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Organization of motor system degrees of freedom during the soccer chip: An analysis of skilled performance

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This study investigated how motor system degrees of freedom were organized as skilled players performed a soccer chipping task. Using an intra-participant analysis, inter-individual kinematics and performance differences were investigated to determine the features governing coordination of skilled chipping actions. Five skilled participants were studied as they performed 10 soccer chips to one target position and another 15 soccer chips to three positions, all with different specific height and accuracy task constraints. Although a 'global coordination pattern' was identified for skilled soccer chipping, subtle inter-individual differences in coordination, displacement of center of mass (COM), selected kinematic variables for the kicking limb and the role of the non-kicking limb were also observed. It was noted that participants were able to adapt foot velocity to different target positions in successfully meeting the task goal. Results highlighted advantages of examining intra-participant data for understanding how skilled performers re-organize motor system degrees of freedom in achieving functional movement behaviors.

KEY WORDS: Coordination, motor system degrees of freedom, task constraints, soccer chip, skill.

Introduction

In recent years the soccer kicking action has been studied from a variety of perspectives, for example examining characteristics of the soccer instep kick (e.g., Lees & Nolan, 2002), comparing kinematic differences between the dominant and non-dominant foot (e.g., Dorge, Andersen, Sorensen & Simonsen, 2002), distinguishing between the mechanical features of instep and side foot passes (e.g., Levanon & Dapena, 1998, Numone, Asai, Ikegami...
& Sakurai, 2002) as well as investigating coordination changes after practice (e.g., Anderson & Sidaway, 1994, Hodges, Hayes, Horn & Williams, 2005).

However, there have been few attempts to study coordination of kicking actions in skilled individuals confronted with specific height and accuracy constraints such as the soccer chip (for an exception see McLean & Tumilty, 1993). The function of the soccer chip is to allow the player with the ball to loft a pass over opponents and within short distances into space or towards a desired target (see Hargreaves, 1990). The emphasis on accuracy and weighting of the kick is crucial in dead-ball situations, as well as open passages of play, particularly at the elite level where space and time are limited. The soccer chip is a multi-articular movement model that offers the possibility of gaining unique insights into how skilled players satisfy both height and accuracy constraints, unlike other soccer kicking techniques (which generally focus on achieving maximum ball or foot velocity, e.g., instep pass or low drive). In McLean and Tumilty's study (1993), no attempt was made to theoretically interpret how the motor system degrees of freedom are organized by skilled performers in satisfying these unique task constraints in kicking.

One worthy model of learning with emphasis on movement re-organization over time to describe skilled performance was proposed by Newell (1985). There are three stages of learning in Newell's model: Coordination, Control and Skilled stages. Briefly, at the Coordination stage of learning, the learner attempts to identify and establish basic relationships among motor system components to achieve functional, goal directed movements (Williams, Davids, Williams, 1999) and awkward, rigid movements are likely to emerge. At the Control stage of learning, skilled performance is characterized by relevant manipulation and variation of movement parameters, with the skilled player becoming more attuned to higher order derivatives of movement information like velocity and acceleration (Williams et al., 1999). At later stages of learning, emphasized in the present investigation, skilled performance can be observed in coordinated, patterned relationships between limbs involved in functional movements. Specifically, during practice, the skilled player attempts to explore and establish strong relationships between movement of body segments as well as the forces generating the movements to achieve a particular task goal. At the Skilled stage of learning, the performer is able to optimize movement parameters to enable efficient utilization of available energy for example in the reactive forces of limb segments, resulting in more functional variability and producing movements that are fluid as well as in synchrony with the demands of the task (see Bernstein, 1967).

In recognition of the dearth of literature on control during skilled kicking performance, Lees and Davids (2002) suggested the need to examine
higher order displacement variables like velocity or acceleration of limb movement. For example, an interesting question concerns whether skilled players can alter joint angular velocities, foot velocity or acceleration to chip the ball under different height and accuracy constraints (e.g., lower foot velocity to nearer and lower target positions and vice versa) as inferred from Newell’s (1985) model. Additionally, execution of fluid and stable movements, often associated anecdotally with skilled performance, has been proposed as a possible marker of performers at the Skilled stage of learning by Newell (1985). The center of mass (COM), an estimate of the location at which the mass of the individual is concentrated, could be a suitable indicator to examine fluidity and stability of movement. For instance, in one study of strength training effects on soccer instep kicks for amateur players, Manolopoulos, Papadopoulos and Kellis (2005) found that displacement velocity of the COM during the kick was indicative of the stability of the player’s positioning relative to the ball. COM positioning and COM velocity of the players increased in the horizontal direction after the training intervention. Based on their findings, it is possible that players at the Skilled stage of learning may demonstrate less displacement variability of COM and greater stability in joint motion control during the soccer chip.

Another interesting question concerns how skilled players make adjustments to the non-kicking limb so that the forward swing phase of the kicking limb remains stable. Kellis, Katis and Gissis (2004) examined the effect of approach angle on the non-kicking limb for an instep kick and concluded that an oblique angle of approach induced significant loads on the knee joint structure of the non-kicking limb. Although knee angular displacement data for the non-kicking limb were recorded, these measures were not associated with concurrent changes in kinematics variables for the kicking limb. Therefore, it is currently not clear whether refined adjustments in angular displacement occur in the non-kicking limb to provide stability during chipping performance. In addition, data on location of the position of the planting foot for the non-kicking limb relative to ball position could augment information about the role of the non-kicking limb in skilled performance, although it has not been explicitly investigated (Lees & Nolan, 1998). Low variability in positioning of the planting foot should allow the player to establish a stable base of support to generate a kicking motion in the kicking limb that is consistent and functional in relation to the task goal. However, to date, it is not known whether knee angular displacement and variability in planting the foot of the non-kicking limb could be considered useful markers for identifying individuals at the Control or Skilled stages of learning (Newell, 1985).
Of course, examination of skilled soccer chipping coordination patterns alone would not actually demonstrate whether skilled players have been successful in their execution of the soccer chip. Chen, Liu & Mayer-Kress (2005) highlighted the need for research on movement coordination to examine changes in higher order kinematic variables relative to performance outcome measures to allow a meaningful examination of skilled performance. There has been few attempts to determine performance outcomes measures for skilled performances in soccer chipping. Such an outcome measurement tool would necessarily be a complex undertaking, incorporating height clearance, target accuracy as well as appropriate weighting of the chip pass (to enable a receiver to control the ball comfortably). This methodological advance would be a valuable addition to the sports science literature by providing a benchmark of success in the soccer chipping technique.

Another limitation in the literature is that most previous work has considered coordination of kicking at a group level of analysis. Although, there are benefits to undertaking data analysis at the group level, many useful insights can be achieved with the use of intra-participant analyses (Bates, James & Dufek, 2004). For example, an intra-individual investigation mode can be used to provide insights into how individuals solve coordination problems in a multi-articular lower limb interceptive action. It is likely that individual differences would be observed even among the skilled players for a soccer chipping task since in relatively simple motor tasks involving few degrees of freedom, subtle differences have been revealed between individuals when in-depth analyses of patterns of movement were conducted (e.g., Beek, Rikkert & van Wieringen, 1996; Port, Lee, Dassonville & Georgopoulos, 1997).

In this paper we examine the coordination and performance characteristics of a soccer chip in skilled players as defined according to the model of Newell (1985) and we determine the presence of inter-individual differences in utilizing motor system degrees of freedom in chipping strategies at the elite level. Based on Newell's (1985) model, and findings of previous research on the soccer chip we expected to observe: a) skilled players altering higher order derivatives like foot velocity to chip to different target positions with varying height and accuracy constraints; b) low variability in COM displacement for skilled players during the chip and at ball contact; c) changes in angular displacement of the knee joint of the non-kicking limb to allow for movement adaptation during the kick; d) low variability in positioning of the planting foot relative to the ball in skilled players; and e), refined differences in coordination patterns for the soccer chip between individual skilled players as they explored ways to satisfy task constraints.
coordination patterns of players have been successful. Mayer-Kress (2005) coordination to examine performance outcomes. There are measures for performance outcome. The current study by providing a formal advance in the literature by providing a more detailed analysis of individual differences. Although, there are many useful insights from previous research. Performance characterizing the model of individual differences in chipping strategies at the following landmarks: sphenoid, mandible, acromion process, lateral epicondyle (elbow), lateral point on the radial styloid, medial point on ulnar styloid, superior iliac crest, greater trochanter, lateral epicondyle (knee), medial epicondyle (knee), lateral malleolus, medial malleolus, 1\textsuperscript{st} metatarsal head (only for non-kicking foot) and 5\textsuperscript{th} metatarsal head.

Methods

Participants

A total of 5 male skilled players (age: 20 ± 1.58 yrs) participated in the study. All had at least 10 years of competitive football experience and were current members of the Singapore national squad. Singapore was ranked 92 out of 205 as at January 2006 by the Federation International Football Association (FIFA). All were experienced at chipping the ball during practice and in competitive matches. Voluntary and informed consent were obtained from all players and procedures employed in the study are in accordance with the participating institution's ethical guidelines.

Task and Apparatus

All players were asked to chip a soccer ball over a barrier to a skilled receiver with their dominant foot. No explicit verbal or visual instructions were provided on how to chip the ball over the barrier. Players were informed that the task goal was to kick the ball over the height barrier to land at the feet of a receiving player or within the landing zone in front of the receiver and appropriately weighted to allow for easy control of the pass. Video film capturing ball flight only on the receiver's feet was shown to ensure understanding of the task goal. Players performed the task within a kicking area (2 x 2 m) on a synthetic surface within a laboratory. Target positions were located on a field outside the laboratory with the player kicking the ball onto the field for all trials. A horizontal bar (length 4 m) supported by two adjustable vertical poles (2 m each) provided the height barrier for the task. Colored bands (approx 0.5 m) attached to the horizontal bar were used to simulate a perceptual barrier without occluding the receiver's view of the participant. All players were required to kick to four target positions located between 10 m to 14 m perpendicular to the kicking position and with bar height manipulated between 1.50 m to 1.70 m from the ground. (see Figure 1 for detailed information of the setup).

A FIFA-approved size 5 soccer ball was used in the kicking task and all players wore soccer indoor shoes and shorts for the test session. Kinematic data were captured by 6 infrared cameras (ProReflex, Model MCU 1000). The cameras were connected to the Qualysis On-line Motion Analysis system (Gothenburg, Sweden) and data were recorded at 240 Hz. Twenty nine spherical reflective passive markers were placed on key anatomical joints\textsuperscript{1}. The Visual 3D software (C-Motion) was used to construct a 15-segment model (head, upper arms, lower forearms, hands, thorax, pelvis, thigh, shank and feet) of each player and to calculate 3D kinematic variables, including the position of center of mass of individual participants. 3D Euler joint angles of flexion and extension were derived for hip, knee and ankle from the respective segments as defined by the marker sets. In addition, 8 semi-spherical markers were placed equidistant on

\textsuperscript{1}The joint markers were placed on the following anatomical landmarks: sphenoid, mandible, acromion process, lateral epicondyle (elbow), lateral point on the radial styloid, medial point on ulnar styloid, superior iliac crest, greater trochanter, lateral epicondyle (knee), medial epicondyle (knee), lateral malleolus, medial malleolus, 1\textsuperscript{st} metatarsal head (only for non-kicking foot) and 5\textsuperscript{th} metatarsal head.
the ball to determine the center of mass of the ball to allow derivation of ball spin during trajectory. A 20 m measuring tape was used to calculate chipping error, defined as the distance between the landing position of the ball on the field (when ball did not contact the receiver) and the respective target position. All measurements were taken by three research assistants who were trained and supervised for two weeks as part of the pilot phase of the study.

**PROCEDURES**

Players performed 5 warm up trials by kicking the ball out to the field without any requirement for satisfying height clearance or target accuracy. Thereafter, all players performed 10 trials kicking to T1. Subsequently, players performed another 5 trials each to T2, T3 and T4 in a randomized order, completing a total of 25 test trials for the whole session. The
10 trials to T1 were used to determine the coordination of the kicking action and the 13 trials to T2, T3 and T4 were used to identify if players were able to vary their foot velocity to achieve the task goal under different height and accuracy constraints. Players were allowed as much rest as they needed between trials.

**DATA ANALYSIS**

i) Performance outcome

Performance of the kicking task was assessed by how accurately and effectively weighted the chipped passes were to the receiver's feet. The outcome scores were determined from a 7-point Likert rating scale devised by the researcher and validated by two certified coaches from the Asian Football Confederation (AFC) (see Table I). For example, functional soccer chips that satisfied the task goal of successfully crossing the height barrier, landing accurately at the feet or within a set error distance (0 to 0.6 meters) and weighted comfortably for the receiver to potentially control the pass scored a maximum of 7 on the rating scale. Validity of the rating scale was verified in a series of pilot studies conducted on groups of skilled and less skilled participants to examine performance scores. Significant differences as a function of skill were found using the Likert performance scale (Kruskal Wallis One-Way Analysis of Variance by ranks test, p=0.009). In order to determine inter-scorer reliability between the experimenter

### Table I

**Performance Rating Scale for Soccer Kicking Task Emphasizing Weightage and Accuracy of Passes**

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>• Ball played to feet (below knee) or within landing zone in front of receiver (0m to 0.6m) and appropriately weighted for ease of control</td>
</tr>
</tbody>
</table>
| 6     | • Ball played to the thighs (between the knee and the abdomen) and appropriately weighted for ease of control  
        • Ball played to feet (below knee) or landing zone but not weighted for ease of control  
        • Ball played to the sides of the receiver at any level below the head (which challenges the receiver to move one step to control the pass) and the ball lands within 1m from the receiver but outside of landing zone (0.6m to 1m) |
| 5     | • Ball played to chest (above the abdomen) and appropriately weighted for ease of control  
        • Ball played to the thighs (between the knee and the abdomen) but not appropriately weighted for ease of control  
        • Ball played to the sides of the receiver at any level below the head (which challenges the receiver to move one step to control the pass) and the ball lands between 1.01m and 1.5m from the receiver |
| 4     | • Ball played to the head  
        • Ball played to chest (above the abdomen) but not appropriately weighted for ease of control  
        • Ball played to the sides of the receiver at any level below the head (which challenges the receiver to move one step to control the pass) and the ball lands between 1.51m and 2m from the receiver |
| 3     | • Ball lands between 2.01m to 2.5m from the receiver |
| 2     | • Ball lands between 2.51m to 3m from the receiver |
| 1     | • Ball lands more than 3m from the receiver  
        • Ball fails to cross the net barrier or touches the net barrier prior to reaching the receiver |
and the certified coaches, a sample of 25 trials were captured on video film and presented to
two certified coaches for scoring. Inter-scorer reliability between the experimenter and each
coach was 100% and 96% respectively. The performance rating scale allowed the magnitude
of error from the task goal to be determined for all trials since some kicks might have inadvert­
etly contacted the receiver's body, preventing error distance from being measured.
Means and SDs of individual players for all performance outcome scores were determined.

ii) Kinematic data for kicking limb

Kinematic data were collected for the duration of the limb movement sequence begin­
ning from the instant of initiation of knee flexion (before ball contact) to the end of peak hip
flexion (after ball contact) of the kicking limb (see Hodges et al., 2005). Data were filtered
using a low pass Butterworth digital filter with the Visual 3D software at frequency 7Hz. All
trials were normalized to 100 data points between the start event (initiation of knee flexion)
and end event (peak hip flexion) to allow for simultaneous comparison across individuals and
trials. Selected kinematic data from the 10 trials to target position T1 and 15 trials to target
positions T2, T3 and T4 were determined and analysed.

Discrete and relative kinematic variables provided information about specific kinematic
characteristics of the kicking coordination modes of all participants. The following discrete
kinematic variables were measured: Joint range of motion for the hip, knee and ankle (deg),
maximum resultant foot velocity (MFV) (m.s⁻¹), maximum resultant foot acceleration (MFA)
(m.s⁻²), maximum hip and knee angular velocity (MHAV and MKAV) (deg.s⁻¹), foot velocity at
ball contact (FV_BC) (m.s⁻¹) and foot acceleration at ball contact (FA_BC) (m.s⁻²). Relative
kinematic variables were calculated to examine segmental interactions of the kicking limb
including time of initiation of knee extension relative to instant of MHAV (SKE/IMHAV)
(%), instant of MHAV with respect to the instant of MKAV (IMHAV/IMKAV) (%) and
occurrence of MKAV with respect to MFV (IMKAV/IMFV) (%) (see also Anderson & Sid­
away, 1994). Data used for the calculation of the foot velocities and acceleration were
recorded at the instance before ball contact (one frame prior to ball contact) to ensure that
they were not distorted by smoothing routines around ball-foot impact².

Descriptive statistics for individual players were subsequently determined for all kinematic
variables and compared across different individuals via One-Way Analysis of Variance (ANOVA).
To protect against the increased probability of making a Type I error, Bonferroni correction fac­
tors were applied to analyses of all kinematic dependent variables. Variability in relationship
between the joint angles was examined using the NoRMS (Normalized Root Mean Square Error)
procedure (Sidaway & Schoenfelder-Zohdi, 1995) interpreted by Mullineaux, Bartlett and Ben­
ett (2001). NoRMS was used to provide an index of consistency in intra-limb coordination and
a higher value for NoRMS indicated greater variability for the joint coordination while a lower
NoRMS value suggested lower levels of variability in the joint angle relationship.

iii) Kinematic data for non-kicking limb

The range of motion for the knee of the non-kicking limb during the stance phase (i.e.,
from foot contact of the non-kicking limb on surface to ball contact for the kicking limb) was

² It is recognized that ball impact may distort the raw displacement data and subse­
quently foot velocity and acceleration data. However, errors have been limited and controlled
as far as possible by visually inspecting the raw data and applying suitable filtering routines to
ensure minimal distortion to the data set.
determined for all trials to T1 for all players. The distance between positions of planting foot (non-kicking limb) to ball positions was also determined for all trials to T1. Position of the centre of mass of the non-kicking foot was used as the point indicating the position of the planting foot and the centre of mass of the ball was determined as the point for ball position. X-Y coordinates from the respective foot segment and ball were used to calculate absolute distance between the planting foot and ball.

iv) Centre of mass (COM).

The centre of mass of individual players was determined from geometric modelling of segments (15 segment full body model) based on the individualised joint markers positions established with the Visual 3D software. Displacement of COM was plotted within individual players to examine variation characteristics over trials to position T1.

v) Ball Back Spin.

Ball back spin, in terms of angular velocity about the Y-axis of the local coordinate system of the ball was determined between frames 10 to 30 after ball contact through the Qualysis motion analysis system and Visual 3D software for all trials to T1. In the soccer chip, a greater amount of back spin allows the ball to ‘sit up’ (i.e., slower resultant trajectory velocity during flight of ball and greater hyperbolic trajectory) and improves the likelihood of an appropriately weighted pass to be received, which presents a useful indicator for determining the functionality of the soccer chip in meeting the task goal. In relation to the performance rating scale, the presence of ball back spin provides a performance-related indicator in capturing successful soccer chip shots although it is not explicitly described in the performance rating scale.

Results

The results are presented according to the categories of dependent variables presented in the previous section.

i) Performance Outcome

Skilled players accurately chipped the ball to positions T2, T3 and T4 as well as T1 (see Table II), suggesting that they were able to adapt their technique to cope with different target positions under varying height and accuracy constraints.

| TABLE II |

<table>
<thead>
<tr>
<th>Participants</th>
<th>T1 Mean (SD)</th>
<th>T2, T3 &amp; T4 Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>3.5 (1.65)</td>
<td>4.5 (2.13)</td>
</tr>
<tr>
<td>S2</td>
<td>4.4 (1.71)</td>
<td>3.5 (1.73)</td>
</tr>
<tr>
<td>S3</td>
<td>5.0 (1.85)</td>
<td>4.1 (1.59)</td>
</tr>
<tr>
<td>S4</td>
<td>4.5 (1.38)</td>
<td>4.7 (1.03)</td>
</tr>
<tr>
<td>S5</td>
<td>4.2 (2.15)</td>
<td>4.3 (1.80)</td>
</tr>
</tbody>
</table>
ii) Kinematic Data for Kicking Limb

Discrete kinematic data for all skilled players are shown in Table 3 and One Way ANOVA was used to compare inter-individual differences between means of kinematic variables for the skilled players.

From Table III, it can be observed that all skilled players achieved a small ROM (hip), ranging from 25.31 ± 3.56° to 42.12 ± 5.23° (despite significant differences among the players (F(4, 45)= 8.575, p=0.000)). FA_BC for all players occurred close to the MFA, i.e., skilled players were using close to maximum foot acceleration at ball impact for the soccer chip.

Interestingly, all skilled players exhibited foot velocity at ball contact (FVT1_BC) ranging from 9.31m.s\(^{-1}\) to 10.40m.s\(^{-1}\) with no significant between-participant differences and with low coefficients of variation (<10.7%). Table III highlights the between-participant differences for rele-

| Table III |
| Mean, Sd (In Parentheses) and Coefficient of Variation of Discrete Kinematic Data for Kicking Limb of All Skilled Players to T1 |

<table>
<thead>
<tr>
<th>(S1)</th>
<th>(S2)</th>
<th>(S3)</th>
<th>(S4)</th>
<th>(S5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHAV* (deg.s(^{-1}))</td>
<td>325.40</td>
<td>324.17</td>
<td>352.69</td>
<td>216.29</td>
</tr>
<tr>
<td>MKAV* (deg.s(^{-1}))</td>
<td>35.63</td>
<td>24.50</td>
<td>32.06</td>
<td>84.09</td>
</tr>
<tr>
<td>MKAV* (deg.s(^{-1}))</td>
<td>10.2%</td>
<td>21.4%</td>
<td>19.0%</td>
<td>19.8%</td>
</tr>
<tr>
<td>MKAV* (deg.s(^{-1}))</td>
<td>3.56</td>
<td>5.23</td>
<td>5.32</td>
<td></td>
</tr>
<tr>
<td>FVT1_BC (m.s(^{-1}))</td>
<td>9.31</td>
<td>10.40</td>
<td>9.63</td>
<td>9.34</td>
</tr>
<tr>
<td>FVT1_BC* (m.s(^{-1}))</td>
<td>9.7%</td>
<td>10.0%</td>
<td>10.0%</td>
<td>10.0%</td>
</tr>
<tr>
<td>ROM(hip)* (deg)</td>
<td>39.6%</td>
<td>9.8%</td>
<td>12.4%</td>
<td>14.1%</td>
</tr>
<tr>
<td>ROM(knee)* (deg)</td>
<td>41.7%</td>
<td>5.7%</td>
<td>4.1%</td>
<td>4.8%</td>
</tr>
<tr>
<td>ROM(ankle)* (deg)</td>
<td>39.6</td>
<td>30.70</td>
<td>42.12</td>
<td>25.31</td>
</tr>
<tr>
<td>ROM(ankle)* (deg)</td>
<td>5.32</td>
<td>4.82</td>
<td>4.82</td>
<td></td>
</tr>
<tr>
<td>FAT1_BC* (m.s^2)</td>
<td>13.3%</td>
<td>6.6%</td>
<td>4.5%</td>
<td>5.6%</td>
</tr>
</tbody>
</table>

*p<0.005 for all skilled players

MHAV: Maximum Hip Angular Velocity; MKAV: Maximum Knee Angular Velocity; MFV: Maximum Foot Velocity; FVT1_BC: Foot Velocity at Ball Contact to T1; MFA: Maximum Foot Acceleration; ROM(hip): Range of Motion for Hip; ROM(knee): Range of Motion for Knee; ROM(ankle): Range of Motion for Ankle; FAT1: Foot Acceleration at Ball Contact to T1
n Table 3 and differences between players achieved a 23° (despite sig-
ificant absolute kinematic variables and clearly shows that there are variations
in technique even among the players and there were no significant differ-
ces for foot velocity at ball contact to T1.
IMHAV/IMKAV ranged from 0.79 to 0.97, indicating that IMHAV
occurs earlier than IMKAV, signaling a proximal to distal segmental sequenc-
ing of limbs (see Table IV for data on relative kinematic variables). The pre-
ence of fluid segmental sequencing resulted in effective speed of the distal
joint for all players. In relation to SKE/IMHAV values, players acquired val-
ues ranging from 0.79 to 0.97, with SKE occurring slightly before IMHAV.
Table V shows selected higher order derivatives like foot velocity
(FV_BC) and maximum foot velocity (MFV) to T2, T3 and T4. All players
revealed a common trend by achieving the lowest FV_BC for T2 and highest
FV_BC for T4, the nearest and furthest target position respectively with the
highest height barrier, with coefficients of variation for all players being less

TABLE IV

<table>
<thead>
<tr>
<th></th>
<th>(S1)</th>
<th>(S2)</th>
<th>(S3)</th>
<th>(S4)</th>
<th>(S5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMHAV/IMKAV</td>
<td>0.95 (0.12)</td>
<td>0.97 (0.04)</td>
<td>0.81 (0.08)</td>
<td>0.79 (0.12)</td>
<td>0.82 (0.03)</td>
</tr>
<tr>
<td>IMKAV/IMFV</td>
<td>1.05 (0.01)</td>
<td>1.02 (0.03)</td>
<td>1.02 (0.01)</td>
<td>1.05 (0.01)</td>
<td>1.03 (0.01)</td>
</tr>
<tr>
<td>SKE/IMHAV</td>
<td>0.82 (0.11)</td>
<td>0.79 (0.02)</td>
<td>0.91 (0.07)</td>
<td>0.97 (0.15)</td>
<td>0.94 (0.04)</td>
</tr>
</tbody>
</table>

IMHAV: Instant of Maximum Hip Angular Velocity; IMKAV: Instant of Maximum Knee Angular Velocity; IMFV: Instant of Maximum Foot Velocity; SKE: Start of Knee Extension

TABLE V

<table>
<thead>
<tr>
<th></th>
<th>(S1)</th>
<th>(S2)</th>
<th>(S3)</th>
<th>(S4)</th>
<th>(S5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FVT2_BC (m.s⁻¹)</td>
<td>8.23 (0.83)</td>
<td>9.94 (0.34)</td>
<td>9.31 (0.47)</td>
<td>9.19 (0.36)</td>
<td>8.96 (0.65)</td>
</tr>
<tr>
<td>FVT3_BC (m.s⁻¹)</td>
<td>9.82 (0.64)</td>
<td>10.85 (0.35)</td>
<td>10.17 (0.37)</td>
<td>10.07 (0.22)</td>
<td>9.76 (0.67)</td>
</tr>
<tr>
<td>FVT4_BC (m.s⁻¹)</td>
<td>6.3%</td>
<td>7.3%</td>
<td>6%</td>
<td>5.2%</td>
<td>5.2%</td>
</tr>
<tr>
<td>MFV_T2 (m.s⁻¹)</td>
<td>10.53 (0.41)</td>
<td>11.26 (0.15)</td>
<td>10.86 (0.33)</td>
<td>10.34 (0.14)</td>
<td>10.96 (0.24)</td>
</tr>
<tr>
<td>MFV_T3 (m.s⁻¹)</td>
<td>3.9%</td>
<td>4.1%</td>
<td>3.2%</td>
<td>3.1%</td>
<td>3.1%</td>
</tr>
<tr>
<td>MFV_T4 (m.s⁻¹)</td>
<td>2.6%</td>
<td>2.7%</td>
<td>2.7%</td>
<td>2.7%</td>
<td>2.7%</td>
</tr>
<tr>
<td>MFV_T5 (m.s⁻¹)</td>
<td>2.5%</td>
<td>2.5%</td>
<td>2.5%</td>
<td>2.5%</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

FVT_Bc: Foot Velocity at Ball Contact; MFV: Maximum Foot Velocity
FV_BC and MFV were the only variables that demonstrated the trend of lowest value to nearest and lowest target position and highest value to furthest and highest target positions for all skilled players. Other variables that did not demonstrate this trend were not reflected in this table.
than 10%. Interestingly, participant 2 displayed the highest FV\_BC to all three target positions. A similar trend was also observed for MFV to T2, T3 and T4 with coefficients of variation less than 5%. As for FA\_BC (foot acceleration at ball contact) and MFA (maximum foot acceleration), a less clear trend of lower values for the nearer and lower target position (T2) and higher value for the further and higher target position (T4) was observed, although values were consistent (i.e., low coefficient of variation <12.2%). Similarly, although there were no clear trends seen in MKAV (maximum knee angular velocity) and MHAV (maximum hip angular velocity), the values were consistent with low coefficients of variation especially for MKAV (less than 10% except for MKAV\_T2 for S1).

All players demonstrated relatively similar hip-knee and knee-ankle angle-angle plots except for player 1 who demonstrated qualitatively bigger differences in the angle-angle plots, compared to the other players (See Figure 2 and 3). Visual inspection of the trials performed by player 1 revealed that two slightly different techniques were used during the 10 test trials to T1. For trials 2, 3 and 5 to T1, player 1 adopted a 'scooping technique' with an exaggerated hip range of motion and follow through of the kicking limb which is reflected in the hip-knee angle-angle plots (see Figure 2 and 3). In the remaining trials, player 1 used a technique with a stab like action on the ball with minimal follow through similar to that seen in the other four players (see Figure 4 for a representative soccer chip exhibited by skilled players and the scoop technique shown for certain trials by player 1).

In terms of NoRMS values, player 1 exhibited the highest variability for hip-knee and knee-ankle intra-limb coordination a finding which might be explained by the two different techniques used during the test session (see Figure 2 and 3). However, skilled player 1 was still able to achieve a respectable performance score of 3.5, although it was the lowest value among the skilled players. Within individual skilled players, similar NoRMS indices for hip-knee and knee-ankle intra-limb coordination were observed.

**iii) Non-Kicking Limb**

Figure 5 shows the qualitative pattern of the non-kicking knee ROM. There were no clear qualitative differences in terms of displacement trends in the knee ROM between all players except for player 3. Player 3 demonstrated a decreasing and then increasing knee ROM during the stance phase. One Way ANOVA showed significant differences among the skilled players (F(4, 4.5)= 30.654, p=0.000) for the non-kicking knee ROM. Player 2 exhibited the lowest non-kicking knee ROM at 12.89 ± 3.03°, which was different from all other players except for player 3 (p=0.209). The smaller ROM for

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test FV, BC to all or MFV to T2, T3 (A, BC (foot acceleration), a less clear on (T2) and higher observed, although 12.2%). Similarly, num knee angular values were con-AV (less than 10% e and knee-ankle qualitatively bigger players (See Fig- player 1 revealed the 10 test trials to ng technique' with f the kicking limb figure 2 and 3). In like action on the re other four players 1). hest variability for g which might be be test session (see able to achieve a est value among r NoRMS indices observed.

player 2 could have a functional role in providing stability for ball contact while the planting foot is ahead of the ball for his soccer chipping action.

Significant differences were found between all players for distance of foot to ball position (F(4, 41)= 18.520, p=0.000). However, post hoc Scheffé testing showed that only player 3 was significantly different from all other players (p<0.05). Qualitatively, there were no clear differences in terms of variability of foot position with ball position for all players. But there were
some inter-individual differences in location of the planting foot (see Figure 6). Skilled player 2 used a foot planting position ahead of ball position while other skilled players showed planting foot positions slightly to the side and behind the ball (0.27m to 0.31m away from the ball).

iv) Displacement of COM

From Figure 7, it was observed that COM moved upwards just prior to ball contact for players 2 and 3, while it moved forwards for players 4 and 5.
Skilled Player: Representative Chip

Skilled Player 1: Scoop

Initiation of Knee Flexion
Ball Contact
Peak Hip Flexion

Fig. 4. Skeletal representation of a representative soccer chip by skilled players and a scoop kick by skilled player 1.

Player 1 demonstrated both forward and upward displacement of COM during the chipping trials.

v) Ball Back Spin

All players demonstrated back spin on the ball. (See Table VI). Ball spin data provides a useful indicator to suggest the appropriate weighting of the soccer chips to the receiver, allowing the successful attainment of the task goal.

<table>
<thead>
<tr>
<th>Participants</th>
<th>T1 Mean (SD) *x1</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 n=9</td>
<td>2694.82 (384.82)</td>
</tr>
<tr>
<td>S2 n=9</td>
<td>2005.62 (599.13)</td>
</tr>
<tr>
<td>S3 n=8</td>
<td>1975.40 (341.12)</td>
</tr>
<tr>
<td>S4 n=8</td>
<td>1906.43 (234.0)</td>
</tr>
<tr>
<td>S5 n=8</td>
<td>1894.75 (645.21)</td>
</tr>
</tbody>
</table>

*Due to occlusion of some reflective markers on the ball during ball flight, incomplete ball spin data were noted for some trials. Refer to n values for individual players in the table.
Fig. 5. - Figure showing non-kicking limb knee (ROM) for skilled player 3 and a representative non-kicking limb knee (ROM) for skilled players.
Means and SD (in parentheses) of distance between planting foot and ball position shown within individual plots.

Fig. 6: Figure showing planting foot position to ball position for all skilled players to T1.

Discussion

The purpose of this study was to examine the coordination of soccer chipping performance in participants defined as skilled according to Newell's (1985) model of learning. To achieve this aim, we adopted both intra- and inter-individual levels of analyses in investigating coordination patterns and associated performance outcomes for a soccer chipping task.
From the performance outcome results, it was apparent that all skilled players were able to achieve successful outcomes to different target positions under varying accuracy and height constraints (see Table II). We interpreted this finding as evidence that these players were at least at the Control stages of learning as described by Newell (1985). In addition, the high Likert scale scores achieved by the skilled players indicated that the chips were also appropriately weighted. Accordingly, the performance scores obtained by
the skilled players in this study clearly suggest that the data are useful as a benchmarking reference for studying the performance of players of different skill levels in future research.

Based on analysis of kinematic variables and intra-limb coordination patterns, skilled players demonstrated similarity in technique, generally displaying a low level of joint involvement at the proximal joints (hip) and greater joint involvement at the distal joints (knee). The hip angle changed over a small range of motion and the knee angle altered over a bigger range during the execution of the soccer chip in this study. Hip-knee and knee-ankle angle-angle plots (see Figures 2 and 3), revealed that most players displayed a similar inter-segment coordination pattern except for player 1. Visual examination of movement trials for player 1 revealed that he used a different kicking technique that mimicked a scooping action for three of the ten trials to target position T1. For the remainder of the trials, he adopted a stabbing action with minimal follow through similar to the soccer chips executed by the other skilled players (see Figure 4). It seems that the stabbing action on the ball with little follow through allowed the players to generate adequate height and more importantly, back spin for the ball to “sit up” during ball flight to afford easier control for the receiver. The pattern of coordination shown by the skilled players signals that they were able to establish strong relationships between movements of body segments and the forces generating the movements, to achieve the specific task goal, suggesting that they were at least at the Control stage of learning according to Newell (1985).

In addition, movement fluidity seemed to be evidenced in the values for relative kinematic variables like IMHAV/IMKAV and SKE/IMHAV, allowing proximal segments to acquire peak angular velocity slightly before the distal segments (similar to the findings of Anderson & Sidaway, 1994). In some instances, both distal and proximal segments acquired peak angular velocity at a similar point in time (see IMKAV/IMFV values in Table 4). It seems that skilled players were able to better achieve a summation of speed for the kicking limb with higher foot velocity generated through rapid rotation of lower distal segments about the knee joint near to ball contact. The demonstration of this sophisticated coordination pattern by the skilled players also supports the suggestion that they were at least at the Control stage of learning described by Newell (1985).

The players were able to vary foot velocity (both FV_BC and MFV) under the varying height and accuracy constraints to T2, T3 and T4, with lowest FV_BC and MFV values being observed to T2 (shortest distance and with lowest height barrier) and highest FV_BC and MFV to T4 (furthest distance and highest height barrier). The data indicated that they were adept at
manipulating higher order derivatives of movement displacement information, like foot velocity in this case (see Lees & Davids, 2002 for a discussion on biomechanical analyses of control in kicking). In addition, the low coefficient of variation values observed for most of the higher order derivatives to T1, T2, T3 and T4 (other than MHAV) suggested that the skilled players were able to maintain consistency in movement production, yet at the same time they functionally adapted their coordination patterns to successfully chip the ball to different target positions, clearly indicating that they were at least at the Control stage of learning, with the possibility that some players were transiting to the Skilled stage.

In relation to variability of intra-limb coordination, similar intra-individual NoRMS values of skilled players for the proximal and distal segments were observed for the hip-knee and knee-ankle intra-limb coordination. This finding indicated that the skilled players exhibited low variability between trials to achieve successful performance outcomes, another feature of the Control stage of learning.

Inter-individual differences between the players were evident in the kinematics of the kicking leg (see Table IV), as well as the COM displacement data and kinematic data of the non-kicking limb. From the COM displacement data, two distinct skilled coordination patterns can be observed. Players 2 and 3 displayed similar COM displacement characteristics (see Figures 7), with observable upwards and forwards displacement of COM nearing ball contact. This characteristic indicated that movement of the body was in synchrony with the task demand of projecting the ball upwards, although this strategy was not seen in performance of players 4 and 5. They showed a short acceleration towards the ball contacting the ball with mainly forward movement of the body as indicated by the continued forward movement of the COM. Moreover, minimal variability in COM displacement suggested that the players relied on a similar movement strategy over their respective soccer chipping trials (although player 1 did not follow this trend). Such an observation supports the theoretical idea of degeneracy (Edelman & Gally, 2001), where different functional coordination solutions are possible for the same task demands (see Hong and Newell, 2006). From the data, it seems that the presence or absence of forward and upward displacement of COM prior to ball contact may not present itself as a requisite feature of skilled performance in terms of movement fluidity and synchrony in the skilled stage of learning.

Skilled players generally demonstrated a low level of within-individual variability in terms of distance of foot relative to ball position (0.021m to 0.041m). However, although there were no clear differences among skilled
For a discussion on the low coefficients of the derivatives to skilled players, yet at the same time to successfully plant the foot forward and to the side of the ball distinct from the patterns shown by other players. The smaller ROM (knee of non-kicking limb) for player 2, together with the forward planting position of the foot, could have provided functionality in enhancing stability at the moment of ball contact. Closer examination of the 15-segment, full-body model revealed that player 2 performed the soccer chip with an angled kicking motion, contacting the ball with the inside of the foot. This pattern exhibited a hybrid pattern of a 'traditional' soccer chip and an instep drive as described in soccer coaching manuals (see Hargreaves, 1990). This observation of individual coordination patterns even among skilled performers supports the idea that a common optimal kinematic pattern for a chipping action may not exist (see Brisson & Alain, 1996). Further research is needed to examine how foot planting positions change with alterations to coordination patterns as a function of practice.

Qualitatively, there were no clear differences among the skilled players for ROM (knee of non-kicking limb) in relation to the pattern of change except for player 3. He demonstrated a decreasing followed by an increasing ROM (knee of non-kicking limb) during the stance phase (See Figure 3), indicating that the non-kicking limb was used to push the body upwards as the ball was projected forward and upward. Such an observation about the non-kicking limb movement warrants further investigation in future studies since compensatory joint motion about the non-kicking knee joint could allow reactive forces in the non-kicking limb to be effectively managed so that stability during the stance phase could be optimized. To evaluate this idea in more detail, future studies could measure ground reaction forces of the planting foot to determine the nature and level of reactive forces present during the stance phase in the soccer chip.

In conclusion, the data revealed insights into how motor system degrees of freedom were subtly re-organized during task performance. Globally similar coordination patterns in skilled players for the soccer chip were characterized by a low level of involvement at the proximal joint (small range of motion at the hip) and higher involvement at the distal joints (larger range of motion at the knee). In relation to the predictions of this paper, it can be concluded that a) skilled players were able to alter foot velocity effectively to chip the ball to different target positions with varying height and accuracy constraints; b) skilled players demonstrated low levels of variability in COM displacement during the chip and at ball contact even though some of the players exhibited slightly different characteristics of COM displacement nearing ball contact; c) skilled players showed low levels of variability in posi-
tioning the planting foot relative to the ball; d) typically, there were no clear changes in displacement of the knee joint in the non-kicking limb to allow for movement adaptation during the kick; and e), there were subtle variations among skilled players within these global coordination patterns, evidenced by kinematic data, foot placement, and COM displacement data.

In general, the skilled players in this study evidenced key features of being at least at the Control stage of learning. They were able to manipulate higher order derivatives like foot velocity to meet the task goal effectively under varying height and accuracy constraints, and their coordination patterns showed very little variability (although the variability observed should be seen as functional for skilled performance). Data from the current study confirmed the utility of using foot velocity as a criterion for the Control stage of learning in the soccer chip. However, indicators for fluidity and synchrony of movement were more difficult to ascertain for the Skilled stage of learning. Nevertheless, adopting an intra-individual analysis provided valuable insights into how motor system degrees of freedom were re-organized during goal-directed performance by individuals that would have been masked if data were grouped and analyzed. Skilled performance can be categorized along a continuum as some skilled players demonstrated similar coordination and performance indicators while others differed subtly. This study has revealed the merits of Newell's (1985) model of learning to examine coordination of actions in skilled individuals. Further work is needed to tease out how performance can be better described at the skilled stage of learning (e.g., directly examining energy expenditure) as well as to understand the role of movement variability in satisfying different task constraints in multi-articular actions such as the soccer chip.

REFERENCES


here were no clear limb to allow for subtle variations in the current study. Evidence in the literature suggests that key features of the Control stage of learning are organization and synchrony. These are often masked if the control group is categorized with the experimental group. In this study, the Control stage was observed during the performance of the pedaloc. A number of techniques were employed to tease out the stages of learning. The results showed that the Control stage was characterized by organization and synchrony. This study has implications for practitioners in the field of sports science.


