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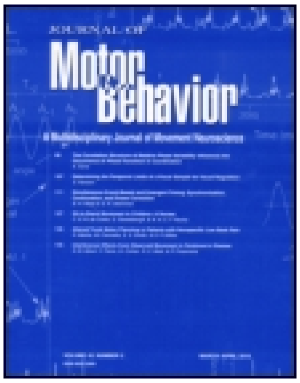
published in
Journal of Motor Behavior
2007

DOI (link to publisher)
10.3200/JMBR.39.5.423-432

document version
Publisher's PDF, also known as Version of record



Journal of Motor Behavior
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/vjmb20

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Version of record first published: 07 Aug 2010.

To cite this article: Christopher D. Egan, Martine H. G. Verheul & Geert J. P. Savelsbergh (2007): Effects of Experience on the Coordination of Internally and Externally Timed Soccer Kicks, Journal of Motor Behavior, 39:5, 423-432

To link to this article: http://dx.doi.org/10.3200/JMBR.39.5.423-432

Journal of Motor Behavior, 2007, Vol. 39, No. 5, 423–432

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ABSTRACT. The authors investigated differences in the soccer kick between 8 experienced and 10 less experienced participants in 2 different task conditions (kicking a stationary ball or a moving ball at a target). The experienced participants were more accurate than their less experienced counterparts, whereas there were no differences in maximum foot velocity between groups or between conditions. When compared with their performance in the stationary condition, participants kicked the moving ball with a smaller range of movement at the knee of the kicking leg, maintaining a proximodistal coordination pattern. Because of their significantly shorter knee-flexion phase, the participants in the experienced group displayed a significantly shorter time between initiation of the forward swing of the kick and ball contact than that of those in the less experienced group. The rapid knee flexion may have been a strategy of exploiting passive dynamics to increase accuracy rather than velocity. Members of both groups showed a proximodistal initiation sequence in the kicking leg, which suggests that players can acquire that coordination pattern with relatively little structured practice and that further practice leads to improvement possibly through the increased exploitation of passive dynamics.

Keywords: motor control, passive dynamics, proximodistal, range of movement, skill

In the present study, the authors focused on experienced and less experienced adults' coordination of internally timed and externally timed soccer kicks (i.e., kicking a stationary ball and a moving ball, respectively). Several researchers have described the characteristics of the expert soccer kick (e.g., Browder, Tant, & Wilkerson, 1991; Lees & Nolan, 2002; Shang & Westerhoff, 2005) and its differences from that of a novice coordination pattern before and after a period of practice (Anderson & Sidaway 1994). There is a noticeable absence of research focusing on kicking a moving ball, however. There are two main reasons why researchers must study the coordination of an externally timed kick. First, kicking a moving ball requires a high level of prospective control, and players must control the timing of the initiation of the movement and the speed with which they perform every aspect of the movement in relation to the movement of the ball. In accordance with the theme of this special issue, kicking a moving ball is a task in which performers must have perceptual skill and successful motor coordination. Moreover, integration of perception and action is required—an aspect of skill that is more developed in experienced soccer players. Second, in the game of soccer, players frequently have to kick a moving ball, whereas they limit their kicking of a stationary ball to "dead ball" situations (i.e., free kicks, corner kicks, and penalties), and only specific players on the team perform such kicks. It is therefore surprising that in research on the soccer kick, investigators have focused solely on the task of kicking a stationary ball.

Coordination is the relative movement between interacting body parts and the object to be intercepted during goal-directed behavior (Newell, 1985). Bernstein (1967) provided a framework for research into complex motor tasks that are characterized by the involvement of multiple degrees of freedom. He noted that when researchers consider the surplus number of degrees of freedom in the neuromotor system, it is clear that the motor system must control sections of degrees of freedom by rigidly fixing them. With practice, those so-called frozen degrees of freedom are gradually unfrozen (Vereijken, van Emmerik, Whiting, & Newell, 1992). After extensive practice, a mature and adaptable coordination pattern will emerge. In an experiment examining participants'

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recruitment of degrees of freedom when they were learning a ski-simulation task, Vereijken et al. found that the ranges of movement at the joints of the legs and torso were small at the early stages of practice. After practice, however, those ranges had significantly increased in all participants as they used previously eliminated degrees of freedom to produce a more expedient and economic movement. Bernstein suggested that after releasing the degrees of freedom, performers could achieve further improvement by exploiting passive forces. With practice, learners on the ski-simulator task were found to exploit the elasticity of the ski-simulator belt on which the sliding platform is mounted (Nourrit, Delignières, Caillou, Deschamps, & Lauriot, 2003). Learners reduced muscle activation during the knee-flexion phase when the platform slid back to its middle position, thus decreasing energy cost.

When investigating coordination changes in the soccer kick with practice, Anderson and Sidaway (1994) compared the coordination pattern of 3 experts with that of 6 novices who kicked a stationary ball. Experts coordinated the kicking leg in a proximodistal sequence, resulting in a whip-like action. The interaction of the novices' hip and knee became more expert-like after practice. The novices' ranges of knee and hip movements after practice were the same as the ranges they had shown before practice, but the ranges were still limited compared with those of the experts. Shang and Westerhoff (2005) recently confirmed that a greater hip range of movement characterizes experts' kicks. Those findings provided evidence for Bernstein's (1967) theory of degrees of freedom because participants with more practice at a skill showed less rigidity in their coordination patterns.

When learning a new skill, performers will try to discover the best movement pattern within the constraints of the task, contrary to previous notions that they reduce the variability of their performances (Deutsch & Newell, 2001). By reducing the degrees of freedom, novice performers initially lessen the variability of their movement. Novices can be expected to show the same rigid movement pattern for different variations of a task (e.g., when asked to kick a ball hard, accurately, high, or low). Once novice performers have developed a simple movement pattern, however, they may start to explore their biological workspace to find more efficient movement patterns. The term *biological workspace* defines the theoretical space that contains all possible movements. While novices are searching the biological workspace, they will show an increase in variability both within and between situations. Researchers can expect experts to display a reasonably stable coordination pattern within a particular situation and to be able to adapt the stable movement pattern with the smallest alteration in the task.

In light of the numerous degrees of freedom involved when people perform a complex movement, there are many ways they can successfully achieve the desired endpoint. Bernstein (1967) referred to that concept as *motor equivalence*. If performers consistently achieve a successful outcome, then they do not necessarily produce intertrial variability as a by-product of their exploration of the biological workspace, and researchers can consider the variability to be functional. If the performers seldom achieve the intended outcome, then researchers can consider their inconsistent coordination pattern to be dysfunctional. Skilled performers display functional variability when they adapt their highly complex and dynamic coordination pattern to suit the constraints of the task. Skilled performers base their adaptation on sensory information (Bennett, Button, Kingsbury, & Davids, 1999). They are able to modify complex movements involving many degrees of freedom, such as the soccer kick, when they perceive that the situation has changed. When a player while taking a shot at a goal is nudged by an opponent, for example, the player still may be able to adapt his or her coordination pattern to successfully strike the ball. Researchers must therefore consider mature coordination a flexible and responsive activity rather than an independent one (Bernstein).

Several researchers have focused on functional variability in expert kickers. Zebas and Nelson (1990) varied the distance from which a highly skilled American football player kicked a stationary ball to the goal. They concluded that the skilled player relied on a highly stable coordination pattern and made no attempt to reduce the speed for shorter distances. Zebas and Nelson implemented only two-dimensional analysis in their study, and they had only 1 participant. Moreover, the player did not need to alter the coordination pattern in that situation because the same ball trajectory met the task constraints in each condition.

Lees and Nolan (2002) investigated the soccer kick in 2 highly skilled professional soccer players and found evidence for functional variability. They required the players to kick a ball in the top right-hand corner of the goal as hard as possible in a simulation of a penalty kick, although no goalkeeper was present. The participants then had to kick the ball at the same target as accurately as possible. Under the accuracy condition, the participants' pelvic rotation and thigh movement were less variable but their foot velocity was greater. Lees and Nolan attributed those findings to the players' need to make last-minute adjustments. That suggestion is credible because higher levels of variability in foot velocity can be indicative of highly skilled participants' adaptation to task constraints (Davids, Lees, & Burwitz, 2000), supporting Bernstein's (1967) view of mature coordination and the idea of functional variability described by Bennett et al. (1999). Lees and Nolan argued that because the 2 players were highly skilled, it is likely that other skilled players would also exhibit the same differences in performance. However, Lees and Nolan reported individual differences between the players in terms of accuracy scores, knee extension, angular velocities, and foot velocity, and we believe that 2 participants is an insufficient sample from which to draw definitive conclusions on the population of skilled footballers as a whole.

Our aim in the current study was to examine the effects of experience and task conditions on the coordination of the soccer kick by using three-dimensional kinematic analysis. Our aim in particular was to provide insight into functional variability in soccer players in the perception–action domain: (a) Do players adapt their movement pattern when the task requires a higher level of integration of perception and action? (b) Does such adaptation involve a change in relative timing between joints, or do players preserve the coordination while they scale down the whole action in terms of size, time, or both? (c) Do more experienced players' and less experienced players' strategies differ? (d) Furthermore, does extensive soccer experience translate into enhanced skill, as assessed on the basis of the players' achievement of the task goal (i.e., kicking a soccer ball fast and accurately toward a target)? (e) If so, is skill associated with an improved pattern of relative timing (coordination pattern), a larger or faster execution of the kick, an enhanced ability to exploit the passive dynamics, or with some but not all of those factors?

Three-dimensional analysis is an essential technique researchers use to identify important features of the kick, such as an angled approach (Davids et al., 2000), and it allows them to accurately measure angles outside of the sagittal plane. The success of the soccer kick depends on the accuracy and speed with which performers hit the ball at the target. We therefore made clear to the participants the importance of both foot velocity and accuracy, and we considered those measures to be important dependent variables in this study. Because major expert–novice differences have been reported to occur in the kicking leg's knee and hip ranges of movement (Anderson & Sidaway, 1994), those difference, as well as the angle of approach, were an important focus in this study (Davids et al.). Anderson and Sidaway noted a proximodistal coordination of joints when participants kicked a stationary ball. Temprado, Della-Grasta, Farrell, and Laurent (1997) and Putnam (1991) also noted proximodistal coordination during the volleyball serve and the punting of a ball in American football and soccer. To our knowledge, no investigators have conducted research on the soccer kick with an approaching ball. We therefore investigated the temporal organization of the kick in this study.

In line with previous research, we hypothesized that the experienced group would kick with greater velocity and accuracy and show greater ranges of movement at the hip and knee of the kicking leg than would the less experienced group in both the stationary- and moving-ball conditions. We expected that the experienced participants' initiation of hip flexion and knee extension during the forward swing would follow a proximodistal sequence (first hip, then knee). Moreover, we expected that the experienced participants would adapt their coordination pattern as the task constraints changed. By contrast, we expected that the less experienced participants would display more variability within each condition (higher coefficients of variation), indicating instability and learning.

The importance of coordinating the soccer kick relative to a moving ball has been overlooked in much of the scientific literature. Because kicking a moving ball presents greater complexity than does kicking a stationary ball, we hypothesized that the less experienced group would display lower outcome scores and smaller hip and knee ranges of motion in the moving-ball condition than in the stationary-ball condition and would also have lower values than those of the experienced group. We expected the less experienced group to revert to a more primitive coordination pattern when presented with a more difficult task.

Researchers must carefully interpret variability in coordination of the soccer kick. Variability can be viewed as instability in the coordination pattern. It is, however, an essential component of learning. It allows the performer to explore different movement patterns, or it indicates highly skilled performance in which the performer is able to adapt his or her coordination pattern on the basis of perceived changes in the environment. Experts in many motor tasks display a greater range of movement than novices do. Because the variability associated with a large movement is likely to be greater than the variability associated with a smaller movement, we used here the coefficient of variation (*CV*) to provide information regarding the variability of the coordination of the soccer kick.

Method

Participants

The participants were 10 nonsedentary right-footed men (aged 22.59 ± 3.35 years [*M* ± *SD*]) who had competitive soccer experience and 10 nonsedentary right-footed men (aged 29.99 ± 4.89 years) who had no competitive soccer experience. The local research ethics committee approved this study, and we obtained written informed consent from participants. Participants in the experienced group had competitive soccer experience ranging from playing for the university first team to playing professionally. All of the experienced participants had played in competitive matches since secondary school (age 11 years). Those participants who played for the university trained for 4 hr/week and played one or two competitive games per week during the season. One of the members of the experienced group was a semiprofessional player who trained 4–6 hr/week and played once a week during the season and another was an ex-professional who was a coach at a Premiership club and was involved with training for 10 hr/week. Because of coaching commitments the ex-professional was no longer involved in competitive soccer matches on a weekly basis during the soccer season. The experienced participants all reported that they participated in noncompetitive games during the rest of the year. The less experienced group had no competitive soccer experience and no experience in any other sport that involves kicking a ball.

Procedure

We instructed participants to use a two-step approach run to kick a size-5 soccer ball with the right foot and to direct the ball quickly and accurately toward a vertical target at a distance of 2.9 m. The target consisted of four concentric semicircles. The radius of the inner circle was 0.5 m, and the radius of each subsequent circle increased by 0.5 m. We located the center of the target 1.4 m above the floor (an artificial grass surface).

We used a cross marked on the floor to specify the location from which the participants had to kick the ball (Figure 1). We positioned a ball-projection device 3.2 m from the cross to the participant's right, perpendicular to the direction in which the participant had to take a shot (from the cross to the target). The device projected the balls 3 m/s.

Each participant performed a total of 20 kicks: 10 kicks by using a stationary soccer ball and 10 kicks by using a moving ball that approached from his right side. We administered the conditions in alternating blocks of five trials to negate any learning effect, and we counterbalanced the order of the conditions across participants. At the beginning of each trial, participants had to take two steps away from the cross (no angle was specified). In the stationary-ball condition, we placed the ball on the cross. In the moving-ball condition, the ball approached the cross from the ball projector. We gave participants one familiarization trial under each condition before we tested them. We gave no further instructions.

Equipment

We attached infrared markers to the participant's (a) feet (fifth metatarsal), (b) ankles (lateral malleolus), (c) knees (between the head of the fibula and lateral epicondyle), (d) hips (greater trochanter), (e) shoulders (greater tubercle), and (f) head (left temple). Two CODAmotion units (Charnwood Dynamics, Leicestershire, England) tracked the markers. Sampling frequency was 200 Hz. We used low-pass filter with a cut-off frequency of 20–50 Hz. We positioned the CODAmotion units to the left of the participant at a distance of 5 m and at the right side of the participant at a distance of 3.4 m. We placed a timing gate consisting of an infrared light and a reflector directly in front of the ball projector. When the ball crossed the infrared beam at the moment it was released from the ball projector, a jump in the analogue signal fed to the computer was registered.

The ball projector was a custom-built adjustable slope on which the ball rolled down onto the artificial grass in the laboratory. At the beginning of each trial, an experimenter held the ball in position at a marked location at the top of the slope and then manually released it. The pre- and posttest calibrations of the slope revealed a high degree of consistency, with an average ball velocity of 3 m/s, ranging from a minimum velocity of 2.9 m/s to a maximum velocity of 3.1 m/s. To reduce potential variability in the ball velocity, the same experimenter operated the ball projector throughout the experiment. The ball was visible to the participant once it had left the slope and entered the artificial grass surface in the laboratory.

We videotaped each trial with two high-speed digital video cameras (JVC Digital Video Camera GR-DVL 9700EG), positioned so that both the participant and the target were clearly in view.

Data Analysis

To determine the accuracy of the kick, we analyzed video recordings of each trial. Depending on how close the ball was to the center of the target, we awarded a score between 0 and 4: a score of 4 for hitting the inner circle, 3 for hitting

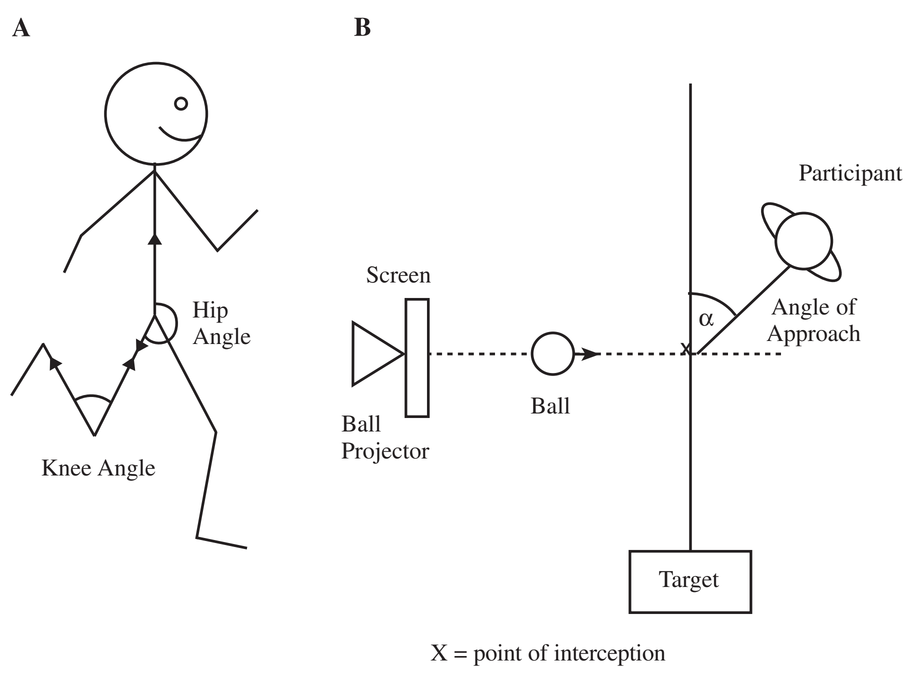

FIGURE 1. (**A**) Measurement of hip and knee angles and (**B**) the experimental setup.

the next circle, 2 for hitting the one after that, 1 for hitting the outer circle, and 0 for missing the target.

The CODAmotion units captured the three-dimensional locations of the markers; we used those locations for kinematic analysis. Because Lees (1996) reported that foot velocity is the main determinant of ball velocity, we analyzed the effects of experience and ball condition on foot velocity. Kicks were characterized by a sharp increase in foot velocity during the second half of the forward swing of the leg, followed by a rapid deceleration on impact with the ball as the impulse was transferred. We therefore chose the moment of maximum foot velocity as the indicator of the moment of ball contact.

We analyzed other kinematic measures from the start of the forward swing of the kicking leg, signified by the maximum extension of the hip, to the point of ball contact. We calculated hip and knee (of the kicking leg) ranges of movement as the difference between the largest and smallest angles of the hip and the largest and smallest angles of the knee, respectively. We calculated hip and knee angles from the three-dimensional positions of the shoulder, hip, and knee markers (for the hip), and the hip, knee, and ankle markers (for the knee). Figure 1 depicts those angles and the angle of approach. We calculated the latter measure from the position of the head marker at the beginning of each trial relative to the origin (the marked location on the surface where we had told the participants to kick the ball).

We analyzed (a) the timing of maximum hip angle of the kicking leg (initiation of forward swing) relative to ball contact (i.e., the time between the moment that the hip was fully extended and the moment of ball contact), (b) the timing of the maximum hip angle relative to minimum knee angle (i.e., the time between the moment that the hip was fully extended and the moment that the knee was fully flexed), and (c) the minimum knee angle relative to ball contact (i.e., time between the moment that the knee was fully flexed and the moment of ball contact). We also investigated (d) the timing of maximum velocity of the hip relative to ball contact (i.e., the time between the moment that the hip achieved maximum rotational velocity and the moment of ball contact).

We calculated the within-participant *CV* for all the spatiotemporal variables as an indication of stability of the coordination of the soccer kick within participants. We calculated that measure by dividing the standard deviation by the mean for all the spatiotemporal variables for each participant under each condition. We then used the resulting data to provide the mean *CV* for each group.

We conducted mixed design 2 (group) × 2 (condition) repeated measures analyses of variance (ANOVAs) to statistically examine differences in the dependent variables between ball conditions and participant skill levels and interactions between participant skill level and ball condition. Significant differences between conditions revealed changes in the coordination pattern as a result of the different task constraints (i.e., functional variability). We estimated effect sizes by using partial eta-squared (η_p^2). We set statistical significance at $\alpha = .05$.

Results

Figure 2(A–D) depicts a typical example of a kick under the two conditions for both groups. In comparison with that of the less experienced participants (A and B), the experienced participants' (C and D) knee flexion was more rapid during both conditions. Figure 3 shows the changes in hip and knee angles over time in a less experienced participant who was kicking a moving ball. The less experienced group's average hip range of movement was 49° (*SD* = 13°) and the experienced group's was 50° (*SD* = 15°). The less experienced group's average knee range of movement was 62° (*SD* = 10°) and the experienced group's was 71° (*SD* = 13°). The peak in the foot velocity curve indicated the moment of ball contact. The general pattern of a successful football kick, which we observed in all participants, showed a period in which both hip and knee flexed followed by a period in which the knee extended while the hip flexed. A relatively long knee-flexion phase of approximately 200 ms or more was typical of the less experienced participants.

Accuracy Data

Table 1 displays accuracy scores and kinematic variables for each group in both conditions. The experienced participants had significantly higher scores than the less experienced participants did, $F(1, 16) = 54.5$, $p < .001$, $\eta_p^2 = .77$. The interaction of experience and condition approached significance, $F(1, 16) = 4.25$, $p = .056$, $\eta_p^2 = .21$. The experienced participants scored higher in the moving-ball condition than in the stationary-ball condition, and the less experienced participants scored higher in the stationary condition than in the moving condition. We found no main effect of condition, $F(1, 16) = 0.03$, $p = .89$, $\eta_p^2 = .02$.

Foot Velocity

Maximum foot velocity of the kicking foot was 13.4 m/s, on average (*SD* = 1.8 m/s). We observed no main effects of group, $F(1, 16) = 0.33$, $p = .46$, $\eta_p^2 = .03$, or condition, $F(1, 16) = 3.8$, $p = .07$, $\eta_p^2 = .18$; neither did we find an interaction effect between group and condition, $F(1, 16) = 1.74$, $p = .21$, $\eta_p^2 = .09$.

Joint Range of Movement

Hip and knee ranges of movement results are shown in Table 1. We observed no significant effects for the hip range of movement between levels of experience, $F(1, 16) = 0.01$, $p = .94$, $\eta_p^2 = .0$, nor between conditions, $F(1, 16) = 0.95$, $p = .34$, $\eta_p^2 = .06$. The interaction effect approached significance, $F(1, 16) = 4.3$, $p = .06$, $\eta_p^2 = .21$. Hip range of movement varied between 27° and 74° across all trials and participants (*M* = 50°, *SD* = 14°). Knee range of movement varied between 44° and 93° (*M* = 66°, *SD* = 12°). We found the range of movement of the knee to be significantly greater in the stationary condition (*M* = 69°, *SD* = 13°) than in the moving condition

(M = 63°, SD = 11°), $F(1, 16) = 11.03$, $p < .01$, $\eta_p^2 = .41$. On average, the experienced group displayed a greater range of movement of the knee in both conditions by approximately 9°, but the difference was not statistically significant, $F(1, 16) = 2.87$, $p = .11$, $\eta_p^2 = .15$. We did not observe a significant interaction between ball condition and experience level, $F(1, 16) = 0.2$, $p = .66$, $\eta_p^2 = .01$.

Timing

The average time between initiation of the forward movement of the upper segment of the kicking leg after backswing (signified by the maximum angle of the hip) and ball contact was 246 ms (SD = 46 ms). The duration of that part of the forward swing (i.e., the time between maximum hip angle and ball contact) was significantly shorter in the experienced group (M = 223 ms, SD = 35 ms) than in the less experienced group (M = 263 ms, SD = 47 ms), $F(1, 16) = 5.12$, $p < .05$, $\eta_p^2 = .24$. It was also significantly shorter in the stationary-ball (233 ms) than in the moving-ball (257 ms) condition, $F(1, 16) = 7.99$, $p < .05$, $\eta_p^2 = .33$. No significant interaction between experience level and ball condition was found, $F(1, 16) = 7.99$, $p = .55$, $\eta_p^2 = .02$.

The average time between the maximum hip angle and the minimum knee angle was 190 ms (SD = 42 ms). That time interval was also significantly different between groups, $F(1, 16) = 4.76$, $p <. 05$, $\eta_p^2 = .23$, and between ball conditions, $F(1, 16) = 6.14$, $p < .05$, $\eta_p^2 = .27$. On average, it was 30 ms shorter for experienced participants than for less experienced participants and 20 ms shorter in the stationary than in the moving-ball condition. No significant interaction effect was found, $F(1, 16) = 1.16$, $p = .3$, $\eta_p^2 = .07$.

We found no effects for the interval between the minimum knee angle and ball contact between the two groups of participants, $F(1, 16) = 0.25$, $p = .62$, $\eta_p^2 = .02\%$. There was no significant effect for conditions, $F(1, 16) = 3.96$, $p = .06$, $\eta_p^2 = .2$. The average time between the minimum knee angle and ball contact was 55 ms. No significant interaction effect was observed, $F(1, 16) = 1.82$, $p = .2$, $\eta_p^2 = .1$.

Maximum hip velocity occurred, on average, 188 ms after initiation of the forward swing (moment of maximum hip angle) and 58 ms before ball contact. The timing of maximum hip velocity relative to ball contact did not differ significantly between groups, $F(1, 16) = 0.3$, $p = .59$, $\eta_p^2 = .02$, or between ball conditions, $F(1, 16) = 0.3$, $p = .59$, $\eta_p^2 = .02$. Nor was

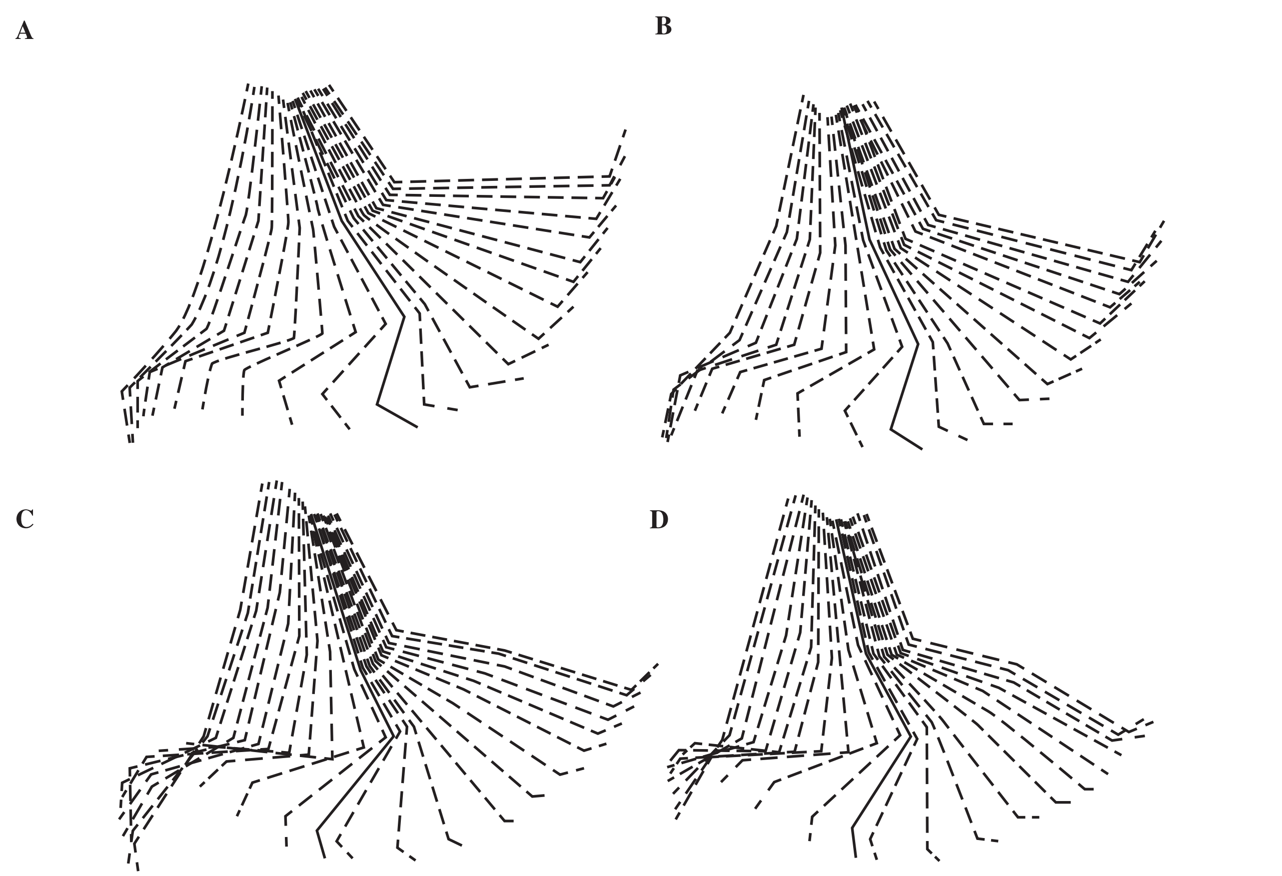

FIGURE 2. Time frame sequence of the soccer kick. The space between each stick figure is 5 ms, except for the figure drawn with a solid line, which shows the moment of ball contact. Figures represent less experienced participant with (**A**) stationary ball and (**B**) moving ball and experienced participant with (**C**) stationary ball and (**D**) moving ball.

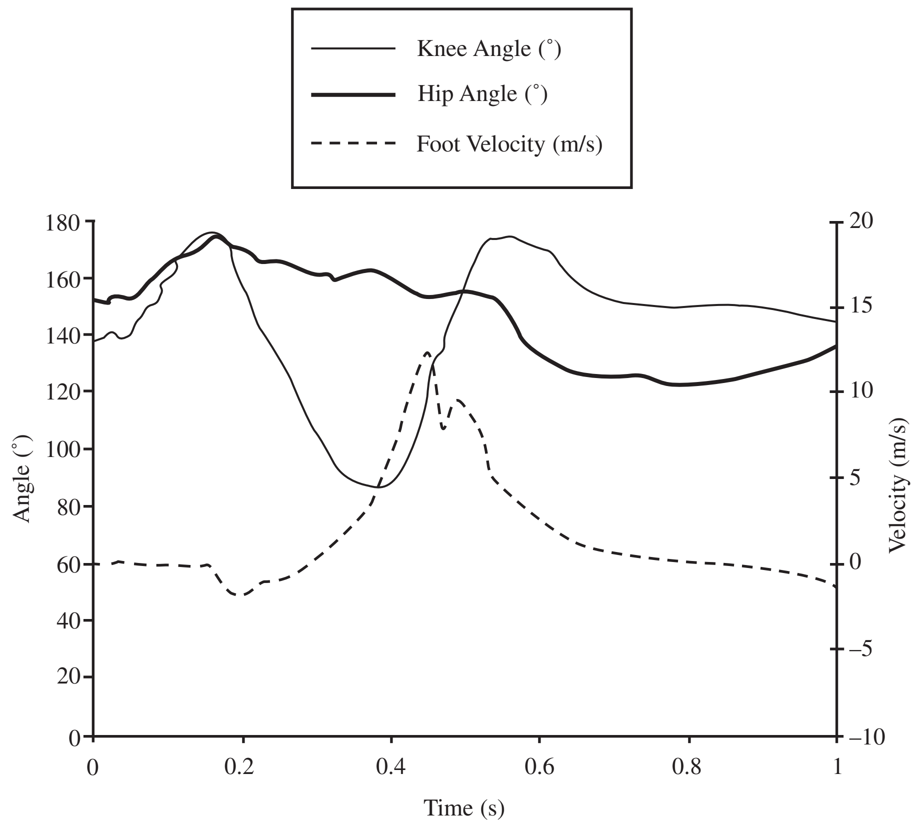

FIGURE 3. Hip and knee angles and foot velocity during the soccer kick for a typical less experienced participant kicking a moving ball.

TABLE 1. Kinematic and Outcome Variables for the Less Experienced and Experienced Groups in the Stationary-Ball and Moving-Ball Conditions

	Less experienced				Experienced				
	Stationary		Moving		Stationary		Moving		
Variable	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*CV*
Accuracy score *g*	1.9	4.7	1.7	7.2	2.9	3.7	3.2	5.5	
Max foot velocity (m/s)	13.1	1.5	12.9	1.6	14.5	2.7	13.4	1.8	0.15
Hip ROM (°)	48.1	11.4	50.6	14.7	53.3	14.4	46.4	16.2	0.19
Knee ROM (°) *g*	64.7	13.1	59.4	6.3	74.2	12.6	67.3	13.4	0.13
Time max hip angle (s) *cg*	0.25	0.05	0.27	0.04	0.21	0.03	0.24	0.03	0.18
Time min knee angle (s)	0.05	0.02	0.06	0.01	0.05	0.01	0.06	0.01	0.27
Time max hip velocity (s)	0.07	0.04	0.06	0.03	0.05	0.04	0.05	0.04	0.87
Timing of max hip angle relative to timing of min knee angle (s) *cg*	0.20	0.04	0.21	0.04	0.16	0.03	0.19	0.03	0.23

Note. Timing variables are relative to ball contact unless stated otherwise. Significant effects for the mean of the variable are indicated by *c* (condition) and *g* (group) next to the variable. *SD* refers to between-subject variability. ROM = range of motion.

there a significant interaction between group and ball condition, $F(1, 16) = 0.135$, $p = .72$, $\eta_p^2 = .008$. The moment of maximum knee velocity occurred, on average, 5 ms before ball contact (as indicated by maximum foot velocity). We obtained those results by using a data-sampling frequency that was too low to allow us to accurately measure that particular variable.

Angle of Approach

We calculated the angle of approach by using the spatial position of the marker attached to the left shoulder at the start of the run up relative to the cross marker from which the participants had to kick the ball. The average angle of approach was 43° (*SD* = 12°). There were no significant differences between the experienced and less experienced participants, $F(1, 16) = 0.094$, $p = .76$, $\eta_p^2 = .006$, or between ball conditions, $F(1, 16) = 2.495$, $p = .14$, $\eta_p^2 = .14$. There was no significant interaction, $F(1, 16) = 0.022$, $p = .89$, $\eta_p^2 = .001$.

CV

Table 1 shows the *CV*s for all spatiotemporal dependent variables. Variability was lowest for the range of motion of the knee and the maximum foot velocity, and it was highest for the timing of the maximum hip velocity relative to ball contact. There were no significant differences or interactions between the groups and between conditions for any of the *CV*s.

Discussion

In this study, we examined differences between experienced and less experienced participants' coordination when they kicked a stationary ball and a moving ball. As expected, the experienced participants were more accurate than the less experienced ones. Experienced participants' use of a technique that sacrifices speed in favor of accuracy cannot explain that finding because the groups did not differ in the velocity of their kicking foot at ball contact. We can then view the experienced group as more skilled than the less experienced group. The almost significant interaction effect of condition and experience ($p = .056$) on the accuracy scores was less predictable. The experienced participants scored higher during the moving-ball condition than during the stationary condition, whereas the less experienced participants scored higher in the stationary condition than in the moving-ball condition. Because kicking a moving ball is much more prevalent than kicking a stationary ball during a game of soccer, it is likely that the experienced participants had more experience kicking a moving ball than kicking a stationary one; therefore, they scored higher in the moving-ball condition than in the stationary one. The stable nature of the stationary condition, and thus the finding that participants did not need to make changes to the coordination of the kick on the basis of any perceived changes in the ball's direction and velocity, is probably why the less experienced participants performed better in the stationary condition than in the moving-ball condition.

Kinematic data showed that both the experienced and the less experienced participants performed a mature soccer kick in terms of relative timing between the hip and the knee of the kicking leg. Both groups' initiation of hip flexion and knee extension and timing of maximum angular velocity of hip and knee occurred in a proximal-to-distal sequence. Anderson and Sidaway (1994) also observed that pattern, and researchers have described it as the typical coordination pattern for experienced kickers (e.g., Davids et al., 2000). Our finding of that pattern in the present study, and the similar angles of approach we observed in both groups, suggests that one should not classify the less experienced participants as novices. In fact, the data showed that the less experienced participants' time between the initiation of hip flexion and knee extension during the forward swing of the kicking leg was significantly longer than that of the more experienced participants.

The results of Anderson and Sidaway (1994) and Newell (1986) have indicated that once players have assembled a coordinative structure, they will scale or parameterize the coordination pattern in the next stage. Anderson and Sidaway stated that expert players show a greater range of movement of the hip than novice players do. The results presented in the current article suggest that the experts do not always do so. Although the less experienced participants in this study were not novices, they would have met Anderson and Sidaway's criteria for being classified as novice, except that organized soccer games in physical education lessons at school are compulsory in the United Kingdom. Some potential reasons for those different findings may include the differential abilities between the participants in our study and in theirs and that both men and women participated in Anderson and Sidaway's study. Women display a somewhat different coordination pattern of the soccer kick from that of men (Tant, Browder, & Wilkerson, 1991). Another important difference between the two studies is that Anderson and Sidaway instructed their participants to start the two-step approach from almost directly behind the ball to reduce the movement outside of the sagittal plane. That constraint restricted participants' rotation of the hip and shoulder and therefore could have caused them to make changes to the coordination pattern. Our inclusion of an accuracy requirement in the present study is another important difference between the two studies that may have caused the contrasting findings.

Although the less experienced participants in the present study may not have been novices, the two groups' experiences differed substantially. The finding that both groups showed a proximodistal coordination pattern, which researchers have previously noted as a sign of expertise, suggests that the mature coordination pattern is acquired with relatively little structured practice. That finding is in line with research on the ski-simulator task—a task that researchers also regard as a complex full-body coordination task (Nourrit et al., 2003). In spite of its perceived complexity, participants systematically acquire the mature or expert coordination pattern very early in their training period (Teulier, Nourrit, & Delignières, 2006; Vereijken et al., 1992). As in the present study, researchers have found the acquired coordination pattern to be more robust to the manipulation of task constraints than to manipulation of movement amplitudes (Deschamps, Nourrit, Caillou, & Delignières, 2004).

The experienced participants in the present study showed a greater knee range of movement and a more rapid flexion of the knee than did the less experienced participants. A greater range of knee movement affords players an increase in maximum foot velocity because they can accelerate the foot over an increased distance. But that was not the case in this study or in the study of Browder et al. (1991). A rapid knee flexion allows the performer to store potential energy because of the mechanoelastic properties of the knee's surrounding structures (ligaments and muscles) and therefore also presents the possibility of increased foot velocity. However, the performance of experienced participants differed significantly from that of the less experienced participants in accuracy, and not in kicking velocity. The present findings suggest that the increased knee range of movement and the rapid flexion of the knee were contributing factors.

In the rapid flexion of the knee, players use the mechanoelastic properties of the knee's surrounding structures, resulting in a contribution of passive forces to leg extension. Because the motor system uses those elastic forces to extend the knee, it can reduce the amplitude of the force-producing signal to the effectors. Because the noise around any motor command is related to the amplitude of the signal (Jones, Hamilton, & Wolpert, 2002), the noise around that signal would be reduced and should have less of an adverse effect on the movement outcome, possibly contributing to the higher accuracy scores observed in the experienced participants. Through practice, the experienced participants have found optimal coordination patterns that allow them to kick accurately. Those optimal coordination patterns could be a result of low-amplitude signals from the motor system with little noise. Without neuromuscular evidence, however, the findings from this study cannot allow us to draw conclusive statements regarding the role of motor noise in the coordination of the soccer kick.

In addition to the group effects, we found an effect of ball condition. Participants performed the kick faster when they kicked a stationary ball than when they kicked a moving ball (i.e., shorter duration between maximum hip extension and ball contact). Their knee flexion was more rapid and their range of knee movement was greater in the stationary condition than in the moving condition. They maintained the proximodistal coordination pattern, which suggests that the pattern of relative timing between joints is more robust than the parameterization or scaling at a local level.

The kinematic differences between the two conditions were the result of the extrinsically timed nature of the moving-ball condition. In that condition, participants had to regulate their kick in accordance with the movement of the ball. In the stationary condition, the participants could coordinate their kicks to strike the ball without being overly concerned with the timing of the kick. The temporal constraint of a moving ball makes the coordination of the kick more complex. During the moving-ball condition, the participants must regulate the coordination of the kick in an ongoing manner on the basis of visual information regarding the ball and proprioceptive information. In the stationary condition, the ball's location was highly stable, and therefore the participants could regulate their coordination to a greater degree on the basis of proprioceptive information.

When considering variability within conditions (*CV*), we found no significant effects. Variability was evident equally in all participants in all conditions. We can interpret the high variability between trials under the same condition as the result of (a) a lack of control, (b) exploratory variability associated with learning, or (c) motor equivalence (Bernstein, 1967). Because the level of variability was comparable in the two participant groups, the first two explanations for the within-condition variability observed in the current study appear less likely. Multiple realizability of motor actions or motor equivalence, which can be considered the implementation of different means to achieve the same motor outcome (e.g., Hebb, 1949, Lashley, 1930), is typical for whole-body actions (Marteniuk, Ivens, & Bertram, 2000). We can view significant changes in the coordination pattern as a result of ball condition as functional variability because the performer systematically adjusts the coordination pattern to meet the demands of the task.

Future Research

Researchers need to perform more studies of the soccer kick in which they use appropriate three-dimensional analysis techniques and sufficient numbers of participants. In this study, we examined, among other factors, the effects of ball condition. It would be interesting for future researchers to study the effects of varying velocities and directions of an approaching ball because it is unclear to what extent the coordination differences between the conditions are a result of the speed or the direction of the approaching ball, or both. Further research focusing on the effects of varying ball speed and direction would highlight the external validity of the current study. In future research protocols, investigators should include experts, novices, and particularly children, because the development of the soccer kick in children has received very little research interest over the last 20 years (Scott, Williams, & Horn, 2003). In this study, we found no significant difference in hip range of movement between experienced and less experienced participants. Rotation of the hip and the shoulder may play an integral part of the coordination of the soccer kick. Researchers have yet to investigate that issue. Future researchers should examine the role of upper body kinematics, including shoulder and arm movements, in the control of the kick.

The results of the current study showed an important difference between experienced and less experienced participants in their speed of the movement from the initiation of the forward swing to ball contact. There is a need for researchers to examine whether the speed of the movement is developed after the basic construction of a coordination pattern or whether the increase in the speed of the kick is, for instance, a by-product of a training-induced increase in the quadriceps' muscular power. Future investigators also need to use equipment that records neuromuscular activity to test Harris and Wolpert's (1998) hypothesis that the coordination pattern for any task is usually a result of the motor command that has the least noise.

ACKNOWLEDGMENTS

The authors thank Simon Bennett for his help with the data filter and Hayley Ness for her help with the figures.

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Submitted June 1, 2006
Revised March 2, 2007
Second revision April 23, 2007