Males, Trained	1220 (332)
Rodano and Tavana (1993)	Males, Trained	1206 (218)

(Nunome et al. 2006a). The same authors (Nunome et al. 2006a) also suggested that among high-skilled players, those who demonstrate higher knee extension moment during the kick they achieve a higher foot velocity. Further research is necessary to examine effects of limb dominance on soccer kick biomechanics. Such data is important for soccer training and performance, as modern soccer requires strikers with ability to score goals with both legs.

Fatigue effects

Fatigue involves the development of less than the expected amount of force as a consequence of muscle activation that is associated with sustained exercise and is reflected in a decline in performance (Rahnama et al., 2003).

Fatigue causes biomechanical and biochemical changes such as decline in leg power, maximum isometric force alterations and activity of the quadriceps, (Nicol et al., 1991) decline in the vertical jumping ability (Rodacki et al., 2001), changes in ground reaction forces and joint kinematics of running (Mizrahi et al., 2000; Williams et al., 1991) and increased lactate production (Bangsbo, 1997).

During soccer games fatigue or reduced performance seems to occur at three different stages in the game: after short-term intense periods in both halves, in the initial phase of the second half and towards the end of the game (Mohr et al., 2005). Although metabolic demands of the game is a well studied area (Mohr et al., 2003; Rahnama et al., 2003; Reilly, 1997), fatigue effects on technical skills have not received the appropriate attention. As already explained, most studies examined soccer kick performance under non-fatigued conditions. Only three studies have examined the effects of fatigue on soccer kick performance (Apriantono et al., 2006; Kellis et al., 2006; Lees and Davies, 1988).

Lees and Davies (1988) applied a 6-min step exercise protocol and found lower maximum velocity of the foot and the ball. The lack of coordination between the upper and the lower leg after the fatigue protocol seemed to be the main reason the above results were observed (Lees and Davies, 1988). Apriantono et al. (2006) examined the effect of leg muscle fatigue on instep kicking kinetics and kinematics. Fatigue was induced by repeated, loaded knee extension and flexion motions. Slower leg swing, decreased toe velocity, lower leg angular velocity and smaller muscle moment and interactive moment during the kick led to reduced ball velocity after fatigue. It was concluded that together with the force capacity results, fatigue disturbed the effective action of the segmental interaction during the final phase of the kick, which led to an alteration of the inter-segmental coordination. In a another study (Kellis et al., 2006), a decreased ball speed values and ball/foot speed ratios was found after the implementation of an exercise protocol simulating soccer game conditions. Although ground reaction forces and joint displacement curves remained unaltered after fatigue, the maximal knee extension angular velocity of the swinging leg significantly decreased and the linear speed of the toe and ankle showed an (insignificant) decline of 8-10% which can partly explain the decline in ball speed after the implementation of the exercise protocol. Further research of fatigue effects on biomechanical characteristics of soccer kick performance (such as electromyography) is necessary.

Conclusion

Kicking motion is achieved by a combination of muscle moments and motion-dependent moments. Muscle moments are the result of high activation patterns of several muscles such as vastus lateralis, vastus medialis and iliopsoas whereas some muscle activity serves to stabilize the involved joints and segments in order to achieve a fine coordinated movement. The quality of ball – foot impact and the mechanical behavior of the foot are also important determinants of the final speed, path and spin of the ball. Ball speed values during the maximum instep kick range from 18 to 35 msec^{-1} depending on various factors, such as skill level, age, approach angle and limb dominance. Accurate kicks are generally slower than powerful kicks. This indicates that feature research on successful kick biomechanics should identify the appropriate mechanisms leading to a powerful and accurate instep kick. Further research is required to identify soccer kick biomechanics during specific game conditions and to provide useful information for the soccer player and the coach.

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Key points

- Soccer kick is achieved through segmental and joint rotations in multiple planes and via the proximal-to-distal sequence of segmental angular velocities until ball impact. The quality of ball – foot impact and the mechanical behavior of the foot are also important determinants of the final speed, path and spin of the ball.

- Ball speed values during the maximum instep kick range from 18 to 35 msec^{-1} depending on various factors, such as skill level, age, approach angle and limb dominance.

- The main bulk of biomechanics research examined the biomechanics of powerful kicks, mostly under laboratory conditions. A powerful kick is characterized by the achievement of maximal ball speed. However, maximal ball speed does not guarantee a successful kick: in each case, the ball must reach the target. As already explained, when the player is instructed to hit the ball accurately, joint and segment velocities are lower as opposed to a fast and powerful kick performance. It is therefore apparent that future research should focus on biomechanics of fast but accurate kicking.

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