DECLARATION CONCERNING THESIS PRESENTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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Coordination and its Acquisition in a Lower Limb Multi-Articular Interceptive Task

(a) That work was done by me, personally

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Signature: . Date: 12th March 2007
COORDINATION AND ITS ACQUISITION IN A LOWER LIMB
MULTI-ARTICULAR INTERCEPTIVE TASK

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Abstract

Human movement is mostly multi-articular in nature, involving numerous joint movement possibilities. This complexity in human movement has provided a theoretical challenge for movement scientists to comprehend the underlying processes controlling these joint movements in a functional and goal-directed manner. Although there has been an increase in research on examining coordination in multi-articular actions, it is still in its infancy. The aim of this thesis was to examine the acquisition of coordination of a discrete multi-articular movement action from the theoretical perspective of Dynamical Systems Theory. Specifically, four different studies (comprising Chapters 2, 3, 4 and 5) examined key research questions raised (Chapter 1) about understanding the coordination and control of a lower limb multi-articular interceptive action. The thesis concludes in Chapter 6 with a brief discussion on the key findings and the implications for practitioners in physical education pedagogy relating to a games teaching approach.

The empirical work began with an analysis of the variation in coordination as a function of skill (Chapter 2). A discrete multi-articular kicking action with specific task constraints (kicking over a height barrier and to different target positions) was utilised as a research vehicle to examine differences in coordination between three groups of participants: skilled, intermediates and novices. From group analysis, it was determined that skilled and intermediate groups demonstrated a functional coordination mode involving a lower joint involvement at the proximal joints and higher joint involvement at distal joints, mimicking a ‘chip-like action’ in soccer. In contrast, large range of motions in the kicking limb was seen for the novice participants who demonstrated a ‘driving-like action’. Analysis of ball trajectory data confirmed that novice participants were not able to successfully project the ball over the height barrier. Findings from
this study demonstrated that joint involvement is dependent on skill level and task constraints rather than a proposed universal ‘reducing to increasing’ involvement of degrees of freedom strategy as suggested by previous research. Functional foot velocity at ball contact to various target positions demonstrated by skilled and intermediate players further highlighted the possibility of using a model of learning focusing on coordination to examine progression through the different stages of learning. Given the findings in Chapter 2 and how averaging group data may mask valuable data at the individual level of analysis, a multiple-single participant design was warranted to examine how intra-participant coordination may differ within the skilled group. In Chapter 3, coordination of skilled players was further investigated to determine if refined differences could be present at the skilled level of performance using the same research design in Chapter 2. From the investigation, although global similarities in terms of the use of a chipping action in projecting the ball was found, differences in foot position for non-kicking foot and centre of mass displacement near ball contact emphasised that even skilled individuals can demonstrate different coordination solutions to meet the same task goal, highlighting the concept of degeneracy in the control and coordination of human movement. Such an observation provided the impetus to further examine coordination changes in novice learners as a function of practice using multiple-single participant analysis (Chapter 4). From the study, individual learners demonstrated different progression trends in terms of joint motion changes while achieving the same task goal. Intra-participant analysis showed how the ball can be projected accurately across the height barrier with both a ‘scooping’ and a ‘chipping’ action. When referenced to a model of learning (Newell, 1985), foot velocity at ball contact was functionally manipulated by the novice participants to target positions with varying height and distance constraints by later stages of learning. It was further suggested that the dynamics of the learner prior to practicing the task could influence the eventual kicking action that emerged. To further investigate learning from a dynamical systems perspective, key features like transitions between preferred movement
patterns and role of movement patterns variability in effecting such transitions was examined in Chapter 5. It was determined through the use of cluster analysis procedures that increased movement pattern variability was not a pre-requisite for a transition between preferred movement patterns across participants. Informational and intentional constraints can have a role to play in effecting the search for pathways of change in movement patterns especially in discrete trial-based multi-articular actions.

This thesis has contributed novel knowledge regarding examining coordination changes for a selected discrete multi-articular lower limb action. Focusing on investigating changes in coordination has enabled a detailed examination on the process of change with practice and referencing these changes to a model of learning based on concepts in dynamical systems theory. Specifically, a greater understanding on the role of movement pattern variability and transitions between preferred movement patterns using refined cluster analysis procedures was an advancement of previous work in this area of study. In addition, the empirical findings provided theoretical support for a pedagogical approach, Nonlinear Pedagogy, based on key concepts in dynamical systems theory (Chapter 6). Nonlinear Pedagogy can help inform practitioners on the relevance of manipulating task, environmental and performer constraints to enable functional movement solutions to surface in a learning situation without the need to provide explicit and the delivery of a top-down teaching approach commonly observed in skills teaching. The relevance of Nonlinear Pedagogy was further emphasised in this thesis with a discussion on a games teaching approach that is increasingly popular in Physical Education. Future studies should continue to examine coordination in multi-articular actions to provide theoretical, experimental and practical implications for understanding human movement.
Preface

Acknowledgements

I will try not to leave anyone out who have assisted, pressured or cajoled me to complete this quest for P (permanent) h (head) D (damage).

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1.1 General Introduction

The purpose of this thesis is to examine the processes underlying acquisition of coordination of a discrete multi-articular action from the theoretical perspective of Dynamical Systems Theory.

From my experience as a Physical Educator, I have been perplexed by how some learners are able to become skilful at a particular movement task quite easily compared to other learners. I have also observed learners achieve successful performance after spending some time searching for a movement solution, a process in which learners vary their movement patterns to try to meet the goals of a learning situation. Moreover, the pathways of progress for individual learners seem to take on different trajectories involving different practice time extents.

The varied individual learning characteristics demonstrated in the physical education lessons fuelled my desire to better understand the nature of the individual differences shown by learners in exploring and acquiring complex sports skills, usually required in sports and team games. Specifically, the questions of concern to me included: How do learners modify the movements of their individual body parts to generate a purposeful and effective movement as a function of practice? Are there appropriate theoretical frameworks or models in the motor control literature that could take into account the dynamic interaction between the performer and task-environmental interaction that is present in all learning contexts? And, if such a theoretical perspective is available, could it adequately describe and explain the individual differences in learning usually seen by practitioners in a group of learners?

This General Introduction will serve to clarify the theoretical presuppositions and basis for the empirical studies reported from Chapters 2 to 5. First, a discussion will be provided to
present the challenge of acquiring coordination within a neurobiological system, captured in terms of the ‘degrees of freedom problem’\(^1\). Subsequently, a framework for understanding interacting constraints affecting coordination (Newell, 1985, 1996) will be discussed. Next, an appropriate theoretical approach that accommodates and embodies the dynamic interaction between various components in a learning situation will be presented to examine changes in human movement. This section will overview key concepts in Dynamical Systems Theory specifically related to learning. A model of learning (Newell, 1985) emphasising coordination changes within the dynamical systems framework will also be discussed. In addition, a brief review will be presented on the functional role of movement variability in providing flexibility as well as adaptability in generating movements to achieve consistent performance. Specifically, the section will examine how movement variability can be functional in helping learners explore possible movement solutions to perform consistently in different task settings. Thereafter, concepts relating to the search and exploration of movement solutions (Müller & Sternad, 2004) will be shared. The concepts on exploring movement solutions will be elucidated to examine how they can be used to identify differences in performance and concurrent movement solutions for various skilled learners. Next, a discussion on the needs and benefits of studying coordination of discrete multi-articular actions will be undertaken. Specifically, a lower limb discrete multi-articular action will be used as a research vehicle since sport and work are good contexts to study the coordination of multi-articular discrete actions. Finally, a preview of the ensuing chapters in the current thesis will be provided.

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\(^1\) The term neurobiological system will be used throughout this thesis as it encompasses the neural basis of perception and action in biological movement systems such as the human movement system
1.2 Degrees of Freedom Problem: The Challenge of Acquiring Coordination

1.2.1 Degrees of Freedom Problem

The human body can be considered as a complex neurobiological system that consists of numerous moving components that have to function in synchrony for effective behaviour to occur. Considering that the average human body contains close to 792 different muscles, over 100 different joints and infinitely large movement possibilities, it certainly becomes a challenge to comprehend the control of movement (Kelso, 1982).

It comes as no surprise that Bernstein (1967) highlighted the challenge in studying human movement as one of understanding the control of a complex neurobiological system. Coordination refers to the process by which movement system components are assembled and brought into proper relation with each other during a goal-directed activity (Turvey, 1990). And, Bernstein viewed the basic coordination problem as the process of mastering redundant degrees of freedom (dof)\(^2\) of the moving organ, into a controllable system. The ‘problem’ in terms of controlling movement is to determine how the numerous parts of the neurobiological system are brought together to form stable movement patterns from the huge possibilities that components within the system offers. Furthermore, it was largely unknown how the control of these dof may change when a movement skill is learnt.

According to Bernstein (1967), three changes to motor system dof can be identified with learning in human movement and a 3-stage model was proposed. At the early stage of learning, coordination solutions are employed that reduce the number of dof involved at the periphery to a minimum, ‘freezing’ or reducing the involvement of the dof. The second stage is characterised by

\(^2\) The term ‘degrees of freedom’ used in this thesis refers to the mechanical dof at joint space. ‘Degrees of freedom’ refers to the number of independent planes of motion at the joints that can be coordinated and controlled by an individual (Bernstein, 1967).
a releasing of the dof or increasing the involvement on the constrained dof. At this stage, all possible dof are incorporated in movement coordination. The last stage of learning is characterised by the learner utilising and exploiting the reactive forces that arise from the interaction of the performer with the environment (e.g., from segmental interactions and friction).

Numerous studies have since been undertaken to examine the suggested progression in the reduction and increase of involvement of dof. One early study by Vereijken, van Emmerik, Whiting and Newell (1992) investigated how the level of involvement of dof changes in adults from learning a ski simulator task. Empirical data in support of Bernstein’s ideas of reducing to increasing dof were reported across participants. Specifically, kinematic analysis of the limb and torso showed evidence that participants reduced dof involvement for the joint segments of the whole body in initial learning and only introduced active motion at the ankle, knee and hip joints to increase dof involvement during the last practice phase. Studies on single joint movements like hand writing task (Newell & van Emmerik, 1989), dart throwing (McDonald, van Emmerik & Newell, 1989) and pistol shooting (Arutyunyan, Gurfinkel & Mirskii, 1968, 1969) have also found evidence for reducing and increasing involvement of dof.

In their study of coordination in a lower limb interceptive task, Anderson and Sidaway (1994) found that dof for novice players were originally reduced early in practice, indicated by a constrained range of motion at the hip and knee joints. However, by the end of the training phase, level of joint involvement at the hip and knee increased and a greater range of motion was observed. Increases in the mean foot linear velocity and more effective summation of speed from the hip to the knee were also observed with practice, resulting in observable changes similar to an expert model for the soccer instep drive. These results from Anderson and Sidaway (1994) supported Bernstein’s ideas of an increasing dof involvement as a consequence of practice.
1.2.2 Non Uni-Directional Change in Degrees of Freedom

However, more recent studies on coordination changes have provided some indication that the increasing involvement of dof in joint motions with practice may not be an observation generalisable to all learning tasks. For example, Broderick and Newell (1999) investigated the coordination patterns in ball bouncing as a function of skill levels. The task required participants to bounce the basketball with their dominant hand for as long as possible in one place at a comfortable pace. Broderick and Newell (1999) argued that directional changes in organisation of the task limb (shoulder to fingers) were neither proximal to distal nor the reverse. Instead dof organisation was bidirectional in the basketball bouncing task, changing from the ends of the effector chain to its centre with high couplings of all joints present at higher level of skill. The results from Broderick and Newell (1999) supported the argument that changes in the involvement of dof would be task dependent, citing the importance of how specific characteristics of the required task (i.e., continual regulation of force output at the end effector) would impact the emergence of directional changes in coordination patterns (Newell, 1986).

Further studies on examining coordination in dynamic balance tasks (Haken, 1996; Ko, Challis & Newell, 2003; Slobounov & Newell, 1994), also found that an increasing involvement of dof were absent during skill acquisition. In the study by Ko et al (2003), dof were released initially to allow for exploration and search for a more stable as well as efficient postural coordination mode. With practice, stronger couplings between joints emerged, reducing the level of involvement of dof. Similarly, additional dof were utilised by young children early in practice while practicing a balancing task (Slobounov & Newell, 1994) as well as learning a pedalo task (Haken, 1996) before a reduction in the level of joint involvement was observed later in practice.
It is likely that the characteristics of the balancing tasks in these studies required a similar progression in the dof changes.

In a soccer kicking task, Hodges, Hayes, Horn and Williams (2005) found evidence that involvement of dof in the kicking limb were initially reduced early in practice but subsequently increased as a learner spent more time in practice. However, it was later observed that dof of the kicking limbs were reduced again at the end of the practice phase in the study. This observation was demonstrated by the results of change in the range of motions (ROM) of the hip, knee and ankle joints. In their study observing one novice learner over a 9-day practice period, Hodges et al (2005) found that the hip range of motion was relatively large compared to knee and ankle joints, suggesting that more active control was maintained by the individual at the hip. Hodges et al (2005) also observed that the control of segmental interaction changed from proximal to distal and then to proximal again. This change in segmental interaction was accompanied by a progression in control from many to few and to many dof. Joints were increasingly controlled independently through reduction in cross-correlations. Hodges et al (2005) reported that such changes in dof and segmental interaction could be seen only if the amount of practice was high and that the task was challenging in terms of the skill requirement. This sequence of change in the level of joint involvement is an indication that the learner is challenged to ‘explore’ the most suitable coordination solution to achieve the goal of the task and highlights the need to provide adequate practice time to allow coordination changes to emerge from the neurobiological system.

The requirement of the kicking task in Hodges et al (2005) was highly specific, requiring a scoop-like action for success due to the proximity of the target (250cm) and height barrier (75cm high and 175cm away) to the participant. It is possible that reducing, increasing and reducing levels of joint involvement in the lower limb, as observed by Hodges et al (2005) could have
been a highly specific strategical response to the constrained nature of the kicking task employed in that study.

Therefore, the implication from many previous studies is that changes in organisation of motor system dof during the acquisition of coordination may not be unidirectional as suggested by Bernstein, simply from reducing to increasing, but would be task dependent (Newell, 1996; Newell & McDonald, 1994; Newell & Vaillancourt, 2001) (see Chapters 2 and 4). For example, it has been found in Broderick and Newell (1999) that the task goal of bouncing a ball on a specific spot could have constrained the changes in joint involvement towards the centre of the effector chain (neither proximal or distal segments) as a function of practice to facilitate a coupling between the vertical movement of the ball and movement of the arm.

From the theoretical analysis so far, it is clear that coordination emerges as a consequence of the interaction of numerous variables in the learning environment. It is therefore to be expected that the change in coordination is dependent on the variables within the learning environment encompassing the learner as well as the task. Certainly, the non-unidirectional change in the involvement of dof could be expected when dynamics of movement are considered as emergent properties of the variables influencing action (Kugler & Turvey, 1987). Newell (1985) provided a relevant framework to describe the emergence of coordination and goal-directed behaviour.

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3 Refers to some behaviour being perceived to bring about the goal. And if behaviour is brought about because of this perception, then the behaviour is goal-directed. (Kugler, Shaw, Vincente & Kinsella-Shaw, 1990)
1.3 Emergence of Coordination from Interacting Constraints

From a motor control perspective, Kugler, Kelso and Turvey (1982) and Newell (1996) emphasised the role of constraints in channelling motor behaviour because the stability of functional coordination patterns can be altered by constraints imposed on performers. Constraints have been defined as the boundaries or features which influence the expression of the form achieved by the movement system seeking a functionally preferred state of organisation (Newell, 1986). Moreover, the interaction of different constraints allows the learner to effectively search for such a state of behaviour that is goal-directed. Newell (1986) classified constraints into three distinct categories to provide a coherent framework for understanding how movement patterns emerge during task performance. The three categories of constraints are related to the performer (termed organismic by Newell, 1986), environment and task.

Performer or organismic constraints refer to existing structural and functional characteristics of the individual, including height, weight, body composition (physical attributes) and connective strength of synapses in the brain, motivations, emotions, intentions and cognitions (functional characteristics). An important performer constraint is the neuroanatomical design of the muscles and joints of the human body. Learners of different ages may present intrinsic differences in development of the neuroanatomical features specific to the stage of development of their body. Such neuroanatomical characteristics would impinge on how coordination is acquired, specifically how the muscles and joints of various physical and biological characteristics coordinate with each other in the production of movement.

Environmental constraints are often physical in nature and could include ambient light, temperature or sound. In any movement tasks, gravity is a key environmental constraint that influences how movement coordination may be adjusted. Other environmental constraints include
social factors like peer groups, social and cultural expectations. In the example of a lower limb interceptive action like soccer kicking, the surface of the kicking area could affect how coordination emerges. Kicking on grass as compared to kicking on a synthetic surface presents very different environmental constraints and the coordination patterns adopted could vary between the two environmental contexts. A performer is more likely to be able to ‘dig’ into the grass at ball impact to enable a greater lift of the ball while the synthetic surface would discourage such a ‘digging’ action since the surface is hard.

Task constraints are more specific to particular performance contexts than environmental constraints. Task constraints include the rules of a movement task, the equipment used and the information sources present in specific performance contexts. It has been argued that biological organisms, including humans, are surrounded by huge arrays of energy flows that can act as information sources (e.g., optical, acoustic, proprioceptive) to support movement behaviour, including decision making, planning and organisation, during goal-directed activity. The role of information in constraining movements was particularly emphasised by Gibson (1979) who suggested that movement generates information that, in turn, supports further movement in a cyclical process. The processes of intention, detection, action and constraint toward ‘goal state’ all become interrelated through this perceiving-acting cycle (Shaw & Kinsella-Shaw, 1988). In soccer kicking, important task constraints include the mass of the ball and the positioning of defenders which require different types of coordination patterns for kicking a ball. For example, a side-foot pass would be executed for accurate kicks, an instep kick for power and the soccer chip for gaining height over defenders and distance.

Specific and functional patterns of movement coordination emerge as a consequence of the interaction of the various performer, environmental and task constraints and not as pre-
determined fixed anatomical linkages (Newell, 1996; Newell & McDonald, 1994). The model highlights the role and impact of constraints, providing the over-arching theoretical framework to understand how acquisition of coordination is closely dependent on the mutual interaction present in the movement context (See Figure 1.1).

![Diagram of Newell's Constraints Model]

Nevertheless, the constraints model requires further expansion and description on how coordination could possibly ‘emerge’ or ‘self-organise’ from the interaction of constraints. Specifically, a theoretical perspective that incorporates a testable framework is required to empirically investigate how coordination changes with practice. One such theoretical approach with which the constraints model is harmonious is Dynamical Systems Theory.

1.4 Dynamical Systems Theory: A Theoretical Framework for Investigating the Acquisition of Coordination in Human Movement

1.4.1 Neurobiological Systems as Nonlinear Complex Systems

The behaviour of many different phenomena in the world can be explained by the principles of chaos theory (Gleick, 1987). A systems approach can be used to explain and
describe the changes and emergence of patterns within seemingly natural and man-made complex systems. Chaos theory attempts to explain how systems which appear to be seemingly disordered actually possess characteristics of underlying order in random data set (Williams, 1997). For example, in open complex systems like the weather, financial stock markets and the human brain, patterns of behaviour in terms of signal or event occurrence can be identified and are repeatable over time. A common thread that ties these open systems together from a chaos theory perspective is that complex behaviour occurs as a consequence of the interacting subcomponents within each of these systems. Moreover, open systems in nature are capable of exchanging energy and matter with the environment, which means that they are sensitive to small changes in the energy flows within and around them (Prigogine & Stengers, 1984). A small change in the initial conditions within a system can potentially have a drastic effect on the long term behaviour of a system and have been classically described by the ‘butterfly effect’ (Stewart, 1989):

‘The flapping of a single butterfly's wing today produces a tiny change in the state of the atmosphere. Over a period of time, what the atmosphere actually does diverges from what it would have done. So, in a month's time, a tornado that would have devastated the Indonesian coast doesn't happen. Or maybe one that wasn't going to happen, does.’ (pp. 141)

Although the ‘butterfly effect’ may seem like a hugely exaggerated example of this idea of interaction between and among subcomponents in a system, the underlying theoretical message is clear. The exchange of energy and matter is an important characteristic of open systems feeding a dynamical interaction with the environment (see Haken, 1996). And, nonlinearity in behavioural changes becomes a hallmark of such systems. The idea that small changes may produce large effects and that sometime larger changes may produce no effects duly
captures the characteristics of a nonlinear system (Kelso, 2003). So, in a human movement system where numerous subsystems interact and are in turn dependent on the function of other subsystems, it is reasonable to describe the neurobiological system as complex, open and nonlinear. Certainly, Clarke and Crossland (1985) recommended that the neurobiological system requires an investigative approach based on a systems perspective:

‘In a highly complex system like the human mind or body all parts affect each other in an intricate way, and studying them individually often disrupts their usual interactions so much that an isolated unit may behave quite differently from the way that it would behave in its normal context.’ (pp. 16)

Characterising and investigating neurobiological systems as examples of complex, open systems, has led to increasing support for a nonlinear dynamics approach to study human movement (e.g., Beek, Peper & Stegeman, 1995; Kelso, 1995; Schöner & Kelso, 1988; Turvey, 1990). It has been argued that the control of movement is nonlinear and the neurobiological system should not be decomposed into biomechanical and neurophysiological building blocks for the purposes of study (Bongaardt, 1996). Concepts from dynamical systems theory have been proposed to provide a viable theoretical framework for investigating coordination changes and these are discussed in the following section..

1.4.2 Key Concepts in Dynamic Systems and Self-Organisation

Dynamical systems theory provides a suitable framework to explain and predict pattern changes. Spontaneous pattern formation between component parts has been found to emerge through processes of self-organisation and these systems are typically thermodynamically open systems engaged in constant energy transactions with environment (Kugler & Turvey, 1987).
In dynamic systems, a collective state of the system can be characterised by variables that are defined as order parameters. And, in an interdependent integrated system, the order parameters of relevance will be those that describe the relations between subcomponents in a system (Kelso, 1995). Discontinuous changes to the macroscopic order of a system, effected by continuous changes in the value of a control parameter (i.e., a variable that provide an important source of information for a particular system and exerts considerable influence over system stability), is called a phase transition (Kelso, 1995). This conceptual framework and language can be used to describe characteristics of pattern changes in terms of control and order parameters. And, such systems exhibit a general inclination for stability (Kauffmann, 1993). Stable states are called attractors in dynamical systems theoretical terminology because the system settles into that pattern from a wide variety of initial positions and tends to return to that pattern if perturbed for any particular task or event (Kelso, 1995).

The use of dynamical systems theory to describe and explain human movement coordination was exemplified by the Haken-Kelso-Bunz (HKB) Model of rhythmical movement. From their study on a bimanual finger waggling task, it was found that spontaneous coordination dynamics of the left and right index fingers could occur (phase transitions) when the frequency of the finger movements was manipulated by a metronome. When the frequency of the metronome (control parameter) was gradually increased from 1.25 to 3.5 Hz, the relative phase (order parameter) of the finger coordination spontaneously changed from anti-phase parallel motion of fingers to an in-phase symmetrical pattern. A critical feature of the observed transition was a loss of stability (increased variability) of the relative phase when the control parameter ‘frequency’ was scaled. The change between patterns or relative phase in the HKB model

4 Also commonly known as the HKB model
occurred in the absence of a ‘central control mechanism’ in the central nervous system (CNS). The system self-organised under the non-specific influence of movement frequency which acted as the control parameter. This observation provided further support for how neurobiological systems operate as open and complex systems where changes in the mechanisms of subcomponents can effect a change in the behaviour of the system. Moreover, the transitions between patterns seen in the HKB model can be considered as a relevant framework to examine how the dof problem (Bernstein, 1967) can be overcome by understanding the processes of self-organisation (Kelso, 1995). Following Haken et al’s (1985) work, further studies on coordination between hands and feet (Carson, Goodman, Kelso & Elliot, 1995), arms and legs (Kelso & Jeka, 1992) and coordination between individuals (Schmidt, Carello & Turvey, 1990) confirmed empirical support for phase transitions in neurobiological systems. Kelso (1995) further emphasised the concept of self-organisation as being an emergent phenomenon:

‘…the system organizes itself, but there is no “self”, no agent inside the system doing the organizing.’ (pp. 8)

Indeed, Edelman (1987, 1992), through his theory of neuronal group selection (TNGS), proposed that thoughts, emotions, ideas, beliefs, images and actions are merely the neural traffic constantly being produced between billions of neurons in the CNS. Connections between neuronal groups can be strengthened when a functional behaviour, such as an idea or action occurs. The neural network patterns associated with less successful behaviours are unlikely to be selected. From a Neo-Darwinism perspective, more functional connections will be selected over time as the individual executes appropriate movements and behaviours successfully, embodying the mind and the brain (see van Gelder & Port, 1995) and this is likely to be facilitated by the
strengthening of neural pathways connecting different parts of the brain by a chemical neurotransmitter acting as a ‘value system’ (Edelman, 1992).

With respect to the ‘degrees of freedom problem’, dynamical systems theory provides a suitable framework to explain how coordination is acquired. The ideas of dynamic interaction and interdependency between system components discussed earlier present the building blocks to understand the nonlinear processes involved in the acquisition and control of coordination. This is exemplified by the concept of coordinative structures and degeneracy in the following section.

### 1.4.3 Coordinative Structures and Degeneracy: How Coordination is Controlled

Coordination can be viewed as the function that constrains the potentially free variables (degrees of freedom) of the system into a functional behavioural unit (Newell, 1996). Each individual degree of freedom does not need to controlled, but they can be organised into coherent larger collectives which are easier to regulate. Such larger collectives can be accomplished through the formation of functionally-effective muscle synergies or coordinative structures, which are specific collectives of muscles and joints constrained by the nervous system to act cooperatively to produce an action. Kugler, Kelso and Turvey (1980) described coordinative structures as flexible, temporary and specific to the task at hand. The implication for understanding acquisition of coordination is the removal of the need to control a high-dimensional collection of muscle units and neurons through the formation of low-dimensional coordinative structures. Complexity of the neurobiological system is reduced by the formation of coordinative structures, allowing the performer to exploit the inherent anatomical linkages in the body (Davids, Glazier, Araújo & Bartlett, 2003). In addition, such coordinative variables capture the evolutionary process of change in spatiotemporal pattern in a specific movement task.
(Balasubramaniam & Turvey, 2004) and provide an appropriate theoretical approach to investigate human movement.

Certainly, in complex movements\(^5\), there are many ways in which components of neurobiological systems can interact to allow a goal-directed movement to be generated. The inherent degeneracy of neurobiological systems provides the basis for this level of flexibility and adaptability. The concept of degeneracy captures how neurobiological systems have the capacity to achieve the same or different outcomes in varying situations, with structurally different components of the musculo-skeletal sub-system (Edelman & Gally, 2001; Hong & Newell, 2006). For example, Hong and Newell (2006) found that different learners were able to demonstrate different inter-limb coordination dynamics to achieve global changes in movement outcome in a ski-simulator learning task. Specifically, both in-phase and anti-phase knee motion relations were observed across different learners while the desired outcome of coupling between the centre of mass and the ski platform was similar. So, at the local level, the joint relations were organised differently although similar functional results were observed at the global level.

Degeneracy in neurobiological systems is inherent in the networks existing at the molecular, genetic, and musculo-skeletal levels. Degenerate systems demonstrate the flexibility and adaptability to organise themselves to fit continuously evolving task constraints as well as the information-rich environments present in many sports context such that functionally relevant movement goals can be achieved (Edelman & Gally, 2001). The diversity of actions available from complex neurobiological systems is a highly desired quality for the organisation and control of movements based on the interacting task, performer and environmental constraints. However,\(^5\)

\(^5\) Seen as naturally occurring motor activities with high relevant dimensionality and these dimensions include number of joints, muscles and level of force (Cordo & Gurfinikel, 2004)
it is still not exactly clear how neurobiological systems are coordinated and controlled, especially for complex sports movements where the task outcome is not the movement itself. For example, although Hong and Newell (2006) were able to describe the effects of degeneracy in their ski-simulator study, the performance outcome of the task and the movement patterns produced by learners was directly linked. There is a need to also study degeneracy in tasks where the performance outcome is separated from the movement pattern. Clearly, how individual learners acquire effective movements as a function of practice requires detailed investigation to better understand learning progressions within and between learners (see Chapter 3, 4 and 5).

The discussion on coordinative structures and degeneracy sets the scene to examine movement skill acquisition processes from a nonlinear perspective. Specifically, learning investigated from this perspective encompasses some of the key dynamical systems concepts discussed earlier in this chapter and provides a relevant framework to examine the acquisition of coordination.

1.4.4 Learning a Movement: A Nonlinear Perspective to Understanding Acquisition of Coordination

The development of phylogenetic skills, like crawling, reaching and walking has been investigated intensively (e.g., Gesell, 1929; McGraw, 1943; Thelen & Smith, 1994) and these studies have provided valuable information about how such skills develop. In motor learning research, greater emphasis has been placed on understanding and investigating how learners acquire ontogenetic skills (e.g., playing the guitar or learning the Fosbury Flop in high jump). Certainly, investigations on the processes of how movement behaviour changes during learning have attracted interest in the attempt to understand the complexities of human movement. The research focus on skills development has shifted from examining performance outcome to
investigating how movement patterns of learners alter with practice (see Handford, Davids, Bennett & Button, 1997).

Undoubtedly, the application of concepts and tools from dynamical systems theory to understanding learning has emerged as a popular theoretical framework to describe and examine skill acquisition processes (e.g., Handford et al., 1997; Kelso, 1995; Newell, 1996, 2003). As mentioned earlier, a central tenet in the dynamical systems theoretical perspective posits that dynamical structures of control spread across several levels of analysis and their functioning are bound by dynamical principles of self-organisation (Davids, Glazier, Araújo & Bartlett, 2003; Kelso, 1995). Hence, patterns of behaviour are suggested to emerge as a consequence of the conditions present in specific contexts rather than due to a central control mechanism within a system (Schmidt & Fitzpatrick, 1996).

From this perspective, learning is viewed as a process of searching for appropriate attractors, specific coordination patterns for a skill, into which a system can settle during a task or activity (Handford et al, 1997). As with the study of other dynamical systems, particular interest has focused on the phase transitions that can emerge spontaneously in neurobiological systems (e.g., Carson, 1996; Carson & Riek, 1998; Kelso, Bressler, Buchanan, DeGuzman, Ding, Fuchs & Holroyd, 1992; Kelso, Scholz & Schöner, 1990). Specifically, learning a new skill is viewed as the transition from one stable state organisation towards another (Beek & van Santvoord, 1992; Mitra, Amazeen & Turvey, 1998; Schöner, Zanone & Kelso, 1992; Zanone & Kelso, 1992). This transitional process encompasses a change in intrinsic dynamics, which represent the learner’s inherent coordination tendencies resulting from a mix of innate biological constraints, development and previous learning (Huys, Daffertshofer & Beek, 2004). At the behavioural
level, the intrinsic dynamics of the learner would have to be modified and be adapted to generate a coordination state that will meet the dynamics of the task goal.

The process of change within the learner’s intrinsic dynamics can then be seen as a competition between the ‘instructed’ new coordination state and the current preferred coordination tendencies of the system, with a subsequent modification of intrinsic dynamics as a product of learning (Schöner & Kelso, 1988; Zanone & Kelso, 1992, 1994, 1997). Thus, not only does learning alter the behaviour of the to-be-learned pattern, it also changes the entire layout of the coordination dynamics (Schöner et al., 1992). So, learning a new skill is not just about acquiring the new movement pattern. As a new movement is acquired in a particular learning environment and under specific task constraints, the underlying dynamics of the learner also changes as a consequence of the learning experience. In this sense, acquisition of coordination is perceived to be an on-going dynamical interaction of various constraints in the performance context (Newell, 1986).

Fittingly, learning is not necessarily a smooth linear process. Instead, depending on the strength of cooperative and competitive mechanisms, it may involve nonlinear and abrupt transitions (Kelso, 2003; Liu, Mayer-Kress & Newell, 2006; Newell, Liu & Mayer-Kress, 2001, 2003). Prevailing, a power law for learning was seen as the global pathway of change in learning (A. Newell & Rosenbloom, 1981; Salo, 1989). However, previous practices in investigating learning research in motor learning literature may have inadvertently presented a skewed view that the power law for describing behavioural change is the most accurate reflection in examining learning. Specifically, averaging data across participants or across large number of trials may mask the persistent changes (i.e., long term changes) and transient changes (i.e., trial to trial changes) which could reflect pathways of change other than the power law commonly
reported. In addition, the investigation of learning with a single or short practice time could also limit the effective interpretation of learning progression (Newell et al., 2001). The dynamical systems perspective is well placed to account for the nonlinear interactions that would occur in learning situations such that other learning functions like exponential functions, hyperbolic functions, logistic functions and functions with discontinuities can emerge (Newell et al., 2001). Particularly, any specific learning function that emerges is a consequence of the interaction of dynamical subsystems where each has its own time scale of change and evolves continuously. Surely, an investigation on the relationship between multiple time scales of change in learning with the concept of degeneracy in individual learning over an extended period of practice deserves further investigation. (see Chapters 4 and 5).

However, it is also important to move beyond describing process changes and more investigations are required on how learners search for movement solutions amidst the numerous coordination solutions possibilities for a specific movement. Examining progression of learning in a stage-like approach could be an appropriate channel to investigate how coordination changes as a function of practice. Undeniably, a model of learning that focuses on the coordination and control of dof will be relevant for investigating changes to the complex neurobiological system. And, one such model based on dynamical systems theory, is that proposed by Newell (1985).

1.5 Newell’s Stages of Learning

In the motor control literature, there have been various stage-based models of learning (see Adams, 1971; Anderson, 1982; Fitts & Posner, 1967; Gentile, 2000; Snoddy, 1926). For example, the Fitts and Posner three-stage model (Fitts & Posner, 1967) describes a cognitive stage, associative stage and an autonomous stage which focuses on the role played by cognition in learning and refining skills. It has been postulated that the three stages are part of a continuum
of practice time and learners progress gradually through the three stages. Gentile’s two-stage model (2000) that encompasses an Initial and Later stage emphasises the role of regulatory and non-regulatory conditions in the environmental context when performing a skill and categorises the stages of learning from the perspective of the learner’s goal in each stage. One model of learning that investigates changes in coordination movement patterns, and has its tenets in dynamical systems theory, was proposed by Newell (1985). This model emphasises the transition through three stages of learning that are complementary and interconnected. Furthermore, the model is based on the interaction of task dynamics and the intrinsic dynamics of the learner, which could provide insights to further understanding of how coordination changes as a function of learning.

Newell (1985) proposed three stages of learning incorporating the Coordination, Control and Skill stages. In the Coordination stage of learning, learners seek to assemble body segments in a way that approximate solutions to the task goal. Temporary coordinative structures are formed at this stage to allow learners to achieve the required task goal although the movement pattern employed may be rigid and inflexible, suggesting that there could be temporary reduction in level of involvement in dof as a means of overcoming the dof problem (Newell, 1996). It is plausible to also observe continuous adaptation and rebuilding of coordination patterns utilised in the specific task as the learners are still in the process of ‘searching’ for a stable movement pattern. This exploration of ‘perceptual-motor workspace’ occurs as the learner ‘seeks’ to establish a fit between the intrinsic dynamics of the learner and the demands of the task. See Figure 1.2 for a visual description of a perceptual-motor workspace.

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6 The perceptual motor workspace is seen as a dynamic landscape where coordination emerges as a neurobiological system flows dynamically through its state space seeking stability. Deep regions in the landscape represent attractors and shallow regions are less stable (Thelen, 1995).
In the Control stage, the learner becomes perceptually tuned to the consequences of different combinations of key variables impacting the task behaviour. The learner also searches for tighter couplings between body segment relations previously assembled and the forces generating goal-directed movement (Williams, Davids & Williams, 1999). It is possible that coordinative structures assembled early in learning are progressively released to reorganise into different configurations to enhance the attunement to higher order derivatives like velocity and acceleration of the movement although coordination patterns observed may be dependent on specific task constraints (Newell & Vaillancourt, 2001). The formation of coordinative structures as a consequence of the constraints present in the task-specific context enhances the learners’ flexibility to adapt a stable coordination pattern to approximately fit changing performance
environments. It is likely that learners can interchange swiftly between Coordination and Control stages of learning and that the boundaries between the two are not that clear. (see Chapter 4)

As learning progresses and the laws governing control are discovered, the learner is challenged to assign ‘optimal’ values to the variables controlling the movement in the Skill stage. Newell (1985) used the term ‘optimal’ to describe the idea of energy efficiency as a quality present in skilled coordination. Williams et al (1999) suggested that skill or optimal organisation emerges when the components of the control structure are quantitatively scaled such that the reactive forces present in the limbs are utilised for movement. It is further purported that coordinative structures become extremely stable with the additional involvement of dof. Fluid movement is subsequently observed as the numbers of controllable joint movement possibilities are increased (Handford et al., 1997).

Although the Newell’s model has provided important theoretical concepts for motor learning from such a nonlinear perspective, there has been inadequate empirical work to describe how learners move between Coordination and Control as well as Skill stages for a specific movement skill. One exception by Anderson and Sidaway (1994) reported that novices were able to acquire a set of relative motions for a soccer kicking task and were in the Coordination stage of learning, based on the similarities in the topological characteristics of the expert and novice kicking patterns. However, insufficient range of motion at hip and knee as well as inadequate hip angular velocity suggested that appropriate parameterising of movement pattern was absent in for the novices. This observation indicated that learners were short of attaining the Control stage of learning. However, no data on coordination were collected during the practice sessions to determine how the coordination patterns changed over the practice trials.
Certainly, there is inadequate knowledge on how learners actually progress from Coordination through to Control and Skill stages of learning for any specific movement skill. More data are needed to enhance understanding of the transitions of learners through these stages of learning. No single study has provided a test of the proposed stages of learning for a specific skill mainly because of the relatively short practice periods of most studies in motor learning (Newell, 1996; Newell & Vaillancourt, 2001). Key questions relating to the coordination and control of joint motion require further investigation. Specifically these questions include: What is the role of task constraints in shaping the reorganisation of motor system dof in a multi-articular action? What are the characteristics of coordination patterns demonstrated by different skilled performers to attempt to meet the task goal afforded by a multi-articular action? (see Chapter 4)

One contention in relation to recruiting different skill participants is the validity of categorising ‘expert’ players in previous coordination studies. Indeed, were the ‘expert’ players truly skilled players as indicated in Newell’s model for skill stage of learning? In Anderson and Sidaway (1994), the expert players were ‘experienced’ intercollegiate soccer players from the varsity team, therefore they could actually be performers in the Control stage of learning. Similarly, it is important to justify that the novices observed in future studies on soccer kicking or chipping should be truly unskilled performers with little or no playing experience. The lack of an intermediate group in most studies results in an absence of information that could be important for examining changes in coordination through the stages of learning. The presence of indicators (coordination and performance) for individuals at the Coordination, Control and Skill stages of learning in multi-articular actions could be obtained by investigating different skill performers (skilled, intermediate and novice) although the skill levels may not necessarily coincide with the stages of learning. It is not surprising that the recruitment of only ‘novice’ and ‘expert’ participants in Anderson and Sidaway (1994) or a single ‘novice’ participant in Hodges et al
(2005) could not adequately capture the possible kinematic and performance indicators that would surface in understanding the nature of coordination changes as a function of different skill levels. Sampling coordination patterns for multi-articular movements at various skilled levels could provide insights to understanding the re-organisation of motor system dof with practice, which is limited in current motor learning research (see Chapter 2).

Definitely, greater emphasis on studying coordination could be placed on examining a more diverse range of participants in terms of skill levels. Nevertheless, the focus of investigation should also be on the pathways of change through the different stages of learning. At a micro level, how do learners transit between preferred movement patterns during acquisition of coordination? As discussed earlier, critical fluctuation is a suggested phenomenon present prior to a change in functionally preferred states and it has been proposed as a pre-requisite for phase transition in dynamical systems. In the following section, the role of movement variability on the search for novel movement solutions will be analysed.

1.6 Movement Variability and the Search for Solution Manifold in Learning

1.6.1 Functional Role of Movement Variability

Performance variability has sometimes been seen as a product of a signal that is contaminated at some point by ‘noise’ in the information processing pathway (Broadbent, 1958) and must be minimised for optimal performance at a given task (Davids, Bennett & Newell, 2006; Newell & Corcos, 1993). However, variability in motor control can play a functional role and allows the performer to explore movement solutions more effectively in specific task contexts to meet the task goals (Davids, Shuttleworth, Button, Renshaw & Glazier, 2003; Handford et al., 1997; Kelso & Ding, 1993; Newell & Corcos, 1993; Riley & Turvey, 2002; Schöllhorn, 2002; Thelen & Smith, 1994). And, variability in neurobiological systems offers
room for flexible and stable adaptation for control of movement (Liebovitch, 1998; Mitra, Riley & Turvey, 1997; Rosengren, Savelsbergh & van der Kamp, 2003), which can be crucial in skilled performance. In addition, it has been suggested that variability can facilitate transitions between behavioural modes (Riley & Turvey, 2002). In the HKB model, the presence of critical fluctuations was an important phenomenon for transition of the relative phases as frequency of finger movement was scaled. Newell and Slifkin (1998) suggested that variance in movement can actually present more information about system organisation than the lack of variance. For these reasons, it is important to examine whether variability in human movement can play a functional role and to determine how it may ‘assist’ learners in acquiring movement behaviours to meet particular task goals (see Chapter 5).

It has been argued that the dichotomy of development and learning is not a meaningful demarcation. From a dynamical systems perspective, the processes of development and learning occurs in tandem and it is not realistic to differentiate them when both these processes are inter-related (Rosengren et al., 2003; Thelen & Smith, 1994). Research in motor development provides exemplar studies to explain how variability is relevant for changes in movement patterns. From a motor development and learning perspective, a dynamic view predicts high variability in configurations initially, representing a wide exploration of phase space, followed by a narrowing of possible states to a few patterns, and a progressive stability as patterns become practiced and reliable (Thelen, 1995). For example, Vereijken and Thelen (1997) investigated the acquisition of locomotion in infant and found that instability at the initial learning stage provided opportunities for a new and efficient movement to emerge. It has been suggested that the introduction of instability encourages the acquisition of a novel skill. This instability affords the learner opportunities to experience more varied sensory situations, both proprioceptive and visual, promoting a better understanding of the relation between action and environment. Subsequently,
an adoption of a movement optimally suited to the task and the characteristics of the learner can be encouraged. The functional role of movement variability can also be supported by the ideas from TNGS (Edelman, 1987, 1992) on the development of movement. The emphasis was on the need for a diverse and variable repertoire of movement patterns to be available early in development as this allows a more effective selection of an appropriate solution to a given movement problem (Thelen & Smith, 1994).

From the motor learning literature, Haibach, Daniels and Newell (2004) observed that learners displayed more variability in the juggling motion at the beginning of practice in a cascade juggling task. But, as learning progressed, there was less variability and a more constrained pattern emerged that was similar to an expert model. Although variability that is intrinsic in the juggling motions decreased throughout the learning process and was even present at the expert level (Beek & Lewbel, 1995), the presence of variability early in learning may indicate that learners were searching for coordination solutions to meet the task goal of juggling. In their study, there were strong indications of a nonlinear transition in terms of coordination solutions between three to four catches early in learning, and it is noteworthy that previous unpublished research (reported in Haibach et al., 2004) indicated that the transition from ball 3 to ball 4 was a critical feature in learning to cascade juggle. Importantly, in the study by Haibach et al (2004), no analysis was undertaken on the presence of high movement variability and subsequent transitions to juggling improvement. An interesting question concerns whether high movement variability could be present prior to a transition between preferred coordination states in learning. The indication that high levels of movement variability could facilitate a change in coordination might provide important insights into understanding of individual differences in rates of learning during practice. (see Chapter 5)
In a more recent study, Liu et al (2006) showed that generally, a higher variability in ball acceleration in a novel roller ball task was observed prior to a change in successful acceleration profile. However, it was also reported that for ‘slow’ learners, large variability in ball acceleration was seen but without any lasting change to a new acceleration profile. It was suggested that the exploratory search process was poor and ineffective for these slower learners. However, no specific investigation was undertaken to examine coordination between the relevant limb segments in the rhythmic roller ball task. Certainly, the role of variability in movement performance deserves more investigation in effecting a change from one preferred movement pattern to a novel preferred movement pattern during learning, especially for multi-articular actions. (see Chapter 5)

Undeniably, while the role of variability in movement has been suggested to aid exploration of coordination solutions, more investigation is required to explain how movement variability can assist learners search within a perceptual motor workspace for a particular task (Davids, Button & Bennett, 2007). The following sub-section on theoretical concepts regarding search in solution and task space espoused by Müller and Sternad (2004) provides a stepping stone to understanding how learners explore movement solutions to achieve a task goal.

1.6.2 Exploration of Solution Manifold and Task Space in the Acquisition of Coordination

The examination of coordination changes as a function of practice would provide valuable information on how learners adapt and modify the coordination of the movement limbs to meet specific task goals. However, there is a need to relate changes in coordination at the behavioural level with performance outcome changes as well (Chen, Liu, Mayer-Kress & Newell, 2005). For example, variability and consistency of action can only be interpreted in relation to achievement of performance outcome goals. Interestingly, a theoretical concept proposed by Müller and
Sternad (2004) on the idea of task and solution space (subsequently re-termed ‘solution manifold’) as performance indicators could potentially inform how changes in coordination can be reflected in changes to performance outcomes.

In Müller and Sternad’s (2004) study, the search for movement solutions concurrent with changes in movement variability in a virtual skittles throwing task was explored, using the concepts of task space and solution manifold. Müller and Sternad (2004) defined the task space as the space for all possible combinations of variables (angle of the paddle at release and release velocity of the ball in their study) required of an action. The subset of the task space that contains combination of variable solutions that meet the task goal is referred to as solution manifold. Müller and Sternad (2004) described how a sequence of data points can be viewed as a search through a ‘gradient field’ within the task space until the best location in the solution manifold is found. This idea has important implications since it could mean that learners could explore different regions within the task space and solution manifold as a function of skill.

Although Müller and Sternad (2004) have provided some important theoretical ideas on task space and solution manifold in their study, there are a few issues that remain unanswered from a motor learning perspective. Participants in their study were required to operate a lever arm only in one angular dimension (single degree of freedom) to simulate arm movement for the preparatory phase in the virtual skittles throwing action. It is not clear whether these findings can be generalised to the study of discrete, multi-articular actions. The absence of multi-articular joint actions in the movement restricted any possibility of examining coordination changes between limb segments for the task to determine how control of dof varies with learners at different skill levels (see Chapter 2).
The use of task space and solution manifold offers a potentially viable conceptual framework to examine changes in coordination at the behavioural level and to relate those changes to performance. The investigation of coordination changes in a multi-articular interceptive task and its’ concurrent relationship to changes in searching task and solution manifold offers practitioners as well as researchers potential insights to learning processes. For example, higher ‘task tolerance’ is deemed to be present when projectile trajectories within solution manifold occur closer to trajectory combinations that offered success, increasing the likelihood of better performance outcomes. Particularly, it would be useful to understand whether, in a lower limb interceptive task like kicking a ball for example, skilled performers could find appropriate combinations of variables (e.g., direction of ball projection, velocity of ball projection and angle of ball projection) within the solution manifold that have greater task tolerance compared to novice performers. Investigations about how skilled performers search task space and solution manifold with specific coordination patterns could provide insights about skilled performance. It is not clear how investigating skilled performers can help us understand the relationship with exploration during motor learning. For example, how is solution manifold ‘explored’ by performers of different skill levels? And, what are the concurrent coordination patterns demonstrated by performers at different skill levels with exploration of solution manifold (see Chapter 2)?

1.7 Search for Research Vehicle: A Discrete Multi-Articular Lower Limb Interceptive Action

The study of single degree of freedom movements like finger flexion-extension (e.g., Haken et al., 1985) and sliding of levers using the forearm in ellipsical drawing task (Lee, Swinnen & Verschueren, 1995) alleviates the challenge of managing the degrees of freedom problem. Moreover, the study of simple, single degree movement adopts a reductionist approach and complex movements cannot be reconstructed from the sum of simple motor activities
Undoubtedly, many past studies in motor learning tended to involve fewer motor system dof than required in many typical sports movements, such as kicking or throwing a ball, and have limited range of scaling for key variables such as spatial and temporal constraints. In addition, movements with fewer dof include a lower level of intentional constraint on behaviour and typically have a reduced amount of perceptual information needed to regulate action (Davids, Button, Araújo, Renshaw & Hristovski, 2006).

Hence, if movement coordination is to be investigated and specifically, the control of coordination, there is a need to understand and use tasks that involve multiple motor system dof. Important knowledge about kinematic relationships between limb segments and how motor system dof are harnessed over time as a consequence of practice could only be mapped with multi-articular actions. Such complex multi-articular actions abound in the performance contexts of work and sport and can exemplify how performers harness motor system dof in coordinating actions with respect to the environment. And, in the case of interceptive actions, analysis of complex movement models allows adaptive behaviour to be studied from a process-oriented and time-continuous approach (Cordon & Gurfinkel, 2004; Schöllhorn, 2002). The idea of degeneracy, as mentioned earlier in the chapter, could also be invoked to determine how learners can exploit the different pathways of change that the components within the human system can exploit such that they can be modified and constrained to work as a functional unit. Particularly, multi-articular movements can provide windows revealing insights into how the property of degeneracy is exploited by neurobiological systems.

Previous studies that have examined multi-articular movements include cyclical movement tasks like ski learning on a ski simulator (Hong & Newell, 2006; Vereijken et al., 1992), hula hooping (Balasubramaniam & Turvey, 2004), ball bouncing (Broderick & Newell,
1999), balancing on a moving platform (Ko et al., 2003), learning the pedalo (Chen et al., 2005) and discrete movement actions like basketball free throw shots (Button, McLeod, Sanders & Coleman, 2003), volleyball serves (Temprado, Della-Grasta, Farrell & Laurent, 1997) and soccer instep kick (Anderson & Sidaway, 1994). The data from these studies have tended to demonstrate how coordination patterns emerge as a result of the interaction of constraints present in the movement context. However, more work is needed to examine processes of learning with discrete multi-articular movements involving a large number of practice trials.

In this PhD thesis, a lower limb interceptive action, soccer kicking, will be used as a movement model to investigate coordination changes when learning a multi-articular action. Specifically, a soccer kicking action (soccer chip) with distinct height and distance task constraints will be used as an appropriate research vehicle to examine reorganisation of motor system dof from a nonlinear perspective as a function of both skill levels and practice. Typically, chipping in soccer is a specific lower interceptive action used to project a ball over opponents to space or to a team-mate in a game setting (see Hargreaves, 1990). The demand on participants to project the ball over a height barrier onto specific target positions presents unique task requirements that challenge participants to explore movement solutions such that possible goal directed movement can emerge from the confluence of the interacting 'constraints' in the performing and learning context. In addition, the lower limb interceptive task provides an experimental set up where the movement is clearly distinct from the outcome of the task, allowing insights into the degeneracy of the human movement system (see Chapters 3, 4 and 5). Finally, the soccer chipping task allows investigation of the possible differences between various levels of skilled performers in acquiring different combinations of ball trajectory variables to attempt to meet the task goal and subsequently, explore the 'solution manifold' that the task offers (see Chapter 2).
1.8 The Current Thesis

The current thesis aims to examine coordination and its acquisition as a function of skill and practice from a nonlinear perspective based on the tenets of Dynamical Systems Theory. Specifically, a discrete multi-articular lower limb interceptive action will be used as a research vehicle to exemplify the key concepts associated with learning from a nonlinear dynamics perspective. In the chapters to follow, various empirical research questions will be raised and investigated to shed new insights to understanding coordination changes for performers at different skill levels and as a consequence of extended practice. In Chapter 2, characteristics of level of joint involvement for skilled, intermediates and novices performers for a discrete multi-articular action will be investigated. In addition, the chapter examines whether skilled performers of the soccer chip are able to effectively parameterise foot velocity to target positions with varying height and accuracy requirements compared to intermediate and novice performers. Chapter 2 also describes qualitative differences between skilled, intermediate and novice performers in producing ball flight trajectories in exploring solution manifold and task space for the soccer chip. In Chapter 3, a multiple single participant design will be undertaken to examine differences in higher order variables, coordination patterns, variability in movement and planting foot positions for skilled participants. This chapter will highlight the concept of degeneracy and examines whether different functional movements can be demonstrated even at a skilled level of performance. Chapter 4 will investigate the control and coordination of joint motion change for novice performers as a function of practice over extended practice trials. In this chapter, emphasis will be on examining changes for novice performers at the level of joint involvement as well as coupling between lower limb joints with practice. Newell’s (1985) learning model will also be used as a guiding framework to examine how novice learners progress from the Coordination to Control stages of learning. In Chapter 5, an investigation will be undertaken to determine the
presence or absence of transitions between preferred movement patterns when learning the soccer chip during the acquisition phase for novice performers. In addition, the chapter discusses the role of movement variability prior to a change in preferred movement pattern and cluster analysis procedures will be used as a technical tool for interpreting changes in motor patterning as a function of practice time. In the Epilogue (Chapter 6), practical implications of the findings of the earlier empirical chapters will be discussed in greater detail to inform researchers and practitioners about the novel pedagogical contributions of the thesis.
# Chapter 2

Variation in Coordination of a Discrete Multi-Articular Action as a Function of Skill Level

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This study investigated coordination modes that emerged as a function of the interaction between skill level and task constraints in a multi-articular kicking action. Three groups of 5 participants (skilled, intermediates and novices) attempted to satisfy specific height and distance constraints in kicking a ball over a barrier towards a target. It was observed that skilled and intermediate groups demonstrated a functional coordination mode involving a lower joint involvement at the proximal joints and higher joint involvement at distal joints, mimicking a ‘chip-like action’ in soccer. Conversely, the novice group tended to produce larger ranges of motion throughout the kicking limb in a “driving-like” kicking action. Key differences were also found for task outcome scores, joint angle-angle relations and ball trajectory plots between the skilled and intermediate groups with the novice group. The findings demonstrated that joint involvement during this discrete multi-articular action is a function of skill level and task constraints rather than resulting from a global ‘reducing to increasing’ involvement of dof strategy as suggested by some previous research. This study also highlighted the merit of using a model of the acquisition of coordination in examining how coordination modes for multi-articular actions differ as a function of skill.
2.2 Introduction

Bernstein (1967) originally argued that the acquisition of skill progresses from a reorganisation of motor system degrees of freedom (dof). His insights suggested that a learner initially demonstrates rigid and awkward coordination modes, subsequently known as ‘freezing’ or reducing joint motions to cope with the abundance of motor system dof. As control over dof is gained, joint motion is gradually increased. As a consequence of Bernstein’s suggestions, a body of empirical work examining the processes underpinning motor learning through the regulation of dof has emerged. For example, in support of Bernstein, an early study of learning with a multi-articular action on a ski-simulator by Vereijken et al (1992) reported evidence of this ‘reducing-to-increasing’ (or ‘freezing to freeing’) sequence of active involvement of dof with novices. However, more recent work has questioned whether the acquisition of coordination involving multiple dof always occurs in the universal direction of ‘reducing to increasing’ dof involvement, but rather could be dependent on the specific learning or performance task constraints (e.g., Newell, Broderick, Deutsch & Slifkin, 2003).

Research on coordination of multi-articular movements has been investigated with continuous movements like hula-hooping (Balasubramaniam & Turvey, 2004), cascade juggling (Beek & van Santvoord, 1992; Haibach et al., 2004), simulated ski-ing (Hong & Newell, 2006) and balancing (Ko et al., 2003). Whilst there has been extensive work on coordination of rhythmical movements, somewhat less attention has been paid to studying coordination of discrete movements, particularly those involving the lower limbs. Additionally, Schaal, Sternad, Osu and Kawato (2004) observed that, whereas discrete movements have been intensely investigated in computational and cognitive neuroscientific models of motor control, rhythmical and repetitive movements have tended to be popular in behavioural studies of motor coordination. Although Schöner (1990) attempted to model coordination of discrete movements,
he adopted a limited focus on temporal relations in the coupling dynamics of system components of reaching tasks. There was no attempt in the model to capture how spatial task constraints (e.g., distance to a target) affected performance of multi-articular interceptive actions. For these reasons, a discrete, lower limb, multi-articular action with distinct spatial task constraints, might provide a useful movement model to examine coordination differences between individuals. Additionally, analysis of performance at different levels of skill in kicking (e.g., skilled, intermediates and novices) could result in useful insights into variations in coordination at different stages of learning for a discrete movement.

Newell’s (1985) description of motor learning as shared in Chapter 1, emphasising coordination changes, has emerged as a popular theoretical framework to examine changes in multi-articular coordination as a function of skill level. At the Coordination stage of learning, early learners attempt to establish basic relationships among motor system components to achieve functional, goal directed movements and awkward, rigid movements are likely to emerge. Later in learning in at the Control stage of learning, performance is characterised by variation of movement parameters, with learners becoming more attuned to higher order derivatives of movement displacement information like velocity and acceleration (Williams et al., 1999). Specifically, during practice, individuals attempt to explore and establish strong relationships between movement of body segments and the forces generating the movements to achieve a particular task goal. At the Skill stage of learning, performers are able to produce movements that appear effortless and fluid as well as in synchrony with the demands of the task by optimising movement parameters to enable efficient utilisation of available energy. This feature of skilled kicking performance was exemplified by the research of Young and Marteniuk (1998) who reported how muscle torque production in a lower limb interceptive action became less variable and muscle torque inter-joint dependency increased with learning. Functional movement
variability occurs as the relationship between relevant motor system dof is varied to ensure the production of consistent movement outcomes (e.g., Arutyunyan et al., 1969; Scholz, Danion, Latash & Schöner, 2002). For example, in discrete multi-articular actions like throwing or kicking a ball, functional variability might be exploited by performers to co-vary key movement parameters to achieve a consistent performance outcome (Button et al., 2003; Kudo, Tsutsui, Ishikura & Yamamoto, 2000). Despite these suggestions, it is notable that Newell’s (1985) model only provides a guiding framework to examine coordination differences as a function of skill. It is also not the aim of this study to specifically identify criteria for different learning stages since different tasks may require different coordination and performance indicators in relation to the various stages of learning.

Although the model represents a potentially useful theoretical framework, coordination patterns of individuals at different skill levels (e.g., skilled, intermediates and novices) need to be examined to verify whether/how progression occurs through the stages of learning proposed by Newell (1985). For example, Anderson and Sidaway’s (1994) study on coordination of a discrete multi-articular lower limb kicking action described how coordination for a soccer instep kick changed with practice in novices to resemble the movement patterns of a skilled model. Specifically, the learners demonstrated a greater involvement of joint motion in the kicking limb and improved segmental sequencing from the proximal limb segment (thigh) to the distal limb segment (shank) such that forces created by the motion of the larger muscles of the thigh were continued by the smaller muscles at the shank (see Putnam, 1991). It was suggested that the novices in their study were at the Coordination stage of learning, acquiring an appropriate set of relative motions for the instep kick, compared to the skilled model after the practice phase. However, the novices did not demonstrate evidence of successfully parameterising significant movement variables, such as foot linear velocity. Indeed, the goal in the kicking task of Anderson
and Sidaway (1994) was for participants to maximise ball velocity, and it is feasible that this specific aim was a major constraint on the emergence of the specific coordination pattern observed over practice in the novice group as well as in the skilled model. Lees and Davids (2002) argued that these specific task constraints might have emphasised the build up of velocity in the lower limbs, requiring proximal segments with high moments of inertia to move first followed by smaller distal segments moving later at higher velocities.

Therefore, an important question is whether varying the task constraints of a lower limb kicking action (e.g., kicking for height and accuracy rather than to maximise ball velocity) would result in similar characteristics of organisation of motor system dof in individuals at different skill levels. Some studies of coordination of multi-articular actions have attempted to elucidate the role of task constraints in shaping the emergence of task specific movement solutions. For example, Button, Smith and Pepping (2005) investigated effects of different task goals on soccer kicking and found differences in joints range of motions. It was reported that ranges of joint motion increased for trials in which maximum speed was emphasised while decreased joint ranges of motion were seen for an accuracy condition. Their findings invoked the question of whether a combination of height and accuracy constraints in soccer kicking might result in the emergence of very different coordination patterns during practice. Unfortunately, in the study of Button et al (2005) no attempt was made to theoretically rationalise performance variations according to stages of learning or to investigate how control of joint motions may differ as a function of skill level.

A case study by Hodges et al (2005) examined coordination changes in a ball kicking task which required target accuracy over a low height barrier. One male novice soccer player practiced scooping a ball with the non-dominant foot over a height bar of 75cm located 175cm
away and to a target positioned 250cm away, over 17 training sessions lasting 9 days. Contrary to previous research (e.g., Anderson & Sidaway, 1994), by the end of the intervention period, the authors found that the ankle and knee joint ranges of motion were restricted, indicating a reducing involvement of dof, while the hip joint range of motion was varied and larger. Primary responsibility for control of the movement reverted back to the hip joint at the end of the practice sessions although there was a progression of control from proximal to distal lower limb joints initially. Again, it is important to note that the task constraints in Hodges et al (2005) were quite specific, requiring a scoop-like action for success due to the proximity of the target and height barrier position to the participant. It is possible that the need to generate greater ball height trajectory, to further distances, could result in reduced involvement of proximal joints, coupled with a greater involvement of distal joints allowing skilled or intermediate players to vary the angle and velocity of foot contact with the bottom half of the ball (see Hargreaves, 1990 for information on soccer chipping). In contrast, it is possible that novice players might not be able to elevate the ball adequately early in learning and could demonstrate a greater range of motion about the proximal joints, but a smaller range of motion at distal joints, mimicking a ‘driving action’ of the ball commonly seen in a different kicking action: the instep pass. Such a proposition is plausible since it is unlikely that novice players, early in learning, would possess the required technical skills in projecting the ball over a height barrier and would rather depend on maximising force by ‘driving the ball’ to attempt to elevate ball trajectory.

Kicking for height and accuracy is an important component of many team games such as Rugby Union and American football. In soccer it is known as ‘chipping’ the ball (Hargreaves, 1990). The soccer chip typically involves projecting a ball over an opponent towards a team mate or the goal, requiring performers to 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 shot). Therefore, performance outcome indicators for the chip pass should include the assessment of kicking accuracy and weighting (i.e., the amount of force imparted to the ball by the kicker) for ease of control by the receiver. Other than assessing the suitability of the chip pass for comfortable reception, ball flight information like angle, velocity and direction of trajectory also provide useful performance indicators to ascertain how different skilled players use combinations of these variables to achieve the task goal.

In this respect, Müller and Sternad’s (2004) concept on solution manifold and task space discussed in Chapter 1 provides a relevant framework to examine how changes in coordination can be reflected in changes to performance outcomes. Müller and Sternad (2004) referred to the space of all variable combinations as ‘task space’ and the subset of task space that contained successful solutions was termed ‘solution manifold’. For example, all possible combinations of trajectory will constitute the task space. However, only combinations of trajectory variables that meet the task goal (e.g., projectile landing accurately on a target position) constitutes the solution manifold. Furthermore, Müller and Sternad (2004) showed how some combinations of ball trajectory dependent variables were located within regions of the solution manifold that were more likely to result in successful performance (i.e., greater task tolerance), compared to other regions where slight differences in the combination of trajectory variables will result in less successful performance with combination of variables moving outside of the solution manifold (i.e., less task tolerance). From this perspective, it needs to be empirically verified how combinations of ball trajectory variables differ when performers at different skill levels search regions of the solution manifold in a soccer chipping task.

In this study, we investigated coordination of a discrete, lower limb multi-articular action with specific height and distance constraints as a function of skill level in soccer. The predicted
outcomes of our study were rationalised in light of the collective theoretical influences of Bernstein (1967), Newell (1985) and Müller and Sternad (2004). Specifically, we expected that
(a) skilled and intermediate players were likely to demonstrate reduced involvement of the proximal joints and increased activity at the distal joints (i.e., stabbing the ball in a chipping action), whereas the converse pattern of joint involvement would characterise novice performance (i.e., driving the ball), (b) skilled players would be more likely to parameterise foot velocity to target positions with varying height and distance requirements more effectively than intermediate players, who, in turn, would outperform novice players, (c) skilled players would likely achieve higher performance scores emphasising height clearance, accuracy and appropriate weighting of the soccer chips, compared to intermediate and novice players, and (d) there would be qualitative differences in the acquisition of combinations of ball flight variables (i.e., angle, direction and velocity of trajectory) between skilled, intermediate and novice groups as observed through examination of ball trajectory plots. That is, there would be differences in searching the solution manifold as a function of skill level.

2.3 Methods

2.3.1 Participants

A total of 15 male participants (5 skilled, 5 intermediates, 5 novices) took part in the study. Skilled players (age: 20 ± 1.58 yrs; height: 1.81 ± 0.08 m; weight: 68.5 ± 4.63 kg) had at least 10 years of competitive soccer experience and were currently in the Singapore national squad. Singapore was ranked 92 out of 205 teams in June 2006 by the Federation of International Football Associations (FIFA). Intermediate players (age: 25 ± 2.65 yrs; height: 1.74 ± 0.08 m; weight: 80.4 ± 14.57 kg) had a minimum of 5 years of competitive soccer experience and were currently playing at varsity level. Novice participants (age: 27 ± 3.54 yrs; height: 1.75 ± 0.01 m; weight: 73.7 ± 9.64 kg) had never played competitively and had limited playing experience even
at the recreational level. The categorisation of the three groups of participants was not based on the fit with the three stages of learning suggested by Newell (1985). The selection and grouping of the participants were based solely on playing experience and level of representation (if any). Voluntary and informed consent were obtained from all participants and procedures employed in the study are in accordance with the University of Otago’s ethical guidelines.

2.3.2 Task and Apparatus

Participants were required to kick a soccer ball over a height barrier to a receiver with their dominant foot. No explicit instructions about technique concerning how to chip the ball over the height barrier were provided. Participants were simply 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 with appropriate force control (i.e., appropriately weighted to allow for easy control of the pass). Video film exemplifying appropriate ball flight characteristics onto the receiver’s feet was shown to ensure understanding of the task goal. Participants performed the task within a kicking area (2 m x 2 m) on a synthetic surface within a laboratory. Target positions were located on a field outside the laboratory with the participant kicking the ball out into the field for all trials. A horizontal bar (length 4 meters) supported by two adjustable vertical poles (2 meters each) provided the height barrier for the task. Coloured bands (of around 0.5m) attached to the horizontal bar were used to simulate a visual impression of a barrier without occluding the view of the receiver from the participant. Bar height was manipulated between 1.50 m to 1.70 m from the ground. Participants were required to kick to four target positions located between 6 m to 9 m perpendicular to the height barrier (see Figure 2.1). For target positions T1, T2, T3 and T4, variations in location relative to the participant as well as height constraint were apparent, requiring participants to attempt to vary kicking parameters to each of the target positions.
A FIFA-approved size 5 soccer ball was used in the kicking task and all participants wore soccer indoor soccer shoes and shorts for the test session. Kinematic data (recorded at 240 Hz) were captured by 6 infrared cameras (ProReflex, Model MCU 1000), connected to the Qualysis On-line Motion Analysis system (Gothenburg, Sweden). Twenty nine spherical reflective passive markers were placed on key anatomical joints. The joint markers were placed on the following anatomical landmarks: sphenoid, mandible, acromion process, lateral epicondyle (elbow), lateral point on the radial styloid and medial point on ulnar styloid, superior iliac crest, greater trochanter, lateral epicondyle (knee), medial epicondyle (knee), lateral malleolus, medial malleolus, 1$^{st}$ metatarsal head (only for non-kicking foot) and 5$^{th}$ metatarsal head.

FIGURE 2.1. Schematic representation of task set up to T1, T2, T3 and T4
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. 3D Euler joint angles of flexion and extension were derived for the hip, knee and ankle from the respective segments as defined by the marker sets but only the angle in the primary plane of motion were used for further analysis. In addition, 8 hemi-spherical markers placed equidistance on the ball were used to determine the centre of mass of the ball to allow derivation of ball trajectory. A conventional 20 m measuring tape was used to determine distance between the landing position of the ball on the field (when ball did not contact the receiver) and the respective target position. The ball landing position for each trial was established visually and marked by two research assistants with one end of the measuring tape (with a steel peg attached to the tape similar to those used in throwing events in athletics). Measurement of the distance was completed and recorded by a third research assistant. All measurements were taken by the three research assistants, who were trained and supervised for two weeks as part of the pilot phase of the study to ensure measurement reliability.

2.3.3 Procedures

Participants performed 5 warm up trials by kicking the ball out to the field without any requirement for height clearance or target accuracy. Thereafter, all participants performed 10 trials to T1. Subsequently, they performed another 5 trials each to T2, T3 and T4 in a randomised order, completing a total of 25 test trials for the whole session. The 10 trials to T1 were used to determine and sample the coordination pattern of the kicking action and the 15 trials to T2, T3 and T4 were used to identify if participants were able to vary kicking parameters to achieve the task goal. Participants were allowed as much rest as they needed between trials, with intervals ranging between 10 to 30 seconds in duration. Each test session took between 45 and 60 minutes to complete.
2.3.4 Data Analysis

i) Performance Outcomes

Performance of the kicking task was assessed by accuracy and effective weighting of the kicks to the receiver’s feet. Outcome scores were determined from a 7-point Likert rating scale devised by the researcher in conjunction with materials from coaching resources (e.g., Hargreaves, 1990) and expert advice from coaches within the Asian Football Confederation (AFC). The content validity of the rating scale was subsequently endorsed by two certified coaches holding AFC ‘B’ coaching certificates (see Table 2.1 for rating scale). After the completion of each trial, a performance score was recorded by the experimenter. A sample number of 25 trials were captured on video and presented to two AFC certified coaches for scoring. Performance scores recorded by the experimenter were compared against the coaches’ scores to determine the reliability of the assessment technique. Inter-scorer reliability between the experimenter and each coach was 100% and 96% respectively. Validity of the rating scale was verified in a series of pilot studies conducted on groups of skilled and novice participants to examine performance scores. The performance rating scale allowed the magnitude of error from the task goal to be determined for all trials as some kicks might have inadvertently contacted the receiver’s body, preventing error distance from being measured. More importantly, the Likert performance rating scale focuses on how participants are able to execute soccer chips effective for overcoming height, accuracy and weighting constraints of the tasks (although the scoring system does not take into account the ability of the receiver to control the ball).
TABLE 2.1. Performance rating scale for soccer kicking task emphasising weighting and accuracy of passes.

<table>
<thead>
<tr>
<th>Points/ 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 (0.61m 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 |

Scoring was not dependent on how well the ‘live receiver’ controls the ball. The presence of a ‘live receiver’ is to provide a more ecologically valid representation in terms of target attainment for the kicker.
For example, 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. Measuring error distance from the target positions to ball landing positions, does not fully capture the specific kinematic and ball trajectory characteristics of successful performances.

Means of individual participant’s kinematic variables and performance outcome scores were determined and collated with other participants in the same skilled group to establish group Means and SDs for inter-group comparisons. As the Likert performance scale provided ordinal data, the Kruskal Wallis One-Way Analysis of Variance by ranks test was administered for further analysis. Follow up statistical analysis on between-group differences was performed with the Mann-Whitney U test, with alpha levels for all tests set at p = 0.05.

The percentage of successful kicks over the height barrier to T1 and T2, T3 and T4 were also determined. Only kicks in which the ball crossed over the bar without contact were recorded as successful but all trials, regardless of successful or unsuccessful height clearance were included for kinematic analyses. The percentage of successful kicks was determined by calculating the number of successful kicks over the bar as a proportion of the total number of kicks. Data for percentage of successful kicks were transformed to arcsine values\(^7\) to allow One-Way Analysis of Variance (ANOVA) to be used to determine between-group differences (see Hogg & Craig, 1995).

\(^7\) The arcsine transformation allows the data to fit the assumptions for parametric tests such as the One-Way ANOVA for comparing differences between means.
ii) Kinematic Data

Kinematic data were collected for the duration of the limb movement sequence beginning 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 (in line with Hodges et al., 2005). Data collected were filtered using a low pass Butterworth digital filter with the Visual 3D software at a cut-off frequency of 7Hz. All trials were normalised 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. The normalised 100 data points were established for the purpose of the NoRMS (Normalized Root Mean Square Error) procedure (to be discussed further in later sections) and the determination of relative kinematic variables. Dependent discrete kinematic variables were established from actual non-normalised data. Movement time was normalised for the 100 data points.

Discrete kinematic variables.

Discrete kinematic variables provided information about specific characteristics of the kicking coordination modes in the different skill groups, with the following variables measured: Joint range of motion for the hip (ROM_hip), knee (ROM_knee) and ankle (ROM_ankle) (º), maximum resultant foot velocity (MFV) (º.s\(^{-1}\)), maximum resultant foot acceleration (MFA) (º.s\(^{-2}\)), maximum hip and knee angular velocity (MHV and MKV) (º.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.

Time of initiation of knee extension (SKE) relative to instant of MHV (SKE/IMHV), instant of MHV with respect to the instant of MKV (IMHV/IMKV) and occurrence of MKV with
respect to MFV (IMKV/IMFV) were calculated to examine segmental interactions of the kicking limb (in line with Anderson & Sidaway, 1994).

Intra-individual, inter-individual and group data descriptive statistics were determined for all kinematic variables and compared across different skilled groups via One-Way Analysis of Variance (ANOVA). To protect against the increased probability of making a Type I error, Bonferroni correction factors were applied in all analyses of the respective kinematic dependent variables (see Anderson & Sidaway, 1994). Eta-squared ($\eta^2$) was used as a measure of effect size. An effect size of 0.05 was considered small, 0.10 as intermediate and >0.20 as large (after Cohen, 1988) and alpha levels for all tests were set at $p = 0.05$

Variability in relationship between the joint angles was examined using the NoRMS (Normalized Root Mean Square Error) procedure (Sidaway & Schoenfelder-Zohdi, 1995), with normalisation based on range of motion of the movement (Mullineaux, Bartlett & Bennett, 2001). Individual NoRMS indices for hip-knee and knee-ankle intra-limb coordination were averaged across participants within the same skilled group to generate groups means. A higher index for NoRMS indicated greater variability in joint coordination over trials while a lower NoRMS index suggested lower levels of variability in intra-limb coordination.

**iii) Ball Trajectory**

Angle of ball trajectory, linear velocity, direction and ball spin about the Y-axis (vertical-axis) of the local coordinate system of the ball was determined between frames 10 to 30 after ball contact through the Visual 3D software for all trials to T1. Ball trajectory information on angle, velocity and direction provided information on the accuracy of the kick within solution manifold and task space. In the soccer chip, a greater amount of back spin improves the likelihood of an
appropriately weighted pass to be received which provides a useful indicator for determining the functionality of the soccer chips in meeting the task goal. Specifically, more back spin produces a lift force which helps to keep its height, potentially increasing the flight time of the ball (see Carré, Asai, Akatsuka & Haake, 2002). This allows a receiver more time to prepare for reception of the incoming ball, which increases the likelihood of effective control of the pass.

2.4 Results

2.4.1 Performance Outcomes

Skilled, intermediate and novice groups achieved performance scores of 4.32 ± 0.54, 4.16 ± 0.48 and 1.26 ± 0.36 respectively out of a possible maximum score of 7 to T1. There were significant differences in the performance outcome score to target position T1 (10 trials) between groups, \( \chi^2(2, N=15) = 9.488, p<0.05 \). Follow up Mann Whitney U tests showed similar differences at the T1 condition. The novice group performed the worst and there was no significant difference in performance score between skilled and intermediate groups.

For kicks to T2, T3 and T4 (15 trials), skilled, intermediate and novice groups achieved performance scores of 4.24 ± 0.45, 4.12 ± 0.60 and 1.53 ± 0.53 respectively with significant differences between groups, \( \chi^2(2, N=15) = 9.414, p<0.05 \). Follow up Mann Whitney U test showed that between-group differences were significant for the skilled and novice group, \( z = -2.611, p<0.05 \), and intermediate and novice groups, \( z = -2.611, p<0.05 \). Again, there was no significant difference in performance score between skilled and intermediate groups.

The skilled and intermediate groups obtained successful percentage height clearances of 96 ± 5.48% and 96 ± 5.95% to T1 and 94 ± 8.94% and 89.33 ± 13.82% respectively in the batch
of 15 trials to T2, T3 and T4. The novice group could only achieve successful percentage height clearances of $20 \pm 23.45\%$ of trials to T1 and $21.33 \pm 20.76\%$ to T2, T3 and T4. There were significant differences between groups to T1, ($F(2, 12) = 39.380, p=0.000$) and to T2, T3 and T4, ($F(2, 12) = 32.350, p=0.000$). Post hoc Scheffé testing showed that both skilled and intermediate groups also achieved significant differences in successful percentage height clearance over the bar compared to the novice group to both T1 ($p=0.000$) as well as to T2, T3 and T4 ($p=0.000$). There were no significant differences in percentage of successful kicks between skilled and intermediate groups. Skilled and intermediate groups were able to achieve similar performance outcome scores even to target positions with varying height and distance constraints T2, T3 and T4 when compared to T1.

2.4.2 Kinematic Data

i) Discrete Kinematic Variables

Table 2.2 shows the means and standard deviations of discrete kinematic variables for the three skill groups to T1. A significant difference was found between groups for joint range of motion at the hip ($F(2, 12) = 7.207, p=0.009$). The skilled group displayed a mean hip ROM of $32.94 \pm 7.56^\circ$ as compared to the novice group at $69.90 \pm 22.64^\circ$ and post hoc Scheffé testing confirmed that the difference was significant at $p=0.01$. A large effect size was attained at $\eta^2 = 0.55$. There were no statistically significant differences for ROM hip between the intermediate and novice groups (although hip ROM for the intermediate group was higher than the value for the novice group) or between the skilled and intermediate groups.

Foot acceleration at ball contact was significantly different between skilled and novice groups, ($F(2, 12) = 4.214, p=0.041$). Post hoc Scheffé testing showed that FAT1_BC for the skilled group ($165.80 \pm 15.83 \text{ m.s}^{-2}$) was significantly higher than FAT1_BC for the novice group.
(118.16 ± 39.43 m.s\(^{-2}\)), p=0.046. In addition, a large effect size of \(\eta^2 = 0.41\) was obtained. However, there was no significant difference for FAT1\_BC between intermediate and novice groups. There were no statistically significant differences between groups for other discrete kinematic variables.

**TABLE 2.2.** Means and SD (in parentheses) of discrete kinematic variables for all skill groups to T1.

<table>
<thead>
<tr>
<th></th>
<th>Skilled</th>
<th>Intermediate</th>
<th>Novice</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHV (°.s(^{-1}))</td>
<td>287.95 (65.21)</td>
<td>312.86 (47.78)</td>
<td>322.35 (67.86)</td>
</tr>
<tr>
<td>MKV (°.s(^{-1}))</td>
<td>1054.82 (139.53)</td>
<td>1072.24 (143.23)</td>
<td>878.60 (159.11)</td>
</tr>
<tr>
<td>MFV (m.s(^{-1}))</td>
<td>11.36 (0.31)</td>
<td>10.56 (0.37)</td>
<td>10.46 (0.82)</td>
</tr>
<tr>
<td>FVT1_BC (m.s(^{-1}))</td>
<td>9.79 (0.40)</td>
<td>9.67 (0.57)</td>
<td>10.14 (0.65)</td>
</tr>
<tr>
<td>FAT1_BC (m.s(^{-2}))</td>
<td>165.80 (15.83)</td>
<td>151.17 (17.74)</td>
<td>118.16 (39.43)</td>
</tr>
<tr>
<td>ROM(hip) (°)</td>
<td>32.94 (7.56)</td>
<td>44.12 (13.34)</td>
<td>69.90 (22.64)</td>
</tr>
<tr>
<td>ROM(knee) (°)</td>
<td>95.07 (11.95)</td>
<td>90.26 (13.98)</td>
<td>87.08 (16.74)</td>
</tr>
<tr>
<td>ROM(ankle) (°)</td>
<td>27.66 (7.71)</td>
<td>26.71 (6.95)</td>
<td>30.69 (7.88)</td>
</tr>
</tbody>
</table>

*\(p=0.041\)

**p=0.009**

MHV: Maximum Hip Angular Velocity; MKV: Maximum Knee Angular Velocity; MFV: Maximum Foot Velocity; FVT1\_BC: Foot Velocity at ball contact to T1; FAT1\_BC: Foot Acceleration at ball contact to T1; ROM(hip): Range of Motion for Hip; ROM(knee): Range of Motion for knee; ROM(ankle): Range of Motion for Ankle.

Table 2.3 shows foot velocity at ball contact (FV\_BC) to T2, T3 and T4. There were no statistically significant between-group differences in foot velocity at ball contact when kicking to T2, T3 and T4 which had varying height and accuracy constraints. However, intra-group analysis showed that both skilled and intermediate groups demonstrated a similar and successful trend in manipulating foot velocity at ball contact to T2, T3 and T4, although no predictions were made *a priori* for how foot velocity at ball contact might be altered to satisfy different height and target distance constraints. Nevertheless, foot velocity at ball contact for skilled and intermediate groups was lowest for T2, which was nearest to the kicker (10m away) with the lowest height constraint (1.5m), while foot velocity at ball contact was progressively increased to T3 and then T4, which was furthest away (14m) and had the highest height constraint (1.7m). The novice group did not show a similar trend and were not able to functionally vary foot velocity at ball
Contact accordingly to meet the task goal. Further statistical analysis revealed significant differences in FV_BC to T2, T3 and T4 within the skilled group ($F(2, 72) = 34.820, p=0.000$), intermediate group ($F(2, 71) = 24.146, p=0.000$) and novice group ($F(2, 72) = 12.051, p=0.000$). However, post-hoc Scheffé testing showed that there were no significant differences for both the intermediate and novice groups for FV_BC between T3 and T4.

### TABLE 2.3. Mean, SD (in parentheses) and Coefficient of Variation (%) of foot velocity at ball contact (FV_BC) to T2, T3 & T4 for all skilled, intermediate and novice groups.

<table>
<thead>
<tr>
<th></th>
<th>Skilled$^1$</th>
<th>Intermediate$^2$</th>
<th>Novice$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FVT2_BC (m.s$^{-1}$)</td>
<td>9.12 (0.62) 6.8%</td>
<td>9.0 (0.75) 8.3%</td>
<td>9.55 (0.53) 5.5%</td>
</tr>
<tr>
<td>FVT3_BC (m.s$^{-1}$)</td>
<td>10.13 (0.44) 4.3%</td>
<td>10.25 (0.14) 1.4%</td>
<td>10.49 (0.53) 5.1%</td>
</tr>
<tr>
<td>FVT4_BC (m.s$^{-1}$)</td>
<td>10.63 (0.54) 5.1%</td>
<td>10.34 (0.27) 2.6%</td>
<td>10.32 (0.65) 6.3%</td>
</tr>
</tbody>
</table>

$^1$Significant difference for FVT2_BC, FVT3_BC and FVT4_BC within group ($p<0.05$)

$^2$Significant difference between FVT2_BC and both FVT3_BC and FVT4_BC ($p<0.05$). No significant difference between FVT3_BC and FVT4_BC.

The results indicated that only the skilled group was able to demonstrate significant differences in foot velocity at ball contact to T2, T3 and T4. In contrast, the intermediate group showed a foot velocity trend that was not significantly different between T3 and T4 and no foot velocity trend was observed for the novice group at all.

**ii) Relative Kinematic Variables**

There were no significant differences between the three skill groups for all relative kinematic variables (see Table 2.4). Results suggested that segmental sequencing of lower limb segments was similar for the three groups.

### TABLE 2.4. Means and SD (in parentheses) of relative kinematic variables for all skill groups.

<table>
<thead>
<tr>
<th></th>
<th>Skilled</th>
<th>Intermediate</th>
<th>Novice</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMHV/IMKV</td>
<td>0.88 (0.08)</td>
<td>0.92 (0.16)</td>
<td>0.97 (0.29)</td>
</tr>
<tr>
<td>IMKV/IMFV</td>
<td>1.03 (0.01)</td>
<td>1.04 (0.01)</td>
<td>1.06 (0.04)</td>
</tr>
<tr>
<td>SKE/IMHV</td>
<td>0.87 (0.07)</td>
<td>0.84 (0.15)</td>
<td>0.82 (0.23)</td>
</tr>
</tbody>
</table>

IMHV: Instant of Maximum Hip Angular Velocity; IMKV: Instant of Maximum Knee Angular Velocity; IMFV: Instant of Maximum Foot Velocity; SKE: Start of Knee Extension
Variability in intra-limb coordination.

The novice group had the lowest NoRMS (hip-knee) index of 13.53 ± 5.04 and the highest NoRMS (knee-ankle) index of 19.95 ± 10.61. The skilled group achieved similar NoRMS indices for hip-knee (16.76 ± 10.69) and knee-ankle (16.23 ± 10.28). The intermediate group also showed similar consistency for NoRMS indices within group for hip-knee and knee-ankle (14.26 ± 8.81 and 14.07 ± 8.08 respectively). However, there were no statistical differences for the NoRMS index values among the three groups of participants.

Angle-angle plots.

See Figures 2.2, 2.3 and 2.4 for representative hip-knee angle-angle plots for the skilled, intermediate, and novice participants. Whilst the skilled and intermediate plots have similar topographies, they differ markedly with respect to the novice participant. The novices typically demonstrated a distinctly larger hip joint range of motion, compared to both the skilled and intermediate participants.

There were also qualitative differences between the knee-ankle angle-angle plots (see Figures 2.2, 2.3 and 2.4). The representative novice seems to demonstrate greater variability for knee-ankle intra limb coordination when compared to representative plots for both the skilled and intermediate groups.
FIGURE 2.2. Hip-knee (A) and knee-ankle (B) angle-angle plots for one representative skilled participant. Note the bold line represents the mean angle-angle plot across 10 trials to T1 while the broken lines represent individual angle-angle plots for the 10 trials to T1.
FIGURE 2.3. Hip-knee (A) and knee-ankle (B) angle-angle plots for one representative intermediate participant. Note the bold line represents the mean angle-angle plot across 10 trials to T1 while the broken lines represent individual angle-angle plots for the 10 trials to T1.
FIGURE 2.4. Hip-knee (A) and knee-ankle (B) angle-angle plots for one representative novice participant. Note the bold line represents the mean angle-angle plot across 10 trials to T1 while the broken lines represent individual angle-angle plots for the 10 trials to T1.
Visual inspection of the trials demonstrated by the skilled, intermediate and novice groups confirmed that both the skilled and intermediate groups mainly employed a kicking action that demonstrated very little follow-through, with a wedge-like contact at the bottom of the ball at the point of ball impact. In contrast, the novice group generally demonstrated a driving action with an obvious follow-through after ball contact and no visible suggestion of a wedge-like action at the point of ball contact, as exhibited by the skilled and intermediate groups. (see Figure 2.5).

FIGURE 2.5. Skeletal representation of a typical soccer ‘chip’ by (A) skilled and intermediate participants and (B) a ‘drive’ kick by novice participants. N.B. Figures derived from representative kinematic data and subsequently modelled with C Motion software
Ball trajectory scatter plots to target position T1 based on angle, velocity and direction of ball trajectory were plotted for all three skill level groups. A total of 50 trials per group were available for the trajectory plots. However, due to occlusion of some reflective markers on the ball during ball flight, incomplete ball trajectory data were noted for some trials (n=7, skilled group; n=2, intermediate group; n=4, novice group).

Figure 2.6 depicts the ball trajectory plots (velocity with angle, velocity with direction and angle with direction) for all trials to T1 for skilled and novice groups. A clear qualitative difference between the skilled and novice groups can be observed when the angle of trajectory plots are compared with either direction or velocity of trajectory traces. Statistically significant differences were found for angle (t(87)=12.258, p=0.000), velocity (t(87)=-3.617, p=0.000) and direction (t(87)=2.319, p=0.023) of trajectory between skilled and novice groups. For angle of trajectory, it is clear from Figure 2.6 that the novice groups typically demonstrated a lower arc (mainly between 15º to 25º), compared to the skilled group (mainly between 30º to 45º). These data highlight the novice participants’ inability to project the ball over the height barrier in the kicking task and this was further confirmed by the lower successful percentage height clearances. There were no significant differences in the ball trajectory plots for all trials to T1 between skilled and intermediate groups.
FIGURE 2.6. Ball trajectory plots for all trials to T1 for skilled and novice groups: (A) velocity versus angle, (B) velocity versus direction and (C) angle versus direction

However, inspection of ball trajectory plots scoring 6 and 7 points (appropriately weighted trajectories landing to within 1 m of the receiver) on the performance rating scale revealed that the skilled group had qualitatively varied ball trajectory plots compared to the intermediate group (see Figure 2.7) to T1. Based on the performance rating scale, it is appropriate to identify performance scores of 6 and 7 as adequately meeting the task goal of chipping the ball over the barrier with appropriate accuracy and weighting to or near the receiver’s feet. It is conceivable that combination of ball trajectory plots demonstrated for performance scores 6 & 7 should be ascertained as constituting a sample of the ‘solution manifold’ for the current kicking task to T1. From Figure 2.7, it can be seen that the skilled group was able to achieve successful ball trajectories clustered closer together within the solution manifold at angle trajectories of around 35°, velocity trajectories at around 12m.s⁻¹ and direction of trajectories that hovered around 0°. However, the intermediate group showed less clustered successful ball trajectories.
From Figure 2.7, more ball trajectories of the intermediate group demonstrated a wider spread of trajectory plots at lower angles of trajectory (<35°) and directions of trajectory away from 0° (nearer to -5°) but there were fewer clear differences in the velocity of ball trajectory between the skilled and intermediate groups. It is likely that the solution manifold could potentially extend beyond the plots exhibited by the skilled and intermediate groups in Figure 2.7 but that information is not available in the current study as only a sample number of plots have been reported. However, from all kicking trials to T1 for the three groups of participants a sampled solution manifold was constructed, providing some information about the possible shape of the solution manifold (see Figure 2.8).
FIGURE 2.7. Ball trajectory solution plots for trials with performance scores 6 & 7 to T1 for skilled (n=12) and intermediate (n=13) groups: (A) velocity versus angle, (B) velocity versus direction and (C) angle versus direction.
No significant differences were found for the ability to impart ball back spin between groups (See Table 2.5). However, from the descriptive statistics, it is clear that ball spin data for the novice group had a bigger range and the SD was large ($\pm 876.78$). It was also observed that there were some trials in this group which showed forward spin (positive values, maximum of $412.37°.s^{-1}$). Additionally, most of the ball trajectory trials with back spin also had a low trajectory angle which did not satisfy the height constraint as indicated by the poor outcome scores obtained by the novices.

**TABLE 2.5. Descriptive Statistics of ball spin (back spin) for all skill groups.**

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skilled</td>
<td>43</td>
<td>-3393.41°.s^{-1}</td>
<td>-1073.60°.s^{-1}</td>
<td>-2107.54°.s^{-1}</td>
<td>545.30°.s^{-1}</td>
</tr>
<tr>
<td>Intermediate</td>
<td>48</td>
<td>-2692.01°.s^{-1}</td>
<td>-1046.82°.s^{-1}</td>
<td>-2025.594°.s^{-1}</td>
<td>421.43°.s^{-1}</td>
</tr>
<tr>
<td>Novice</td>
<td>46</td>
<td>-3678.64°.s^{-1}</td>
<td>412.37°.s^{-1}</td>
<td>-2124.384°.s^{-1}</td>
<td>876.78°.s^{-1}</td>
</tr>
</tbody>
</table>
2.5 Discussion

The aim of this study was to examine coordination modes in relation to performance outcomes in a discrete multi-articular action for three different skill groups (i.e., skilled, intermediate and novice). Based on previous findings in the extant literature, it was considered that skilled and intermediate players might demonstrate reduced involvement of the proximal joints and increased involvement of the distal joints (i.e., stabbing the ball in a chipping action), while novice players might demonstrate the converse coordination mode (i.e., driving the ball).

In terms of joint motion control, it was observed that the novice group demonstrated a higher hip ROM than both the skilled and intermediate groups, indicating greater involvement at the proximal joint. The smaller and constrained hip ROM for the skilled and intermediate groups suggested a reduced dynamic involvement of the proximal segment in the kicking task, but with distal segments (knee and ankle) moving at a similar range of motion to the novice group. It is likely that reduced motion of the hip joint was necessary for both the skilled and intermediate players to control the accurate placement of the lower limbs to elevate the ball at contact. This finding was also evident in the study by Hodges et al (2005) where control of movement was maintained at the hip for improved performance during their investigation of a ‘scooping’ kick over a low height barrier. The higher foot acceleration at ball contact generated by the skilled and, to a lesser extent the intermediate players, suggested that knee extension during the forward swing occurred rapidly. This observation implies that skilled and intermediate players were able to exploit reactive forces by optimising the stretch-shortening cycle characteristics of the knee extensor to generate high end point speed, a characteristic of mature kicking patterns (Bober, Putnam & Woodworth, 1987). Similarly, interactive torques in the movement limbs can assist or oppose foot acceleration during task acquisition. It is possible that skilled and intermediate players were better able to optimise the inter-segmental dynamics about the hip and knee to allow
a functional movement to emerge as previously noted in studies of shoulder-elbow interactions in drawing or handwriting tasks (see Dounskaia, Ketcham & Stelmach, 2002; Dounskaia, Van Gemmert & Stelmach, 2000). Future empirical work with inverse dynamics methods could specifically verify this notion about the role of interactive torques at the hip and knee joints in lower limb interceptive tasks. The perceived superior fluency in lower limb movement for the skilled and intermediate groups provided some indication of them being categorised at the Control stage of learning (at least) (Williams et al., 1999). The skilled and intermediate groups also seemed able to stabilise the proximal hip joint and allow the shank to pivot rapidly about the knee joint to satisfy the task constraints of height clearance and target accuracy.

Visual inspection of the kicking trials and qualitative analysis from the hip-knee and knee-ankle angle-angle plots indicated that there was minimal follow through in the kicking action for the skilled and intermediate groups (see Figure 2.5). The stabbing action at the bottom of the ball coupled with minimal follow-through afforded the production of back spin on the ball which was functional in satisfying the task goal of getting the ball over the barrier and appropriately weighted for easy control. Although the novice group also demonstrated similar values of knee ROM as the skilled and intermediate groups, indicating a high level of joint involvement at the knee, their magnitude of foot acceleration was lower and the movement of the distal limb segment was dysfunctional in meeting the goal of the task. The prediction on the level of joint involvement for the different groups was confirmed for the skilled and intermediate groups, but it was apparent that the novice groups exhibited high levels of joint involvement for the proximal and distal joints. Moreover, the joint motion control displayed by the novice group was dysfunctional in meeting the task goal, since those participants were ‘driving’ the ball (exemplified by similarities in ROM hip data in this study and those on the soccer instep drive in the study of Anderson & Sidaway, 1994).
The absence of reducing dof at the proximal joint for novice groups, viewed in relation to the constrained movement about the proximal hip joints, observed in both the skilled and intermediate groups, supports the argument that task constraints play an important role in determining how motor system dof are re-organised during practice (Newell et al., 2003). The interaction between the intrinsic dynamics of the learner and the task dynamics remains a key influence in determining the direction of coordination changes as a function of practice (although it needs to be noted that acquisition of coordination was not the main concern in this study of existing coordination modes in all three skilled groups). Certainly, the movement demonstrated by the novices could still be characterised as dysfunctional in meeting the outcome goals of the task even though the level of joint involvement was high.

The second prediction for this study suggested that skilled players would be more likely to parameterise higher order derivatives like foot velocity to varying target positions with different height and accuracy requirements more effectively than intermediate players, who in turn would be more effective than novice players. Observing this characteristic in the data could be interpreted as evidence for the skilled and intermediate players in this study attaining the Control stage of learning (at least). Although there were no differences between groups for foot velocity at ball contact to T2, T3 and T4, an intra-group analysis showed that both skilled and intermediate groups were able to vary foot velocity at ball contact to satisfy different height and task constraints (but difference between foot velocity to T3 and T4 was not significant for the intermediate group). It seems that they satisfied the height and distance task constraints by achieving the lowest values of foot velocity at ball contact to the target position with the lowest height constraint and nearest target distance (T2), and conversely, the highest foot velocity values at ball contact to the highest height constraint and furthest target distance (T4). However, such a
trend, in foot velocity may not necessarily have been predicted under the height and distance requirements for the present kicking task. While it might be anticipated that foot velocities at ball contact should increase from T2 to T3, an increase from T3 to T4 may not have been expected although the height barrier is greater for T4. In the current study, the increased height barrier at T4 could possibly have required a lower foot velocity at ball contact because the angle of projection was below 45º. An issue warranting further research is how manipulation of key task constraints influence angle of release for object projectile tasks, with consequent effects on ‘non-essential’ variables (Kugler et al., 1980), exemplified here by foot velocity.

Alternatively, the foot velocity trend demonstrated by the skilled and intermediate participants could possibly have been a consequence of the specific movement pattern used in the kicking task. The faster stabbing action demonstrated by these groups of participants may have been used to produce a greater lift of the ball (through the generation of back spin) to clear the larger height barrier to T4 (see Carré et al., 2002). This finding could explain the observations of higher foot velocity at ball contact for T4 than T3. More importantly, the foot velocity trend demonstrated by the skilled and intermediate groups was associated with higher performance scores. With increasing skill, foot velocity at ball contact becomes a likely ‘non-essential’ variable (Kugler et al., 1980) that participants learn to manipulate in order to satisfy the task constraints of kicking (or chipping in this case) for distance and height. Further intra-individual analysis may shed more light on how skilled players could effectively vary foot velocity at ball contact (see Chapter 3).

In contrast to these findings, the novice group did not show an ability to vary higher order derivatives in assembling functional coordination solutions to satisfy differing task constraints. In addition, the ability of the skilled and intermediate groups to generate adequate ball back spin
while kicking the ball over the height barrier to the receiver for all target positions suggested that they may have been able to use reactive forces in their lower limbs to achieve specific outcomes and successful goal-directed movement although no specific data were analysed for this purpose. Future work is needed to verify this specific suggestion.

It was also predicted that skilled players would achieve higher performance scores by successful height clearance, greater accuracy, and appropriate weighting of the soccer chips compared to intermediate and novice groups. Data showed that both skilled and intermediate groups achieved similar performance outcome scores for T1 and to T2, T3 and T4, which were set at different target distances with different accompanying height constraints. The skilled and intermediate groups were able to functionally vary kinematic parameters to achieve the task goal, possibly generating tight couplings between limb coordination and the segmental forces required in goal-directed movement (Williams et al., 1999). Certainly, the examination of performance outcomes concurrent with adaptations to movement coordination is crucial to enhance our understanding of how learners modify movement patterns to satisfy task constraints (e.g., Chen, et al., 2005). The lack of significant differences in performance scores between the skilled and the intermediate groups could have been a consequence of the performance rating scale in this study not being adequately sensitive to tease out inter-group differences or because the task itself was not challenging enough to sieve out differences for skill levels. Future studies could fine tune the performance rating scale, examine the impact of modifications to the kicking task or review the selection criteria for the skilled and intermediate participants.

Interestingly, there were no significant differences between the groups for the NoRMS indices for both hip-knee and knee-ankle intra-limb coordination. However, while the NoRMS indices were similar among the groups, low performance outcome scores were associated with
the NoRMS index for the novice players. This observation suggested that the novice players were using dysfunctional coordination solutions and could not adapt their coordination patterns to satisfy the task constraints even though their intra-limb coordination modes were as ‘consistent’ as the skilled and intermediate players. These results suggest that indices for movement variability (e.g., NoRMS in this study) have to be interpreted carefully when examining how functional variability is in meeting specific task goals. The data imply that movement variability has to be examined in conjunction with changes in performance outcome measures to determine how movement variability can be functional or dysfunctional for a performer in a particular task. The presence or absence of movement variability can signal how individuals explore functional coordination solutions to satisfy specific task constraints (see Riley & Turvey, 2002). Certainly, in neurobiological systems, it is becoming clear that variability is not always undesirable, but can play a functional role in the control and coordination of human movement (Hamill, Haddad, Heiderscheit, Emmerik & Li, 2006).

Finally, it was also predicted that qualitative differences would be observed in the functional capacity to vary combination of ball flight variables (i.e., angle, direction and velocity of trajectory) to satisfy task constraints by the skilled, intermediate and novice groups, revealed through examination of ball trajectory plots. From the ball trajectory plots, clear differences between the skilled and novice groups can be observed in relation to angle, direction and velocity of ball trajectory plots which was further confirmed through statistical analysis. It seems that the novice participants were unable to find functional combinations of ball trajectory variables within the sampled solution manifold for the kicking task. Ball trajectories generally lacking in height and direction (see Figure 2.6) were a feature of the performance of the novice participants, since they demonstrated a driving action rather than chipping or lofting the ball.
In contrast, the skilled and intermediate groups were able to achieve a substantial number of ball trajectories in or near the sampled solution manifold (indicated by similar group values for performance outcome scores). However, there were still some subtle differences between the skilled and intermediate groups. Close examination of the trajectory plots (for performance scores 6 and 7) provided qualitative evidence that the skilled group was able to achieve ball trajectory combinations within a clustered solution space, compared to the intermediate group’s more scattered pattern of trajectory plots (see Figure 2.7). The tighter combination of trajectory plots demonstrated by the skilled groups could be an indication of a reduction in ‘noise’ (see Müller & Sternad, 2004), leading to more consistent ball trajectory plots which is widely recognised as marker of skilled performance. Alternatively, it is possible that the intermediate group was able to find combinations of ball trajectory variables that offered greater tolerance for success by covering a more extensive, scattered ‘area’ within the sampled solution manifold, although we may have expected the skilled group to be more effective in optimising task tolerance. The kicking task in this study might have been too narrowly constrained, preventing us from observing how participants in the skilled group could maximise task tolerance for ball trajectory combinations. Speculatively, greater task tolerance might be observed in experimental settings where the task is made more challenging to tease out differences in achieving success within the solution manifold as a function of skill. For example, greater skill differences may be observed in future work if task constraints were made more challenging such as chipping over a moving opponent, chipping a moving ball, chipping to a moving target, or chipping with the non-dominant foot. Studying performance under more challenging task constraints might help us to understand whether skilled participants could deliberately fine tune ball trajectory to cluster kicks in a more scattered pattern within the solution manifold with greater task tolerance, and whether the intermediate participants would regress towards a more localised area of solution manifold.
2.6 Conclusions

With reference to the specific predictions of this study, it can be concluded that a) both skilled and intermediate groups tended to reduce involvement of the proximal segment, with a preferred coordination solution involving the distal segments moving rapidly about the knee joint to execute a stabbing action under the ball, with significantly higher levels of foot acceleration to meet the task goal. In contrast, the novice group increased involvement of both the proximal and distal joints during chipping without meeting the task goal; b) skilled and intermediate groups were able to appropriately vary higher order derivatives like foot velocity to chip the ball to target positions with varying height and accuracy constraints, suggesting that they are at least in the Control stage of learning; c) both skilled and intermediate groups were able to outperform the novices by effectively satisfying the task goal of chipping the ball accurately and appropriately weighted to the respective target positions, and d), there were qualitative differences in the ball trajectory plots in the task space for the chipping task, especially between both the skilled and intermediate groups compared to the novice group. It was also observed that the skilled group demonstrated slight differences compared to the intermediate group in terms of the ball trajectory plots to the solution manifold of the task, with closer clustering of the plots to specific ‘locations’ in the solution manifold for the skilled group. The observed difference in trajectory plots to the solution manifold could be a consequence of a reduction in noise for the skilled group or the demonstration of greater task tolerance for the intermediate group (see Müller & Sternad, 2004).

The interaction of two specific task constraints, height and distance, allowed us to examine the interplay of constraints influencing coordination and performance changes as a function of skill level and relate observed changes to a model of learning that focuses on the acquisition of coordination (e.g., Newell, 1985). While the data suggested that the skilled and intermediate groups were at least in the Control stage of learning as described by Newell (1985),
they also imply that the novice group may not even be in the Coordination stage since they were still struggling to explore and establish a functional movement pattern for the soccer chipping task. The results also emphasised the need for more work to examine concurrent performance outcome changes relative to alterations in coordination patterns to accurately describe the processes involved in the control of goal-directed, multi-articular actions. Future investigations on the role of movement variability could also contribute knowledge on coordination changes during motor learning by comparing the actions of successful and less successful learners (see Chapter 5).
Chapter 3

Organisation 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 (dof) were organised as skilled players performed a soccer chipping task. Using a multiple-case study design, inter-individual kinematics and performance differences were investigated to determine the features governing coordination of skilled chipping actions. Five skilled participants performed 10 soccer chips to one target position and another 15 soccer chips to three positions, all with different specific height and distance task constraints. Although a ‘global coordination pattern’ was identified for skilled soccer chipping, subtle inter-individual differences in coordination, displacement of centre 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-organise motor system dof in achieving functional movement behaviours.
3.2 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 et al., 2005).

However, there have been few attempts to study coordination of kicking actions in skilled individuals confronted with specific height and distance 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 distance 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 dof are organised by skilled performers in satisfying these unique task constraints in kicking.

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 distance constraints as inferred from Newell’s (1985) model of learning. Additionally, execution of fluid and stable movements, often associated anecdotally with skilled performance, has been proposed as a possible marker of performers at the Skill stage of learning by Newell (1985). The centre 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 advanced stages 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 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.

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 et al (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 have 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; Liu et al., 2006). 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 dof, subtle differences have been revealed between individuals when in-depth analyses of patterns of movement were conducted (e.g., Beek, Rikkert & van Wieringen, 1996; Button, Bennett & Davids, 1998; Port, Lee, Dassonville & Georgopoulos, 1997). Certainly,
movement coordination patterns are highly individualised and this is clearly highlighted by Kelso (1995):

‘Because each person possesses his or her own ‘signature’, it makes little sense to average performance over individuals. One might as well average apples and oranges. This does not mean that putative laws and principles of learning cannot be generalized across individual; laws would not qualify as such if it were not possible to do so. It only means that the way the law is instantiated is specific to the individual.’ (pp.147)

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 utilising motor system dof in chipping strategies at the elite level. Based on Newell’s (1985) model and findings of previous research on the soccer chip, we expect to observe a) that higher order derivatives like foot velocity at ball contact to different target positions with varying height and distance constraints were manipulated in a functional manner across all skilled players, b) low variability in COM displacement for skilled players during the chipping action, c) changes in angular displacement of the knee joint of the non-kicking limb to allow for movement adaptation during the kick, and d) low variability in positioning of the planting foot relative to the ball in skilled players.

3.3 Methods

3.3.1 Participants

A total of 5 male skilled players (age: 20 ± 1.58 yrs) who were involved in the earlier study in Chapter 2 were recruited. 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). It was also determined through information provided by the coaches of the team that 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 University of Otago’s ethical guidelines.

3.3.2 Procedures, Task and Apparatus

The procedures, task and apparatus used in this study was the same as described in Chapter 2.

3.3.3 Data Analysis

i) Performance Outcome

Performance outcome for all trials was scored with the 7-point Likert performance scale emphasising accuracy and weightage of passes as described in Chapter 2.

ii) Kinematic Data for Kicking Limb

Kinematic data were collected for the duration of the limb movement sequence beginning 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 and Chapter 2). Data were filtered using a low pass Butterworth digital filter with the Visual 3D software at frequency 7Hz. All trials were normalised 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 (ROM\_hip), knee (ROM\_knee) and ankle (ROM\_ankle) (°), maximum resultant foot velocity (MFV) (m.s\(^{-1}\)), maximum resultant foot acceleration (MFA) (m.s\(^{-2}\)), maximum hip and knee angular velocity (MHV and MKV) (°.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 MHV (SKE/IMHV), instant of MHV with respect to the instant of MKV (IMHV/IMKV) and occurrence of MKV with respect to MFV (IMKV/IMFV) (see also Anderson & Sidaway, 1994).

Descriptive statistics for individual players were subsequently determined for all kinematic variables and compared across different individuals via One-Way Analysis of Variance (ANOVA). 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 et al (2001). See Chapter 2.

**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 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. Root Mean Square Error was determined for the 10 trials to T1 to provide an indication of the variability from the mean trace of the COM displacement.

**v) Ball Back Spin**

Ball back spin, in terms of angular velocity about the Y-axis (vertical 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. As mentioned in Chapter 2, increased back spin produces a lift force, potentially increasing the flight time of the ball (see Carré et al., 2002). This allows a receiver more time to prepare for reception of the incoming ball, which increases the likelihood of effective control of the pass. 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.
3.4 Results

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

3.4.1 Performance Outcome

Skilled players accurately chipped the ball to positions T2, T3 and T4 as effectively as to T1 (see Table 3.1), suggesting that they were able to adapt their technique to cope with different target positions under varying height and distance constraints.

<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 (1.83)</td>
<td>4.1 (1.55)</td>
</tr>
<tr>
<td>S4</td>
<td>4.5 (1.58)</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>

3.4.2 Kinematic Data for Kicking Limb

Discrete kinematic data for all skilled players are shown in Table 3.2 and One Way ANOVA analysis was used to compare inter-individual differences between means of kinematic variables for the skilled players.

From Table 3.2, it can be observed that all skilled players achieved a small ROM (hip), ranging from $25.31 \pm 3.56^\circ$ to $42.12 \pm 5.23^\circ$ (despite significant differences among the players ($F(4, 45)= 8.575$, $p=0.000$)). FAT1_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.
TABLE 3.2. 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></th>
<th>(S1)</th>
<th>(S2)</th>
<th>(S3)</th>
<th>(S4)</th>
<th>(S5)</th>
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</thead>
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<td>MHV* (°.s⁻¹)</td>
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<td>244.17</td>
<td>382.69</td>
<td>216.29</td>
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<td></td>
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<td></td>
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<td>(28.41)</td>
<td>(9.54)</td>
<td>(8.00)</td>
<td>(7.16)</td>
<td>(15.55)</td>
</tr>
<tr>
<td>MFA* (m.s⁻²)</td>
<td>14.7%</td>
<td>5.7%</td>
<td>4.1%</td>
<td>4.8%</td>
<td>8.7%</td>
</tr>
<tr>
<td></td>
<td>39.61</td>
<td>30.70</td>
<td>42.12</td>
<td>25.31</td>
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</tr>
<tr>
<td></td>
<td>(15.68)</td>
<td>(3.02)</td>
<td>(5.23)</td>
<td>(3.56)</td>
<td>(6.19)</td>
</tr>
<tr>
<td>ROM(hip)* (°)</td>
<td>39.6%</td>
<td>9.8%</td>
<td>12.4%</td>
<td>14.1%</td>
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</tr>
<tr>
<td></td>
<td>91.84</td>
<td>79.48</td>
<td>100.20</td>
<td>93.75</td>
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<td>5.1%</td>
<td>4.8%</td>
</tr>
<tr>
<td></td>
<td>36.70</td>
<td>19.73</td>
<td>27.84</td>
<td>33.82</td>
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<td>(6.56)</td>
<td>(1.65)</td>
<td>(2.31)</td>
<td>(1.95)</td>
<td>(3.62)</td>
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<tr>
<td>ROM(ankle)* (°)</td>
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<td>8.3%</td>
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</tr>
<tr>
<td></td>
<td>170.82</td>
<td>155.95</td>
<td>187.59</td>
<td>145.87</td>
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<td>(22.76)</td>
<td>(10.22)</td>
<td>(8.53)</td>
<td>(8.21)</td>
<td>(17.13)</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>
<td>10.1%</td>
</tr>
</tbody>
</table>

*p<0.0055 for all skilled players

MHV: Maximum Hip Angular Velocity; MKV: 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_BC: Foot Acceleration at Ball Contact to T1

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 3.2 highlights the between-participant differences for relevant absolute kinematic variables and shows that there were variations in joint involvement, maximum joint angular velocities and maximum foot velocities even among the players although there were no significant differences for foot velocity at ball contact to T1.
TABLE 3.3. Mean and SD (in parentheses) of relative kinematic data for kicking limb of all skilled players to T1.

<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>IMHV/IMKV</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>IMKV/IMFV</td>
<td>1.05 (0.01)</td>
<td>1.02 (0.03)</td>
<td>1.02 (0.01)</td>
<td>1.03 (0.01)</td>
<td>1.03 (0.01)</td>
</tr>
<tr>
<td>SKE/IMHV</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>

IMHV: Instant of Maximum Hip Angular Velocity; IMKV: Instant of Maximum Knee Angular Velocity; IMFV: Instant of Maximum Foot Velocity; SKE: Start of Knee Extension

IMHV/IMKV ranged from 0.79 to 0.97, indicating that IMHV occurs earlier than IMKV, signalling a proximal to distal segmental sequencing of limbs (see Table 3.3 for data on relative kinematic variables). The direction of segmental sequencing suggests an effective summation of speed of kicking limb for all players. In relation to SKE/IMHV values, players acquired values ranging from 0.79 to 0.97, with SKE occurring slightly before IMHV.

Table 3.4 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 than 10%. Interestingly, participant 2 (S2) 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%. However, some of the values were not significantly different between T3 and T4 for FV_BC and MFV. See Table 3.4. Specifically, three out of five players demonstrated no significant differences between T3 and T4 (S1, S3 and S4). Skilled player 5 (S5) showed no significant difference between T3 and T4 only for FV_BC while skilled player 2 (S2) demonstrated significant differences among all positions for both FV_BC and MFV.

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 MKV (maximum knee angular velocity) and MHV (maximum hip angular velocity), the values were consistent with low coefficients of variation especially for MKV (less than 10% except for MKV_T2 for S1).

**TABLE 3.4. Mean, SD (in parentheses) and Coefficient of variation of selected discrete kinematic data for kicking limb of all skilled players to T2, T3 and T4.**

<table>
<thead>
<tr>
<th></th>
<th>(S1)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>(S2)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>(S3)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>(S4)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>(S5)&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>FVT2_BC (m.s&lt;sup&gt;-1&lt;/sup&gt;)</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></td>
<td>10.0%</td>
<td>3.4%</td>
<td>5.0%</td>
<td>3.9%</td>
<td>7.3%</td>
</tr>
<tr>
<td>FVT3_BC (m.s&lt;sup&gt;-1&lt;/sup&gt;)</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></td>
<td>6.5%</td>
<td>3.2%</td>
<td>3.6%</td>
<td>2.2%</td>
<td>6.9%</td>
</tr>
<tr>
<td>FVT4_BC (m.s&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>10.50 (0.18)</td>
<td>11.59 (0.21)</td>
<td>10.36 (0.41)</td>
<td>10.30 (0.22)</td>
<td>10.41 (0.54)</td>
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<tr>
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<td>1.7%</td>
<td>1.8%</td>
<td>4.0%</td>
<td>2.1%</td>
<td>5.2%</td>
</tr>
<tr>
<td>MFV_T2 (m.s&lt;sup&gt;-1&lt;/sup&gt;)</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></td>
<td>3.9%</td>
<td>1.3%</td>
<td>3.0%</td>
<td>1.3%</td>
<td>2.2%</td>
</tr>
<tr>
<td>MFV_T3(m.s&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>11.78 (0.31)</td>
<td>12.08 (0.33)</td>
<td>11.32 (0.09)</td>
<td>11.19 (0.11)</td>
<td>11.68 (0.25)</td>
</tr>
<tr>
<td></td>
<td>2.6%</td>
<td>2.7%</td>
<td>0.8%</td>
<td>1.0%</td>
<td>2.1%</td>
</tr>
<tr>
<td>MFV_T4 (m.s&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>12.20 (0.31)</td>
<td>12.60 (0.11)</td>
<td>11.49 (0.10)</td>
<td>11.36 (0.18)</td>
<td>12.09 (0.10)</td>
</tr>
<tr>
<td></td>
<td>2.5%</td>
<td>0.9%</td>
<td>0.8%</td>
<td>1.6%</td>
<td>0.8%</td>
</tr>
</tbody>
</table>

FV_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 positions and highest value to further and highest target positions for all skilled players. Other variables that did not demonstrate this trend were not reflected in this table.

a: p<0.05 only between T2 & T3 and T2 & T4 for FV_BC & MFV; b: p<0.05 for T2, T3 & T4 for FV_BC & MFV; c: p<0.05 only between T2 & T3 and T2 & T4 for FV_BC and p<0.05 for T2, T3 & T4 for MFV

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 Figures 3.1 and 3.2). 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 Figures 3.1 and 3.2). 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 3.3 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 Figures 3.1 and 3.2). However, skilled player 1 was still able to achieve a 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.
FIGURE 3.1. Figure showing hip-knee angle-angle plots to T1 and individual NoRMS index. Note the bold dotted line represents the mean trace for the angle-angle plots.
FIGURE 3.2. Figure showing knee-ankle angle-angle plots to T1 and individual NoRMS index. Note the bold dotted line represents the mean trace for the angle-angle plots.
3.4.3 Non-Kicking Limb

Figure 3.4 shows the ROM of the non-kicking knee. 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 analysis showed significant differences among the skilled players ($F(4, 45) = 30.654, p=0.000$) for the non-kicking knee ROM. Player 2 exhibited the lowest non-kicking knee ROM at $12.89 \pm 3.03^\circ$, which was different from all other players except for player 3 ($p=0.209$).
FIGURE 3.4. Figure showing (A) non-kicking limb knee (ROM) for skilled player 3 (S3) and (B) a representative non-kicking limb knee (ROM) for other skilled players (e.g., S4). Bold dotted line represents the mean trace.

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 3.5). 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).

3.4.4 Displacement of COM

From Figure 3.6, 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. Player 1 demonstrated both forward and upward displacement of COM during the chipping trials. Root Mean Square Error (RMSE) for COM displacement was low across all players (from 0.0048 to 0.0128). See Figure 3.6.
Skilled Player 1, 0.27 (0.029)m, n=10

Skilled Player 2, 0.29 (0.023)m, n=10

Skilled Player 3, 0.21 (0.021)m, n=10

Skilled Player 4, 0.30 (0.034)m, n=8

Skilled Player 5, 0.31 (0.041)m, n=8

FIGURE 3.5. Figure showing planting foot position to ball position for all skilled players to T1 with Mean, SD (in parentheses) and n indicated below each figure
FIGURE 3.6. COM displacement and RMSE from initiation of knee flexion to ball contact for skilled players to T1. Note the bold line represents the mean COM displacement.
3.4.5 Ball Back Spin

All players imparted back spin on the ball. (see Table 3.5).

<table>
<thead>
<tr>
<th>Participants</th>
<th>T1 Mean (SD) °.s⁻¹</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.

3.5 Discussion

The purpose of this study was to examine the coordination of soccer chipping performance in skilled participants and referenced 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 successful kicking to different target positions under varying distance and height constraints (see Table 3.1). We interpreted this finding as evidence that these players were at least at the Control stage 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.

Based on analysis of kinematic variables and intra-limb coordination patterns, skilled players demonstrated similarity in global coordination, 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. Hip-knee and knee-ankle angle-angle plots (see Figures 3.1 and 3.2), 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 3.3). 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 concurrent with high performance outcome scores 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 IMHV/IMKV and SKE/IMHV, 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 IMKV/IMFV values in Table 3.3). 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 different height and distance constraints of T2, T3 and T4. The lowest FV_BC and MFV values were observed to T2 (shortest distance and with lowest height barrier) and highest FV_BC and MFV to T4 (furthest distance and highest height barrier). However, as discussed earlier in Chapter 2, this foot velocity at ball contact trend may not be expected for the specific task constraint in the study. From intra-individual analysis, both FV_BC and MFV were not significantly different between T3 and T4 for three out of five players. So, although an ascending trend for FV_BC and MFV was seen across all players from T2 to T4, significant differences between T3 and T4 was not seen for all players. This further confirmed the earlier suggestion in Chapter 2 that a ‘significantly’ increasing FV_BC trend between T3 and T4 may not be expected under the specific task constraints present in this programme of work. However, more importantly, the data from the skilled players provided support 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) even for target positions with different height and distance constraints since the foot velocity profile was associated with high performance scores. In addition, the low coefficient of variation values observed for most of the higher order derivatives to T1, T2, T3 and T4 (other than MHV) 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. This clearly indicated that they were at least at the Control stage of learning, with the possibility that some players were transiting to the Skill stage.

In relation to variability of intra-limb coordination, similar intra-individual NoRMS values 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 3.2), 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 Figure 3.6), 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, low variability in COM displacement seen from the RMSE values 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 & 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 Skill 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 players for distance of foot relative to ball position, the
distribution of the foot location was somewhat different for individuals. Most notably, player 2 planted his 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 3.4), 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 optimised. To evaluate this idea in more detail, future studies could measure ground reaction forces of the planting foot using a force platform 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 dof were subtly re-organised during task performance. Globally similar coordination patterns in skilled players for the soccer chip were characterised 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 distance constraints, b) skilled players demonstrated low levels of variability in COM displacement during the chipping action 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 positioning the planting foot relative to the ball, and 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. Undoubtedly, 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 display 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 at ball contact concurrent with performance outcome as an indicator for the Control stage of learning in the soccer chip. Moreover, adopting an intra-individual analysis provided valuable insights into how motor system dof were re-organised during goal-directed performance by individuals that would have been masked if data were grouped and analysed. Skilled
performance can be categorised 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. However, further work is needed to explore performance at the Skill stage of learning (e.g., directly examining energy expenditure or reactive forces of limb segments). In addition, examination of coordination changes as novice learners progress through the stages of learning as a function of extended practice (see Chapter 4) as well as to understand the role of movement variability in nonlinear learning (see Chapter 5) demands further investigation.
Chapter 4

Coordination Changes in a Discrete Multi-Articular Action as a Function of Practice

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This study investigated how novices re-organised motor system dof when practicing a multi-articular discrete kicking task. Four male participants practiced a soccer chipping task to seven different target positions over 12 sessions for 4 weeks. Data from each participant indicated changes in dof involvement as a function of practice. Further, each participant showed a different progression of change in levels of joint involvement for hip, knee and ankle in the kicking limb. Cross correlations between joints in the kicking limb also showed individual-specific pathways of coupling and de-coupling with practice. Performance outcome scores improved and variability of intra-limb coordination decreased as a consequence of practice for all participants. Angle-angle plots also showed qualitative changes in intra-limb coordination between early and late practice sessions. Evidence suggested that foot velocity at ball contact was functionally manipulated by participants when kicking to target positions with varying height and distance constraints. Referencing data to a model of learning (Newell, 1985) determined that progression through different stages of learning may not be sequential and could alternate between learning stages. The study highlighted individual differences in acquisition of coordination and control of joint motion even under similar task constraints, showing how degeneracy in movement systems facilitates learning.
4.2 Introduction

Recently, there have been increased efforts to study changes in movement coordination as a function of practice (e.g., Broderick & Newell, 1999; Chen et al., 2005; Nourrit, Delignières, Caillou, Deschamps & Lauriot, 2003; Vereijken, van Emmerik, Bongaardt, Beek & Newell, 1997). Knowledge on how motor system degrees of freedom (dof) are re-organised as a consequence of practice can be developed through studying multi-articular actions, which abound in many contexts such as work and sport. Most previous investigations of complex multi-articular actions have examined continuous cyclical movements, with relatively few attempts to study coordination in discrete multi-articular movements like kicking (e.g., Anderson & Sidaway, 1994, Chow, Davids, Button & Koh, 2006), pointing (e.g., Tseng, Scholz & Schöner, 2002; Tseng, Scholz, Schöner & Hotchkiss, 2003) and throwing (e.g., Button et al., 2003; Kudo et al., 2000).

The lack of empirical research in this area of motor learning has been compounded by the failure to distinguish between the concepts of ‘coordination’, ‘control’ and ‘skill’ in human movement (Newell, 1985). Coordination can be defined as the function that constrains available motor system dof into an effective movement pattern (Newell, 1985, 1996). Control refers to the parameterising of the topological relations of the coordination pattern formed between the different parts of the neurobiological system. It is the process by which values are assigned in the coordination function that constrains movement. At this stage of learning, movement variability is functional in adapting behaviour to changing task constraints. In Newell’s (1985, 1996) conceptualising, skilled behaviour occurs when optimal values are assigned to the variables in the function.
Having distinguished between these ubiquitous terms in the motor behaviour literature, Newell (1985) proposed a model of learning focusing on the (re)organisation of motor system components (see also Chapters 1 and 2). In the present study of adult learners, the focus was on examining the acquisition of Coordination and Control stages of learning since it is unlikely that novice participants would acquire the Skill stage of learning within a relatively short practice time.

In previous work, Anderson and Sidaway (1994) reported that novices were able to acquire a set of relative motions for a soccer kicking task and were at the coordination stage of learning, based on emergence of similarities in topological characteristics between the expert and novice kicking patterns. Data indicating insufficient range of motion and lower hip angular velocity in the novices of their study, compared to an expert model, suggested that their participants still lacked the appropriate parameterising of kicking variables to be categorised under the Control stage of learning. Further work on kicking is needed to examine whether higher order derivatives like foot velocity at ball contact to different target positions could provide a suitable indicator for determining if learners can vary such kinematic derivatives functionally when satisfying task outcome goals during practice. Moreover, data on kinematics of the kicking action need to be collected during practice to understand how novices progress towards the Control stage of learning, building on the earlier information of Anderson and Sidaway (1994).

In Chapter 2, coordination differences in the performance of a soccer kicking task in participants of different skill levels was investigated (see Chow, Davids, Button & Koh, in press).

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8 Although the practice time can be described as short, a total of 570 practice trials were provided to the participants and the practice period lasted for 4 weeks with a total of 12 practice sessions (See Methods section in the current chapter). However, it was assumed that novice participants would require a far greater number of trials to reach the Skill stage of learning.
It was confirmed that the most skilled participants were able to functionally adapt foot velocity at ball contact when kicking to target positions with varied height and distance constraints. High levels of performance accuracy and appropriate force control of the passes were observed in the skilled participants, suggesting that relevant kicking parameters (i.e., foot velocity at ball contact) were effectively manipulated to achieve the task goal. However, low performance scores, concurrent with dysfunctional variations in foot velocity at ball contact, were reported for novice participants. It was concluded from the findings in Chapter 2 that the skilled participants demonstrated evidence of attaining at least the Control stage of learning while the novices were still at the Coordination stage of learning as described by Newell (1985).

In addition, it has been indicated from Chapter 2 that more work examining changes to the organisation of motor system dofs involved in joint motions of a discrete multi-articular action in novices as a function of extended practice are required. An interesting issue raised in Chapter 2 concerned the pathways of change that novice participants might adopt over a prolonged practice phase as they attempted acquire the Coordination and Control stages of learning. The questions arising from these observations provide the platform for current study. For example, would novice learners demonstrate an improvement in manipulation of higher order derivatives like foot velocity at ball contact, associated with concurrent increases in performance outcomes over an extended practice time? Would the intra-limb coordination of novices become more consistent with practice?

Here we investigate how joint involvement and coupling between joints in the kicking limb might change during practice as learners attempt to solve the ‘degrees of freedom problem’ (Bernstein, 1967). Specifically, the challenge for learners is to determine how the numerous motor system components can form stable movement patterns from the huge possibilities that the
motor system offers. Bernstein (1967) suggested that the control of biomechanical dof progresses in universal direction (that of reduced to increased involvement). More recently, the trend of reduced to increased involvement of dof with learning has been shown not to be universal, but dependent on task constraints (Newell & Vaillancourt, 2001).

Theoretical emphasis on understanding the direction of change in the organisation of motor system dof with practice has been reinforced by more recent understanding of the inherent degeneracy of neurobiological systems (see for example Davids, Button, Araújo, Renshaw & Hristovski, 2006; Edelman & Gally, 2001; Hong & Newell, 2006; Newell, Liu & Mayer-Kress, 2005). Degeneracy, as discussed in the earlier chapters, refers to the capacity of structurally different components of neurobiological systems to achieve the same or different outcomes in varying contexts. It is exemplified in networks existing at different levels of human movement systems including molecular, genetic, and musculo-skeletal, conveying a significant adaptive evolutionary advantage (Edelman & Gally, 2001). Degeneracy provides the neuro-mechanical basis for the diversity of actions required to negotiate information-rich, dynamic environments from moment to moment as well as to successfully learn tasks such as discrete multi-articular actions (Davids, Araújo, Button & Renshaw, 2007). These ideas strongly support the expectation that individual learners may find different pathways in coordinating and controlling movement, within the same practice task constraints, an issue that needs further empirical examination.

Some limited observations of intra-individual coordination changes during practice of a discrete multi-articular task are consistent with these expectations. Hodges et al (2005) reported that the dof involvement of the kicking limb in one learner was initially reduced early in practice but subsequently increased with more practice time. It was also observed that the range of motion of the kicking limb joints (i.e. hip, knee, and ankle) were restricted again at the end of the
practice phase. Hodges et al (2005) reported cross correlation analyses suggesting that the
direction of control for involvement of dof progressed from increasing to reducing and back to
increasing. In their study, the use of single-participant analysis proved a useful methodology to
contribute some insights into coordination changes throughout practice. However, there is a need
for data from a comparative analysis with additional participants to elucidate how different
functional coordination solutions may emanate from isomorphic structures, supporting ideas of
degeneracy (Edelman & Gally, 2001; Hong & Newell, 2006). In this respect, the use of multiple,
single-participant analyses would contribute additional knowledge about coordination changes
with practice, revealing similarities and differences across individuals in re-organisation of dof.
This was clearly demonstrated in Chapter 3 where a multi-single participant design was
undertaken in investigating skilled players.

Therefore, the purposes of this study were to a) examine changes in coordination through
level of joint involvement and coupling between joints as a function of practice (observations of
non-unidirectional changes in the reduction and increase in involvement of dof across
participants were expected) and b) examine the progress of novice participants as they acquire the
Coordination and Control stages of learning described by Newell (1985). It was predicted that, as
performance outcome scores increased, variability of intra-limb coordination of kicking limb
would decrease and foot velocity at ball contact would be varied functionally to satisfy the task
goal over extended practice.

4.3 Methods

4.3.1 Participants

Four male novice participants (age: 27.25 ± 4.03 yrs) were recruited for this study. The
participants were considered novices as they had no competitive playing experiences in soccer
and also had little playing experience at a recreational level. Voluntary and informed consent were obtained from all participants and procedures employed in the study were in accordance with the University of Otago’s ethical guidelines.

4.3.2 Task and Apparatus

All participants were asked to chip a soccer ball with their dominant (preferred) foot over a barrier to a skilled receiver. No explicit verbal or visual instructions were provided on how to chip the ball over the barrier. Participants 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 with appropriate force control (i.e., appropriately weighted to allow for easy control of the pass). Video film capturing ball flight only onto the receiver’s feet was shown to ensure understanding of the task goal. Participants 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. Coloured 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 participants were required to kick to seven different 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 set up).
Target T1: Bar height (1.6m), Perpendicular distance of ball to bar (5m), Perpendicular distance of ball to T1 (12m)
Target T2: Bar height (1.6m), Perpendicular distance of ball to bar (5m), Perpendicular distance of ball to T2 (12m)
Target T3: Bar height (1.6m), Perpendicular distance of ball to bar (5m), Perpendicular distance of ball to T3 (14m)
Target T4: Bar height (1.6m), Perpendicular distance of ball to bar (5m), Perpendicular distance of ball to T4 (12m)
Target T5: Bar height (1.5m), Perpendicular distance of ball to bar (4m), Perpendicular distance of ball to T5 (10m)
Target T6: Bar height (1.6m), Perpendicular distance of ball to bar (5m), Perpendicular distance of ball to T6 (14m)
Target T7: Bar height (1.7m), Perpendicular distance of ball to bar (5m), Perpendicular distance of ball to T7 (14m)

FIGURE 4.1. Schematic representation of task set up to all target positions

A FIFA-approved size 5 soccer ball was used in the kicking task and all participants wore soccer indoor shoes and shorts for all test and practice sessions. 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 as described in Chapter 2. 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 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 but only the angle in the primary plane of motion were used for further analysis. 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.

4.3.3 Procedures

i) Pre- and Post-Test Sessions

Participants 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 participants performed 10 trials kicking to T1. Subsequently, participants performed another 5 trials each to T5, T6 and T7 in a randomised order, completing a total of 25 test trials for the pre- and post-test sessions. The 10 trials to T1 were used to determine the coordination of the kicking action and the 15 trials to T5, T6 and T7 were used to identify if participants were able to vary their foot velocity at ball contact to achieve the task goal under different height and distance constraints. Participants were allowed as much rest as they needed between trials, with intervals ranging between 10 to 30 seconds in duration. Each test session took between 45 and 60 minutes to complete. Pre- and post-test sessions were separated by a 4 weeks practice phase.

ii) Practice Sessions

Participants performed the warm up routine similar to the pre- and post-test sessions prior to practicing 10 kicking trials each to T1, T2, T3 and T4 (a total of 40 trials per session) in a randomised order. All participants underwent a 4-week practice phase with three sessions per week (a total of 12 sessions). In addition, participants were required to perform an additional 15 kicking trials to T5, T6 and T7 (5 trials to each position) in a randomised order at every second
session (i.e., at the 2\textsuperscript{nd}, 4\textsuperscript{th}, 6\textsuperscript{th}, 8\textsuperscript{th}, 10\textsuperscript{th} and 12\textsuperscript{th} practice session). Similar to the pre- and post-test sessions, the 15 trials to T5, T6 and T7 were used to interpret if participants were able to vary foot velocity to achieve the task goal under different height and accuracy constraints. In total, all participants performed 570 trials during the practice phase. Rest intervals between trials were similar to the pre- and post-test sessions and each practice session took between 60 to 90 minutes to complete. See Table 4.1 for a schematic representation of the test and practice protocol.

**TABLE 4.1. Schedule representation of the test and practice protocol for study.**

<table>
<thead>
<tr>
<th>Sessions</th>
<th>T1</th>
<th>T1, T2, T3 &amp; T4*</th>
<th>T5, T6 &amp; T7**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-test</td>
<td>10 trials</td>
<td></td>
<td>15 trials</td>
</tr>
<tr>
<td>Session 1</td>
<td>40 trials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Session 2</td>
<td>40 trials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Session 3</td>
<td>40 trials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Session 4</td>
<td>40 trials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Session 5</td>
<td>40 trials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Session 6</td>
<td>40 trials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Session 7</td>
<td>40 trials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Session 8</td>
<td>40 trials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Session 9</td>
<td>40 trials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Session 10</td>
<td>40 trials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Session 11</td>
<td>40 trials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Session 12</td>
<td>40 trials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-test</td>
<td>10 trials</td>
<td></td>
<td>15 trials</td>
</tr>
</tbody>
</table>

*: 10 trials each to T1, T2, T3 & T4 in a randomised order

**: 5 trials each to T5, T6 & T7 in a randomised order

**4.3.4 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 2.1 in Chapter 2). Since the Likert performance scale provided ordinal data, a Kruskal Wallis One-Way Analysis of Variance by ranks test was administered on Means and SDs.
ii) Joint Range of Motion

Joint range of motion for the hip, knee and ankle (°) for the kicking limbs were collected for the duration of the limb movement sequence beginning 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 and Chapter 2). Data were filtered using a low pass Butterworth digital filter with the Visual 3D software at frequency 7Hz. All trials were normalised 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.

All trials for the pre- and post-test sessions were analysed. A representative sample of 18 trials per session were analysed for kicks to T1, T2, T3 and T4. Table 4.2 shows the distribution of the selected trials that were analysed for the practice sessions to positions T1, T2, T3 and T4. All trials to T5, T6 and T7 were analysed for pre-test, post-test and practice sessions 2 and 12.

<table>
<thead>
<tr>
<th>Phases of Practice Session</th>
<th>Trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Early</td>
<td>2nd, 4th, 6th, 8th, 10th, 12th</td>
</tr>
<tr>
<td>2 Middle</td>
<td>15th, 17th, 20th, 23rd, 25th, 27th</td>
</tr>
<tr>
<td>3 Late</td>
<td>29th, 31st, 33rd, 35th, 37th, 39th</td>
</tr>
</tbody>
</table>

iii) Cross Correlations between Joints

The linear relationship between joint angles of the kicking limb was examined using cross-correlations with time lags (see Mullineaux et al., 2001). Peak cross correlations between two joints at the respective time lags (± 7) (see Amblard, Assaiante, Lekhel & Marchand, 1994) were calculated to determine the amount of coupling between the joints. Mean cross correlation ratios per session were then determined from the individual cross correlation values for the trials analysed within each session.
A high cross correlation coefficient would indicate highly coupled joint angles moving in the same (positive) or different (negative) directions. A low cross correlation coefficient would indicate that the joint angles are moving independently of each other (see Button et al., 2003; Hodges et al., 2005; Temprado et al., 1997). A peak correlation at zero time lag indicates that two joints are moving synchronously and in the same direction. A negative (positive) time lag indicates that distal joint is moving after (before) the proximal joint at the particular lag at which it occurs. A high peak correlation (r=0.9) at the 7\textsuperscript{th} positive lag (+0.028s with sampling frequency at 240Hz) would indicate that the distal joint is linearly coordinated with the proximal joint when the distal joint moves before the proximal joint by 0.028s. (see Mullineaux et al., 2001)

\textit{iv) Angle-Angle Plots and Normalized Root Mean Square Error (NoRMS)}

Hip-knee and knee-ankle angle-angle plots were determined for the kicking limb per practice session for each individual to depict qualitative changes in intra-limb coordination as a function of practice. Global topological characteristics (e.g., knee flexion and hip extension followed by knee extension and hip flexion during the kicking movement) of the angle-angle plots were also compared between novice participants and a representative skilled participant (taken from Chow, Davids, Button & Koh, 2006). This helped to determine if there were similarities to suggest that novice participants had acquired a basic relationship between the limb segments in the kicking task, thus attaining features of the Coordination stage of learning (see Anderson & Sidaway, 1994).

Variability in relationship between the joint angles for the kicking limb was examined using the NoRMS (Normalized Root Mean Square Error) procedure (Sidaway & Schoenfelder-Zohdi, 1995) interpreted by Mullineaux et al (2001).
v) Foot Velocity at Ball Contact

Foot velocity at ball contact (FV_BC) (m.s\(^{-1}\)) to T5, T6 and T7 was determined for all individuals for pre-test, post-test and practice sessions 2 and 12. Data used for the calculation of the foot velocities 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 impact (see Chow, Davids, Button & Koh, 2006 and Chapter 2).

4.4 Results

4.4.1 Performance Outcome

Performance outcome scores to T1, T2, T3 and T4 (18 trials per session) of all participants (AD, CL, YH and KL) demonstrated a general increasing trend from practice session 1 to session 12 (See Figure 4.2). Significant differences were observed between pre- and post-test performance outcome scores for all participants to T1. Participant AD demonstrated the lowest post test scores and generally performed poorly over the sessions compared to other participants (See Figure 4.2). There were no significant differences in performance scores to T1, T2, T3 and T4 (18 trials per session) across all participants at post-test.
*AD (pre: 1.0±0; post: 2.6±2.07); *CL (pre: 1.0±0; post: 4.3±1.81); *YH (pre: 1.0±0; post: 3.7±2.31); *KL (pre: 1.6±1.26; post: 4.4±2.01), *p<0.05

FIGURE 4.2. Performance score to T1, T2, T3 and T4 for all participants for all sessions

*AD (pre: 1.13±0.52; post: 2.67±1.80); *CL (pre: 1.0±0; post: 4.0±1.89); *YH (pre: 1.33±1.29; post: 3.4±2.29); KL (pre: 2.07±2.02; post: 3.07±1.98), *p<0.05

FIGURE 4.3. Performance score to T5, T6 and T7 for all participants for all sessions
Performance outcome scores to T5, T6 and T7 also showed a general increasing trend (See Figure 4.3). Significant differences between pre- and post-test sessions for all participants were also observed except for participant KL. A Kruskal Wallis test showed that there was a significant difference between practice session 2 and session 12 for participant KL, $\chi^2(1, N=30) = 3.9$, p=0.048. All participants improved their performance scores over practice and showed that they could transfer the skill to kick to different target positions. There were no significant differences in performance scores to T5, T6 and T7 (15 trials per session) across all participants at post-test.

4.4.2 Joint Range of Motion

An intra-individual analysis was employed to examine changes to joint range of motion for all participants (See Figure 4.4 for joint range involvement for all participants in pre-test, post-test and all practice sessions). As suggested by Hodges et al (2005), an increase in range of motion indicates an increase in active joint involvement and vice versa.
FIGURE 4.4. Joint involvement for hip, knee and ankle of kicking limb for all participants over pre-test, post-test and practice sessions

No common trends in change in joint involvement across participants as a function of practice were observed. However, comparison between early and late learning using a paired-sample T-test provided some interesting observations in relation to hip and knee involvement. At post-test, a reduction in hip joint ROM (i.e., indicating a possible decrease in joint involvement) was observed for YH (pre: 101.34 ± 24.78°, post: 63.7 ± 6.63°, t(9)=5.348, p=0.000) while there was no significant difference for KL (pre: 53.03 ± 5.79°, post: 56.59 ± 9.56°). A greater involvement of the knee was seen for YH (pre: 76.19 ± 12.75°, post: 97.38 ± 4.31°, t(9)=-4.954, p=0.001) and KL (pre: 71.01 ± 3.48°, post: 100.6 ± 3.35°, t(9)=-16.882, p=0.000) by post-test.

Participant CL demonstrated greater involvement of the hip (pre: 49.58 ± 4.75°, post: 72.13 ± 2.52°, t(9)=-11.352, p=0.000) and of the knee (pre: 76.82 ± 2.87°, post: 92.95 ± 3.25°, t(9)=-9.284, p=0.000) by post test.
However, participant AD showed greater involvement of the hip (pre: 59.56 ± 3.99°, post: 71.31 ± 6.15°, t(9)=−6.929, p=0.000) and less involvement for the knee (pre: 110.67 ± 5.71°, post: 80.79 ± 5.14°, t(9)=10.654, p=0.000) by post test.

4.4.3 Cross Correlations between Joints

An increase in inter-joint coupling indicated by high cross correlation coefficient would suggest low involvement of dof of the relevant joints and vice versa. Participants AD, CL and YH demonstrated mainly an increasing involvement of dof followed quickly by reducing dof for the distal joints (i.e., knee and ankle) early in practice (See Figure 4.5). Subsequently, involvement of dof at the distal joints was increased by session 12 for two out of four participants (YH and KL). There was also evidence of alternating reduction and increase of dof involvement at the distal joints, especially for participants CL and YH during the practice phase.
Figure 4.5 shows that, in all participants except AD, the proximal segment (hip-knee) remained strongly coupled and involvement was reduced for most sessions. Participant AD showed an increasing involvement of dof from early to mid phases of the practice period. Thereafter, there was clear reduction of dof involvement at the distal joints over practice sessions. There were no clear trends in terms of the pattern of joint release for a proximal-to-distal sequencing across participants from the time-lag data.

### 4.4.4 Angle-Angle Plots (Hip-Knee and Knee-Ankle)

In Figure 4.6, it can be observed that there were qualitative differences between early and late practice sessions for hip-knee and knee-ankle angle-angle plots across all participants. For example, the kicking action of participant AD involved a smaller hip range of motion, increased knee motion and a smaller ankle movement at session 12. Post test data reported earlier in the
section on joint level involvement confirmed the description provided by the angle-angle plots. The greater range of motion at the knee indicated that control of joint motion was moving away from the proximal hip joint to the knee joint for participant AD.

The qualitative analysis demonstrated individual differences across participants in angle-angle plots and a change in intra-limb coordination as a function of practice. In addition, it was observed that the angle-angle plots were generally less variable (as also evidenced by the NoRMS indices presented in a later section) as participants progressed through the practice sessions (See Figures 4.7 and 4.8 for an example of such a trend).
FIGURE 4.6. Mean hip-knee and knee-ankle angle-angle plots for all individuals for session 1 and 12.

FIGURE 4.7. Hip-knee angle-angle plots for a typical participant as a function of practice. S1 indicates session 1. Ascending sessions displayed across the columns through successive rows.
Similar ‘global’ topological characteristics of movement patterns were observed through comparing angle-angle plots between the novice participants and a representative skilled participant (see Figure 4.9 for the angle-angle plots of a typical skilled participant). This would indicate that novice participants were already at the Coordination stage of learning early in practice.
4.4.5 Normalized Root Mean Square Error (NoRMS)

All participants demonstrated a general decreasing trend for NoRMS (See Figure 4.10). The decrease in intra-limb variability of the kicking limb indicated that participants were able to achieve a more consistent movement pattern even while coordination was changing and evolving over the practice sessions.
FIGURE 4.10. NoRMS indices of (A) hip-knee and (B) knee-ankle intra-limb coordination for all participants from session 1 to 12
Foot velocity at ball contact when kicking to T5, T6 and T7 was determined for pre-test, post-test, and practice sessions 2 and 12. No common specific trend was demonstrated across participants in relation to foot velocity at ball contact to T5, T6 and T7 as a function of practice. See Table 4.3. However, foot velocity at ball contact for the post-test was associated with improved and higher performance scores than at pre-test for all participants although it was not significantly different for participant KL.

### TABLE 4.3. Mean, SD (in parentheses) of foot velocities and performance scores to T5, T6 and T7 for all participants to selected test and practice sessions.

<table>
<thead>
<tr>
<th></th>
<th>T5</th>
<th>T6</th>
<th>T7</th>
<th>*Trend (Yes/No)</th>
<th>Performance Score</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Participant AD</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-test</td>
<td>10.18 (0.67)</td>
<td>10.01 (0.54)</td>
<td>9.83 (0.49)</td>
<td>No</td>
<td>1.13 (0.52)</td>
</tr>
<tr>
<td>S2</td>
<td>9.36 (0.50)</td>
<td>9.12 (0.96)</td>
<td>9.24 (0.53)</td>
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<td>1.67 (1.18)</td>
</tr>
<tr>
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<td>10.10 (0.19)</td>
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<td>10.47 (0.20)</td>
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<td>1.67 (0.90)</td>
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<tr>
<td>Post-test</td>
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<td>2.67 (1.80)</td>
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<td></td>
<td></td>
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</tr>
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<td>10.71 (0.45)</td>
<td>10.64 (0.46)</td>
<td>No</td>
<td>3.07 (1.98)</td>
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</table>

*Trend: Lowest foot velocity to T5 and highest foot velocity to T7*
4.5 Discussion

The purposes of this study were to a) examine changes in coordination through level of joint involvement and coupling between joints as a function of practice in novices and b), examine the progression in acquiring Coordination and Control stages of learning described by Newell (1985).

4.5.1 Coordination Changes as a Function of Practice

Changes in coordination for participants over practice undertook different pathways, although there were also some commonalities. Level of joint involvement (as indicated by joint ROM) was generally lower at hip and knee joints for all participants at pre-test compared to post test (except for participant YH for hip and AD for knee). However, less joint involvement early in practice was accompanied by an increasing or low coupling of the distal joints (knee-ankle), as observed in three out of four participants (participants AD, CL and YH). Initial increased involvement of dof at the distal segment was quickly followed by a reduced involvement. This observation on the dynamics of motor learning suggests that reduction of involvement of the joints, especially the distal joints did not occur immediately at the initiation of the practice phase. Novice learners may have required some time to explore and discover control in the movement pattern, leading to a reduced involvement of dof. Hodges et al (2005) reported a similar initial increase prior to a reduced dof involvement in their investigation of learning with a soccer kicking task. These similar observations suggest that an exploration of control might be facilitated by discrete multi-articular task constraints. Under discrete task constraints the adaptation of movement patterns might occur from trial to trial, compared to learning a continuous movement in which there may not be the same natural breaks in action.
Why was there no universal direction of change in the level of joint involvement, i.e. reduced/increased involvement of dof and proximal-to-distal patterns of joint release, as predicted from Bernstein’s (1967) insights? Newell and Vaillancourt (2001) proposed that the directional change in dof and coordination is dependent on task constraints, particularly the required change of the task-relevant intrinsic dynamics in order to meet new tasks. This explanation clarifies why there was an absence of a general learning strategy across the participants. Indeed, there have been some suggestions that alternating reducing and increasing dof could be an ideal strategy for instigating change during skill acquisition (Berthouze & Lungarella, 2004), as evident in the coordination dynamics of some of the participants (e.g., CL and YH for the distal joints). Moreover, it was likely that the intrinsic dynamics for the various individuals were different (although no test was used to specify this). For example, Participant CL had configured motor system dof to execute a mix of a drive (i.e., trying to maximise ball velocity) and a lifting technique early in learning and eventually, a scooping technique emerged from his pre-existing movement repertoire by the end of the study (see Figure 4.11). Certainly, pre-existing behaviour can influence learning a new movement pattern (see data from Faugloire, Bardy & Stoffregen’s (2006) study of learning a new postural pattern). The intrinsic dynamics may play a role in affecting the eventual emergence of the movement pattern seen later in learning and at post-test.
The multi-articular kicking task in the current study, which mimics the soccer chip, is unlike the soccer instep kick. There are many possible movement solutions that can be employed to meet the task goal of chipping a ball over a height barrier to drop it comfortably at a receiver’s feet. In contrast, when learning to kick to maximise ball velocity, successful solutions are likely to be less varied. In line with notions of degeneracy in neurobiological systems (see Edelman & Gally, 2001; Hong & Newell, 2006, Newell et al., 2005; Newell & McDonald, 1994), the present task teased out a number of different pathways that learners could use to acquire coordination and control of joint movement, with isomorphic structural constraints of joints and segments of the lower limb. The functional role of degeneracy was evidenced by the different trends in change to levels of joint and dof involvement shown by the participants as a consequence of practice. Certainly, the non-unidirectional change in the reduction and increased involvement of dof across participants was observed as predicted.
4.5.2 Progression through Stages of Learning

As noted earlier, an initial increased involvement of dof at distal joints followed by a reduced dof involvement quite quickly was observed for three out of four participants. This pattern in the initial phase of practice was indicative of learners being in the Coordination stage of learning, when they would be attempting to identify and search for fundamental relationships among the motor system components to achieve a goal of the task.

Subsequently, there were indications to suggest that at least two out of four participants (YH and KL) were increasing the involvement of dof at the distal joints as a function of practice. This increasing involvement of the distal joints was indicative of the progressive release of coordinative structures assembled in early practice sessions to reform into different configurations for better control of the movement (Newell, 1996; Williams et al., 1999). Moreover, the control of the movement moved progressively to the distal joints, evidencing increasing involvement of dof at those joints over practice. This was a further indication of participants advancing towards the Control stage of learning and the higher performance scores later in practice also reflected improvements in satisfying the task constraints.

Interestingly, as discussed earlier, participant CL adopted a distinctive movement pattern, requiring a reduced dof involvement at the distal joints by the end of practice session 12. Control of movement did not proceed to the distal joints but the movement pattern (a scooping action) became more functional with practice, as indicated by the higher performance scores later in practice. Thus, although control of movement did not progress to the distal joints as frequently described in the Control stage of learning model (Newell, 1985), participant CL was able to reorganise the movement to meet the task goal through alternate reduction and increased involvement of dof at the distal joints during the earlier phases of practice before settling into a
scooping action later when greater success was achieved. The stages of motor learning framework by Newell (1985), and the suggestion of progressive control from proximal to distal joints, can be understood from the perspective that changes in coordination may be based on the functionality of a specific movement pattern in satisfying specific task constraints. In the case of participant CL, the absence of an increasing involvement of dof at distal joints was accompanied by an improvement in performance, suggesting better control of kicking parameters and a possible advance towards the Control stage of learning as well.

Participant AD had consistently achieved lower performance scores during the practice sessions and at post test as well (albeit with improvement). The reduction in dof involvement at both the proximal and distal joints may have been a strategy that allowed him some control and improvement in achieving performance outcomes.

Progression through the stages of learning could also be partly interpreted from foot velocity data from each individual participant. From the results, no clear trends for changes to foot velocity to T5, T6 and T7 were observed as a function of practice across participants. But when these data were related to performance outcome scores, a general increasing trend from early to late practice (i.e. better at meeting task goal later in learning) was present. Previous findings from Chapter 2 and 3 (see Chow et al., in press; Chow, Davids, Button & Koh, 2006) found that skilled players were able to functionally manipulate foot velocity to varying target positions under similar task constraints. They observed lowest foot velocity to T5 (shortest distance with lowest height) and highest foot velocity at ball contact to T7 (similar distance to T6 but with greatest height) in the skilled participants. However, the observed foot velocity trend demonstrated by the skilled participants in Chapter 2 might not necessarily have been expected in the current study. While it might be anticipated that foot velocities at ball contact should increase
from T5 to T6, an increase from T6 to T7 may not have been expected although the height barrier was greater for T7. Instead, the increased height barrier at T7 could possibly have required a lower foot velocity at ball contact if the angle of ball projection was below 45°. The specific movement pattern shown by the skilled participants, with a ‘stabbing’ action to generate ball back spin, might have depended more on foot velocity at ball contact since ball back spin could have played a pivotal role in generating greater ‘lift’ force for height clearance at T7 (see Chapter 2).

Certainly, in the present study, novice players did not demonstrate a ‘stabbing’ action and foot velocity may not necessarily have been varied accordingly as observed in the study of skilled players seen in Chapter 2 and 3. Nevertheless, all participants had higher post test performance scores to T5, T6 and T7, indicating an increased proficiency in varying higher order derivatives like foot velocity in projecting the ball to the live receiver appropriately. Undeniably, individual novice players tended to vary foot velocity differently in the present study.

Analysis of variability of intra-limb coordination (kicking limb) as a function of practice (from NoRMS data), revealed a general decreasing trend. It is evident that greater consistency in the kicking action (kicking limb) was demonstrated by these participants. At the same time, the level of joint involvement as well as coupling between joints evolved during practice with an increase in consistency in intra-limb coordination of the kicking limb. This decrease in variability of intra-limb coordination with concurrent improvement in performance is a probable indication of progress towards the ‘Control’ stage of learning.

With regards to predictions for observing progress in acquiring the Coordination and Control stages of learning, performance outcome scores certainly increased, variability in intra-limb coordination decreased and foot velocity at ball contact was varied functionally in meeting
the task goal with extended practice. However, the progression from Coordination through Control stages of learning did not seem to occur in a serial fashion. In this study, the movement patterns demonstrated by the novice participants were qualitatively different from previous observations of skilled participants under the same task constraints (see Chapter 3) although similar global topological characteristics of the movement was present. Novice participants did not perform a ‘stabbing’ movement at ball contact for the generation of adequate ball back spin for height clearance and appropriate pass weighting observed in skilled participants. Therefore, although novice participants in this study established a basic relationship between the motions of the relevant limb segments, the movement pattern observed may not have been optimal for achieving the task goal. With extended practice, it is worth speculating that novice participants would continue to explore and establish movement solutions to mimic the ‘stabbing’ movement patterns seen in skilled participants. This possibility would suggest that features of learning at the Coordination stage of learning are still present as novice participants continue to improve the parameterisation of movement variables by the end of the practice phase.

These findings are in line with theoretical suggestions that learning stages operate synergistically such that coordination is the organisation of control (Bernstein, 1967). This study highlighted how the Coordination and Control stages are often negotiated at around the same time for most tasks, particularly for adult learners as Newell (1985) proposed. It is clear that participants began to assemble their individual movement patterns in the Coordination stage of learning and that they began to establish better control in manipulating kicks to different target positions (as evidenced by higher performance scores to T5, T6 and T7) later in practice. However, the participants in this study were adults and it is possible that the kicking task employed was not truly novel to them, having had unstructured opportunities to kick objects at some point in their lives. Therefore, it is plausible that coordination did not precede control but
rather coordination was the organisation of control by the participants in this study. Coordination and control can play complementary roles in the regulation of human movement and both constructs can be viewed as interdependent (see Newell, 1996). It seems that the boundaries between the different stages of learning in the model are not clear cut, but instead functionally overlap and are dynamic, to provide opportunities for learners to explore movement solutions as required. To verify these arguments, future studies should consider identifying truly novel movement tasks which minimise effects of prior learning experiences to more effectively investigate coordination changes through the stages of learning as suggested by Newell (1985). Thus, the use of Newell’s (1985) model of stages of learning should be best viewed as a guide.

While, Newell’s modelling did not provide specific criteria for examining joint motion changes through the stages of learning, it highlighted the importance of examining changes in joint motion in relation to concurrent changes in performance outcomes. In this respect, it provides a valuable framework for focusing on how learners may establish, parameterise and optimise movement patterns with progressive task goal achievement. More generally, this framework seems particularly useful for researchers to investigate how degenerate neurobiological systems can vary movement patterns to achieve similar successful performance outcomes.

4.6 Conclusions

It was observed that change in the level of joint involvement and changes in dof for participants in a discrete multi-articular action were not only dependent on task constraints but also on the personal constraints of the degenerate movement system of each individual performer. Individual differences in coordination changes with practice were clearly observed and further support was provided for the methodology of intra-individual analyses in future studies since
important dynamics in the acquisition of coordination may have been masked by grouping data. Data from this study suggested that the pathway to acquiring coordination and control of functional movement may not be universal, even when the task and structural constraints are similar for all learners. A challenge for future research is to explore individuals’ intrinsic dynamics in order to identify why individuals learning pathways are different. Changes in movement patterns as a function of practice and possible nonlinear changes in learning a complex multi-articular action such as the soccer chip certainly demands further investigation. See Chapter 5.
Chapter 5

Dynamics of Movement Patterning in Learning a Discrete Multi-Articular Action

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Based on concepts in nonlinear dynamics, it has been proposed that learning in neurobiological systems occurs as system components are reorganised to facilitate transitions between preferred patterns of movement. Presence of movement variability prior to a change in preferred movement patterns is hypothesised to afford the necessary adaptability and flexibility for seeking novel functional behaviours. The aim of this study was to examine the specific role of movement pattern variability in effecting a transition from one preferred movement pattern to a new preferred movement pattern. In this study, four novice participants practiced a discrete multi-articular movement for 12 sessions over 4 weeks. Cluster analysis procedures revealed how changes between preferred movement patterns were effected with and without the presence of variability in movement clusters prior to a defined change. Specifically, Switch Ratio (SR) index, an assigned indicator for movement pattern variability, increased prior to a change in preferred movement pattern for two of the participants. It was observed that intentional and informational constraints play an important role in influencing the specific pathway of change for individual learners as they searched for new preferred movement patterns.
5.2 Introduction

The question of how neurobiological systems successfully acquire movement skills has been studied from a number of theoretical perspectives including nonlinear dynamics, a theory particularly suited to the study of neuro-behavioural transitions (Newell et al., 2001). From this viewpoint, motor learning has been characterised as a process of change between stable movement patterns (e.g., Liu, Mayer-Kress & Newell, 2003, 2006; Schöner et al., 1992). A central tenet in nonlinear dynamics posits that dynamical structures of control in neurobiological systems is spread across several levels of analysis and are bound by self-organisation under constraints (Kauffmann, 1995). Patterns of behaviours can spontaneously emerge as a consequence of the constraints present in specific learning contexts (Schmidt & Fitzpatrick, 1996). Early work by Kelso and colleagues (e.g., Kelso, Holt, Rubin & Kugler, 1981) provided evidence from bimanual finger coordination studies that transitions between preferred patterns (in-phase and anti-phase) could emerge when certain system control parameters (e.g., frequency of movement) were manipulated beyond a critical range of values. Specifically, interest focused on spontaneous pattern transitions to understand how neurobiological systems could attain different states of organisation under constraints (Newell, 1986).

Studies in nonlinear dynamics have suggested that over time, learning can be characterised as the evolution of a potential landscape describing the destabilisation of previously preferred movement solutions for a ‘to-be learned’ coordination pattern (Thelen, 1995). The acquisition of coordination is viewed as a process of searching for appropriate ‘attractors’, functional coordination patterns, into which a neurobiological system can settle during a task or activity (Liu et al., 2006). Consequently, motor learning can be punctuated by several transitions (including sudden jumps and regressions) between movement patterns that are observable over different time scales (see Liu et al., 2006; Newell et al., 2001).
Studies of the dynamics of motor learning have tended to favour models of bimanual finger coordination (e.g., Schöner et al., 1992) or continuous movements (e.g., Ko et al., 2003; Nourrit et al., 2003; Vereijken et al., 1997). In this study we investigated the learning of discrete multi-articular actions. Although Southard (2002, 2006) previously investigated changes in movement patterns in a discrete throwing task, the emphasis was on manipulating ‘parameters’ as well as instructions in affecting a change in throwing patterns. Few studies in nonlinear dynamics have attempted to examine the process of change and the presence of transitions between preferred\(^9\) coordination patterns in a discrete multi-articular action over extended practice periods.

Discrete movement patterns can provide useful models to investigate the process of change in coordination between distinct trials and practice sessions because they differ from continuous movements in important ways. One critical difference concerns the specificity of the constraints in many continuous and discrete tasks. In many discrete movements, like interceptive actions, positional accuracy in termination of the endpoint is most important in achieving the final goal (Guiard, 1997). Task constraints differ considerably when one is learning to move a limb to a specific spatial location and timing the intended contact of an effector with an object, compared to when one is waving an arm or waggling a finger. Schöner (1990) previously modelled differences between discrete and rhythmical movements, suggesting that the influence of each individual’s intentionality is a unique source of behavioural information stabilising action

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\(^9\) Stable state or stability, strictly in a dynamical systems approach, would entail examining concepts of critical slowing down as a consequence of a perturbation intervention. However, for this study, the term ‘preferred’ was used instead of ‘stable’ to acknowledge that stability of a movement cluster was not determined but rather movement clusters were categorised as being preferred if the use of the movement clusters satisfied certain priori criteria.
pattern dynamics. He showed how performance of a discrete movement could, in principle, be stabilised or perturbed by the intentions of the performer.

Research on discrete movements is theoretically significant because it can provide a window on the interface of cognition and action during motor learning (see Summers, 1998). The impact of intentions and behavioural information such as information from the environment or experience from previous trials and sessions can be examined in detail. Schöner’s (1990) modelling suggests that one might expect a great amount of inter-individual variability during the performance of discrete multi-articular actions. The assumption is that since individuals’ intentions differ, so will the movement patterns produced during motor learning. Between trials, more time and opportunity is available for learners to consider behavioural information (e.g., sensory feedback) that could impact the process of change between preferred movement patterns.

Questions arise over the existence of common kinematic features that characterise changes between preferred movement patterns when learning a multi-articular discrete action. For example, because the potential landscape underpinning discrete multi-articular actions has not previously been modelled, it is uncertain whether transitions may occur in the same ‘clearcut’ fashion as observed in studies of bimanual finger coordination (where a clear ‘bistable’ regime exists). Also, as a function of varying individual constraints, do we expect to see each learner showing distinct preferred movement patterns during the course of learning a skill? As well as pattern transitions, another important hallmark feature of learning in nonlinear dynamics is the presence of critical fluctuations or high levels of movement pattern variability immediately prior to a change in preferred movement patterns (see Chapter 1). Critical fluctuations have been observed in bimanual finger coordination studies and occur readily prior to a change in stable
patterns (either to in-phase or anti-phase). Critical fluctuations or high movement variability\textsuperscript{10} are vital in providing neurobiological systems with the requisite adaptability and flexibility for exploring novel coordination solutions (Riley & Turvey, 2002). In a recent study by Liu et al (2006), it was observed that high variability in the acceleration output in a rhythmic roller ball task was observed prior to a discontinuous change in acceleration profile of more successful learners. However, it was also found in the study that high variability in acceleration output may not necessarily be a pre-requisite for change in acceleration profile or movement dynamics. Certainly, it is not known if high levels of movement variability might be observed during the acquisition of discrete multi-articular actions during a prolonged period of practice.

One of the few studies examining changes between movement patterns using a discrete multi-articular action was a discus throwing task undertaken by Schöllhorn (1998). Two discus throwers (a decathlete and a discuss thrower specialist) were involved in the study over the duration of a competitive year. In the study, only 45 throwing trials from the specialist and 8 trials from the decathlete were recorded during trainings and competition sessions. A cluster analysis approach was used to investigate changes in the preferred movement patterning and the results indicated a change in preferred movement patterning for the specialist without an increase in fluctuations. However, it is not clear whether the low number of trials used over this extensive period of time might have skewed the results. Certainly, the role of movement pattern variability in discrete multi-articular actions as a function of extended periods of practice demands further investigation.

\textsuperscript{10} High movement variability was used in this paper to describe the presence of critical fluctuations as commonly explained in dynamical systems theory. However, movement variability is more suitable in this paper because a cluster analysis was used and ‘high variability’ in movement clusters was regarded as a better reflection of the macro variability that may exists in the use of movement clusters by learners in this study.
For the present study, clustering analysis was adopted as a technical method to investigate the process of change between preferred movement patterns when learning a discrete multi-articular action. Clustering is a useful tool in the data mining process for identifying interesting patterns, distributions and groupings in underlying data (Fayyad, Piatetsky-Shapiro, Smith & Uthurusamy, 1996). The technique has gained prominence in many different fields including studies of gene expression (e.g., Eisen, Spellman, Brown & Botstein, 1998; Slonim, 2002), marketing and sales (e.g., Michael & Berry, 1996), dietetics (Bailey, Gutschall, Mitchell, Miller, Lawrence & Smiciklas-Wright, 2006) and biological conservation (e.g., Trakhtenbrot & Kadmon, 2006). Advances in the use of clustering tools have moved the application of cluster analysis forward from a previously perceived tool bordering on qualitative analysis to one that is more objective and quantitative in nature.

The present study investigated transitional behaviour between preferred states of motor system organisation during practice of a discrete multi-articular action. For this purpose, we studied the process of change in movement patterning for kicking a ball as previously examined in Chapter 4. During practice, we examined movement variability and its effects on the nature of transitions from one preferred movement pattern to another novel preferred pattern. The aim of this study was to investigate learning of a discrete multi-articular action by a) identifying the presence and characteristics of change between preferred movement patterns during the acquisition process, and b), seeking to establish whether levels of variability in movement patterns increased prior to a change in preferred movement patterning.
5.3 Methods

5.3.1 Participants

Four male novice participants (age: 27.25 ± 4.03 yrs) were recruited for this study. All had no competitive playing experience in ball games involving lower limb interceptive actions, such as soccer, at any level. Voluntary and informed consent were obtained from all participants and procedures employed in the study were in accordance with the University of Otago’s ethical guidelines.

5.3.2 Task and Apparatus

The design of the experimental task was the same as in Chapter 4. All participants were asked to kick a FIFA-approved size 5 soccer ball over a barrier to a skilled receiver with their dominant foot. No explicit verbal or visual instructions were provided on how to kick the ball over the barrier. Participants were simply informed that the task goal was to kick the ball over the height barrier to land at the feet of a receiving individual or within a landing zone in front of the receiver, with appropriate force control to allow easy control of the ball by the receiver. Video film capturing ball flight only onto the receiver’s feet was shown to ensure understanding of the task goal. The novice participants learned the task on a 2 x 2 m area of 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. Coloured 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 participants were required to kick to seven different 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 5.1 for detailed information of the set up).
FIGURE 5.1. Schematic representation of task set up to all target positions

All participants wore indoor soccer shoes and shorts for all test and practice sessions. 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 as described in Chapter 2. 3D Euler joint angles of flexion and extension were derived for hip, knee, ankle, pelvis and trunk from the respective segments as defined by the marker sets but only the angle in the primary plane of motion were used for further analysis. A 20 m measuring tape was used to determine distance between the landing position of the ball on the field (when ball did not contact the receiver) and the respective target position. Ball landing
position for each trial was established visually and marked by two research assistants with one end of the measuring tape. 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 to ensure measurement reliability.

5.3.3 Procedures

The procedures undertaken for this study were the same as those described in Chapter 4.

i) Pre- and Post-Test Sessions

Participants performed 5 habituation trials by kicking the ball out to the field without any requirement for satisfying constraints of height clearance or target accuracy. Thereafter, all participants performed 10 trials kicking to T1. Subsequently, participants performed another 5 trials each to T5, T6 and T7 in a randomised order, completing a total of 25 test trials for the pre- and post-test sessions. The 10 trials to T1 provided an indication of the coordination of the kicking action and the 15 trials to T5, T6 and T7 were used to identify whether novices could vary kicking foot velocity to achieve the task goal under the different height and distance constraints (see also Chapter 4 and Chow, Davids, Button & Koh, 2006). Participants were allowed to rest as needed between trials, with intervals ranging between 10 to 30 seconds in duration. Each test session took between 45 and 60 minutes to complete. Pre- and post-test sessions were separated by a 4-week practice phase.

ii) Practice Sessions

Participants performed the warm up routine as in other sessions prior to practicing 10 kicking trials each to T1, T2, T3 and T4 (a total of 40 trials per session) in a randomised order. All novice participants underwent a 4-week practice phase with three sessions per week (a total
of 12 sessions). In addition, they were required to perform an additional 15 kicking trials to T5, T6 and T7 (5 trials to each position) in a randomised order at every second session (i.e., at the 2nd, 4th, 6th, 8th, 10th and 12th practice session) (see Chapter 4). In total, all participants performed 570 trials during the practice phase. Rest intervals between trials were similar to the pre- and post-test sessions and each practice session took between 60 to 90 minutes to complete.

5.3.4 Data Analysis

i) Performance Outcomes

Performance of the kicking task was assessed by how accurately and effectively weighted the chipped passes were to the receiver’s feet. Outcome scores were determined from a 7-point Likert rating scale, with emphasis on accuracy and ease of ball reception (see Chapter 2 for information on the scoring scale). Means and SDs of individual participants’ performance outcome scores are presented only for trials selected for kinematic analysis.

ii) Joint Range of Motion for Cluster Analysis

Joint range of motion data was collected and used in a cluster analysis procedure to determine categorisation of movement patterns for individual participants (the use of cluster analysis will be further elaborated in the follow section). Specifically, joint range of motion data for the hip, knee, ankle for the kicking and non-kicking limbs as well as trunk (angle between pelvis and thorax segments) and trunk lean (angle between the thorax segment and the horizontal plane) (°) were collected for the duration of the limb movement sequence beginning 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 Chapter 4). After visual inspection, data were filtered using a low pass Butterworth digital filter with the Visual 3D software at frequency 7Hz. All trials were normalised to 100 data points between the start event (initiation of knee flexion) and end event
(peak hip flexion) with movement time normalised to allow for simultaneous comparison across individuals and trials. Only selected practice trials were chosen for analysis within each practice session. Specifically, 18 trials per session were analysed for kicks to T1, T2, T3 and T4. Distribution of the selected trials for analysis was the same as in Chapter 4.

**iii) Cluster Analysis and Validation**

Cluster analysis is a technical method for exploring complex data sets where little information is available about the underlying distribution and is also viewed as an effective tool in identifying ‘natural’ group structures in the data (Duda, Hart, & Stork, 2001; Everitt, 1993; Hastie, Tibshirani & Friedman, 2001; Kaufman & Rousseeuw, 1990). The procedure for undertaking the cluster analysis can be described in Figure 5.2. Pre-processing (Step 1) was completed mainly with MATLAB (version 7.0.1) and the subsequent cluster analysis (Step 2) and validation (Step 3) was determined through the R software (version 2.3.1).

Following the methods used by Schöllhorn (1998) and Jaitner, Mendoza and Schöllhorn (2001), a cluster analysis approach was used in order to determine preferred movement patterning. Hip, knee and ankle joint range of motion data for kicking and non-kicking limbs as well as trunk and trunk lean angles were selected as input variables during the pre-processing stage as these 8 variables are observed to be the most relevant in describing the kicking movement. Based on previous work (e.g., Lees & Nolan, 2002) it was expected that differences between kicking patterns would emerge by comparing these selected variables. The angles were time normalised and a matrix for each trial was obtained (see Jaitner et al., 1998). Differences between trials were calculated using the Euclidean distance. The AGNES clustering algorithm in R software (version 2.3.1) was used to construct a tree-like (dendrogram) hierarchy of clusterings of k clusters (where the most suitable value of k is subsequently validated through cluster
validation techniques). A dissimilarity measurement was constructed with the DAISY function in the R software where the dissimilarity between clusters was calculated using the ‘average’ linkage method (see Kaufman & Rousseeuw, 1990).

**The cluster analysis procedure involved three steps. The first step involves the selection of the appropriate kinematic variables relevant for a soccer kick. Normalisation of the variable input was undertaken and subsequently exported to the R software. In step 2, a distance function was used to determine dissimilarity indices between trials for the purpose of administering a hierarchical clustering algorithm. Step 3 involves a multi-scale bootstrap resampling technique and the calculation of a validity index to determine the appropriate number of clusters to be partitioned from the hierarchical clustering dendrogram. The results of a cluster analysis may be affected by the decisions made in the first two steps and the information on the information on the quality of the partitioning can therefore be used to revise these decisions. (adapted from Handl, Knowles & Kell, 2005)**

**FIGURE 5.2. Cluster analysis procedures for current study**

The clustering distribution presented was validated using the multi-scale bootstrap resampling procedure developed by Shimodaira (2002, 2004) in the R software (pvclust R package). This method is applicable to a large class of clustering problems including hierarchical clustering (Suzuki & Shimodaira, 2004), providing an indication of how strong a cluster is supported by the data set. Accuracy of the probability of valid clustering was measured with
alpha values ranging from 0 to 1. For example, if the alpha value of a cluster was recorded as $p=0.90$, it would indicate that there was a 10% chance that the clustering of data under the particular cluster occurred due to chance. The convergence of the bootstrapping procedure was assessed by investigating the standard errors of the p-values.

Further, the Hubert-$\Gamma$ statistic which gives an indication of the partitioning that best fits a given data set (Halkidi, Batistakis & Vazirgiannis, 2002) was used to validate the cluster results. In the plot of a Hubert-$\Gamma$ statistic validity index versus $n$ number of clusters, a significant ‘knee’ that corresponds to a significant increase of the validity index can be found. The number of clusters at which the knee occurs is an indication of the number of clusters that occurs in the data. The Hubert-$\Gamma$ coefficient calculated from the R software using the fpc package, has been shown to be simple, precise and robust (see Zhao, Liang & Hu, 2006) and was used to determine the optimal number of clusters.

**iv) Cluster Movement Switch Ratio (SR)**

Cluster movement switch ratio (SR) provides an index on the preferability of a movement pattern and is defined as the number of switches¹¹ divided by the maximal possible number of switches within a practice session (adapted from Wimmers, Savelsbergh, Beek & Hopkins, 1997). For example, in a first session of four-cluster movement C1 and four-cluster movement C2, i.e., C1C1C1C2C2C2C2, the SR would be 1:7 (or 0.143). In contrast, for the second session C1C2C1C2C1C2C1C2, the SR would be 7:7 (or 1) even though the percentage of occurrence is 50% in both sessions.

---

¹¹ A switch is possible between any two neighbouring trials. For example, in a series of three trials, the maximum number of switches would be two.
v) **Indicators for Change between Preferred Movement Clusters**

In this study, a change from one cluster (e.g., C1) to another cluster (e.g., C2) was deemed to be present when both clusters occurred in at least 14 out of 18 (78%) trials in their respective sessions. In addition, a switch ratio (SR) of not more than 0.235 (4:17) has to be present for those 18 trials within their respective session for a cluster to be considered as a ‘preferred’ movement cluster in that session. Thus, SR $\leq 0.235$ with $\geq 78\%$ occurrence for a particular cluster will have to be observed for it to be categorised as a ‘preferred’ movement cluster. The rationale for these quantitative indicators was based upon subjective analysis of pilot data in the lack of any other relevant research applying the same cluster technique with a similar movement model.

vi) **Indicators for Increasing Variability in Movement Clusters within a Session**

After work by Wimmers et al (1997), it was decided that an increasing switch ratio would signal increasing variability in movement clusters within a session. Similarly, a low or decreasing switch ratio would indicate decreasing variability in movement clusters in a session.

5.4 Results

5.4.1 **Performance Outcomes**

Performance scores to T1, T2, T3 and T4 were captured for 18 trials per session. All participants demonstrated a general increasing trend in performance scores from practice session 1 to session 12 although the scores did not always exhibit an ascending trend from one session to the next session (see Figure 5.3). It was common to observe how performance scores could regress over a few sessions before achieving a higher score in the later sessions (e.g., participant CL from sessions 4 to 6). Nevertheless, there were significant differences between pre- and post-test performance scores for all participants at $p \leq 0.05$. See Figure 5.3.
Cluster analysis was performed on the practice trials for each participant and an intra-individual analysis was undertaken to examine within-participant changes in movement clusters as a function of practice. Results relating to cluster analysis, cluster movement switch ratios, indicators for change between preferred movement clusters and indicators for increasing variability in movement clusters were presented at an intra-individual level in the subsequent subsections.

**Participant YH**

The Hubert-$\Gamma$ index indicated that 7 clusters (with the highest index of 0.6005) would most accurately reflect the number of movement patterns established from the dataset of
participant YH. See Figure 5.4. However, from the multi-scale bootstrap re-sampling procedure (Shimodaira, 2002, 2004), when 7 clusters were included in the dendrogram, cluster 7 exhibited an alpha value of only 0.58. When 6 clusters were constructed, the alpha value rose to 0.74 and above (see Figure 5.5). So, a 6-cluster dendrogram was constructed because it provided a more accurate clustering representation of the data set based on the multi-scale bootstrap procedure (see Figure 5.6). It was observed that standard error for the alpha values was generally low for most clusters between approximately 0.00 and 0.05 (see Figure 5.7) which indicated that the values within the dendrogram were reliable.

FIGURE 5.4. Cluster validation Hubert-Γ index for Participant YH
FIGURE 5.5. Multi-scale bootstrap resampling for Participant YH. Numbers represent the p-values for the cluster of trials under the respective branch in the hierarchical dendrogram. Lowest p-value at 0.74

FIGURE 5.6. Dendrogram with cluster partition for Participant YH. Numbers represent clusters
FIGURE 5.7. p-value vs standard error plot for Participant YH. Each dot in the plot represents one trial. From the figure, it can be seen that most of the trials have $p > 0.7$ and SD near to 0.00

To highlight differences between movement clusters, cluster 1 and 2 (which are the major clusters of trials for YH) were compared. Means were determined for all trials within the respective group of clusters and plotted to ascertain differences (see Figure 5.8). One key difference between cluster 1 and 2 relates to joint motion about the kicking knee (i.e., right knee for participant YH). Specifically, cluster 2 has a higher range of motion about the right knee and knee extension occurred later in the kicking movement when compared to cluster 1. See Figure 5.8.
Figure 5.8 shows the distribution of movement clusters for individual trials as a function of practice sessions for participant YH. It can be observed that participant YH used mainly cluster movement C1 in session 1 before exploring four different movement patterns (C1, C2, C4...
and C5) in session 2. Increasing variability, expressed in the number of movement clusters used, was observed within sessions 2 (SR=0.529) and 3 (SR=0.412). Cluster C6 was preferred at session 4 (SR=0.11, 94% occurrence).

Similarly, increasing variability in movement clusters within session 5 (SR=0.471) was observed before C2 appeared to be preferred at session 7 (SR=0.118, 94% occurrence) (Although variability of C2 at session 6 was lower than session 5 [SR=0.353, 78% occurrence], it was still higher than at session 4). Thereafter, C2 was continually the preferred movement cluster from sessions 8 to 12 (SR=0.235, 88% to 100% occurrence). From the results, some features of pattern transitions were observed in movement clusters between sessions 1 and 4 as well as between sessions 4 and 7. Specifically, increasing variability in movement clusters prior to a change to a preferred movement cluster was clearly evident in participant YH (e.g., from C1 to C6 and C6 to C2 respectively).

FIGURE 5.9. Distribution of movement clusters over practice sessions for Participant YH
Participant KL

Hubert-Γ index indicated 8 clusters to be most appropriate and when referenced to alpha values for the respective clusters (see Figure 5.10 and 5.11), the dataset accurately reflected the clustering of trials in respective clusters since the alpha values were at least $p \geq 0.79$.

![Cluster Dendrogram with Alpha Values (%) (KL)](image)

**FIGURE 5.10.** Multi-scale bootstrap resampling for Participant KL
Cluster C1 was mainly used by participant KL in session 1 before alternating between C1 and C2 in session 2 (see Figure 5.12). The use of C3 appeared in session 3, but the switch ratio was higher for the session (SR=0.471) before reverting back to the preferred movement cluster of C1 in sessions 4 (SR=0.056, 94% occurrence) and 5 (SR=0.235, 89% occurrence). Increasing variability in the use of movement clusters was observed in session 6 (SR=0.706) before the re-emergence of C2 as the preferred cluster in session 7 (with SR=0.235, 89% occurrence). From sessions 7 to 12, mainly C1 and C2 were present. Higher variability was observed in session 8 (SR=0.529) and session 12 (SR=0.588). Although there was higher variability in the movement clusters used in session 8, C1 was still the preferred movement cluster from sessions 9 to 11.
Similar to participant YH, evidence of increased movement pattern variability prior to a transition between movement clusters was observed for participant KL. Certainly, a higher variability of movement clusters was observed at session 6 (SR=0.706) during the transition between C1 (in session 5) and C2 (in session 7). However, there were also instances when a higher variability of movement clusters did not result in a change from one preferred movement cluster to another (e.g., in session 3 and session 8 with SR=0.471 and 0.529 respectively).

**Participant CL**

Hubert-I coefficient indicated the presence of 12 clusters with alpha values of, $p\geq 0.82$. See Figures 5.13 and 5.14.
FIGURE 5.13. Multi-scale bootstrap resampling for Participant CL

FIGURE 5.14. Dendrogram with cluster partition for Participant CL
There was higher movement cluster variability in session 1 (SR=0.412) before C1 appeared to be the preferred movement cluster in session 2 (SR=0, 100% occurrence). Subsequently, C7 was the preferred movement cluster from session 3 (SR=0.118, 94% occurrence) to 4 (SR=0, 100% occurrence) (see Figure 5.15). A sudden jump between movement clusters (C8) was observed in session 5 without a clear increase in variability between movement clusters prior to change in sessions 3 or 4. A change from C8 to C10 was further observed within session 6 with some suggestion of the presence of higher movement cluster variability. Thereafter, a switch back to C1 as the preferred movement cluster was present during session 7, followed by another switch to C6 within session 8. From session 9 to 12, C1 and C6 were the preferred movement clusters, alternating between those sessions.

FIGURE 5.15. Distribution of movement clusters over practice sessions for Participant CL

Interestingly, cluster C1 disappeared in early practice sessions before re-emerging at sessions 7, 10 and 12. Clearly, for participant CL, a non-linear progression of movement clusters was observed between practice sessions. There were even signs of ‘regression’ in the use of
movement clusters (e.g., using C1 during early and late practice sessions). However, the performance outcome score was higher at session 10 and 12 for C1 than at session 2. Although C1 was used in early and late practice sessions, the higher performance outcome attained by participant CL could be explained by the greater consistency of the movement at ball contact. Additional analysis for participant CL on foot velocity at ball contact appeared to be more consistent in sessions 10 (10.06 ± 0.39 m.s$^{-1}$) and 12 (9.58 ± 0.31 m.s$^{-1}$), compared to session 1 (10.04 ± 2.56 m.s$^{-1}$).

There was some evidence of higher variability of movement clusters within sessions, especially session 1 (SR=0.412) and 6 (SR= 0.471). But, in general, SR was low or close to zero for most practice sessions. Distinctive use of movement clusters was observed between sessions (e.g., session 2 to 3 and session 9 to 10) without any variability in the use of movement clusters within sessions. Other than the change from C8 (session 5) to C1 (session7), where higher variability of movement clusters was present in session 6 (SR=0.471), participant CL did not demonstrate a clear trend in variability of movement clusters within sessions in effecting change from one preferred movement cluster to a new preferred movement cluster.

Participant AD

From the Hubert-Γ coefficient, presence of 10 movement clusters was determined. However, alpha values from the multi-scale bootstrapping procedure were not as high as for other participants being only 0.57 at one of the major branches in the clustering tree. This finding suggests that clusters belonging to that branch may not have been a true clustering of trials since the observed sub-clusters may not have been different. It was then determined based on the need to accept higher alpha values (where p=0.94 in this dendrogram), that 3 clusters would be a more accurate clustering of the dataset. See Figure 5.16 and 5.17.
Cluster method: average
Distance: euclidean

FIGURE 5.16. Multi-scale bootstrap resampling for Participant AD

FIGURE 5.17. Dendrogram with cluster partition for Participant AD
For participant AD, mainly one cluster of movement was used throughout the practice phase in this study. There was no evidence of any variability of movement clusters within or between practice sessions. See Figure 5.18.

![Figure 5.18](image-url)

**FIGURE 5.18. Distribution of movement clusters over practice sessions for Participant AD**

5.5 Discussion

The aim of this paper was to investigate learning of discrete multi-articular actions in neurobiological systems by examining a) the presence and characteristics of change between preferred movement clusters during the acquisition process and b), the presence of increasing variability in movement pattern clusters used prior to a change in preferred movements during practice. To summarise the main findings, all participants showed evidence of change between preferred movement clusters and higher variability in the use of movement clusters within a session except for participant AD. Data showed that participants YH, KL and CL evidenced change between preferred movement clusters and high variability of movement clusters within sessions. One participant showed clear evidence of variable movement clusters within sessions
prior to a change in preferred movement clusters, and two others showed mixed trends in this feature of learning. However, there were instances when increasing variability in movement clusters was not accompanied by transition from one preferred movement cluster to another. Moreover, distinct changes in different movement clusters between two neighbouring practice sessions, without the presence of any variability in movement clusters in either of the two sessions, were sometimes observed (participant CL). One participant showed little evidence of movement pattern exploration during practice (participant AD), failing to show preferred movement cluster changes, as well as variability in movement clusters used within or between sessions. A general improvement in performance was observed for all participants as a function of practice although regression of performance scores over some sessions was commonly seen as well.

Participant YH showed clear changes between preferred movement clusters and presence of variability prior to acquiring a different movement cluster within sessions. Specifically, the presence of higher levels of variability highlighted the functional role of movement variability during exploratory practice. Findings from the current study when referenced to Liu et al’s (2006) study on learning a novel roller ball task also showed similarities in terms of the presence of increased variability prior to a change in movement patterns for successful learners. Variability in movement clusters afforded flexibility and adaptability in exploring functional movement solutions when attempting to satisfy specific task goals (see also Riley & Turvey, 2002). These findings suggest that movement variability is an important mechanism for strategically developing new ways to solve coordination problems and that behavioural variability can also lead to the discovery and selection of new cognitive-motor strategies (Siegler, 2000; Summers, 1998). Observations of changes in preferred movement clusters following high variability of clusters used, supports the conceptualisation of motor learning as an exploratory process (see
It seems that movement stability has to be traded off to help learners discover new patterns of coordination and this was evident especially for participant YH. These behavioural trends were also observed to a lesser extent in participants KL and CL.

In the case of participant KL, there were occasions when high variability in movement clusters did not effect a change in preferred movement clusters in subsequent practice sessions. In this case, it was possible that the level of variability exhibited may not have been of sufficient magnitude to effect a change between preferred movement clusters. The absence of a transition to a new movement pattern even with increased variability can still be seen as reflection of exploratory behaviour. However, from a dynamical systems perspective, only a local search was conducted around the original preferred movement pattern that did not result in a successful assembly of a new movement pattern in the epigenetic landscape (Liu et al., 2006). It is notable that the Switch Ratio (SR) in sessions where a change in preferred movement clusters followed in subsequent sessions, was higher than in sessions where a subsequent change in preferred movement cluster failed to occur (e.g., SR=0.706 for session 6 compared to SR=0.471 and 0.529 for sessions 3 and 8). These suggestions require further investigation.

A lack of variability in movement clusters within sessions was also observed for participants CL and AD. It was possible that intentions and informational constraints in meeting the task goal had an impact on the nature of change in the movement clusters shown by participants CL and AD. For participant CL, distinct movement clusters occurred mainly between sessions and very little variability in movement clusters was observed within each session. From the strip-plots between movement clusters and practice sessions, it seems likely that participant CL could have selected a movement strategy based on experiences from the previous practice session(s). Participant CL could have reflected on new and different cognitive strategies for
different sessions to get the ball over the height constraints towards the live receiver, resulting in intentional constraints actually overriding the existing coordination dynamics of the learner. The role of behavioural information in practice deserves further investigation since such information from the task and from previous practice sessions/trials might have influenced the coordination patterns used for subsequent sessions (Button et al., 1998). Elsewhere, it has been acknowledged that the pathway of coordination changes is dependent on the task goal (Ko et al., 2003; Newell & McDonald, 1994). Information in the form of feedback or instructions shapes the intention of the learner and these influences are important in helping us understand how coordination solutions evolve and how the task goal helps to direct learners towards specific movement behaviours (Jirsa & Kelso, 2004). Further investigation is required on the role of intentions, possibly incorporating some qualitative examination of the self-reported cognitive strategies used by the participants during learning, especially for discrete multi-articular actions.

For participant CL, ‘insight learning’ which is characterised by abrupt transition between preferred movement patterns, may have occurred. Although Nourrit et al (2003) suggested that such abrupt transition of movement patterns as described in bimanual finger coordination studies may be infrequently observed during complex skill acquisition, the role of intentional constraints could be a key factor in influencing abrupt emergence of new preferred movement patterns during the skill acquisition process. Undoubtedly, it is clear that learning is an intentional process with future goals determining the changes a learner undergoes. In this study, there were two main intentional constraints, a) one specifying the goal of the action (e.g., getting the ball over the bar) and b) another specifying the goal of learning (i.e., become more skilled) (see Schmidt & Fitzpatrick, 1996). So, learning should also be viewed as a process of searching the important constraints on performance, including those arising from task specificity and the interaction between physical and informational constraints (Rosengren et al., 2003). For participant CL, a
nonlinear and sudden change between preferred movement patterns was established in some instances in the absence of high variability in movement clusters and this could have been the consequence of the influence of behavioural information available in the learning context.

It was also noted how regression to previously explored movement clusters occurred, especially in participant CL (cluster 1 in session 1 and also in session 12). Why regress to previous clusters of movement? Again, a likely constraint on motor learning could have been the specific intentions involved in the process of change in the use of movement clusters. Possibly, participant CL realised that there were certain features of movement solutions inherent in movement cluster C1 that might have been effective through exploration of the perceptual motor workspace during practice. Re-parameterising certain aspects of cluster movement C1 could be observed as an appropriate movement solution for participant CL in achieving the task goal by the end of the practice phase as seen by the improved performance outcome scores. Possibly participant CL had acquired better ‘control’ of the use of movement cluster C1 later in practice compared to using the same cluster in session 1, as evidenced by the more consistent foot velocity values at ball contact in the later practice sessions. Moreover, such an observation aligns to the idea of multiple time scales to learning suggested by Liu et al (2001) where the pathway of change in learning may not necessarily take on a power law function as commonly proposed in the motor learning literature (see A. Newell & Rosenbloom, 1981; Salmoni, 1989). More likely, the pathway of change in learning could take on a nonlinear direction where sudden jumps, regression or change described through exponential learning functions may be relevant. This further highlighted the nonlinearity in pathway of change as well as multiple-time scales in learning and such a proposition requires investigation in future studies.
Participant AD showed little change in the clusters of movement used and this lack of movement variability could have been an indication of the lack of effective exploration of the perceptual motor workspace. The lack of search activity was reflected through the absence of observed variability in the movement clusters used and was associated with a smaller rate of improvement in performance scores between pre- and post-test sessions for this individual. It is possible that the intrinsic dynamics of participant AD is deeply entrenched in a movement pattern that is inappropriate to meeting the present task goal. The lack of variability in movement patterns during the practice sessions suggests that the perceptual motor workspace is too stable and resistant to change. As a consequence, new and functional preferred movement patterns failed to emerge even with extended practice. This observation is similar to the findings in Liu et al. (2006), where no changes, either discontinuous or continuous were observed in movement dynamics adaptations for less successful learners, as apparent for participant AD in the present study. Future investigation could focus on how task constraints such as instructions, equipment and organisation of practice may alter the perceptual motor workspace of less successful learners to provide a learning context where stability of intrinsic dynamics of such learners may be reduced to allow new movement patterns to be established. See Chapter 6.

5.6 Conclusions

This study has shown that progression of learning is different for different individuals and is dependent on the interaction between the intrinsic dynamics of the learner and the task goal. The interaction between intentions and behavioural information were likely constraints on the specific motor learning trajectories observed for each individual. There was also some indication that high variability in movement clusters was present (not always though) prior to a change between preferred movement clusters. Compared to learning in bimanual finger coordination tasks, the target pattern is unlikely to be immediately available in discrete multi-articular actions,
because the pathway of change during learning is not easily predictable. Degeneracy, where different functional coordination solutions are possible for the same task demands (see Hong & Newell, 2006), is omni-present learning multi-articular movements, requiring some exploratory behaviour during the motor learning process. Coupled with the role of informational constraints and intention of the learners, the emergence of movement behaviour can certainly take different pathways of change during learning. Data from this study suggested that observing the nature of changes during practice might reveal insights into how movement variability can be used for adapting and refining complex multi-articular discrete actions when learning.
## CHAPTER 6

Epilogue

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6.1 General Introduction

The purpose of this concluding chapter is to present briefly an overview of key findings from the current PhD thesis. Specifically, a discussion on the implications for theory as well as experimental designs will be shared. The chapter then concludes by examining the relevance of this research for physical education pedagogy, thereby providing an appropriate reflection of my passion and background as a physical educator. Particularly, a pedagogy perspective (Nonlinear Pedagogy) based on concepts from nonlinear dynamics will be presented as a case to support a popular games teaching approach (i.e., Teaching Games for Understanding commonly known as TGfU) in physical education.

6.2 Key Findings and Implications

6.2.1 Degeneracy in Coordination Changes

A general theme across the empirical chapters (especially Chapters 3 and 4) in this programme of work is the discussion on degeneracy. The concept of degeneracy was continuously evident in the series of empirical studies conducted especially illuminated through individual participant analysis.

In Chapter 3, where coordination of skilled players was investigated, it was shown that elite performers demonstrated refined differences in coordination patterns to achieve the same task goal. Specific differences in COM displacement characteristics nearing ball contact and foot to ball position highlighted some of the individual variations in attaining high performance outcome scores. For example, a side foot chipping technique (a hybrid of the drive and the chip) was observed in one of the skilled players, which further consolidated the suggestion that a common optimal movement pattern for any given task is often a deceptive perception (Brisson & Alain, 1996).
Further empirical investigation on learning the multi-articular soccer chipping task as a function of practice (see Chapter 4) highlighted the different learning routes taken by individual performers. These individualised pathways became clear from the angle-angle plots as well as changes in the involvement of dof over the sessions. The proposed universal trend of ‘reducing to increasing’ involvement of dof with practice (Bernstein, 1967) was certainly absent across the novice participants. Specifically, no common trends in the involvement of dof were observed for the novice participants over practice sessions even with similar levels of improvement in performance scores. It was particularly interesting to observe how comparable performance outcome scores could be attained with different coordination patterns by the end of the practice phase in the study. From Chapter 4, it was determined that a scooping technique demonstrated by participant CL was as effective in meeting the task goal as compared to other participants (particularly KL and YH). The exploration and search for a functional movement solution cannot be pre-determined and certainly could take on different pathways of change, highlighting the concept of degeneracy among novice participants. Moreover, it was suggested that changes in coordination are determined to a great extent by the interaction of the task dynamics and the original intrinsic dynamics of each individual learner. This was evident from the example of participant CL where the initial driving and lifting movement pattern appeared to be adapted resulting in the eventual emergence of a scooping technique not seen in the other novice participants (see Chapter 4).

Certainly, the current research has established a basis for further work in exploring the role of intrinsic dynamics for discrete multi-articular actions such as the soccer chipping task. Future work could focus on mapping or scanning the intrinsic dynamics of the individual learner and examine changes to those dynamics after an intervention learning phase. This is especially
important to further test the concept of intrinsic dynamics and their interaction with the task constraints in shaping an altered perceptual-motor workspace (Thelen, 1995; Thelen & Smith, 1994). The concept of degeneracy can then be further investigated in relation to different pathways of change in intrinsic dynamics as a function of learning.

Although learners appear to demonstrate the concept of degeneracy (e.g., Hong & Newell, 2006; Liu et al., 2006), the selection of the research task plays a pivotal role in terms of how this phenomena can be observed. Certainly, in the present programme of work, different pathways of change can be more observable especially when the task has a performance goal that is not measured directly by the form of the movement as in a ski-simulator learning task (e.g., Vereijken et al., 1992). A discrete multi-articular action involving indirect performance measurements provides an ideal research vehicle to examine coordination changes. The use of the soccer chipping task from this programme of work has clearly provided a basis for a series of empirical research studies examining degeneracy. For example, do humans acquire degeneracy more effectively in certain practice conditions (e.g., variable compared to constant practice)?

A further experimental implication is the recognition that a research design using multiple-single participant analysis provides the necessary approach to investigate the concept of degeneracy. Clearly, from Chapters 3, 4 and 5, a multiple-single participant analysis was able to highlight individual differences and variation in coordination changes, which would probably have been masked by averaging data if a group analysis was to be undertaken.

6.2.2 A Dynamical Systems Perspective to Understanding Learning

One of the aims of this PhD programme of work was to examine the acquisition of movement skills from the perspective of dynamical systems theory. The underlying argument
about learning in a dynamical systems perspective is the nonlinearity in the process of acquiring coordination. As discussed in Chapter 1, learning a new skill is viewed as the transition from one stable state organisation towards another (Beek & van Santvoord, 1992; Mitra, Amazeen & Turvey, 1998; Schöner et al., 1992; Zanone & Kelso, 1992). The emergence of a new movement pattern is seen as a consequence of the interaction among the variables in the learning context and encompasses a change in the intrinsic dynamics of the learner as well (Huys et al., 2004). Furthermore, an increase in movement variability prior to a change in preferred movement patterns allows for adaptability and flexibility in the search for functional movement solutions (Riley & Turvey, 2002).

Data from Chapter 5 in particular, provided suggestions that a transition between preferred movement patterns can be observed as a function of learning. However, an important feature was that the change between preferred movement patterns can occur in the presence or absence of increased variability in the movement patterns. The absence of a clear trend across participants in relation to variability and transitions between movement patterns while meeting the task goal also highlighted the role of degeneracy. It was further concluded that informational as well as intentional constraints could play a pivotal role in effecting (or suppressing) transitions between movement patterns. While increased variability in relative phase has been observed prior to transitions in rhythmical tasks (e.g., Haken et al., 1985), the task used in this programme of work could also have an influence on the requirement for critical fluctuations. It is possible that the trial based nature of the learning task in this doctoral programme allows informational and intentional constraints to greater impact learner’s movement dynamics during learning. Certainly, the influence of informational and intentional constraints demands more investigations for discrete multi-articular actions. Nevertheless, this PhD thesis has provided the platform for
further research to examine the underlying processes in transitions between preferred movement patterns and the role of variability in effecting such changes over an extended period of practice.

In terms of experimental implications for data analysis, the use of clustering procedures has provided a more objective approach in examining transitions between preferred movement patterns. This doctoral programme of work has advanced the work conducted by Schöllhorn (1998) and Jaitner et al (2001), providing the necessary tools to identify clusters of similar and dissimilar movement patterns. Particularly, advancement in the use of quantifiable and valid bootstrapping procedures using techniques acquired from the R software (version 2.31) in this programme of work have ensured that the cluster analysis procedures were reflective of the perceived changes in movement dynamics seen in individual learners. This extended analytical technique then allows the examination of changes between preferred movement patterns to be undertaken with greater confidence in future studies investigating learning from a dynamical systems perspective.

6.2.3 Contributions to Newell’s Model of Learning

Findings in the present programme of work have helped to enhance the description of Newell’s three stages of learning model. Newell’s model focuses on examining coordination changes unlike other model of learning (see Chapter 1) and this provides a suitable platform to better investigate the degrees of freedom problem as well as its’ relevance to learning. In this thesis, the guiding framework of Newell’s model was referenced to examine concurrent changes to performance outcome with alteration in coordination both as a function of skill (Chapters 2 and 3) and practice (Chapter 4). Specifically, the challenge to vary higher order variables like foot velocity at ball contact to target positions with different height and accuracy constraints has provided an effective testing context to examine the progress from the Coordination to Control
stages of learning as described by Newell (1985) for this kicking task. Moreover, the kicking task provides opportunity to examine intra-limb coordination changes pertaining to modification of dof involvement as a consequence of practice. This is relevant for investigating progression from early to later stages of learning as proposed by Newell (1985) and it was highlighted in this PhD programme of work that Coordination and Control stages can be embedded within each other. It was also found that learners were able to refine the kicking parameters to achieve the task goal in the empirical work. Moreover, decrease in movement variability (e.g., NoRMS) concurrent with improvement in performance scores and utilising functional foot velocity at ball contact were accomplished through varying levels of joint involvement for learners as they progress through the earlier stages of learning (see Chapter 4).

However, more attention is needed to build on the model especially in relation to describing the features of the ‘Skill’ stage of learning. Ideas of determining reactive torques through the use of inverse dynamics procedures to investigate optimising reactive forces in the kicking limbs to generate a functional movement outcome could be indicative of learners acquiring the Skill stage of learning (see Chapter 2). And clearly, whilst 570 practice and test trials were provided in Chapter 5, a longer extended period of appropriately structures practice would also be required to possibly enable a progression towards this advanced stage of learning.

**6.2.4 Task Space and Solution Manifold**

The concepts of task space and solution manifolds have provided a useful theoretical scaffolding to describe how learners seek effective movement patterns. In Chapter 2, plots within a solution manifold represented the combination of variables (angle, direction and velocity of ball trajectory) that contribute to the performance outcome. It was shown how exploration of the solution manifold differed as a function of skill level, especially between skilled and novice
participants. In addition, these were useful concepts to examine how differences in the acquisition of solution manifold between different skilled participants can be referenced to differences in coordination. It was concluded from Chapter 2 that both the skilled and intermediate participants demonstrated a chipping action (stabbing at the bottom of the ball with little follow through) while the novice participants were driving the ball (contacting the middle of the ball with follow through). From the ball trajectory plots in the solution manifold, it was determined that the novice participants were not able to generate adequate angle of trajectory, thus resulting in few trajectory plots located within the solution manifold.

Further investigation on how novice learners explore task space and solution manifold while relating to the changes in coordination would bridge the gap between examining coordination changes and performance outcome indicators. It would be interesting to investigate how ball trajectory plots shift within the task space into the solution manifold over practice trials. Technically, an interesting question is: can a simulation of task space and solution manifold be modelled for the soccer kicking task for different target positions? And theoretically, would the trajectory plots be located within a region in the solution manifold that has greater task tolerance (and therefore allows a larger margin of variability of the plots) but yet could still be successful at achieving the task goal? Could degeneracy be expected across different individual learners in the acquisition of ball trajectory plots as a function of practice? Last but not least, how will ball trajectory plots within the task space and solution manifold change for incrementing target distances or height constraints? These are just some of the few questions that require further investigation and the present PhD programme of work has provided a starting point.
6.3 Practical Implications for Physical Education

6.3.1 Teaching and Learning: A Case for Nonlinear Pedagogy

A key aim of empirical research is to inform practitioners about the theoretical support for practice. And, one of the final aims of this thesis is to propose a pedagogical approach, Nonlinear Pedagogy, which is based on the concepts from dynamical systems theory. Below, discussion on the relevance of Nonlinear Pedagogy will be highlighted as evidenced by some of the key research findings in this current programme of research.

In the past decades, dynamical systems theory has provided a theoretical stimulus for understanding movement behaviour, as well as the role of decision-making behaviour, intentions and cognitions on motor performance (Carson & Kelso, 2004; Davids, Williams, Button, & Court, 2001; Jirsa & Kelso, 2004). Prominent ideas from dynamical systems theory have also been allied to concepts of ecological psychology (Gibson, 1979) to understand how movements are coordinated and controlled with respect to dynamic environments like sport. And from Chapter 1, it has been clear that a systems perspective has been actively adopted to characterise neurobiological systems as complex, dynamical entities, revealing how the many interacting parts of the body are coordinated and controlled during goal-directed movements (Bernstein, 1967). It is well established that patterns emerge between parts of dynamical movement systems through processes of self-organisation ubiquitous to physical and biological systems in nature (Davids, Shuttleworth, Araújo, & Renshaw, 2003).

Understanding the emergence of behaviour as a consequence of the interaction between the performer, task and the environmental constraints in a learning context is central to the Nonlinear Pedagogy framework (see Chapter 1). Within the current programme of work, novice learners were able to discover for themselves a functional movement solution when challenged to
project a ball over a height barrier to different target positions in the absence of specific instructions on possible effective techniques (see Chapter 4 and 5). Recall that novice participants were only informed of the task goal through a short video clip showing the last few frames of ball flight to the live receiver. The emergence as well as change in coordination demonstrated by the novice learners was a consequence of the interaction among the constraints in the learning context. Particularly, it was evident through improvement in performance scores over practice sessions that the presence of key task constraints (i.e., height and distance) channeled the exploration of movement solutions to meet the task goal without need for explicit instructions or feedback.

It was also suggested how intrinsic dynamics of the learner (i.e., performer constraints) interacted with a range of task constraints (e.g., information and intention) to effect individualised movement patterns as (see also Chapters 3, 4 and 5). Key ideas emanating from Nonlinear Pedagogy are therefore very relevant to the concept that neurobiological systems are able to exploit surrounding constraints to allow functional, self-sustaining patterns of behaviour to emerge in specific contexts. Interest has focused on the transitions between different preferred patterns as a consequence of the interaction between different constraints in a system. The type of order that emerges is dependent on initial conditions (existing environmental conditions) and the constraints that shape a system’s behaviour. Empirical investigation from Chapter 5 highlighted how learners could demonstrate one preferred movement pattern before discovering another, more functional, movement pattern. The role of movement pattern variability in assisting exploration of functional movement solutions was also examined and there were certainly some suggestions that it can assist learners in acquiring effective movement solutions although it may not be pre-requisite for learning. The presence or absence of variability in the movement pattern
prior to a preferred change may be dependent on the class of movement action (i.e., discrete or continuous) and even informational as well as intentional constraints.

In brief, a few key empirical findings have surfaced from the PhD thesis that builds on the Nonlinear Pedagogy approach to teaching and learning. Constraints in the learning environment should be manipulated to guide learners explore functional movement solutions. It is valuable for practitioners to understand that there are different pathways to successful learning and the manipulation of the relevant constraints is an important teaching strategy to allow such goal-directed behaviour to emerge. While movement variability may often be seen as noise, the presence of variability in movement should not be discouraged as the learner may benefit from the increased flexibility and adaptability that movement variability offers for exploring new functional movement solutions. In the following section, the relevance of Nonlinear Pedagogy will be exemplified by discussing its appropriateness as a theoretical underpinning for an increasingly popular pedagogical approach in teaching movement and game skills in physical education.

6.3.2 Nonlinear Pedagogy as a Theoretical Basis for a Games Teaching Approach (Teaching Games for Understanding)

Teaching Games for Understanding (TGfU) has emerged as a popular approach for games teaching in physical education for the last two decades (Griffin & Butler, 2005). The TGfU approach was originally developed because of dissatisfaction with how motor skills were taught in schools in the early 1980s. Traditional approaches were viewed as being technique dominated, following a series of highly structured lessons in which a list of movement skills was sequentially taught to groups of learners (Werner, Thorpe & Bunker, 1996). However, the important focus of TGfU is to design learning experiences for individuals to acquire tactical skills of the major
games through playing modified versions of a target game, considered suitable for their physical, intellectual and social development.

Unlike some traditional approaches to teaching games, TGfU has a student-centred emphasis for learning tactics and skills in modified game contexts (e.g., Griffin, Butler, Lombardo & Nastasi, 2003; Hopper, 2002). A TGfU practice session typically begins with mini-games encouraging students to think about a targeted tactical problem, such as dribbling past defenders. The modified game usually results in equipment, the playing area or rules being adapted to constrain understanding of learners towards the targeted tactical concept. The introductory game is followed by presentation of questions and explanations by the teacher on how tactics may be used in the modified game. Performance is assessed by observing the outcomes of decisions as they are executed by learners during game play (Turner & Martinek, 1999). In summary, the main stages for TGfU are (a) Teacher sets up game form, (b) teacher observes play or practice, (c) teacher and students investigate the tactical problem and potential solutions (game-related practices), (d) teacher observes play, (e) teacher intervenes to promote skill (if necessary), and (f) teacher observes the game and intervenes to teach.

However, the TGfU approach currently lacks a sound theoretical underpinning to explain the processes for its relative efficacy as a pedagogical approach. Nonlinear Pedagogy, with its basis on dynamical systems theory, can however provide the theoretical grounding for a nonlinear approach to pedagogy in physical education (Chow, Davids, Button, Shuttleworth, Renshaw & Araújo, 2006). Specifically, the great flexibility with which the central nervous system organises motor system dof into functional coordination patterns can indicate why TGfU is effective (Chow, Davids, Button, Shuttleworth, Renshaw & Araújo, 2006). Particularly relevant to TGfU, the interaction of the task, performer and the environment provides the
‘boundaries’ for an individualised goal-directed behaviour to surface and this dynamic interaction between the constraints in the learning context is inherent in situational games in a TGfU lesson. A major implication of a Nonlinear Pedagogical perspective on motor learning suggests that a key aim of games teaching in physical education is for learners to become attuned to the relevant properties that produce unique patterns of information flows in specific environments. Since flow patterns are specific to particular environmental properties, they can act as invariant information sources to be acquired by individual performers to constrain their actions (Davids & Araújo, 2005). The use of task constraints and specifically, informational constraints in TGfU will allow learners to successfully couple their movements to critically important information sources in specific contexts, similar to how the novice learners in Chapters 4 and 5 explore kicking actions to project the ball over the height barrier. Learners can attune their movements to essential information sources available through practice, thus establishing information-movement couplings that can regulate behaviour (Jacobs & Michaels, 2002). For example, in a striking and batting game like baseball where the tactical problem in a TGfU lesson could be ‘Stopping Scoring’, outfielders will need to develop effective information-movement couplings by successfully perceiving positional and timing information of ball flight and coupling with appropriate movements to make a successful catch.

It is also important to note that the interacting nature of key constraints shapes the emergence of motor behaviour in the form of actions, intentions and decisions. The presence of task constraints does not influence the emergence of a decision to act per se, but determines how the specific intentions of a performer and information-movement couplings interact to allow a functional movement pattern to emerge in a modified game context (Araújo, Davids, Bennett, Button & Chapman, 2004). It seems that a rich mix of structural, task and intentional constraints interact to shape the emergence of stable, coordination modes, a finding that has strong
implications for learners needing to use equipment in performance (e.g., rackets, oars, balls and bats).

The constraints-led perspective based on the tenets of Nonlinear Pedagogy could provide further insights into how sports expertise is acquired. Possession of superior knowledge, organisation of task-specific knowledge, superior recognition of patterns of play and effective perception of kinematic information are all reportedly characteristics of sports expertise (e.g., Abernethy, 1994). It is plausible that skilled games players are able to form effective information-movement couplings through appropriate practices that focus on presenting various task constraints that interact with performer and environmental constraints. Task specific actions that satisfy goal-directed behaviour could generally be seen as qualities of effective decision making, which could help in improving understanding of game tactics in TGfU.

The emergent characteristic of movement coordination also suggests that the existence of a common optimal motor pattern for performing a skill is a fallacy owing to the variability often observed in human motor performance (Brisson & Alain, 1996 and also see Chapter 3). Individuals can use the great abundance of movement possibilities offered by our body to vary the way in which they solve movement problems, and an optimal movement pattern for one individual may not be optimal for another in relation to a specific task goal (see also Chapters 3, 4 and 5). This idea contradicts many traditional approaches to teaching motor skills predicated on the notion of an idealised, common optimal motor pattern towards which all learners may aspire (often presented by demonstrations from an expert model). Rather, the concept of emergence under constraints emphasises the individualised nature of movement solutions as learners attempt to satisfy the unique constraints on them (Davids et al., 2001). Although similar movement patterns can be adapted and subsequently refined for motor performance, detailed analysis of
movement kinematics are revealing that the specific movement patterns employed by different individuals to achieve similar outcomes are not the same (Davids, Shuttleworth, Button, Renshaw & Glazier, 2003). Such an observation fits with the findings from Chapters 3, 4 and 5 which further highlights the role of degeneracy in understanding learning.

The functional role of movement variability expressed in Nonlinear Pedagogy also provides a strong theoretical fit with pedagogical claims on the efficacy of a TGfU perspective. It has been suggested that individuals find it extremely challenging to repeat a movement pattern identically across practice trials (Davids, Shuttleworth, Button, Renshaw & Glazier, 2003). Variability in movement patterns encourages exploratory behaviour in learning contexts, a feature of relevance when engaging in games for understanding. The paradox between stability and variability explains why skilled individuals are capable of both persistence and change in motor output during physical education (Davids, Shuttleworth, Button, Renshaw & Glazier, 2003). Certainly, this feature of human movement systems actually provides performers with the capacity to invent novel ways to solve typical motor problems and to adapt to the changing task constraints of modified games (such as a scoop-kick in soccer). For example, den Duyn (1996) observed that:

‘One of the interesting aspects of the game sense\textsuperscript{12} approach is that incorrect technique is not necessarily seen as a ‘bad thing’ that must be immediately changed. Many athletes use unorthodox techniques that still achieve the right result (and often bamboozle their opponent)’ (pp. 7).

\textsuperscript{12} The name given to the TGfU approach adopted in Australia.
However, this is not to say that coaches and physical educators allow ‘free play’ and hope that learners complete a set task/game situation in whatever way the learners deem appropriate! The teacher must consider the constraints within the learning environment so that an appropriate response can be used by the learner to achieve the desired learning outcome planned for the session. Below, a sample TGfU lesson will be described to emphasise the emergence of goal-directed behaviour as a consequence of manipulating task constraints.

Constraints that need to be satisfied by each learner and which may be manipulated by the physical educator in a typical TGfU lesson are outlined in Figure 6.1. In this lesson, the physical educator can provide a tactical problem to learners with an emphasis on ‘setting up to attack’ in a volleyball game (i.e., net-barrier game). Learners can be challenged to ‘decide’ when, where and how to set up an attack in the game of volleyball. In Figure 6.1, it can be seen that an introductory game presents an appropriate context for learners to explore how best to make an attacking hit into the opponents’ court (assuming that learners have previously learned how to ‘dig’ a ball in previous TGfU lessons).

Suitable task constraints can be manipulated to provide the necessary boundaries to encourage learners to execute an attack. For example, equipment constraints can be manipulated so that only badminton nets can be used which are lower in height than actual volleyball nets. In addition, specific instructional constraints can emphasise ‘playing the ball towards an opponent by contacting the ball above your head’, encouraging learners to ‘set’ the ball up for an attack above the head. Other constraints which allow for a bounce between hits within the same team and tossing for service provide opportunities for greater success in the situational game.
LESSON PLAN (UNIT: Net- Volleyball)

Level: 8th Grade
Lesson No.: 3
Class Time/ Duration: 30 mins
Venue: Indoor Courts

Date: _______

Equipment needed: 3 sets of badminton posts and nets
16 volleyballs, markers and cones

Tactical Problem: Setting up to attack

Lesson Focus: Set up volley pass for attack hit

<table>
<thead>
<tr>
<th>Situational Game 1: Goals:</th>
<th>Organization:</th>
<th>Observation/ Evaluation:</th>
<th>Time: 8mins</th>
</tr>
</thead>
</table>
| 1) Score points to win rally  
2) 10 points to win set | 3 v 3 in half a badminton court | Ball to be set high near the net |             |
| Conditions: | net | | |
| 1. Bounce between passes allowed 
2. No consecutive hits by the same player 
3. Ball has to be hit above head when played over to opponents 
4. Toss to serve 
5. Maximum 3 hits per side | | | |

<table>
<thead>
<tr>
<th>Question &amp; Answer:</th>
<th></th>
<th></th>
<th>Time: 2mins</th>
</tr>
</thead>
</table>
| 1) Where is it easiest to attack from? Ans: Near the net 
2) How would you score a point? Ans: Execute an attack hit above the head 
3) What must your team do to prepare for an attack hit? Ans: Set up to attack | | | |

<table>
<thead>
<tr>
<th>Practice Task:</th>
<th>Organization:</th>
<th>Teaching Points:</th>
<th>Time: 8mins</th>
</tr>
</thead>
</table>
| Volley pass from setter to spiker | net | 1) For setting, get under the ball 
2) Bend knees 
3) Contact ball with finger pads, flick wrist, elbows bent and wide 
4) Set the ball high 
5) Face direction of pass | | |
| Goals: | | | |
| 1) Successful pass to spiker 
2) 3 good passes before rotation | C (catch) | | |
| Condition: | B (set) | | |
| 1) Toss, set, catch 
2) A to toss, B to set and C to catch the ball above head | A (toss) | | |

<table>
<thead>
<tr>
<th>Situational Game 2: Goal:</th>
<th>Organization:</th>
<th>Evaluation:</th>
<th>Time: 10mins</th>
</tr>
</thead>
<tbody>
<tr>
<td>To execute setting up to attack effectively (as a team)</td>
<td>net</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition:</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| 1. As per Situational Game 1 
2. Point won only with set pass prior to attack hit | | | |

FIGURE 6.1. Representative TGfU lesson plan for net-barrier (volleyball) game
The task constraints in this lesson guide the learners to search for appropriate goal-directed movements to attempt to outplay their opponents. With the appropriate task constraints in place, learners should realise that for an attack hit to be played across to the opponents’ court, the pass prior to the attack hit will have to be high and elevated. In turn, the learners will possibly attempt to ‘set’ the ball high, either by ‘digging’ the ball or trying a ‘volley’ set. In this sense, goal directed behaviour emerges without the need to provide explicit and prescriptive instructions for executing an overhead set pass for an attack hit. Subsequently, skill development occurs after the question and answer session (which confirms the demonstration of the desired movement behaviour and decision for setting up an attack). Task constraints can be manipulated further to provide ‘tighter’ boundaries for learners to set up an attack with the modified instructions, ‘to execute set pass prior to attack hit’. Through attempting to satisfy constraints manipulated by the physical educator, learners will gradually acquire technical skills as well as the appropriate decision making skills to set up an attack and therefore solve the tactical problem for this particular TGfU lesson. The use of modified games and questioning techniques within a TGfU approach serves to encourage learners to actively seek and explore a variety of solutions to tactical problems rather than receiving information passively. The delivery of exploratory or discovery learning promotes functional variability in practice and exploration of movement dynamics which enhances the search process by increasing learner’s exposure to varieties of task solutions (Newell & McDonald, 1991).

Such a hands-off approach emphasises the central theme of Nonlinear Pedagogy where learning occurs under a self-organising construct through the manipulation of constraints, which sets the boundaries for solution exploration. Undoubtedly, Nonlinear Pedagogy has the potential to provide strong theoretical support in explaining the underlying processes not just for TGfU,
but more broadly to inform physical education pedagogy research that learning is a consequence of nonlinear interactions between constraints.

6.4 Conclusion and the Way Forward

This PhD thesis has set out to investigate the acquisition of coordination of a multi-articular action from a nonlinear perspective. Based on key concepts from dynamical systems theory, the series of empirical work undertaken has provided valuable information about differences and changes in coordination of a multi-articular lower limb kicking action as a function of both skill level and practice. The application of nonlinear concepts allows the investigation to focus on the process of change and further presents valuable contribution to the body of literature in the field of motor learning/ control. While key theoretical and experimental findings were established from investigating the research questions raised in this PhD thesis, more research issues emerged during the investigation process as well. Nevertheless, the empirical work has also provided a suitable platform to further embark on long-term research examining coordination changes as well as theoretical and practical implications for pedagogy in physical education.

Hopefully, the current findings would provide researchers as well as practitioners a way forward to better understand the coordination and control of human movement. Specifically, coordination should be investigated with multi-articular movements adopting multiple-single participant analysis. Also, alteration in coordination should be referenced to concurrent changes in performance outcome to better determine the functionality of the movement. Last but not least, key concepts in dynamical systems relating to learning should still be actively investigated to continually build on the existing body of knowledge so that more researchers and practitioners can be informed of new development in this area of study.
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Publications

Journals


Manuscripts under Review


Conference Communications

Chow, J. Y., Davids, K., & Button, C. (2007). Movement variability as noise. It is not that noisy after all. European Workshop on Movement Science. 31st May to 2nd June, Amsterdam, Netherlands. Abstract has been accepted as part of a symposium presentation.


