

ANGLIA RUSKIN UNIVERSITY

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REDEFINING THE DEVELOPMENTAL STAGES OF OVERARM THROWING
ACTION FROM A DYNAMICAL SYSTEM THEORY PERSPECTIVE

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A thesis in partial fulfilment of the
requirements of Anglia Ruskin University
for the degree of Doctor of Philosophy

Accepted: October 2019

ACKNOWLEDGEMENT

I would like to express my sincere thanks to the following people:

First and foremost, my supervisory team, Dr Genevieve Williams, Dr Dan Gordon and Dr Lee Smith. The opportunity to work with you all has been a huge honour. The support and guidance that you have provided has been invaluable throughout this research and for my future career. Gen, thank you for your continued support and guidance as my supervisor and for the opportunity to work with you and Professor Karl Newell.

I would like to offer thanks to my fellow postgraduate students and academic colleagues especially Dr Eldre Beukes, Ahoora Baranian and Flavia Bueno for your support with academic work. Special thanks go to Chris Spice and Nathan Thompson for their assistance in the laboratory.

This research would not have been possible without the participants who so enthusiastically took part in the study. The generosity of their time is much appreciated.

A special thanks to my family and friends for their continued encouragement and support over the last few years.

ABSTRACT

Considerable research has focused on identifying the series of stable states in technique that occur when practising complex motor tasks. From an applied perspective, forming a model of motor learning in this way informs interventions to elicit the most efficient and effective practice. From a theoretical perspective, models of motor learning provide an insight into qualitative and quantitative states that reflect how movement is controlled. Assimilating these two perspectives, the overall aim of this research was to increase understanding of the key characteristics of technique change during learning a complex whole-body movement skill.

In order to achieve the overall aim, two experimental studies were conducted. The first was a longitudinal learning study in adult participants. Non-dominant overarm throwing action was practiced over a 3-week period consisting of 9 sessions. This was followed up with a cross sectional study in which technique in dominant overarm throws at 6, 10 and 14 years of age was examined.

The application of different approaches to analyse technique changes provided a platform to better understand motor learning. Findings showed that the use of a macroscopic collective variable was able to provide an overarching view of dynamical changes of the system with practice and age. Alternatively, changes in joint range of motion was found to be individual specific among adults and children with no clear direction of change related to practice or age. From a practical perspective the components model (Robertson & Halverson, 1984), particularly the step action, underpinned the macroscopic changes and provided a tool that can be more easily applied by practitioners and educators to facilitate and fast track learning.

The resulting research philosophy emerged: the application of a theoretically underpinned, multi-disciplinary approach to quantify technique change during learning has the potential to move researchers closer to a generalised model of motor learning.

Word count: 299

Key words: motor learning, biomechanics, throwing, dynamical systems theory, coordination, skill development

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Nomenclature and Definitions

CoM	Centre of Mass
CoP	Centre of Pressure
DoF	Degrees of Freedom
DST	Dynamical Systems Theory
Hz	Hertz
PT	Participant
ROM	Range of Motion
VC	Vector Coding

Symbols to abbreviate statistical terminology:

ANOVA	Analysis of Variance
CV	Coefficient of Variation
d	Effect size
SD	Standard Deviation
p	Probability level
r	Pearson's correlation coefficient
RM	Repeated Measures

Symbols used to represent variables in equations:

f	Force acting on segment
y	Horizontal direction (anterior-posterior direction)
m	Mass
z	Vertical direction

Definition of key terms used throughout this thesis:

<u>Balance</u>	The ability to maintain the CoM within the base of support
<u>Biomechanics</u>	The application of mechanical principles to the biological organism
<u>Centre of Mass</u>	The point at which the mass of the body is balanced regardless of the body's position
<u>Centre of Pressure</u>	The location at which vertical ground reaction force vector is located and represents a weighted average of all the pressure experience by an individual over a surface, typically the foot
<u>Collective variable</u>	A high order, low dimension space variable that is representative of multiple joints at the muscular-articular level and provides information of the overarching macroscopic organisation the system
<u>Constraints</u>	Boundaries or features, which interact to eliminate certain movement patterns to self-organise the system towards a particular pattern known as an attractor state
<u>Control parameter</u>	Any variable which when scaled beyond a critical value, results in the system reorganisation and the emergence of a new movement pattern
<u>Coordinative structure</u>	The integration of multiple redundant mechanical degrees of freedom and the resulting movement pattern
<u>Coordination</u>	The process by which a system assembles movement in relation to the goal of the task
<u>Dynamical systems theory</u>	A multidisciplinary systems-led approach that describes the constantly evolving dynamics system over time

<u>Ecological validity</u>	Extent to which the research environment reflects the real world situation which it is trying to simulate
<u>Macroscopic</u>	Overarching organisation of the dynamic system
<u>Motor learning</u>	The changes in technique as a novice practices a new motor skill with the aim of successfully completing the skill
<u>Order parameter</u>	Variables that identify the macroscopic or collective behaviour of a system
<u>Perturbation</u>	A deviation of the human system from its current state, caused by a change in the systems constraints
<u>Redundant degrees of freedom</u>	Segments not required for a participant movement
<u>Self-organisation</u>	The spontaneous pattern formation between component parts and is characterised by relative stability or instability through the temporary assembly of muscle complexes called coordinative structures
<u>Segmental lag</u>	The transfer of angular velocity from the heavier distal segment to lighter proximal segment.

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CHAPTER 1: Introduction

1.1 Research Overview

Considerable research has focused on identifying the series of stable states in technique that occur when practising complex motor tasks. From an applied perspective, forming a model of motor learning in this way informs interventions to elicit the most efficient and effective practice. From a theoretical perspective, models of motor learning provide an insight into qualitative and quantitative states that reflect how movement is controlled.

The overarm throw for force was chosen as the vehicle to explore technique changes for this research as it provides a discrete, complex, whole-body movement skill. Moreover, it allows for balance and coordination to be viewed in the same problem, providing an ecologically valid insight into motor control. The overarm throwing action encompasses the observation of this skill across the lifespan, since it is a fundamental movement task that develops during childhood. In addition, greater and lesser ability levels can be explored with the same participant by observing dominant and non-dominant arm actions.

The overarm throw for force is an example of a motor action that has received substantial study and its own model of technique change. The components model (Robertson & Halverson, 1984) for overarm throwing consists of a series of stable states related to four key components of the body. Using this approach, components can ‘advance’ or ‘retreat’ through the stable states in technique for each component in

different ways. This can be illustrated with the leg stance as while this advances, the arm configuration may retreat to a less developed stage. After 7 years of longitudinal study Roberton and Halverson (1984) developed the model arguing that it comprehensively captured technique change during learning by permitting flexibility in technique change through components that could change independently of each other.

However, overarm throwing is a movement that requires coordination of the whole body. From a dynamical systems theory perspective (Newell, 1986) components (arms, legs) do not operate independently of each other. Changing the operation of one component will drive the system to subsequently self-organise and compensate by altering another component to maintain a consistent performance (Southard, 2006). Thus, from a dynamical systems theory perspective the components model (Roberton & Halverson, 1984), which provides qualitative information, may not fully capture dynamic changes in overarm throwing technique. It is the endeavour of this work to examine technique changes of the system through the components model (Roberton & Halverson, 1984) and through novel analysis techniques from a dynamical systems perspective. This approach will facilitate exploration of how different levels of the system change during learning, exploring the advantages and disadvantages of different models in working towards a theoretically underpinned overall approach to stages of motor learning.

To delve deeper, the application of a dynamical systems theory perspective to movement development provides a way to explain the complex and ever-changing perturbations that occur at multiple levels of the system through the process of self-

origination of the task, environmental and organism constraints (Newell, 1986). Self-organisation of the system refers to the spontaneous pattern formation between component parts into the assembly of muscle complexes called coordinative structures (Kugler et al., 1980; Kelso, 1981; Kelso, 1984; Kugler, Kelso, Turvey, 1982; Haken, Kelso & Bunz, 1985; Kugler & Turvey, 1987; Beek & Beek, 1988). Self-organisation occurs through non-linearity of the system as a result of the constraints placed upon the system with individuals finding solutions based on constraint in action. Components within the systems act with mutual influence to maintain an overall stable state of the coordination of the whole body and therefore, cannot act independently (Kugler, Kelso & Turvey 1980; Newell, 1986; Turvey, 1990).

This thesis explores motor control and learning from a dynamical system theory perspective alongside the perspective of Robertson & Halverson (1984). The approach is novel both from the theoretical perspective used to investigate learning of throwing action and adds to the limited literature already available which addresses motor control in adults (i.e. in football (Chow et al., 2008) ski simulator (Vereijken, Whiting & Beek, 1992) or gymnastics skills (Williams et al., 2015).

1.2 Statement Aim and Purpose

Informed by stages of learning models from a dynamical system theory approach to motor learning and through data collection, analysis and interpretation, the overall aim of this research was to increase understanding of the key processes of motor learning and biomechanical variables during learning a complex whole body movement skill.

Through evidence of technique changes in motor control and biomechanics, the overall aims of this research were threefold:

1. Provide a template of a motor learning analysis framework during skill acquisition underpinned by the dynamical system theory in adults over a period of practice and children at difference chronological ages.
2. Conduct and provide research that is ecologically valid, therefore, providing evidence towards a general theoretical approach to understand technique change that characterises motor learning in adults and children or support for current motor learning approaches.
3. Provide evidence-based advice to health sport practitioners and educators in informing skill development in overarm throwing.

In order to achieve the aims of this research, two experimental studies were conducted. The first study was a longitudinal learning study involving adult participants. This involved non-dominant overarm throwing action which was practiced by ten participants over a 3-week period consisting of 9 sessions. The second study was a cross sectional study: technique in dominant overarm throws at 6, 10 and 14 years of age were examined. The overarm throw for force is the vehicle used in this research to study the process of learning. A number of approaches were used to explain changes with practice in the adult study and across ages during childhood. In order to direct the research towards achieving the aims of this research 13 research questions were provided and addressed in chapters 3 to 6.

1.3 Organisation of Chapters

1.3.1 Review of Literature (Chapter 2)

Chapter 2 discusses and critiques existing motor learning and biomechanics literature that is relevant to learning whole body movement skills. Firstly, a review of the motor learning literature is given where the dynamical system theory and associated stages of learning models are reviewed and discussed. Secondly, the methodological consideration of a dynamical system theory approach to motor learning is explored through the literature to inform this current study and the methods used in subsequent experimental chapters. Thirdly, a review of biomechanical literature is presented to highlight key kinematic and kinetic characteristics associated with technique changes in overarm throwing action in adults and children. The literature reviewed in chapter 2 provides the backdrop for this thesis and underpins the research philosophy, the overall aims of this research and the methods used to address these aims.

1.3.2 Qualitative and quantitative change in the kinematics of learning a non-dominant overarm throw (Chapter 3)

Chapter 3 outlines the participants, methods and collection of data involved in the longitudinal learning study. Data was collected for 10 adult participants over a 3-week practice period consisting of 9 practice session with the non-dominant arm. Three approaches of motor learning were used to examine qualitative and quantitative technique changes over non-dominant overarm throwing practice: Newell's (1985) stage of learning coordination, control and skill, the components model (Robertson &

Halverson, 1984) of overarm throwing and Bernstein's (1967) observation of freezing and freeing the redundant degrees of mechanical freedom. The three models were used concurrently in order to determine if current models of motor learning are able to explain technique changes in overarm throwing action. Research question i, ii and iii are addressed in chapter 3.

i. With practice, does the collective variable CoM-wrist become more complex and less variable in line with Newell's (1985) learning stages of coordination, control and skill?

From a motor control perspective Newell's (1985) learning stages of coordination, control and skill are based on the theoretical proposition that motor control is associated with the overall system dynamics rather than the control of individual degrees of freedom as traditionally proposed by Adam (1971) and Schmidt (1975). Variables to describe technique changes between the constructs of coordination, control and skill were deliberately not defined by Newell (1985) as it was hypothesised that the variables would be task specific. However, Newell (1985) went on to suggest that coordination variability was a key indicator associated with technique changes. Newell's more recent work (Ko, Challis & Newell, 2014; Wang et al., 2014; Dutt-Mazumder, Challis & Newell, 2016; Dutt-Mazumder & Newell, 2017) has focused on the use of collective variables to assess the three constructs of learning. In this view, a collective variable provides information of the overarching macroscopic organization of the system, particularly postural and limb control although not necessarily a quantitative or mechanical degree of freedom.

ii. With practice how do changes in technique occur in-line with the components model of overarm throwing (Robertson & Halverson, 1984)?

The components model (Robertson & Halverson, 1984) of overarm throwing provides qualitative information of technique changes. As the only throwing specific model it has been used substantially within the literature to categorise qualitative technique changes in overarm throwing action and is traditionally used in the analysis of children (Robertson & Konczak, 2001; Langendorfer & Robertson, 2002; Stodden et al., 2006a,b) and older adults (Williams, Haywood & VanSant, 1998).

iii. With practice how do changes in ROM occur in-line with Bernstein's (1967) observations of freezing and freeing redundant mechanical degrees of freedom?

From a biomechanical and motor control perspective, Bernstein's (1967) observation of freezing and freeing the redundant degrees of mechanical freedom were applied to the overarm throwing action of the non-dominant arm in adults. Bernstein's (1967) observations provide quantitative information regarding individual units of the body. Changes in Range of Motion (ROM) (Newell et al., 1989; Vereijken et al., 1992; Chow et al., 2008) and coordination variables (Ko, Challis, & Newell, 2003; Verhoeven & Newell, 2016) have been studied during practice of novel tasks. However, the process of freezing and freeing the mechanical degrees of freedom has been suggested to be task specific (Newell & Vaillancourt, 2001; Hong & Newell, 2006).

1.3.3 Movement form and scaling properties of the overarm throw for children at 6, 10 and 14 years of age (Chapter 4)

Chapter 4 outlines the participants, methods and collection of data involved in the cross-sectional study of children of different ages throwing with their dominant arm. Children were recruited in three age groups: 6 years of age, 10 years of age and 14 years of age. Analysis was performed on 18 participants. Chapter 4 details the cross-sectional changes throughout childhood and adolescence utilising the same three complementary approaches used in Chapter 3: Newell's (1985) stages of learning coordination, control and skill, the components model of overarm throwing (Robertson & Halverson, 1984) and Bernstein's (1967) observations of freezing and freeing the redundant mechanical degrees of freedom. The models were used to track and assess changes in dominant overarm throwing action present at 6, 10 and 14 years of age to establish if current models of motor learning are able to explain technique changes in overarm throwing action at different ages across childhood. In addition, it was hoped to establish if technique changes in overarm throwing of children were consistent with technique changes observed in adult participants in chapter 3. Research questions iv-vi are addressed in chapter 4.

iv. With age, does the collective variable CoM - wrist become more complex and less variable in line with Newell's (1985) learning stages of coordination, control and skill?

Newell's recent work (Ko, Challis & Newell, 2014; Wang et al., 2014; Dutt-Mazumder, Challis & Newell, 2016; Dutt-Mazumder & Newell, 2017) has focused on collective variables to assess constructs of the stage of learning model (Newell, 1985).

From this perspective, a collective variable provides information of the overarching macroscopic organization of the system. As an initial attempt, the CoM and wrist were chosen as the collective variables to examine technique changes at the dynamical levels of the system. Specifically, the CoM was selected as it provides information of the overall postural control of the movement and the wrist joint was chosen as it provides information of limb control with the wrist being the end effector of overarm throwing.

v. With age, how do changes in technique occur in-line with the components model of overarm throwing (Robertson & Halverson, 1984)?

The components model (Robertson & Halverson, 1984) of overarm throwing was developed following seven years of longitudinal study with the same cohort of children from kindergarten to 7th grade. The components model has subsequently been used to examine technique changes in children and adults (Robertson & Konczak, 2001; Langendorfer & Robertson, 2002; Williams et al., 1998) and compared to kinematic changes in technique (Stodden et al., 2006*a,b*).

vi. With age, how do changes in ROM occur in-line with Bernstein's (1967) observations of freezing and freeing redundant mechanical degrees of freedom?

Bernstein's (1967) observation of freezing and freeing the redundant degrees of mechanical freedom was applied to overarm throwing with the dominant arm in children at 6, 10 and 14 years of age. Changes in ROM (Newell et al., 1989; Vereijken et al., 1992; Chow et al., 2008) and coordination variables (Ko, Challis, & Newell, 2003; Verhoeven & Newell, 2016) have been studied during practice of novel tasks.

It has been suggested that the process of freezing and freeing the redundant degrees of freedom could be task specific (Newell & Vaillancourt, 2001; Hong & Newell, 2006).

1.3.4 Age and practice related changes in upper limb tri-joint synchrony in learning to throw (Chapter 5)

Chapter 5 details Cluster Phase, a novel multivariate method for exploring coordination, to examine changes in technique in the upper limb joint synchrony during the overarm throwing action. Tri-joint synchrony of the shoulder, elbow and wrist joint is examined as a function of age throughout childhood and adolescence during dominant overarm throws. In addition, tri-joint synchrony is also examined following a 3-week period of non-dominant overarm throwing in adults. The Cluster Phase approach is employed to detect changes in phase synchronization between these joints, overcoming the shortcomings of bivariate measures of coordination. The importance of this study lies in the application of multivariate techniques to understand coordination changes across childhood, and as a function of practice in adults when performing a complex gross whole-body motor skill. Specifically, this study examines the characteristics of coordination during the dominant overarm throwing action as children develop the appropriate movement strategies for the task, and during non-dominant arm throwing action in adults over a period of practice. This chapter provides an exciting contribution to knowledge within motor learning and helps to explain technique changes during learning. Research questions vii to ix are addressed in chapter 5.

vii. What differences were observed in the tri-joint synchrony at 6, 10 and 14 years of age compared to adults following a 3-week period of practice?

Cluster Phase is a multivariate technique that affords determination of the synchrony between multiple components (Frank & Richardson, 2010). The application of Cluster Phase analysis has been used to show coherence between multiple moving components. Researchers have used Cluster Phase analysis in the study of rhythmic coordination during: cascade juggling (Haibach, Daniels & Newell, 2004), rocking chair (Richardson et al. 2007; Richardson et al., 2012) and football (Silva et al., 2016). More specifically, Diss et al. (2019) used Cluster Phase to examine changes in lower limb synchronization as a function of ageing in runners. Currently no studies have investigated synchrony of the three key upper limb joints that make up the arm. An analysis of the synchronization characteristics of the upper limb during dominant overarm throwing at different time points during childhood and non-dominant arm throwing action in adults would provide an additional contribution to knowledge within motor learning and help explain technique changes during learning.

viii. What differences were observed in the individual joint synchrony at 6, 10 and 14 years of age compared to adults following a 3-week period of practice?

A central issue is how the multiple redundant degrees of freedom are organised in light of the constraints in action (Newell, 1986) which are individual specific (Langendorfer & Roberton, 2002; Burton et al., 2017). The majority of human movements involve multiple joints, therefore, there is a need to examine multiple components of the system and how they interact with one another during motor tasks. Exploring how the three joints that make up the arm segment synchronise as a function of age in children

whilst throwing provides a new insight and theoretically relevant information to inform motor control theory.

ix. What differences were observed in the variability of synchrony in the upper arm at 6, 10 and 14 years of age compared to adults following a 3-week period of practice?

A key indicator of learning is suggested to be a reduction in coordination variability (Newell, 1985). Coordination variability is thought to have different functional roles during skill acquisition and refinement from allowing the exploration of possible movement solutions to allowing flexibility in technique to compensate for changing constraints (Davids et al., 2003; Newell, 1985; Hamill et al., 1999). Coordination variability is likely to be present in children and adults alike and provides pathways in which movement can successfully be achieved. However, the way in which these pathways occur and how they may be similar between children and adults remains unknown (Novak, 1998; Busquets et al., 2016).

1.3.5 Centre of Pressure pathways during overarm throwing action at 6, 10 and 14 years of age (Chapter 6)

Chapter 6 details the cross-sectional changes in postural control strategies via centre of pressure (CoP) analysis employed throughout childhood and adolescence during dominant overarm throws. The importance of this chapter lies in understanding the pathways of change and the development of kinetics during fundamental whole-body skill acquisitions tasks via CoP that captures the facilitator of the variable the body is trying to control CoM.

x. What is the difference in displacement of the Centre of Pressure change at 6, 10 and 14 years of age?

Total displacement of CoP during overarm throwing action at different time points during childhood and adolescence provides a good representation of the stability of the children as it delivers information of overall postural control and has been used as a variable during a dynamic standing task (Winter, 2009). Moreover, examining displacement in the anterior-posterior and medial-lateral direction provides information of the direction in which the centre of pressure is most greatly displaced.

xi. What is the difference in velocity of the Centre of Pressure during overarm throwing action at 6, 10 and 14 years?

The velocity of the CoP during overarm throwing action provides an indication of the momentum that is being generated in relation to the stance of the child, specifically, the process of weight transfer from the back leg to the front leg during the propulsive phase of overarm throwing action. Measuring velocity in the anterior-posterior and medial-lateral direction provides information of the direction of force as an effect of age from 6 to 10 to 14 years of age.

xii. What is the difference in acceleration of the Centre of Pressure motion during overarm throwing action at 6, 10 and 14 years of age?

Changes in CoP acceleration are altered by adjustment to muscle activation which leads to the CoP moving in different directions. Therefore, the rate of movement of

the CoP is dependent upon the build-up of muscular force and is achieved partly by passive elastic forces. These forces develop partly through the stretching of the tissues during movement and partly by changes in muscle activity. Assessing acceleration in the anterior-posterior and medial-lateral direction provides an understanding of age-related development of forces.

xiii. What is the difference in Centre of Pressure path length at 6, 10 and 14 years of age?

Total path length provides information regarding the dynamic strategies employed to organise the overall body motion during overarm throwing. Undertaking this measurement provides knowledge of the strategies employed at 6, 10 and 14 years of age.

1.3.6 General Discussion (Chapter 7)

Chapter 7 discusses the findings of this thesis with regard to the 13 research questions outlined in chapter 1 - section 1.3 and considers this in line with the theoretical biomechanical and motor learning issues associated with a learning fundamental movement skill. The theoretical theme of this research is apparent throughout chapter 7 and explores the complementary nature of the work being addressed, so bridging the gap between the current qualitative and quantitative approaches of quantify the biomechanics and motor learning changes in technique in overarm throwing action in children and adults. In conclusion, this thesis highlights the novel contribution to the literature, the suitability of the methodological approaches used to examine technique

changes and the potential direction for future work is suggested in light of current findings.

CHAPTER 2: Review of Literature

2.1 Introduction

This chapter synthesises, examines and discusses existing literature from motor learning and biomechanics associated with the development of movement skills. Firstly, an overview of motor learning literature and stages of learning models is provided. Secondly, methodological considerations associated with collecting and analysing kinematic and kinetic data during motor learning is reviewed and critically discussed to help inform the methods of this thesis. Thirdly, a review of the literature focussed specifically on the technique changes associated with learning the overarm throw is presented. This review of literature underpins and informs the overall aims and research questions of this thesis.

2.2 Motor Learning

Motor learning is the process by which humans develop coordinated and controlled movement patterns. Motor learning is defined here as the changes in technique as a novice practices a new motor skill with the aim of successfully completing the skill (Schmidt et al., 2018). Motor learning and development are characterised by the continuous emergence of new motor behaviours (Newell, Liu & Mayer-Kress, 2001). A key issue in the development of motor control theory is understanding the process by which the redundant degrees of freedom are coordinated and controlled to satisfy the requirements of the motor tasks and the postural stability demands. Understanding the process by which people initially learn motor skills and then adapt with practice is

of great interest to movement science practitioners. However, capturing the collective behaviour of the many interacting segments and multiple levels of the dynamics system continues to be a problem.

It is understood that infants are born with minimal control over their own motor function, but within a year or so they have developed the motor control to reach, grab, sit, crawl, walk, feed themselves and even say a few words (Thelen, 2000). Initial motor pathways developed in the first year of a child's life occur when the genetics urge them to do so. It is suggested that infant behaviour is obedient to genetic sequences ensuring similar growth pathways for full term, pre-term and post term infants (Gesell, 1929). By two years, normally developing children are able to run, ride a tricycle, climb and string words together into sentences. However, motor development is almost impossible to fast track with the timing of motor development, specifically growth in children influenced by both the environment and genetics (Gesell, 1929).

While central timescales for learning to walk occur from around 1 year of age, proficient postural control is said to occur around 6 to 7 years of age (Nolan, Grigorenko & Thorstensson, 2005; Condon & Cremin, 2014). By 10 years of age children have developed more efficient movement strategies and greater muscle strength, enabling them to consistently reproduce dynamic movement that may lead to more consistent measures of postural control than younger children, and more closely resemble postural control of adults (Taguchi & Tada, 1988; Faigenbaum et al., 2014). This is illustrated by Taguchi and Tada (1988) who reported that children aged between 9 and 12 years of age presented similar postural control performance to adults

during eyes open condition. Meanwhile, Hirabayashi and Iwasaki (1995) found that during an eye closed condition only children aged between 12 and 15 years of age were similar to adults. However, there is the suggestion that adult-like postural control in children is task-dependent and influenced by sensory manipulation and muscle strength (Faigenbaum, et al., 2014).

Initial motor tasks demonstrated by children include seating, crawling, reaching and walking which lay the foundation for the potential to learn and perform more complex movement with practice such as running, skiing, gymnastics and team sports. It is highlighted that constraints exist for adults that limit performance despite proficient motor control. Williams et al. (2012) demonstrated kinematic changes in long swing performed by a group of novice gymnasts. Their results demonstrated that individual constraints to action prevented all participants becoming proficient in long swing after 8 weeks of training. Overall however, for children during motor development and adults during motor learning, it is important to study skill development since it informs skill learning and the processes and mechanism by which changes to the system occur. This knowledge can then be used to make training and practice more efficient and effective, fast-tracking learning as key constraints to technique learning have been identified.

Theories of motor learning are moving towards a dynamical system theory (DST) perspective, and away from computational approaches of motor learning (Schmidt, 1975; Adams, 1971). From a computational approach, Adams (1971) closed loop theory of motor learning proposed that there are two states of memory: (i) memory trace responsible for initiating movement which is developed through knowledge of

results and over practice (ii) perceptual memory which is responsible for guiding the limb into the correct position and is developed through past experiences. Adams (1971) suggested that information feedback played a vital role in motor skill acquisition. Schmidt's schema theory (1975) of motor learning provided a representation of the relationship between variables rather than the absolute instantiations of the variables themselves. The perspective nature of the 'computational approach' (Adams, 1971; Schmidt, 1975) suggests that a movement sequence has already been assigned to the task constraints. This idea has been challenged from a DST perspective (Kugler, Kelso & Turvey, 1980; Kugler & Turvey 2015; Turvey & Kugler, 1984) as the Schema theory (Schmidt, 1975) of motor learning is unable to account for the acquisition of new coordination modes and movement forms that adapt to a variable environment.

The transition from 'computational approach' towards a DST perspective has been in part motivated by the degrees of freedom problem (Bernstein, 1967; Kugler et al., 1980; Newell, 1985; Turvey & Kugler, 2015; Turvey, 1990; Newell et al., 1989; Thelen, 1995; Van Emmerik & Van Wegen, 2000; Van Emmerik et al., 2004; Mayer-Kress, Liu & Newell, 2006). Bernstein (1967) suggested that the key issues for human movement researchers was to understand how the emergence of order in the behaviour and control occurred from such a complex system. In this view, Bernstein (1967) defined coordination as the 'the process of mastering redundant mechanical degrees of freedom of a moving organ, in other words its conversion into a controllable system' as the basis for emergence of behaviour (Bernstein, 1967, p. 127). Coordination was subsequently defined by Turvey (1990) as the process by which a system assembles movement in relation to the goal of the task. The human body consists of 792 muscles

which work together to transfer kinetic energy across the skeletal joints. Even if the human body was viewed as only its hinges that would leave 100 mechanical degrees of freedom which highlights the intricacy of the human body (Turvey, 1990). The challenge of understanding the process of motor learning and control lies in understanding how these multiple components are organised to effectively perform every movement.

A key aspect of motor learning is the redundancy and degeneracy that exists within human movement which affords the biomechanical system with the flexibility to adapt with changing perturbations (Bernstein, 1967; Latash, 2000). While redundancy affords flexibility, it adds to the complexity of understanding technique changes in motor tasks within trials and between individuals. The DST perspective to motor learning provides a multi-disciplinary systems-led approach that describes the system over an evolving time scale. From the DST perspective, motor learning can be viewed as the building blocks for the emergent patterns of coordination, and provides an explanation of how individuals overcome constraints to action to utilise the redundant mechanical and dynamical degrees of freedom over time. Through processes of self-organisation, coordination and control emerge between components of the dynamical movement system (Newell & McDonald, 1994).

Self-organisation of the system refers to the spontaneous pattern formation between the component parts and is characterised by relative stability or instability through the temporary assembly of muscle complexes called coordinative structures (Kugler et al., 1980; Kelso, 1981; 1984; Kugler et al., 1982; Haken, Kelso & Bunz, 1985; Kugler & Turvey, 2015; Beek & Beek, 1988). Coordinative structure refers to the integration of

multiple redundant mechanical degrees of freedom and the resultant movement pattern (Bernstein, 1967). The framework for encompassing the common trends is provided by constraints on action (Kugler et al., 1980; Newell, 1985). Constraints act to eliminate certain movement patterns helping to self-organise the system towards a particular pattern known as an attractor state (Newell, 1986, Thelen, 1992, Southard, 2002). Newell (1986) proposed three general constraints to action: the organism, the task and the environment (Fig 2.1). Newell (1986) defined constraints as the boundaries within which a functional set of patterns occur towards a goal focused behaviour.

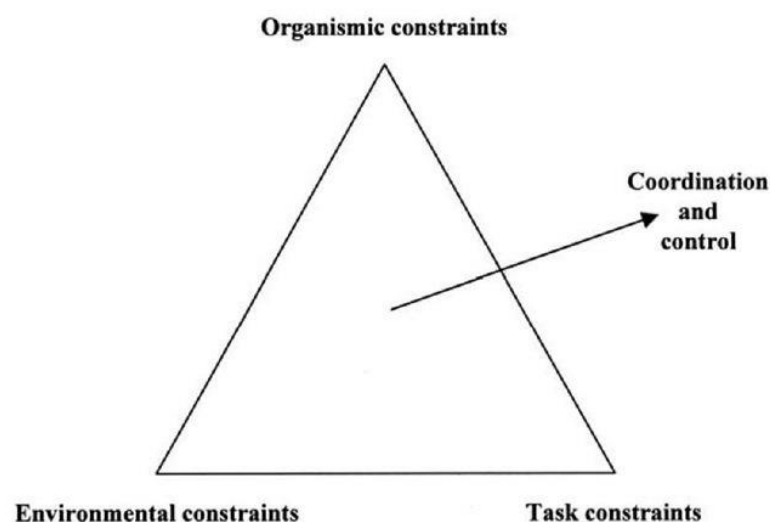


Figure 2.1 **Constraints to action: the organism, the task and the environment**
– adapted from Newell (1986)

Organismic constraints to action are relatively time independent and typically interpreted as structural constraints with examples including height, mass and somatotype. Task constraints to action relate to the goals or rules specifying or

constraining the response and limiting the number of coordination patterns that can be produced. Task constraints include the goal of the task and rules of the task, more specifically in throwing the distance to target, size of target, weight and size of throwing object, and the type of throw being undertaken. Environmental constraints to action are external to the organism and are those that cannot be manipulated by the experimenter. Environmental constraints include gravity, natural light, natural ambient temperature and pressure.

Optimal patterns of coordination and control emerge from a unique combination of constraints imposed on an individual system through a process referred to as ‘self-organising optimality’. Constraints optimisation states that the behaviour of a biological system will always be optimal for the specific organisation of the constraints acting upon the system at any time. Since the constraints imposed on an individual’s dynamical system are innately changeable, the optimal pattern of coordination and control for any motor activity will change accordingly (Glazier & Davids, 2009). The organismic, environmental and task constraints, therefore, dictate the optimal pattern of coordination and control for specific individuals by eliminating certain patterns. Nevertheless, not all constraints are equally weighted with some having a greater influence over the movement pattern (Newell, 1986; Glazier & Davids, 2009).

By definition, dynamical systems are characterised by non-linear phase shift which describes the transition from one dynamic attractor state to another through the reorganisation effects of bi-directional interactions of transitions. A nonlinear model goes beyond a simple transactional model to predict changes within the system

resulting in a qualitative as well as a quantitative change in behaviour. Novak (1998) gave the following example of the interaction between an infant and mother: a smiling baby increases smiling in the presence of a smiling mother. This increased maternal smiling which in turn may further increase the baby's smiling. At this point the increased smiling of the baby has further effects on the mother's behaviour with smiling being replaced by laughter. Up until this point, the interaction is linear, however, now the high rate of baby smiling has caused an emergent behaviour in the mother. Laughing is qualitatively and quantitatively different from the initial behaviour, this qualitative change is a nonlinear shift.

An attractor state is a consistent pattern of response, which is determined in light of the constraints (Van Emmerik & Van Wegen, 2000). The Haken-Kelso-Bunz model (HKB) (Haken et al., 1985) has been applied to the study of inter-limb coordination in human movement (Kelso, 1995) and was derived from the theory of non-linear oscillations and provides a theoretical model that predicts when the system is in an unstable anti-phase pattern. If the control parameter is changed, the pattern of movement would be attracted to the more stable in-phase pattern as it is easier to control.

Kelso (1981; 1984) investigated the relative phase relation between participants' index fingers during a 'finger wagging' experiment. Speed of participants' index finger wagging was varied. The study revealed two relative phases: in-phase coupling, where both index fingers moved forwards and backwards together and, anti-phase coupling where the index fingers were differentiated from each other. At low oscillation frequency, participants were able to wag their finger in either in-phase or anti-phase.

Starting finger wagging in anti-phase followed by an increase in oscillation led to spontaneous transition to in-phase coupling. If finger wagging started in-phase and oscillation frequency changed no transition took place. These experiments showed that abrupt changes from one stable state to another occur at critical values as the movement frequency gradually increased. In a discrete dynamical system this frequency would be a bifurcation parameter and the phase difference of movement would be regarded as a collective variable. However, little is known about the dynamics underlying upper limb action during overarm throwing action.

During stable in-phase, a change in the control parameter would not cause transition to another phase unless a critical value is reached. A system can shift to a new attractor state through the destabilisation of the existing stable form through the self-organisation of the system. The attractor state is where the system prefers to reside, although it is not obligated to do so. Such attractor states may be more or less stable, but unstable configurations can spontaneously shift into a new attractor (Newell & Vaillancourt, 2001). This is an interesting problem when applied to motor learning.

The degrees of freedom that are required to define the attractor states in the perceptual-motor workspace are usually lower than those evident at the behavioural level in the coordination model. In this view, the redundant degrees of freedom are defined by an abstract perceptual-motor workspace and not the observable joint space of the coordination model. The emphasis of this theoretical coordination is to understand the degrees of freedom of the attractor state and how these degrees of freedom are organised to produce coordinated and controlled movements (Newell & McDonald, 1994). The progression from one attractor to another over time is the result of a variety

of factors, including the ongoing interaction of the performer with the environment. The period of transition from one attractor state to another is of great interest to researchers as it provides a window of opportunity for understanding how coordination emerges (Davids, Renshaw & Glazier, 2005).

In defining these states, an attractor state reflects the self-organisation of the biological system rather than specification from some prescriptive motor programme or schema. Moreover, the redundancy of the system affords the flexibility of motor skills that individuals are able to perform (Bernstein, 1967). Control parameters are the relevant dynamics that can lead to transition and reveal regions of stability and instability in coordination, so enabling transition from one attractor to another. A control parameter is any variable which when scaled beyond a critical value results in the system reorganisation and the emergence of a new movement pattern, specifically this has been shown in throwing, (Southard, 2002), walking (Van Emmerik et al., 2013), finger wagging (Haken et al., 1985) and dynamic balancing tasks (Ko, Challis & Newell, 2014). The control parameter does not dictate how the pattern should change but rather sets up the condition for change to occur (Kelso, Scholz & Schöner, 1986; Thelen & Smith, 1994).

Order parameters are variables that identify the macroscopic or collective behaviours of a system (Van Emmerik et al., 2013). Order parameters can be described in high order or low order dimensional variables that capture the interaction among the segments, muscle or joints of the system. It does not refer to the physical mechanics of moving masses and is directly measurable around the transition (Van Emmerik & van Wegen, 2000; Southard, 2006). The relative phase between oscillatory segments

could be a possible order parameter for movement due to its fundamental reflection of cooperativity between components (Kelso, 1981; Kelso, 1984; Vereijken, et al., 1997; Van Emmerik & Van Wegen, 2000; Ko et al., 2014). For example during gait, patterns are characterised by changes in the phase relationship between the legs as the phase relation reflects the order parameter. This changes between the different gait frequency, but remains invariant within the particular gait model. The stability and transition of movement patterns can be revealed by the systematic manipulation of a non-specific control parameter (Van Emmerik et al. 2013). The identification of order parameters of the complex system is a key issue which needs to be resolved (Ko et al. 2014).

Newell and McDonald, (1994) suggested movement should be studied in the perceptual-motor workspace rather than the focus being limited to the observable behavioural level characteristics. A key element in the analysis is identifying the essential parameter that captures the macroscopic changes and the most appropriate control parameters that will lead to an efficient and effective change in the system organisations to induce a new steady state of behaviour that is consistent with the production of a task outcome (Newell & Vaillancourt, 2001).

Skill learning provides an effective paradigm for understanding the incremental yet non-linear changes that characterise human development. Fischer (1980) viewed a skill as a systematic variation in behaviours which are under the control of organismic and environmental conditions. Meanwhile, Novak (1999) stressed the importance of emphasising that the structures are organised as skills by response-stimulus and response-response relationships, not formal structures. This is an important difference

between the skill-learning model taken in behavioural system theory and traditional theories. Zimmerman and Whitehurst (1979) suggests that such nonlinearities may result from the strong contingencies produced by a newly emergent cognitive skill. Thus, a new skill may be so much more functional that is quickly strengthened while less functional forms are not.

A development framework first proposed by Gesell (1929, 1946) suggested that motor learning and organization is maturational. Maturation and the learning theory of motor learning share important assumptions in the development of movement coordination. Namely, maturational and learning perspectives assume that the development of coordination is due to the development of prescription for action, either through a genetic code or learning theory formulation; where ‘prescription’ is a general label for symbolic knowledge structure at some level or a representation prescribing the course of action (Newell, 1986). Typically, ‘stages of motor development’ refers to the order and regularity of the emergence of coordination exhibited by infants and in early childhood, rather than a general set of motor behaviours. The primary, although not exclusive, theoretical account of these developing movement patterns had been the maturational formulation. However, this theory associated with stored instructions lacks theoretical underpinning of how the information is initially obtained. Thelen (1989) referred to this issue as a ‘logical hole of infinite regresses’.

2.2.1 Stages of Learning Models

From a contemporary DST perspective of motor control, two stages of learning models have been suggested for the development of general motor skills: Newell's (1985) learning stages of coordination, control and skill and Bernstein's (1967) freezing and freeing the redundant mechanical degrees of freedom. Newell's (1985) model provides information of macroscopic organization of the system through the use of a collective variables to assess the constructs of the learning stages (Ko et al., 2014; Wang et al., 2014; Dutt-Mazumder, Challis & Newell, 2016; Dutt-Mazumder & Newell, 2017, Palmer et al., 2018). Newell's (1985) stages of learning offers a functional distinction between the constructs of coordination, control and skill with the stages of learning model based on the interaction of organism, environmental and task dynamics as functions of learning (Newell, 1986). The stages are as follows:

Stage 1 – Coordination: associated with novices trying to establish a basic relationship between the components in order to meet the task demands.

Stage 2 – Control: inherently linked to the coordination stage of learning. Adult learners are suggested to progress quickly from the coordination stage to the control stage (Newell, 1985). During the control stage parameters are assigned to the coordination mode and dysfunctional variability decreases as movement consistency increases (Chow et al., 2008).

Stage 3 – Skill: defined by the ability to assign optimal parameters to the controlled variables to achieve efficient or consistently successful performance in light of the constraints to action (Newell, 1985).

Variables to quantify stages of learning were specifically not provided by Newell (1985) as it was hypothesised that variables would be task specific. Instead Newell's most recent work has used collective variables to explore the constructs of learning (Ko, et al., 2014; Wang et al, 2014; Dutt-Mazumder, Challis & Newell, 2016; Dutt-Mazumder & Newell, 2017). The term 'collective variable' is defined by Kelso (2019) as 'relational quantities that are created by the cooperation among the individual parts of the system' and by Mitra et al. (1998) as 'a collective variable by definition is a higher order low dimensional variable that captures the overarching pattern of spatial and temporal details among the degrees of freedom of the movement system'. Another term that is used to capture this concept are 'macroscopic variable' defined by Kelso (1995) as the variable that captures the collective state of the organisation of the system dynamics. The collective variable is generated by some pattern of relations among the individual components of the system and conversely constrains the motion of the individual components. Ko et al. (2014) defined a macroscopic variable as something that provides information of the real pattern of behaviour that emerges and represents the relationship between the mechanical components of the system. Recently, the work of Newell has reemphasised the idea of a candidate collective variable (Ko, Challis & Newell, 2014; Wang et al., 2014; Dutt-Mazumder, Challis & Newell, 2016; Dutt-Mazumder & Newell, 2017). Specifically, during a postural balance task Ko et al. (2014) used centre of mass (CoM) and the centre of pressure (CoP) as the candidate's collective variables. Results showed that all participants

moved between in-phase coupling and anti-phase coupling with transition between two phases being subject dependent. Additionally, when surface frequency was low, the postural system was regulated by a smaller number of joints. As surface frequency increased the joints were re-organised in an attempt to dissipate force. It is interesting to consider if these ‘couples’ of macroscopic variables are the optimal solution or if the individual is limited mathematically to quantifying the phase relations between only two oscillators. A collective variable is likely to be task specific. In this view, a collective variable provides information of the macroscopic organization of coordination of the system (Ko et al., 2014).

A collective variable is defined in this thesis as a high order, low dimension space variable that is representative of multiple joints at the muscular-articular level and provides information of the overarching macroscopic organisation the system.

The assumption is that the collective variable delivers a clear representation of the system’s coordination patterns by observing synergies (Ko et al., 2014). Further research is required to understand the variable or variables that would provide knowledge of the macroscopic organisation of the system.

Synergies refer to the muscular articular links and generate high order variables, which help create suitable movement patterns. Lower synergies occur when performing non-redundant tasks with the intention directed to internal body segments motions. Higher synergies occur when the system is performing redundant coordination tasks, with the intention directed to the external effect of movement. Essential steps for research are associated with identifying key collective variables that control the interactions among

the various segments, muscles or joints of a complex system (Ko et al., 2014). Coordination of movement can be understood as the result of coupling the dynamics of different components (Newell et al., 2001).

Recent work has used collective variables to assess the constructs of the learning stages (Ko, et al., 2014; Wang, et al., 2014; Dutt-Mazumder, Challis & Newell, 2016; Dutt-Mazumder & Newell, 2017). Specifically, during a postural balance task Ko et al. (2014) used centre of mass (CoM) and the centre of pressure (CoP) as the candidate's collective variables. Results showed that all participants moved between in-phase coupling and anti-phase coupling with transition between in phase and anti-phase being subject dependent. Additionally, when frequency is low, the postural system was regulated by a smaller number of joints. As frequency increased the joints were re-organised in an attempt to dissipate force. It is interesting to consider if these 'couples' of macroscopic variables are the optimal solution or if the individual is limited mathematically to quantifying the phase relations between only two oscillators.

As previously highlighted the human muscular-skeletal system is a highly complex and nonlinear system with a high number of redundant degrees of freedom that need to be accounted for. Bernstein (1967) highlighted the formation of specific functional muscle-joint linkages as a method employed by humans to control the large number of redundant degrees of freedom. Bernstein (1967) recognized that the analysis of human movement could not simply focus on the muscular forces provided by a human, but must also include inertia and reactive forces.

Bernstein's (1967) observation of freezing and freeing the redundant mechanical degrees of freedom captures qualitative and quantitative technique changes. In this view Bernstein (1967) postulated that movement is coordinated through a three-stage approach in which the number of degrees of freedom change with motor learning and development:

Stage – Freezing: during the early stages of in learning a new movement skill the distal degrees of freedom are reduced (freezing of the redundant mechanical degrees of freedom) making the dynamical system easier to control.

Stage 2 – Freeing: as learning progresses and practice time increases an individual begins to gradually release the previously constrained (frozen) redundant mechanical degrees of freedom, so allowing for the involvement of all possible degrees of freedom.

Stage 3 – Efficiency: individuals utilise and explore the reactive phenomena (gravity and passive dynamics) which occur between the individual and their environment resulting in a more energy efficient movement.

One key issue that is central to the development of a general theory of motor control is mastering the redundant mechanical degrees of freedom (Bernstein, 1967; Newell & McDonald, 1994). The interaction of contralateral and ipsilateral joints, segments, and/or muscles can play a crucial role in the organisation of certain movement patterns. The number of degrees of freedom involved in a given movement is strongly dependent upon the task, organism and environmental constraints. The general

perspective is that the phenomena of freeing and freezing (Bernstein, 1967) refers to the mechanical degrees of freedom rather than the dynamical degrees of freedom and suggests that additional principles of coordination are beyond those outlined by Bernstein's (1967) original perspective. Bernstein did not explicitly state if he was referring to the mechanical or dynamical degrees of freedom, but did however propose that synergies which consist of muscles and joints are used by the developing nervous system help organise and control movement skill. Overall, it is assumed that Bernstein was referring to the redundant mechanical degrees of freedom.

To date, changes in mechanical degrees of freedom such as joint angle range of motion (ROM) (Newell et al., 1989; Vereijken, Whiting, & Beek, 1992; Chow et al., 2008) and dynamical degrees of freedom, such as coordination variables (Ko, Challis, & Newell, 2003; Verhoeven & Newell, 2016; Palmer et al., 2018) during learning novel tasks have been investigated. Contrasting patterns of change have, however, been shown in a range of tasks including, the initial stages of learning of the long swing in gymnastics (Williams et al., 2016), high jump (Bobrownicki et al., 2015), basketball free-throw (Button et al., 2003), juggling (Haibach, Daniels & Newell, 2004), ski-simulator (Hong & Newell, 2006) and soccer skills (Chow et al., 2006).

The coordination of balance and propulsion processes in learning to ride a unicycle was examined by Lee, Liu and Newell (2016). Participants practiced unicycle riding during 28 sessions. The findings showed that the number of components required to reflect the organization of the movement properties decreased with practice for most of the participants. This is consistent with the general postulation that unicycle learning is a process of reducing the dimensionality of the organization of the joint

space degrees of freedom. However, the participants did not freeze the joints at the beginning of practice (Bernstein, 1967; Vereijken et al., 1992), but rather appeared to use a search process to engage the DoF of the torso and limbs in order to control balance. After participants learned how to control the unicycle, they began to decrease the redundant DoF by coupling leg and torso motions. This pathway of change in reorganizing the joint space DoF is in contrast to Bernstein's (1967) three stages of learning which hypothesized the progression from freezing redundant DOF to releasing DOF, and the use of reactive forces with the environment to optimize learning and performance.

While Hodges et al. (2005) suggested that freezing the redundant mechanical degrees of freedom is perhaps a temporary strategy used by learners to aid performance and with practice more refined independent control is developed to achieve the task demands in a consistent and effective way. It has been proposed, however, that the direction of freeing and freezing is task specific and dependent on the level of the system being analysed during learning (Hong & Newell, 2006; Newell & Vaillancourt, 2001). Bernstein's (1967) hypothesis of freezing and freeing the redundant mechanical degrees of freedom captures properties of qualitative and quantitative technique changes. There is a need to observe the dynamical degrees of freedom of body segments of behaviour in conjunction with the mechanical degrees of freedom (Newell & Vaillancourt, 2001).

2.3 Methodological Considerations

Existing literature provides a number of methodological considerations for different approaches of qualitative and quantitative methods to examine technique changes during skill acquisition from a DST perspective. Based on the review of literature it is apparent that there is a need to use ecologically valid methods that are applicable to a multiple subject design and have the ability to provide a detailed insight into the multidimensional nature of human movement development. There is a need to explore the use of multivariate techniques where more than two variables can be viewed simultaneously in order to explore the system in greater detail. These issues surrounding methods of data collection mentioned above are explored in the following sections.

2.3.1 Ecological Validity

Ecological validity refers to how representative research is to a real life situation outside of experimental data collection. The more ecologically valid the research, the more applicable the research is to real life making it an important consideration before undertaking data collection. Ecological task analysis gives insight into the dynamics of movement behaviour by viewing movement in relation to the constraints of action of the performer, environment and task. The ecological task analysis model applies DST to the assessment of movement development and was first developed by Davis and Burton (1991). Technological advances have meant there is now greater access to portable equipment making it easier to collect data in the field.

A number of motor learning experiments have been undertaken within a laboratory setting: finger wagging (Kelso, 1981), hand writing (Newell & Van Emmerik, 1989), multi-degrees of freedom task throwing (McDonald, Van Emmerik & Newell, 1989), skiing (Vereijken et al., 1992; Hong & Newell, 2006), gait (Chang, Van Emmerik & Hamill, 2008) and dynamic balance task (Ko et al., 2013; Dutt-Mazumder & Newell, 2017; Dutt-Mazumder et al., 2018). By performing these studies in a laboratory it is possible to ensure greater control over the environment and therefore, reducing the potential for error.

Dart throwing was examined by McDonald et al. (1989) to identify the movement patterns of the dominant and non-dominant limbs. For this task, higher cross-correlations between joints in the non-dominant limb were associated with a reduction in the redundant degrees of freedom early-on in learning. As a function of practice there was an overall reduction in trajectory variability while the amount of joint-space variability was generally maintained.

For the task of bouncing a basketball, Broderick and Newell (1999) examined the role of variability in the precision of this motor task. Participants were of different ages ranging from 4 to 22 years and with varying skill levels. By identifying the coordination patterns of people with a range of skill levels, less skilled participants were found to be more variable in their performance compared to more skilled participants. The coordination patterns showed that the less skilled participants displayed greater variability than participants with a greater skill level. As a function of skill level, a directional change was present in the articulator's motion both proximally and distally towards the centre of the kinetic chain. The findings showed

the importance of studying the changes in the organisation of the system in order to understand the control and coordination of the system.

The self-organisation of postural coordination during a dynamic balance task on a moving platform was investigated by Dutt-Mazumder et al. (2018). The findings reported that CoM-platform coupling at higher frequencies was less deterministic compared to lower platform frequencies. Coupling progressed to intermittent strategies of postural control which oscillated between periodic-chaotic transitions, presumably in order to help the participant maintain upright posture. From the results it is suggested that multiple dynamics modes of coupling were present for postural control that can interchangeably exist simultaneously.

Some environmental constraints to action can be replicated in a laboratory setting such as gravity, temperature and equipment. Other constraints to action prove more challenging for researchers to replicate in the laboratory such as the psychological factor of knowing you are being tested and the association between perception and action which is something that cannot be fully accounted for (Renshaw et al., 2010). An inevitable trade-off is always present between laboratory and field testing, and it is particularly important for researchers to acknowledge this trade off and ensure every effort is made to collect the most ecologically valid data (Elliot, Alderson & Denver, 2007). However, it has often been near impossible to conduct research in human movement that is completely ecologically valid. The factors that influence this could be the environment that has changed, the placement of active markers on the participants or the psychological strain of the participants knowing that their

movement is being measured (Liu, Mayer-Kress & Newell, 2006; Liu et al., 2012; Williams et al., 2016).

2.3.2 Time Scales

During motor learning the time scales for learning may vary among individuals. It is suggested that the time scale of technique change is due to the intrinsic dynamics and constraints of each individual (Newell & Vaillancourt, 2001; Langendorfer & Robertson, 2002). The determination of learning was traditionally confined to the evaluation of a continuous learning curve. This theoretical strategy has been rationalised in traditional and contemporary theories of learning by the general assumption that the influence of practice on the rate of learning decreases systematically due to the biological system limits (Newell & Vaillancourt, 2001). Transitory phases in performance over time are usually averaged out in the assessments of motor learning and control. The persistent changes that characterise learning and development are those that are relatively slow and occur over a single practice session, days, months and years. In contrast, the transitory changes are relatively fast such as those that occur within particular segments of a single practice session (Newell & Vaillancourt, 2001). The largest change occurs during the warm-up decrement where performance is brought up to the current stable level. Warm-up decrement time reduces as skill level increases (Newell & Vaillancourt, 2001).

Longitudinal data collection over years has been conducted to examine technique changes in overarm throwing action as a function of ageing in both children (Robertson & Langendorfer, 1984; Robertson & Konczak, 2001; Langendorfer & Robertson, 2002)

and older adults ranging in age from 61 to 82 years (Williams et al., 1998). Langendorfer & Robertson (2002) reported that despite the presence of commonality in overarm throwing development during a 3.3 year period in both the order of technique and pathway change, individual differences occurred in the profiles. This was displayed across the group at any given age and in some of the pathways from profile to profile were large enough that they did not form a common, developmental sequence. Other longitudinal studies conducted over weeks rather than years include Kernodle & Carlton (1992) and Southard (2006) who investigated the effect of information feedback on learning gains with non-dominant arm over a period of overarm throwing practice. Newell et al. (2001) provided evidence to suggest that learning rate is individual and task specific even when a persistent change is present across all individuals of a study (Langendorfer & Robertson, 2002; Haibach, Daniels, & Newell, 2004; Williams et al., 2012; Williams et al., 2015; Liu & Newell, 2015; Lee et al., 2016; Pacheco & Newell, 2018; Dutt-Mazumder & Newell, 2018). The use of longitudinal study design during motor learning studies would provide novel insight of biomechanical technique changes.

Another approach to studying technique changes in motor tasks is the collection of cross sectional data. This study design involves studying individual who differ on a single aspect with data collected at the same time. Differing characteristics between the cohorts could be age, income, or geographic location. Cross sectional data analysis is able to recognise which inter and intra technique characteristics of performance might change in order to reach high performance levels. It can imply progress, however, longitudinal data is needed to reveal the nature of this development. Cross-

sectional studies have identified technique changes (Robertson, Williams & Langendorfer; 1980; Stodden et al., 2006*a,b*; Wilson et al., 2008; Robertson, 2013).

In conclusion, a longitudinal study design is held as the gold standard for revealing motor development. However, longitudinal data collection is not without its disadvantages making it an unattainable option in some cases, such as: challenges associated with a longitudinal study design (e.g. time scale, funding, availability of laboratory space, participants) and retaining participants throughout the study. A cross-sectional study offers a much more attainable study design, which is not limited by the previously mentioned challenges of longitudinal data collection; however, it is only ever able to imply changes in technique.

2.3.3 Variability

Traditionally coordination variability was associated with noise, lack of skill and was detrimental to skill acquisition with a reduction in coordination variability associated with aiding skill development (Davids et al., 2003; Schmidt et al., 1979; Slifkin & Newell, 1999). There is also growing evidence that the nature of movement variability is driven by the interaction of the various sources of constraints on action, and this leads to the uniqueness of the system dynamic for a particular performer under a specific task constraint (Davids et al., 2003). Even with elite athletes after years of practice, they may be unable to reproduce identical movement patterns. An increase in expertise does not lead to movement invariance and the constrictions of a single, pre-determined motor pattern, as argued in cognitive science theories of motor control (Davids et al., 2003).

From a DST perspective, movement variability is a central theoretical issue of motor learning (Hamill et al., 1999; Davids et al. 2003). Within motor learning Newell (1985) suggested variability to be a functional distinction between coordination and the control stage of learning. Coordination variability is thought to have different functional roles during skill acquisition and refinement (Davids et al., 2003; Newell, 1985).

When an individual performs the same motor skill multiple times it may be anticipated that they are trying to use the same technique each time. The human system has a redundant combination of release parameters that can result in the same outcome through variation in the kinematics which are utilised. It is now understood that with each attempt there will be variability in the kinematics (Newell & Corcos, 1993; Wilson et al., 2008; Ko et al., 2017). It should always be established how movement variability is related to the completion of the skill, and the presence of increased movement variability should not simply be attributed to higher or lower levels of performance.

An increase in variability can be associated with releasing the redundant degrees of freedom during skilled performance (Newell, 1985). An increase in variability allows the performer to cope with perturbations presented by the task and the environment. High variability in skilled performance is referred to as functional variability where the occurrence of more variability plays a functional role in stabilising or creating movement consistency (Hamill et al., 1999; Van Emmerik, Hamill & McDermott,

2005). In other words it affords the system with a certain amount of flexibility that allows the individual to meet the change perturbations.

It has been hypothesised by Newell et al. (2001) that the function of change at the task level provides the necessary evolving set of movement strategies for the dynamical system at multiple levels of analysis. This is related to the organism-environment interaction, each with its own changing time scale. Movement variability has been suggested to decrease as a function of practice (Newell 1985; Chow et al., 2008). With the role of functional variability enabling individuals to adapt to the ever-changing constraints imposed on them (Davids et al., 2003; Piek, 2002) and therefore offers flexibility to these changing perturbations rather than being a characteristic of unskilled movement (Hamill et al., 1999; Van Emmerik & Van Wegen, 2000). Low variability is a characteristic of a stable state consistent over time, while high variability is associated with exploration of the system and the refinement of a movement skill (Hamill et al., 1999). This has been supported in a range of motor skills: running (Hamill et al., 1999), triple jump (Wilson et al., 2008) and gymnastics long swing (Williams et al., 2015; Busquets et al., 2016).

Coordination variability within movement is present in adults and children alike and provides pathways in which movement can successfully be achieved (Novak, 1998; Busquets et al., 2016). The system interpretation of the imposed constraints is individual specific leading to an alternative pattern of coordination for the same task. Inter-individual variations in movement patterns may, therefore, be interpreted as adaptive behaviour as part of the dynamical neurobiological system exploiting the surrounding constraints to shape the functional, self-sustaining patterns of behaviour

that emerge in specific performance or rehabilitation contexts (Glazier & Davids, 2009). Therefore, variability is not necessarily good or bad, but instead indicates the range of coordination patterns of the motor control systems and enables the system to adapt to changing perturbations (Haken et al., 1985; Schöner & Kelso, 1988; Van Emmerik & Van Wegen, 2000; Chow et al., 2006; Preatoni et al., 2013; Verhoeven & Newell, 2016; Ko et al., 2017).

Intra-limb coordination variability was examined by Wilson et al. (2008) in 5 competitive male triple jumper to determine the influence of skill on coordination variability. The findings suggested that individuals of intermediate skill level displayed the lowest coordination variability. Wilson et al. (2008) proposed that coordination variability was consistent with a 'U' shape relationship with the greatest variability present for beginners and experts. High variability was present during early stages of skill acquisitions as participants began to explore appropriate movement strategies to meet the task demands. Meanwhile, high variability for skilled participants has been associated with greater inter-limb variability (Bernstein, 1967; Wilson et al., 2008; Broderick & Newell, 1999; Chow et al., 2008).

Measures of variability during a series of dominant and non-dominant arm free-throw shots in a group of college age basketball players have been demonstrated by Verhoeven and Newell (2016). Poor shooters were characterised by releasing the ball lower to the ground and having significantly higher CoM speed compared to good and elite shooters. Good shooters were characterised by greater variability of speed of release compared to poorer shooters. The synchronization between the time of peak CoM and time of release increased as a function of skill level. This implies that more

skilled participants were able to successfully control trial-to-trial variability in addition to coordination of postural control and release properties.

The coordination and variability of posture and pistol motion for skilled pistol shooters and novices in a pistol-aiming task was investigated by Ko et al. (2017). The findings showed that pistol and posture motion (CoP) was lower for the skilled pistol shooter compared to the novice pistol shooter group. The coordination pattern of posture and pistol motion for the novice group was more variable with the motion of the pistol leading the posture motion in the novice group while it lagged in the skilled group. The findings of Ko et al. (2017) support the proposition that skill acquisition reduces the kinematic variables into a lower collective dimension and that postural control was a vital component of skilled arm-pistol shooting with different qualitative and quantitative dynamics present at different skill levels.

It has been suggested by Busquets et al. (2016) that variability has differing roles for novices compared to skilled individuals with variability taking either a ‘U’ shaped hypothesis (Wilson et al. 2008) or an L-shaped hypothesis following a cross-sectional change of inter-trial variability during long swing performance of 113 male gymnasts of beginner, intermediate and advanced skill level. Vicinanza et al. (2018) investigated the macroscopic dynamics of the long swing in 16 mixed ability gymnasts ranging from elite to novice level. Coordination variability of lower limb kinematics for skilled participants during the longswing was consistent with the ‘U’ shaped hypothesis (Busquets et al. 2016; Wilson et al. 2008). Vicinanza et al. (2018) suggested that the level of the system examined will show different aspects of coordination variability and this is something that should be taken into consideration before testing.

Biological movement variability of international level female gymnasts was investigated by Farana et al. (2014). Skilled gymnasts showed that less repeatability was present for internal/external rotation angles during fundamental skills suggesting that they may have employed different strategies to complete the motor skill. Burton, et al. (2017) provided support for individual specific coordination variability during backwards handsprings. Burton et al. (2017) investigated the influence of upper limb coordination variability during backward handsprings. Findings reflected the individual specific nature of coordination pattern with each gymnast self-organising movement in order to achieve the skill, despite all individuals completing the same skill. In addition, variability was present between trials despite all trials been classed as successful.

2.3.4 Variables to Describe Technique

Existing literature tends to define the process of motor skill acquisition through applying constraints to the system such as information feedback (Kernodle & Carlton, 1992), instruction (Southard, 2006), scaling tasks (Southard, 1998, 2002; Van den Tillaar & Ettema, 2004; Hirashima et al. 2008; Zhu, Dapena & Bingham, 2009), altering stride length (Ramsey, Croft & White, 2014), and attention (Southard, 2011). However, simply defining the end position is not enough to provide in-depth analysis and understanding of motor control underpinning the movement. There are three complementary approaches used for quantifying technique changes in human movement which include: the components model of overarm throwing, which is throwing specific model (Robertson & Halverson, 1984), Newell's (1985) learning

stages of coordination, control and skill and Bernstein's (1967) observation of freezing and freeing the redundant mechanical degrees of freedom.

The components model of overarm throwing (Robertson & Halverson, 1984) tracks qualitative technique changes through the relative changes of four components: 'step', 'trunk', 'humerus' and 'forearm'. This model has been examined extensively in the study of overarm throwing during childhood (Robertson & Langendorfer, 1984; Robertson & Konczak, 2001; Langendorfer & Robertson, 2002; Stodden et al. 2006*a,b*) and older adults ranging in age from 61 – 82 years (Williams, et al., 1998).

From a contemporary DST perspective of motor control, two stages of learning models have been suggested for the development of general motor skills. Newell's (1985) stage of learning model provided a functional distinction between the constructs of coordination, control and skill, which were paralleled with stages of learning. In Newell's (1985) framework variables that describe technique and directions of change were purposefully not defined as it was hypothesised that both were task specific. More recent work however, has used collective variables to assess the constructs of the learning stages (Ko et al., 2014; Wang et al, 2014; Dutt-Mazumder, Challis & Newell, 2016; Dutt-Mazumder & Newell, 2017).

Bernstein's (1967) observation of freezing and freeing the redundant mechanical degrees of freedom captures qualitative and quantitative technique changes through either changes in joint angle ROM (Newell et al., 1989; Vereijken et al., 1992; Chow et al., 2008) and coordination variables (Ko et al., 2003; Verhoeven & Newell, 2016) during practice of novel tasks. It has also been explored in line with the notion of

freezing before freeing during motor learning. Overall, freeing degrees of freedom during learning has been suggested to be task specific and dependent upon the level of analysis during learning (Newell & Vaillancourt, 2001; Hong & Newell, 2006).

An independence in the pattern of change of mechanical degree of freedom compared to the dynamical degree of freedom during learning a ski simulator task has been identified by Hong and Newell (2006). The results suggested that the anatomical and task constraints influence the recruitment of the mechanical degree of freedom while principal components analysis showed that the degrees of freedom did not change. Chow et al. (2008) observed changes in movement patterns during the learning of a discrete multi-articular action (kicking a football). The authors reported that over practice there was no clear pattern in variability in the mechanical degree of freedom (joint ROM), while dynamical degree of freedom (angle-angle plots and cross correlation) became more similar to an expert's movement pattern. These studies highlight the multi-dimensional nature of learning and the changes in technique that accompany it including the importance of understanding learning mechanical and mastering the degrees of freedom. More recently research has begun to explore the nature of the control parameters and order parameter of movements (Southard, 2006, 2011; Ko et al., 2014; Chow et al., 2008; Dutt-Mazumder, Challis & Newell, 2016; Dutt-Mazumder & Newell, 2018; Dutt-Mazumder et al., 2018, Palmer et al., 2018). However, little progress beyond the HKB (Haken et al., 1985) model has been made to date.

2.3.5 Coordination and Measures of Coordination

Traditionally angle-angle plots have been used to gain understanding of coordinative patterns between variables, however, this approach does not provide a direction for coordination. Vector coding is a non-linear bivariate method used by DST theorists to examine coordination and the associated variability (Sparrow et al., 1987; Hamill, Haddad & McDermott, 2000). Vector coding provides a measure of the continuous interaction dynamics in time between two variables. This results in a coupling angle value between 0° and 360° (Sparrow et al., 1987, Hamill et al., 2000). Based on Chang, Van Emmerik & Hamill's (2008) four key coordination patterns were defined for vector coding:

- Anti-phase coupling ($112.5 \leq \gamma < 157.5^\circ$, $292.5 \leq \gamma < 337.5^\circ$) – variables are moving in opposite direction
- In-phase coupling ($22.5 \leq \gamma < 67.5^\circ$, $202.5 \leq \gamma < 247.5^\circ$) – variables are moving in the same direction
- Wrist-led phase coupling ($0 \leq \gamma < 22.5^\circ$, $157.5 \leq \gamma < 202.5^\circ$, $337.5 \leq \gamma < 360^\circ$) – wrist is a more predominant variable
- CoM-led phase coupling ($67.5 \leq \gamma < 112.5^\circ$, $247.5 \leq \gamma < 292.5^\circ$) – CoM is the more predominant variable.

Vector coding analysis has been applied in the investigation of gait analysis (Needham, Naemi, Chockalingam, 2015; Takabayashi et al., 2018; Harrison et al., 2019), gymnastic long swing (Williams, et al., 2016; Vicinanza et al., 2018), between football players (Moura et al., 2016) and backwards handspring (Burton et al., 2017).

Human movement is inherently complex with researchers seeking to identify methods that adequately demonstrate the complexity of the system. Traditionally, researchers have been limited to bivariate methods of analysis such as principal components analysis and vector coding due to the mathematical limitations (Richardson et al., 2012). A multivariate method to try and understand the level of coordination within or between individuals was proposed by Frank and Richardson (2010). The Kuramoto based Cluster Phase approach proposed a quantitative method to detect phase synchronization in noisy experimental data. Cluster Phase analysis provides a value of coherences between multiple moving components on a scale from 0 to 1. With a value of 1 representing complete coherence, so variables are moving in unison together and 0 representing differentiated timing of variables. The most commonly used quantifications are the mean and standard deviation of the relative phase time-series that occurs between variables, where the relative phase time series is calculated as the difference between the phase angles of the two movement time series. Cluster Phase and standard deviation Cluster Phase can be used to determine whether individuals are coordinated to the group as a whole in an in-phase or antiphase manner or in some other stable relative relations (Richardson et al. 2012).

Cluster Phase has been applied to study of the pattern of fireflies flashing (Hanson, 1978), cricket synchronization (Walker, 1969) and intrapersonal rhythmic movement in humans (Haken et al., 1985; Kelso, 1984; Schmidt, Shaw & Turvey, 1993). In a social science setting, Cluster Phase has also be used to examine synchronization of people (Richardson et al., 2007; Richardson, et al., 2012; Néda et al., 2000*a,b*), synchrony of players of a football team during match play (Duarte et al., 2013; Silva

et al., 2016) and changes in lower limb synchrony during running in ageing adults (Diss et al., 2019). More specifically, Diss et al. (2019) used the Cluster Phase method to examine changes in lower limb (ankle, knee and hip) synchronization as a function of ageing adult runners. Data was collected twice with a 7 year gap between testing session. The study reported that during the absorption phase tri-joint synchrony of the lower extremities (hip, knee and ankle) Cluster Phase increased with ageing. This finding suggests that the participants' movement action had become more rigid and synchronous with ageing that was thought to be due to the less healthy state. This is an analysis technique that could be applied to understand throwing action. Since the joints in the throwing arm segments have the ability to be much freer than those in the leg during running, there is a possibility that this increased ability for the upper limb joint to be 'freer' could lead to lower synchrony values than those reported by Diss et al. (2019). Currently no studies have investigated coordination in the three key joints that make up the upper limb.

2.3.6 Overarm Throwing

Overarm throwing is a fundamental, discrete, action that requires the coordination of the whole body (Knudson, 2007). Throwing can be described as an open chain movement meaning the distal end of the moving segment (the wrist joint) is free to move in space. An example of a closed movement would be the feet during weight lifting (Grimshaw et al., 2007). Overarm throws are normally characterised by external rotation of the upper arm in the preparation phase and internal rotation during the action phase. Individuals who are able to effectively utilise this transfer of energy through positive use of stride length, pelvis and trunk rotation, horizontal extension

and lateral rotation at the shoulder, elbow flexion and wrist hyperextension will ultimately demonstrate more advanced throwing capabilities (Knudson, 2007).

Overarm throwing is a skill for which non-dominant arm actions generally provide a less advanced movement organization pattern (Southard, 2006; Kernodle & Carlton, 1992; Newell et al., 1989). Therefore, non-dominant overarm throws can be directly compared to an individual's dominant overarm throw. Two key studies have investigated the effect of instruction and feedback on the development of non-dominant overarm throwing in adults (Kernodle & Carlton, 1992; Southard, 2006). Describing characteristics of technique changes following a 5-week practice period consisting of 10 practice session, Southard (2006) reported an increase in the arm and trunk segments experiencing positive segmental lag. Kernodle & Carlton (1992) examined technique changes following 4-week period of practice consisting of 12 practice sessions. Findings suggested that key cues to technique change related to the lag of the upper arm and elbow with respect to the shoulder. Interestingly, whilst segmental lag provides a biomechanically relevant technique parameter, it is not emphasised in the stages of learning models proposed in motor control literature.

Overarm throwing provides a rich movement task for which to study motor control and learning for three key reasons. Firstly, the overarm throw is a gross motor skill, which means it requires activation of large muscle groups including the whole body or multiple limbs (Cratty, 1964). Throwing in particular requires both upright, dynamic postural control with the legs and torso, and specific arm action. Conversely, fine motor skills involve smaller muscle groups and are related to smaller actions which tend to occur at the wrist, hands, fingers, feet and toes (Cratty, 1964). Fine

motor skills have been studied in work such as finger wagging (Kelso, 1984) and hand writing (Newell & Van Emmerik, 1989) and provide basic science information on the nuances of motor control; however, a limitation of this work is the ability to generalise findings to many real world gross and complex motor skills. Therefore, studying a gross motor skill such as throwing enables an understanding to be gained of how the body is organised as a whole to produce a coordinated and controlled movement which a fine motor skill would be unable to provide. This is beneficial because the process of self-organisation is particularly relevant when there are many redundant degrees of freedom (Lui et al. 2012; Ko et al., 2014; Lee et al., 2016; Ko et al., 2017), providing a rich landscape to study technique change. In addition, gross motor skills such as throwing are classed as fundamental skills.

Secondly, fundamental motor skills are defined as the building blocks of complex movements (Clark & Metcalf, 2002) that involve the activation of large muscle groups (Logan et al., 2001). Fundamental motor skills are classified as either locomotor or object control (Haywood & Getchel, 2009), with locomotor skills referring to movements that propel the body such as running, jumping or leaping (Logan et al., 2011), and object control skills as those that involve reception and/or propulsion of an object, such as throwing, catching and kicking. Throwing is included in this category due to its link to our fundamental existence in hunting, gathering and building (Isaac, 1987). The use of a fundamental motor skill means that the work is particularly ecologically valid. In the modern world, the skill of overarm throwing is taught to children and is a critical element of primary health and physical education programmes, as children develop basic movements for life. Moreover, throwing is a prevalent skill for many sporting activities. In addition, understanding practices that

facilitate throwing should be included in instruction and practice that facilitates motor learning in general. Therefore, using throwing as a vehicle to study technique change during practice has advantages over previous research that has studied how adults learn novel skills, such as the gymnastics longswing (Williams et al., 2012, 2015). These skills were useful for providing a mechanism to study technique changes in adults, however, it is not relevant to skill development in populations such as those recovering from injury or stroke, for example, who may never need this skill. With throwing it is possible to study the learned action through the dominant arm, and the more unskilled action through the non-dominant arm (Southard, 2006; Kernodle & Carlton, 1992). Therefore, throwing is an ecologically valid skill to develop in children, and provides a more novel skill when transferred to the non-dominant side in adults. In light of this advantage, one of the research questions in this thesis is in understanding whether technique changes were similar between adults learning with the non-dominant hand and children at different ages throwing with their dominant arm.

Lastly, based on the gross and fundamental nature of the throwing action, there are major theoretical challenges associated with understanding developmental technique which include: at what level of the system research should be focused e.g. that of muscle action, kinematics (joints or limb or centre of mass), kinetics, or energetics; and how best to capture technique change over time (longitudinal or cross sectional). These challenges are key to the understanding of motor control and learning in general. Initial attempts to capture technique change during learning to throw have been made, and resulted in the development of models, such as Robertson and Halverson's (1984) components model, and principals such as proximal to distal order of arm extensions.

This body of work provides a platform to help guide motor learning research in this particular skill.

2.4 Developmental Stages of Throwing

Considerable research has focused on identifying the series of stable states that occur when practising complex motor tasks. In particular, the overarm throw has received substantial study with Robertson and Halverson's (1984) components model being referred to frequently within the literature (Halverson, Robertson & Langendorfer, 1982; Williams et al., 1998; Yan, Payne & Thomas 2000; Robertson & Konczak, 2001; Langendorfer & Robertson, 2002; Runion, Robertson & Langendorfer, 2003; Southard, 2006; Stodden et al., 2006*a,b*; Robertson, 2013; Palmer et al., 2018). The components model (Robertson & Halverson 1984) is based on years of longitudinal study of the same cohort of children from kindergarten to 7th grade. The components model refers to a series of stable action levels of four separate body segments involved in overarm throwing where components can 'advance' or 'retreat' up and down a continuum of action levels (Table 2.1).

Support was provided for the components model (Robertson & Halverson, 1984) by Yan et al. (2000) in their study involving observation of 3 to 6 years old. They found that 3 and 4 year olds showed greater timing difference between peak velocity and ball release than 6 year olds. Three and 4 year olds were unable to fully utilise their whole-body during throwing movement. This is in comparison to 6 year old group who appeared to have eliminated some immature movement such as trunk flexion and used

mature throwing forms. They released the ball at a greater elbow angle than the 3 to 4 year olds which could result in faster angular velocity of the elbow extension.

Table 2.1 **Developmental sequence for overarm throwing for force**
(Robertson & Halverson, 1984)

Action Level	Humerus action	Forearm action	Trunk action	Stepping action	Length of final stride
1	Humerus oblique	No action	No trunk actions	No step	Short
2	Humerus aligned but independent	Forearm lag	Upper trunk rotation or total trunk. Spine and pelvis rotate away from the intended line of flight and then begin to move forward.	Ipsilateral step. Step forward with the same foot as throwing arm.	Intermediate
3	Humerus lags	Delayed forearm lag	Differentiated rotation. Pelvis rotates prior to upper spine. The body is twisted away from the intended line of the ball flight and then begins forward rotation with the pelvis while the upper spine is still twisting away.	Contralateral step. Step with opposite foot as throwing arm	Long
4				Contralateral long step	

Kinematic changes in overarm throwing of children aged between 3 and 15 years of age were compared to the components model (Robertson & Halverson, 1984) by Stodden et al. (2006*a,b*). The results strongly supported categorisation of the components by the kinematic variables. Greater stride length, faster pelvis linear velocity, faster upper torso linear velocity and greater trunk tilt were all associated with advanced developmental levels of stepping and trunk action as well as faster throwing velocity.

In older adults aged between 62 and 71 years, Williams et al. (1998) studied overarm throwing action during a 7 year period. The findings were similar to intermediate developmental profiles reported by Halverson et al. (1982). Williams et al. (1998) suggested that changes in components, for example, the step length and rotation of the trunk rotation, suggests that developmental action levels are not necessarily as sensitive to change as kinematic parameters. Over time, changes that were unable to be categorised were present through a decrease in ROM and increased trial-to-trial variability was associated with a change in action level.

An impressive longitudinal study was undertaken by Halverson et al. (1982) who observed the development of overarm throwing from kindergarten to 7th grade. The paper concluded that by 7th grade, skill acquisition of overarm throwing was still not fully attained, meaning instruction should still be provided within schools. Longitudinal data is in some ways prized as the gold standard for motor learning research due to the information it can provide for how an individual changes over time. However, the repeated multiple practice bouts has the potential to make the participants unrepresentative of their age group because this in itself allows skill

development. Moreover, longitudinal data can confound generational or cohort differences. In this view, Runion, et al. (2003) examined throwing technique of 13 year olds during 1999 and compared this to data collected in 1979 from children of the same age. The findings demonstrated that the throw of a cohort of children who were 13 years of age in 1999 were essentially the same as those of 13 year-olds in 1979 despite changes in life style of some teenagers.

2.4.1 Throwing Control and Order Parameters

In an attempt to identifying throwing and control parameters, researchers have studied technique change during scaling tasks. Southard (1998) tried to quantify parameters by altering task constraints through changing the mass and velocity of the upper limb segment during throwing action. Altering the mass of upper limb segment during throwing action increased velocity of segmental lag through trunk rotation in less skilled throwers. Segmental lag refers to the transfer of angular velocity from the heavier distal segment to lighter proximal segment. Velocity acted as a control parameter, driving the system beyond its normal range, which forced reorganisation of components into a new coordination pattern.

In order to try and establish if commonality was present in overarm throwing development Langendorfer and Robertson (2002) reviewed previous work (Halverson et al., 1982, Robertson et al., 1979) to try and identify profiles from the components model. Specifically, they were looking to see if the profiles were 'linked' across trials within time and to identify 'pathways' by which individuals changed from one profile to another over time. Results indicated that while some pathways were more attractive

than others, no single, common, developmental pathway occurred. In addition, it was suggested that early in throwing development, changes in the trunk rotation may drive changes in the arm segment actions.

2.4.2 Biomechanics of Throwing

The goal of throwing is generally a combination of distance and accuracy but will be determined by the task goal (Bartlett, 2007). Throwing movement can be subdivided into three phases: preparation phase, pulling phase and follow through phase. The preparation phase occurs from initial backwards hand movement to maximal horizontal extension of the shoulder. The preparatory phase facilitates eccentric contraction of the shoulder in the anterior direction by the abduction and horizontal extension of the shoulder. This enhances the velocity of the movement and allows for a greater impulse to develop (Grimshaw et al., 2007). In the pulling phase, throwing velocity is developed through the sequential acceleration of joints from the proximal to distal segments. During early pull muscles contract concentrically, overcoming external forces, allowing for the sequential rotation of the pelvis and trunk. The shoulder then internally rotates and the elbow rapidly extends in the late pulling phase as the radius of the arm is increased to generate maximum velocity in the distal segment (Grimshaw et al., 2007). During late pull, eccentric elbow flexion torque is produced throughout arm deceleration to slow elbow extension. Maximum elbow compressive force occurs just after ball release to prevent elbow distraction. In the follow through phase, the aim is to bring the movement to a controlled stop. Follow through can be classified from ball release to maximum shoulder extension (Grimshaw et al., 2007). The elbow flexes into a compensatory position as the trunk and the arm

rotate forwards (Fleisig et al., 1996). During initial follow through muscles of the shoulder are still very active in the deceleration of the throwing arm. Lower extremities and the trunk help dissipate energy in the throwing arm during this phase (Fleisig et al., 1996).

Table 2.2 **Joint movement during overarm throwing action (Grimshaw et al., 2007)**

Joint	Preparation phase	Early pull	Late pull	Follow through
Trunk	Lateral extension	Rotation	Rotation	Rotation
Shoulder	Rotation	Flexion	Flexion	Flexion
	Horizontal extension	Horizontal extension	Internal rotation	Shoulder adduction
	Abduction	External rotation		
Elbow	Flexion	No movement	Extension	Flexion
Wrist	Extension	No movement	Flexion	Flexion Pronation

2.4.3 Kinematics of Throwing

Overarm throwing can be regarded as a whole-body movement with energy thought to be transferred from the lower extremity along the kinetic chain to the upper extremity and finally the ball. The ability to regulate forward momentum is related to throwing arm performance with the lower extremity contribution influencing the sequential and coordinated transfers of energy along the kinetic chain. Ramsey et al. (2014) suggested that step length provides a pivot for which the pelvis can rotate, altering total body linear momentum. Step length, thereby, alters the proportion of

throwing arm momentum relative to the total body with the drive leg initially generating total body linear movement and is then arrested by the stride leg at stride foot contact.

Pelvis orientation is an important aspect in overarm throwing and has been highlighted as a characteristic which separates less and more skilled throwers (Stodden et al., 2006a). Adopting an open pelvis provides a pivot for trunk rotation when compared to a closed pelvic position, this rotation of the trunk results in successful transfer of kinetic energy from lower extremity to the upper extremity.

During the early pull phase, the shoulder moves from the horizontal abduction to horizontal adduction and back in the direction of horizontal abduction just prior to ball release. Late pull is described from maximal external rotation of the shoulder to ball release with ball release marking the end of acceleration. Following the acceleration of the throwing arm, the arm needs to decelerate. Flexion of the lower extremity and flexion with a rotation of the trunk. The shoulder goes from a minimal abduction to adduction with internal rotation.

The instant of maximum internal rotation torque during the pull phase and the instant of maximal compressive force during arm deceleration were identified as two critical points for the shoulder (Fleisig et al., 1996). The shoulder of the non-throwing arm is an important pivot for the trunk and throwing arm to rotate around. Murata (2001) found that reduced shoulder joint movement of the non-throwing arm reflected higher skill level in male baseball players. The trunk twisted around an axis located near the

shoulder of the non-throwing arm and was free to tilt from side to side and lower the vertical position of the shoulder.

The action of shoulder internal rotation, elbow extension and wrist flexion was studied by Hirashima et al. (2008). They found that skilled throwers utilised the interaction torques to generate large angular velocities for all three joint rotations. The muscle torque at the joint mainly produces acceleration at the leading joint. This joint motion generates a powerful interaction torque at the other subordinate joints. The muscle torque at the subordinate joint regulates the interaction torque to fulfil the task demands. This is consistent with Bernstein's (1967) suggestion that the role of muscle activity is not only to accelerate the limb but also to control the intersegmental interaction. In this regard, the stretch shortening cycle is also utilised. The stretch-shortening cycle is the process of two muscles phases: firstly eccentric loading followed by rapid concentric shorting. This process of loading and constraint generates stored elastic energy which can sustainably be utilised in the movement (Zatsiorsky & Prilutsky, 2018).

The mechanics of coordination that enables the skilled arm of recreational baseball players to throw at fast speeds and with a smooth motion was studied by Gray et al. (2006). Eight male right-handed throwers completed 30 throws at a slow speed and 30 throws at a fast speed. Findings indicated that kinematic differences were present between the skilled and unskilled arm. This was associated with differences in the ability of the two arms to control interaction torques. Specifically, it is proposed that skilled throwers have developed the mechanism in their skilled arm that enables them

to exploit interaction torques at the elbow and wrist. These mechanisms which are associated with deceleration of proximal segments are complex.

An examination of the differences between non-dominant and dominant limb throwing accuracy was undertaken by Hore et al. (1996). They measured the 3 three-dimensional rotations of the shoulder, elbow, wrist and finger joint in 'good' throwers. Participants completed 150 throws from a seated position. Findings suggested that hand trajectories and rotations at all joints were, in general, more variable for non-dominant arm than those of the dominant arm. Decreased accuracy with the non-dominant arm was primarily caused by increased variability in the timing onset of finger extension and therefore in the timing of ball release, not by a decrease in variability in the proximal joints affecting hand trajectories.

2.4.4 Kinetics

Research has examined the timing and sequencing of the segments involved in complex movement through examining scaling tasks in order to alter segmental lag (Southard, 1998, 2006; Zhu et al., 2009; Zhu & Bingham, 2010; Van den Tillaar & Cabri, 2012). Segmental lag refers to the transfer of angular velocity from the heavier distal segment to lighter proximal segment. This results in an increase in velocity of the most distal segment and conserves angular momentum between the segments. This creates a kind of domino effect of the limbs starting with the feet and moving upwards towards the hand. In throwing movement this would be the hand and subsequently ball. This whip-like action occurs if the mass of the distal segment is less than the mass

of its proximal neighbour and if the distal segment lags behind its proximal neighbour (Southard, 1998).

The effect of time-scaling of joints during dominant and non-dominant throwing action in skilled participants was examined by Hore, O'Brein and Watts (2005). Findings showed that time-scaling was present for non-dominant arm throws for the majority of the upper limb joint rotations measured. Many non-dominant joint space patterns were not significantly different from those predicted by time-scaling which eludes to the possibility that time-scaling could apply for a completely unskilled arm. It is also suggested that the joint space pattern of the upper limb resembled that of predicted time-scaling during an unskilled action. Other work by Hirashima et al. (2008) examined the impact of joint torque and velocity-dependent torque on joint angular acceleration during baseball pitching. Their findings were consistent with the kinetic chain principle where the acceleration of the distal segments are generated by powerful muscles located in the proximal segments.

Another constraint acting upon a thrower is the stiffness of the ground where the throwing is being undertaken. In comparison to segmental dynamics, the ground is considered to be rather stiff. Therefore, if force is applied over a short period time, for example transferring weight from back foot to forefoot or taking a contralateral step, this may increase the ground reaction forces experienced by the body, even though the change in segments position/velocity is small (Zajac, Neptune, and Kautz, 2003). Muscles are important as they produce force and provide support for the body and allow for redistribution of the work load as internal and gravitational forces alone are insufficient to achieve task goals requiring the support of the muscles.

2.4.5 Balance

Balance is a multidimensional construct (Atwater et al., 1990) and is defined as the ability to maintain the CoM within the base of support (Shumway-Cook & Woolacott, 2012). This is achieved via muscle action to excursion of CoP. Balance is integral to the safe execution of movement with the ability to maintain and control balance recognised as a fundamental component of motor control.

The CoP refers to the location at which vertical ground reaction force vector is located and represents a weighted average of all the pressure experience by an individual over a surface, typically the foot. Therefore if a single foot is located on the ground the CoP will lie within that single foot; if both feet are located on the ground the CoP will be located somewhere in between both feet. Moreover, the location of the CoP is directly related to the neural control of the muscles at the ankle joint, and therefore an increase in plantar flexion of the ankle would cause the CoP to move anteriorly. The CoP is completely independent of the CoM (Winter, 1995).

It has long been recognised that the mechanical constraints on preserving stability in postural stance is for the CoM to remain within the base of support and that the development of CoP pathways demonstrates the mastery of the redundant degrees of freedom, in order to produce coordinated and controlled movement (Fujinaga, 2008). Postural control can be examined during static (upright standing) and dynamic (motor skill performance) situations (Verbecque et al., 2015; Shumway-Cook & Wollacott, 2001; Karlsson & Frykberg, 2000). Balance has predominantly been used to examine postural stability during static tasks. This can be illustrated in static tasks where the

CoM needs to remain within the base of support by controlled muscle action to excursion of the CoP. The smaller the CoP excursion is the greater the stability achieved by the individual (Hof, 2007). The effect of stance position such as two feet, one foot with eyes open and eyes closed conditions have been examined (Hof, 2005). CoP movements have also been studied when weight is shifted in the medial-lateral, anterior-posterior direction and in line with the effect of having arm extended sideways (Hof, 2007). Postural control during a dynamic action, such as throwing, provides a valuable insight into how the perceptual-motor system is re-organised to meet the spatial and temporal constraints of the environment. Measuring the CoP can provide information on postural stability (Haas et al., 1989).

Skilful throwing action is characterised by accuracy in reaching the target whether that be a team mate or through the hoop at the end of the court. With respect to understanding throwing action during childhood a major implication of the DST is the constraints of the developing movement system as many cannot be isolated to unique influences, such as perceptual skill (Thelen, 1995). When completing an overarm throw for force there is a sudden shift in the CoM due to the sudden movement of the throwing arm. The postural system has to compensate for a sudden shift in order to keep the CoM within the support surface in order to maintain equilibrium (Van der Fits et al., 1998). Less skilled throwers may not have the ability to maintain equilibrium, which in turn would influence positioning of the distal component of the throwing arm then impacting on performance. The capacity of an individual to adapt to the postural demands of overarm throwing when standing upright could be the major rate-limiting factor on performance (Davids et al., 2000).

CoP movement has been viewed in different sports as well as balance tasks. Era et al. (1996) observed that internationally ranked shooters were able to significantly stabilise their posture more effectively than national level shooters and novice shooters. This was achieved by significantly lowering the mean moment velocity in the medial-lateral and anterior-posterior directions and significantly decreasing the amplitude of CoP. Similar collective variables were reported by Ball and Best (2007*b*) whilst observing the action of golfers. It was reported that a high correlation was present between the CoP pathway and velocity of CoP. This high correlation demonstrates the organisation of the degrees of freedom. Ball and Best (2007*b*) also found that weight transfer in golf is an important variable in both front and reverse foot swings. However, individual differences should be considered when assessing CoP pathways as individual differences in movement patterns influence the extent of the weight transfer (Ball & Best, 2007*a*).

During childhood proficient development of postural control occurs as age increases and from a child's interaction with their environment (Newell, 1986; Roncesvalles, Woollacott & Jensen, 2001). The flexibility of the movement results in adjusting motor patterns to changing context as discontinuity and new forms emerge from interaction to the environment (Thelen, 1986). The first decade of a child's life is vital in the development of coordinated and controlled movement with children beginning to display similar balance to adults from 6 to 7 years of age (Nolan, et al., 2005). Condon and Cremin (2014) examined performance norms during static balance tasks in children aged 4 to 15 years. Findings demonstrated the range of 'normal' balance ability in children, static balance tests improved with age with a transition period seen from 7 years of age. Studies have suggested that balance is generally established

between 7 and 10 years of age (Roncesvalles et al., 2001; Ferdjallah et al., 2002). Mickle, Munro and Steele (2011) measured postural sway of primary school children using a posturography under the following static conditions: static dual limb stance (feet shoulder width apart), dual limb stance (feet together) and single limb stance (standing on dominant lower limb). The findings suggested that balance is slowly developed and fine-tuned up until 10 years of age, however postural stability is still being developed beyond 10 years of age.

The CoP pathways can represent the development of postural stance and demonstrates the mastery of the redundant degrees of freedom (Fujinaga, 2008). Examining the CoP during overarm throwing action could provide a new variable to describe throwing performance. Previous research has focused on identifying the series of stable states in overarm throwing technique that occur when practising complex motor tasks by observing action of the joints. In particular the components model of overarm throwing (Robertson & Halverson, 1984) is often referred to within the literature (Halverson et al., 1982; Williams et al., 1998; Yan et al., 2000, Langendorfer & Robertson, 2002, Southard, 2006, Stodden et al., 2006*a,b*, Palmer et al., 2018). A better understanding of postural stability and the development of postural control during dynamical movements, such as throwing, is important for many reasons. Specifically, it will provide a valuable insight into how the perceptual-motor system is re-organised to meet the spatial and temporal constraints of the environment and allows for balance and coordination to be viewed in the same problem, providing an ecologically valid insight into motor control.

2.5 Chapter Summary

This chapter has examined and discussed existing literature from motor learning and biomechanics relevant to learning overarm throwing action. Motor learning researchers are yet to fully understand and explain technique changes during motor learning that adequately details changes at all levels of the system. Two stages of learning model are present: Newell's (1985) stages of learning and Bernstein's (1967) hypothesis of freezing and freeing. Newell's (1985) stages of learning model of coordination, control and skill provides functional distinction between the three constructs. Newell (1985) did not suggest as to the variables to study the model since it was hypothesised that both were task specific. Collective variables have been used in Newell's recent work to assess the constructs of the learning stages (Ko et al., 2014; Wang et al., 2014; Dutt-Mazumder, Challis & Newell, 2016; Dutt-Mazumder & Newell, 2017). The components model (Robertson & Halverson, 1984) provides the only throwing specific model to examine change in technique, however the model is based on qualitative described data and therefore could be open to interpretation. Bernstein's (1967) hypothesis has received conflicting support with the suggestion that the process of freezing and freeing is task specific (Newell & Vaillancourt, 2001; Hong & Newell, 2006).

A number methodological issues need specific consideration in future research. Specifically, research needs to be conducted that is ecologically valid and defines the constraints to action (Newell, 1986; Van Emmerik et al., 1989; Vereijken et al., 1992; Hong & Newell, 2006; Renshaw et al., 2010). Moreover, there is a need for integrated mechanical and dynamical technique descriptors to provide a detailed picture of

technique changes (Hong & Newell, 2006). Therefore, overarm throwing is a particularly beneficial vehicle to study the effect of learning human movement from a mechanical and dynamical perspective. Biomechanics literature provides key characteristics of technique associated with optimal throwing action (Kernodle & Carlton, 1992; Southard, 2006; Fleisig et al., 1996; Oliver & Plummer, 2015) and the components model of overarm throwing (Robertson & Halverson, 1984) indicating stages of development during overarm throwing action (Langendorfer & Robertson, 2002; Williams et al., 1998).

This review of literature has provided biomechanical explanation of technique changes in overarm throwing action. Studying non-dominant overarm throwing action in adult and cross-sectional analysis of dominant arm throwing in children and adolescents would provide a novel understanding of overarm throwing action technique. Theoretically, underpinned by DST of motor learning this thesis aims to provide ecologically valid evidence toward a general theoretical framework that characterises motor learning and will help further understand changes in novice technique. This chapter informs the overall aim of this thesis: to study technique changes as a function of practice in adults and across childhood and adolescence associated with learning a fundamental complex motor skill, namely, the overarm throwing action. Research questions to address this aim are proposed in chapter 1.3 and are addressed through a series of analyses reported in chapters 3 to 6. Chapter 2 has helped to inform chapters 3 to 6 by examining current motor learning and biomechanics literature that is associated to the learning of the movement skill. A review of literature on technique changes over childhood and with practice helps to inform the methods of the experimental chapters 3 to 6.

CHAPTER 3: Qualitative and Quantitative Change in the Kinematics of Learning a Non-Dominant Overarm Throw

3.1 Introduction

Chapter 2 provided a critical review of researchers' current understanding of motor learning and control and provided a biomechanical explanation of technique changes in overarm throwing action. Based on the findings of chapter 2, the dynamical system theory (DST) approach to understanding motor learning is at the forefront of current knowledge. While some promising evidence exists (Williams et al., 2016; Hong & Newell, 2006; Chow et al., 2006; Lee et al., 2016; Verhoeven & Newell, 2016; Ko et al., 2013; Dutt-Mazumder & Newell, 2017; Dutt-Mazumder et al., 2018) for the ability of DST approach to identify common changes, there is still more evidence that needs to be gathered, not least because a DST sees skills evolve based on specific constraints related to the task, environment and individual (Newell, 1986). For this reason, ecologically valid skills are best, and those that are fundamental to human beings provide the most impactful information. Throwing is a skill for which some motor learning models exist (Robertson & Halverson, 1984), therefore throwing provides a rich landscape to study technique change with practice.

Robertson and Halverson's (1984) components model for overarm throwing was constructed based on 7 years of longitudinal study with a single cohort of children aged 6 to 13 years. By the end of the 7 years children's overarm throwing action was still not fully developed. Aside from children not being fully skilled longitudinal studies such as Robertson and Halverson (1984) are not practically relevant for a PhD

thesis. As an alternative method learning in adulthood can be studied through examining changes in overarm throwing with the non-dominant arm. This method means that practice can be observed. Therefore, chapter 3 will study non-dominant overarm throwing action in adults to provide a novel understanding of overarm throwing action techniques. This chapter is theoretically underpinned by DST and current models of motor learning to help provide evidence towards a general theoretical framework that characterises motor learning and will aid understanding of changes in novice technique.

Knowledge of the characteristics of technique change during motor learning can provide an insight into how the demands of a task influence the process of motor skill acquisition. As a whole-body motor skill, the overarm throw is a fundamental discrete movement that requires the formation of qualitative kinematic properties in the organization of the limb segments that constrain the quantitative change in movement technique and task outcome (Knudson, 2007; Kernodle & Carlton, 1992; Robertson & Halverson, 1984; Southard, 2006). Qualitative changes are used to develop knowledge of technique change through visual observation of participants. Meanwhile, quantitative changes refers to numerically measureable data where statistical significance can be tested to uncover patterns in technique. Non-dominant overarm throwing action provides a way for researchers to examine movement from a greater or lesser ability level by observing the technique of dominant and non-dominant overarm throwing action of the same individual.

Within a multivariate and dynamic framework it has been possible to integrate several approaches to examine technique changes in the overarm throwing action with the

non-dominant upper limb over practice. Overarm throwing is a skill for which the non-dominant arm action generally has less advanced movement organization than the dominant arm (Hore et al. 1996; Kernodle & Carlton, 1992; Southard, 2006). Whilst investigating the development of non-dominant overarm throwing in adults, two studies have tested the effect of instruction and feedback on performance. Southard (2006) reported an increase in the number of upper limb segments experiencing positive segmental lag, which refers to the transfer of energy from the heavier proximal segment to lighter distal segments. Meanwhile, Kernodle and Carlton (1992) showed evidence that the key cues to performance change related to the lag of the upper arm and elbow with respect to the shoulder as opposed to transitional cues: lag the movement of the upper arm and elbow behind the rotation of the shoulders during the throwing phase; lag the movement of the hand and ball behind the upper arm and elbow during the throwing phase; extend the left arm at ball release; release the ball earlier/later in the movement; good throw. Interestingly, whilst segmental lag provides a biomechanically relevant technique parameter, models of motor learning emphasise the whole body contribution to the skill.

Three distinct though potentially complementary approaches are used here to examine technique changes in non-dominant overarm throw technique over practice: Newell's (1985) learning stages of coordination, control and skill, Robertson and Halverson (1984) components model of overarm throwing and Bernstein's (1967) hypothesis of freezing and freeing the redundant degrees of mechanical freedom. These three approaches are relevant to the study of technique changes as they each emphasize different aspects of change in the system dynamics that can be applied to overarm throwing action.

Firstly, in line with the motor learning model of Newell (1985), dynamical systems approaches to motor skill acquisition seek a macroscopic variable(s) as an order parameter or collective variable which captures the essential macroscopic properties of the system and the global movement pattern arising from the interaction of muscles, joints and segments during action (Haken, 1983; Kelso, 1995). The centre of mass (CoM) represents a higher order, low dimensional global space variable that emerges from actions at the muscular-articular level. This has been illustrated in basketball free throw shooting with the peak height of the motion of the CoM and the release of the ball by the end effector during throwing (wrist motion) becoming more strongly coupled as a function of skill level (Verhoeven & Newell, 2016). In this current study, it was hypothesized that the relationship between the movement of the CoM and the wrist at the distal joint motion in ball release, provides information of the macroscopic organization of the system in this throwing task and the link between postural support and instrumental limb action.

Secondly, Roberton and Halverson (1984) developed the components model of overarm throwing following a 7 year longitudinal study of a single cohort of 39 children in Wisconsin, United States. Data collection began in 1972 when the children were in kindergarten and concluded in 1979 when the children were 13 years of age. As the only overarm throwing specific model, it has subsequently been used to examine technique changes in both children learning to throw (Roberton & Konczak, 2001; Langendorfer & Roberton, 2002; Stodden et al., 2006*a,b*) and throwing in older adults ranging in age from 61 to 82 years (Williams et al., 1998). However, the components model (Roberton & Halverson, 1984) has yet to be applied to technique

changes for young adults learning non-dominant arm throws. From a developmental and general learning perspective, there are important implications associated with whether changes in technique during the learning of fundamental skills occur in a similar pattern in younger (Robertson & Halverson, 1984) and older (Williams et al., 1998) populations, and with the non-dominant limb.

Thirdly, Bernstein's (1967) hypothesis of freezing and freeing the redundant degrees of freedom captures properties of qualitative and quantitative technique changes. To date, changes in mechanical degrees of freedom such as joint angle range of motion (ROM) (Newell et al., 1989; Vereijken et al., 1992; Chow et al., 2008) and dynamical degrees of freedom, such as coordination variables (Ko, Challis, & Newell, 2003; Verhoeven & Newell, 2016) during learning novel tasks have been investigated. It has been proposed, however, that the direction of freeing and freezing is task specific and dependent on the level of the system being analysed during learning (Hong & Newell, 2006; Newell & Vaillancourt, 2001).

3.2 Chapter Aim and Research Questions

The aim of this chapter was to investigate the evolution of changes in technique of the non-dominant overarm throw over practice with respect to three different, but potentially complementary approaches to qualitative and quantitative change of movement dynamics. Methods for examining changes in different variables of the system organisation were: Newell's (1985) stages of coordination, control and skill, Bernstein's (1967) hypothesis of freezing and freeing the redundant mechanical degrees of freedom, and the components model of overarm throwing (Robertson &

Halverson, 1984). It was expected that an index of the macroscopic dynamics that linked the postural and limb effector motions could capture generalizable changes in technique during learning. Furthermore, the quantitative changes in individual joint rotations and CoM motions are embedded within the sequential qualitative changes in trunk/arm relative motion during learning to throw with the non-dominant arm. Thus, the approach focuses on the qualitative and quantitative kinematic changes at the individual participant level as a function of practice to reveal the individual pathways of change. The relevance of this research lies in understanding how individuals learn a fundamental complex whole-body movement in line with models of motor learning that have addressed progressions in the different aspects of qualitative kinematic change with practice. The purpose of this research is to establish: (i) if current approaches to motor learning are able to adequately describe technique differences during overarm throwing action (ii) if the application of the three approaches provides a comprehensive view of technique changes during overarm throwing action.

In order to address the aim of this chapter, the following specific research questions are answered:

- With practice, does the collective variable CoM-wrist become more complex and less variable in line with Newell's (1985) learning stages of coordination, control and skill?
- With practice how do changes in technique occur in-line with the components model of overarm throwing (Robertson & Halverson, 1984)?
- With practice how do changes in ROM occur in-line with Bernstein's (1967) observations of freezing and freeing redundant mechanical degrees of freedom?

3.3 **Methods**

3.3.1 **Participants**

Written ethical approval was gained from the faculty research ethics panel (FREP-16-645) Anglia Ruskin University Ethics Committee prior to study initiation. Ten participants (PT) (4 females, 6 males; age 22 ± 2 years, stature 1.71 ± 0.60 m, and mass 73 ± 14 kg), all of whom had no specific experience with non-dominant arm throwing gave informed, written, voluntary consent and successfully completed a Physical Activity Readiness Questionnaire (PAR-Q). The Physical Activity Readiness Questionnaire (PAR-Q) was, created by the British Columbia Ministry of Health and the Multidisciplinary Board on Exercise (Warburton et al., 2011). The PAR-Q was considered suitable as it is a standardised form which was designed to be a self-screening tool that is user friendly with closed ended questions which limit interpretation. The questionnaire aims to uncover any issues that would make participation in physical activity difficult or dangerous. Specifically it asked questions relating to any balance or joint problems which are both key attributes required for overarm throwing action.

Inclusion criteria were as follows: participants were not participating in a throwing-based activity, had a dominant hand (were not ambidextrous; as determined by Oldfield (1971) Edinburgh handedness inventory), and were free from musculoskeletal injury that would hinder throwing action.

3.3.2 Procedure

Participants completed 9 practice sessions, three times per week (Monday, Wednesday and Friday) for 3 consecutive weeks. The same procedures were conducted for each session. Between testing sessions participants were instructed not to practice throwing with either their dominant or non-dominant arm. Baseline data was collected for each participant during 10 overarm throws for force towards a target. Overarm throws were completed in a standing position with each participant free to choose their stance for each throw. A standard issue tennis ball (Slazenger) was used. Participants were given the ongoing aim of hitting a 0.4m target located 14m in front of them. Target height was adjusted to each participant's standing eye level using a measuring tape. The target placement necessitated a forceful and accurate throw from the participant. Participants were instructed to hit a 0.4m target located 14m in front of them. Target height was adjusted to each participant's eye height. The target distance and placement necessitated a forceful and accurate throw from the participant and provided a task constraint to the movement. Participants were encouraged to hit the target. However, as the target was only there as a visual and motivational aid, providing the ball progressed forward it was accepted as a good throw. Criteria for not including a throw was if the ball moved backwards or hit either wall perpendicular to the target. Knowledge of results from the target centre and verbal encouragement were provided, phrases included: "nice", "well done" and "good job".

3.3.3 Data Collection

Kinematic data (200Hz) was collected using a 3D motion capture system (CODAmotion, Charnwood Dynamics Ltd, UK). Three CX1 scanners provided a 360° field of view around the participant. Centre of rotation for each joint was estimated and active markers were located on the right and left lateral side of: 3rd metacarpal, ulnar styloid process, forearm, lateral epicondyle of the elbow, shoulder joint at the centre of rotation, xiphoid process, greater trochanter, femoral condyle, lateral malleolus, calcaneus and 2nd metatarsal. The same researcher marked up each participant for each session. Data was collected for every trial performed by the participant. The throwing trials were also recorded using a two-dimensional camera (Fastcam high speed video camera, Ultima 512 Photron, Model 32K) placed perpendicular to the sagittal plane of the participant. Raw marker data in the horizontal and vertical direction were identified from the 3D CODA output. Following a residual analysis on a selection of markers (shoulder, elbow and wrist), a Butterworth low-pass fourth-order filter was applied to the kinematic data at a cut-off frequency of 6Hz (Winter, 2009). Data was analysed during the propulsive phase of the throw which was defined as the first forward movement of any marker to the point of release of the ball.

3.3.4 Variables

3.3.4.1 Newell's (1985) Learning Stages of Coordination, Control and Skill

The assumption is that a macroscopic variable provides a fundamental feature of the organization of the system's movement coordination patterns. A collective variable is

defined as a high order, low dimension space variable that is representative of multiple joints at the muscular-articular level and provides information of the overarching macroscopic organisation the system. It should be noted that this thesis is not claiming that CoM and wrist are the collective variables for overarm throwing, but instead acted as a first attempt to investigate the problem of the relationship between candidate postural variable (CoM) and candidate ball release property variable (wrist). Vector coding (VC) was performed on the displacement of the CoM and wrist in the anterior posterior direction based on Equation 3.1 (Sparrow et al., 1987). According to Chang, Van Emmerik & Hamill (2008), four key coordination patterns were defined for vector coding: (1) anti-phase coupling ($112.5 \leq \gamma < 157.5^\circ$, $292.5 \leq \gamma < 337.5^\circ$) – variables are moving in opposite directions (2) in-phase coupling ($22.5 \leq \gamma < 67.5^\circ$, $202.5 \leq \gamma < 247.5^\circ$) – variables are moving in the same direction (3) wrist-led phase coupling ($0 \leq \gamma < 22.5^\circ$, $157.5 \leq \gamma < 202.5^\circ$, $337.5 \leq \gamma < 360^\circ$) – wrist is a more predominant variable (4) CoM-led phase coupling ($67.5 \leq \gamma < 112.5^\circ$, $247.5 \leq \gamma < 292.5^\circ$) – CoM is the more predominant variable. VC profiles were run for the propulsive phase of every throw for every session for all participants. Average standard deviation of the within-session VC profiles was used to determine variability of the movement coordination pattern as a function of practice.

$$\theta_{VC}(i) = \tan^{-1} \left[\frac{\theta_2(i+1) - \theta_2(i)}{\theta_1(i+1) - \theta_1(i)} \right], i = 1, 2 \dots, n-1 \quad \textbf{Equation 3.1}$$

Phase plane was constructed of θ_1 on the x-axis and θ_2 on the y-axis. θ_1 and θ_2 coupling was quantified by the θ_{VC} coupling angle between consecutive coordinates

in the phase plane (Equation 3.1). i indicates the point within the time series suggesting that they remained in the ‘coordination’ stage due to variability of coupling angle remaining high or variability increasing with practice (Newell, 1985).

3.3.4.2 Components Model (Robertson & Halverson, 1984)

The components model tracks qualitative technique changes via ‘action levels’ in four segmental components: ‘step’, ‘trunk’, ‘humerus’ and ‘forearm’. The action level for each component for each throw was recorded and classified by the principal investigator and verified by another author in line with the components model on a continuum from 1 to 4 for the ‘step’ and 1 to 3 for all other components. An action level of 1 is representative of the least skilled action level with action levels 3 or 4 representative of a skilled action for that component (Robertson & Halverson, 1984; Table 3.1). If a participant’s technique was split across two action levels for a component within a session the action level with the highest number of trials was recorded.

Table 3.1 **Action levels for components of overarm throwing action**
(Robertson & Halverson, 1984)

Action level for components
Step component
Level 1: No step
Level 2: Ipsilateral step
Level 3: Contralateral short step
Level 4: Contralateral long step
Trunk component
Level 1: No trunk action
Level 2: Upper trunk rotation
Level 3: Differentiated trunk rotation
Humerus component
Level 1: Humerus oblique
Level 2: Humerus aligned by independent
Level 3: Humerus lag
Forearm component
Level 1: No forearm lag
Level 2: Forearm lag
Level 3: Delayed forearm lag

3.3.4.3 Bernstein's (1967) Joint Range of Motion

Bernstein (1967) defined coordination as the process of mastering redundant mechanical degrees of freedom (DoF), suggesting that movement is coordinated through a three-stage embedded approach of freezing, freeing, and finally exploiting the reactive forces of the joint space DoF. Changes in the ROM of the mechanical degrees of freedom provides an understanding of the contribution of individual joints during movement. ROM informs the degree to which redundant degrees of freedom are involved.

The ankle joint motion was defined from the 2nd metatarsal, lateral malleolus and calcaneus. Knee joint motion was defined from lateral malleolus, femoral condyle and greater trochanter. The motion of the hip joint was defined from femoral condyle, greater trochanter and xiphoid process. Shoulder joint motion was defined from shoulder joint at the centre of rotation, xiphoid process and lateral epicondyle of the elbow. Elbow joint motion was defined from shoulder joint at the centre of rotation, lateral epicondyle of the elbow, styloid process of ulna. The motion of the wrist joint was defined from the 3rd metacarpal, styloid process of ulna and lateral epicondyle of the elbow.

ROM was calculated during the propulsive phase of each throw in each session for every participant for every trial. For each participant's data was then averaged across a session. Angles were defined in 3D where an angle of 180° would represent maximum extension, while 0° would represent minimal flexion. ROM of CoM in the anterior-posterior direction was also calculated, where the whole-body CoM was

defined based on the average of mass and position of the individual segments CoM of: both hands, forearms, upper arms, shank and feet with the head and torso considered to be a single segment. Segment CoM's and relative contribution to the whole body CoM were calculated based on the anthropometric data provided by Plagenhoef, Evans, and Abdelnour (1983).

3.3.5 Statistical Analysis

After testing for normality of data using the Shapiro-Wilks test, repeated measures analysis of variance (ANOVA) were run for each participant for each dependent variable. The level of statistical significance was set prior ($p < 0.05$) and Bonferroni's post hoc correction was used for multiple comparison tests. Mauchly's test was used to determine the sphericity assumption within the data; and where sphericity was violated, probability was corrected according to the Greenhouse-Geisser procedure. Comparisons of vector coding coordination variability were examined before and after practice for non-dominant arm trials and before practice with dominant arm and baseline trials with dominant arm. Differences between discrete variables across testing sessions were quantified using Repeated Measures Analysis of Variance (RM ANOVA), based on a single subject design ($p < 0.05$).

Effect size was determined using Cohen's d for all significant data to establish the standardised difference of synchrony before and after practice. Effect size was ranked as follows; large effect size ($d = 0.8$), medium effect size ($d = 0.5$) and small effect size ($d = 0.2$).

$$d = \frac{M_1 - M_2}{SD_{pooled}} \quad \textbf{Equation 3.2}$$

3.4 **Results**

3.4.1 Newell's (1985) Learning Stages of Coordination, Control and Skill

Two key profiles of the vector-coding angle were identified among participants before and after practice with the non-dominant arm. The first profile (Fig. 3.1a) started the propulsive phase with in-phase coupling (22.5–67.5°) and progressed to wrist-led coupling (0–22.5°) at ball release (Fig. 3.1a) where the wrist is moving forward and the CoM is nearing stationary (zero degrees). At the start of practice, all participants demonstrated this coupling relation. The second profile (Fig. 3.1b) started with wrist-led coupling (157.5–202.5°) where the wrist moved backwards and progressed through the following couplings: anti-phase coupling (112.5–157.5°) where the CoM is progressing forward as the wrist moves backwards, CoM-led coupling (67.5–112.5°) followed and is associated with the forwards movement of the CoM. Beyond 60% of the propulsive phase, the coupling angle passes through in-phase coupling which is characterised by forward progression of CoM-wrist towards wrist-led phase coupling at ball release (Fig. 3.1b). With practice, 7 of 10 (PT03, PT04, PT05, PT06, PT08, PT09 and PT10) participants demonstrated the second profile. The remaining 3 of 10 participants (PT01, PT02 and PT07) continued to display in-phase coupling followed by wrist-led phase coupling at ball release for the duration of practice (Fig. 3.1). Specific changes in CoM-wrist coupling (Fig. 3.1) occurred at the same session as components model (Robertson & Halverson, 1984) (PT01 and PT03) and ROM (PT01, PT03, PT06 and PT10).

By the end of practice non-dominant arm throws were more closely representative of dominant arm throws for the majority of the participants. Seven of the 10 participants (PT03, PT04, PT05, PT06, PT08, PT09 and PT10) were characterised by wrist-led coupling moving towards zero at ball release. Three of 10 participants (PT01, PT02 and PT07) dominant arm throws were characterised by in-phase coupling progressing to wrist-led phase at ball release.

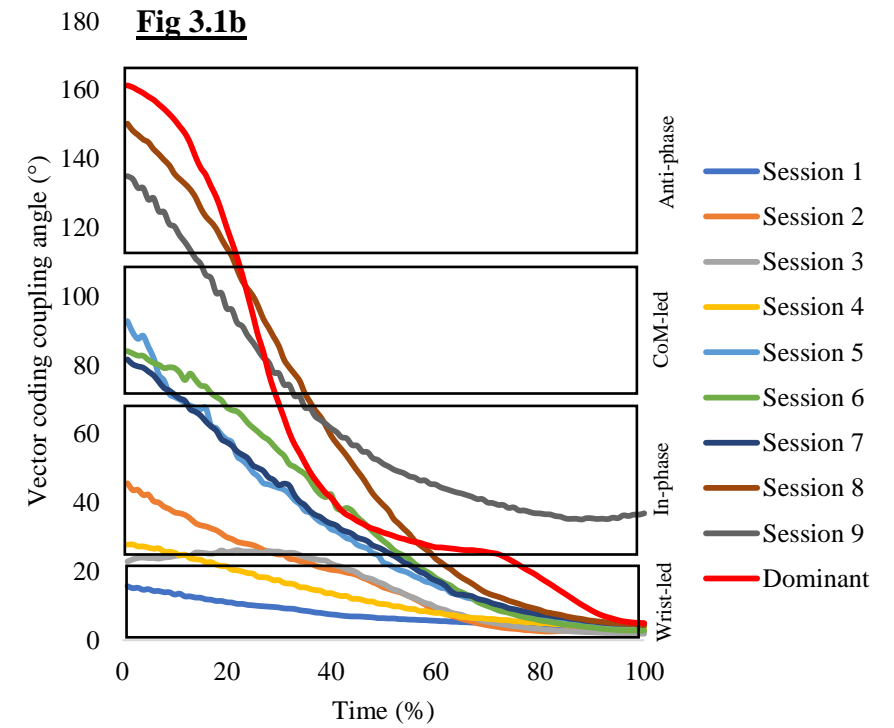
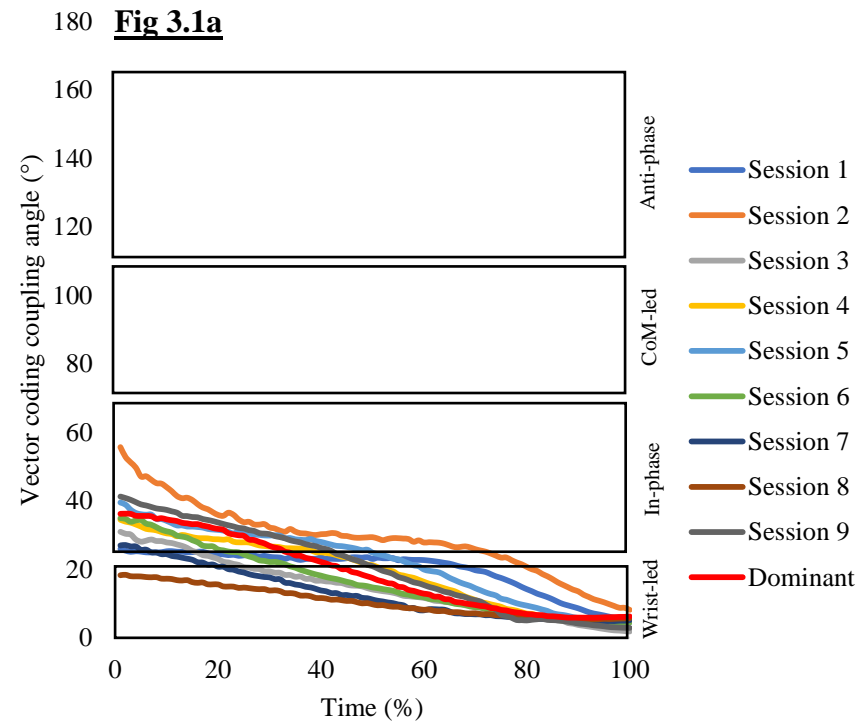


Fig 3.1 **Centre of mass-wrist coupling for single trial per session for PT06 (representative of PT03, PT04, PT05, PT08, PT09 and PT10) and PT07 (representative of PT01 and PT02)**

Table 3.2 Coordination variability of the centre of mass-wrist coupling in the anterior posterior direction with practice

($p < 0.05$ indicated by *)

Average variability (°)										
Participant	S1	S2	S3	S4	S5	S6	S7	S8	S9	Dominant
PT01*	5.14	7.25	6.52	18.47	32.29	42.76	46.40	42.49	53.31	19.51
PT02*	31.15	34.78	37.65	49.67	34.67	38.65	28.52	35.69	30.33	30.81
PT03*	18.84	32.45	6.98	31.89	21.82	58.27	47.13	32.15	30.23	37.00
PT04*	32.71	37.25	16.88	28.71	40.51	38.77	48.42	65.86	64.50	41.80
PT05*	60.41	58.30	53.40	59.43	58.02	65.89	57.40	55.45	66.57	71.23
PT06*	23.52	29.38	24.64	34.55	48.09	49.60	50.45	48.53	52.33	48.83
PT07*	41.01	19.48	32.79	23.28	16.53	15.88	18.42	26.03	23.07	18.89
PT08*	30.64	29.06	34.36	29.21	52.39	59.23	62.17	65.98	42.58	42.68
PT09*	11.60	10.16	12.00	27.39	12.20	23.05	41.27	15.50	24.53	36.06
PT10*	41.75	19.23	13.60	55.99	40.16	49.16	42.24	42.22	13.91	30.98

Coupling variability was defined by the average standard deviation of the vector coding profile throughout the propulsive phase. With practice, 7 of the 10 participants (PT01, PT03, PT04, PT05, PT06, PT08, and PT09) experienced a significant increase ($p < 0.05$) in coordination variability of CoM-wrist coupling (Table 3.2). A significant decrease ($p < 0.05$) in coordination variability was present for 3 of 10 participants (PT02, PT07, and PT10). Seven of 10 participants (PT02, PT03, PT05, PT06, PT07,

PT08, and PT09) more closely resembled dominant arm baseline trials with practice (Table 3.2).

3.4.2 Components Model of Overarm Throwing (Robertson & Halverson, 1984)

No participants were categorised as action level 1 or retreated down the action levels. Eight of 10 participants (except PT01 and PT10) progressed up an action level with practice (Table 3.3). Specifically, from Session 6 onwards, 7 of 10 participants were categorised as action level 3 for the ‘step’ and 3 of 10 participant’s level 4 for the ‘step’. For the ‘trunk’ 2 of 10 participants were categorised as action level 2 and 8 of 10 participants were categorised as action level 3. For ‘humerus’ and ‘forearm’ 3 of 10 participants were categorised as action level 2 and 7 of 10 participants were action level 3. Key changes occurred at Session 2 (PT05), Session 4 (PT02, PT04, PT07), and Session 6 (PT03, PT06). Dominant arm throw configurations were characterised in higher action levels; however, a few participants were not in the highest category (Table 3.3).

Table 3.3 **Developmental action level with practice for non-dominant and dominant arm throws**

	Action	Non-dominant session									Dominant session								
Segment	level	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
Number of participants in each level for a given session																			
Step	1																		
	2	1	1	1															
	3	9	8	8	8	8	7	7	7	7	4	4	4	4	4	4	4	4	4
	4		1	1	2	2	3	3	3	3	6	6	6	6	6	6	6	6	6
Trunk	1																		
	2	3	2	2	1	1	1	1	1	1	3	2	2	1	1	1	1	1	1
	3	7	8	8	9	9	9	9	9	9	7	8	8	9	9	9	9	9	9
Humerus	1																		
	2	2	2	2	1	1	1	1	1	1	4	3	3	3	3	1	1	1	1
	3	8	8	8	9	9	9	9	9	9	6	7	7	7	7	9	9	9	9
Forearm	1																		
	2	3	3	3	2	2	1	1	1	1	3	3	3	3	3	2	2	2	2
	3	7	7	7	8	8	9	9	9	9	7	7	7	7	7	8	8	8	8

3.4.3 Bernstein's (1967) Joint Range of Motion

There was a significant increase in ROM of the lower limb joints and shoulder with practice (9 of 10 participants at the ankle and 8 of 10 participants at the knee, hip and shoulder) ($p < 0.05$). Six of 10 participants significantly decreased ROM at the elbow and 7 of 10 participants at the wrist ($p < 0.05$). Eight of 10 participants significantly increased ROM of the CoM in the anterior-posterior direction ($p < 0.05$) (Fig. 3.2).

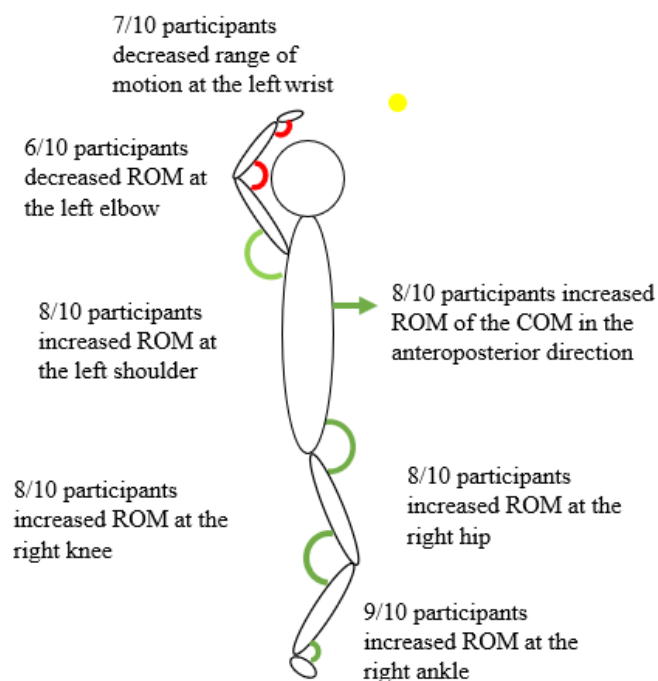


Fig 3.2 Representation of group changes in joint range of motion and anterior posterior displacement of the centre of mass following 3-weeks of non-dominant arm throwing practice

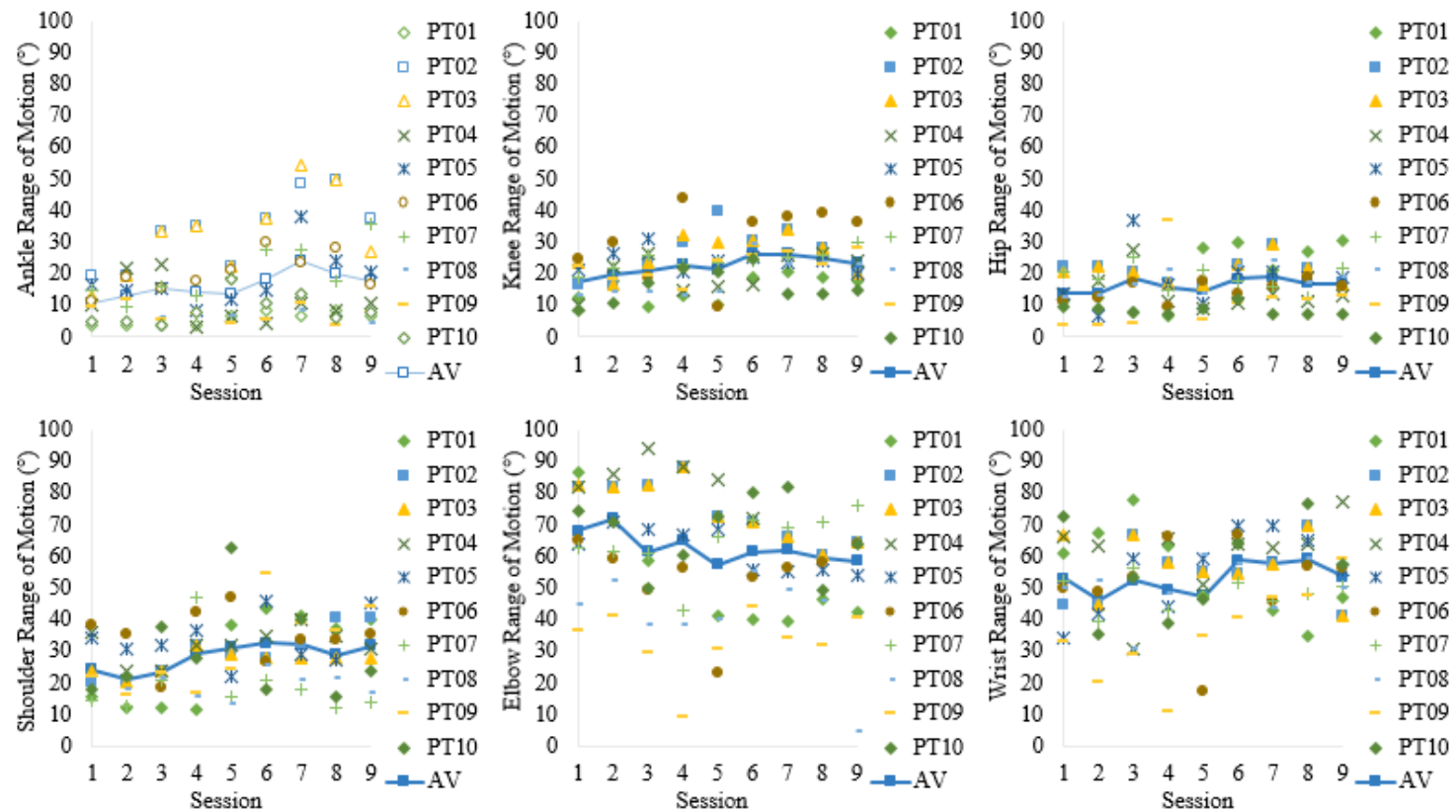


Fig 3.3 **Group joint range of motion development at the right ankle, knee, hip and left shoulder, elbow and wrist joint**
during 3 weeks of non-dominant arm throwing practice

A general trend showed significant increase in ROM of the lower limb and the shoulder (9 of 10 participants of the ankle and 8 of 10 participants of the knee, hip and shoulder) ($p < 0.05$) with practice. Six of 10 participants significantly decreased ROM of the elbow and 7 of 10 participants of the wrist ($p < 0.05$) with practice (Fig 3.2). Eight of 10 participants significantly increased ROM of the CoM in the anterior-posterior direction ($p < 0.05$) (Fig 3.2).

Effect size (Cohen's d) showed that a large effect size ($d = 1.10$) was present when comparing before and after practice ($d = 1.10$) with the non-dominant arm. A small effect size ($d = 0.30$) was found when the effect size was examined before and after practice with the dominant arm and a medium effect size ($d = 0.68$) was found when comparing non-dominant throwing after practice to dominant arm throws.

3.4.4 Model Integration

The three complementary approaches captured technique changes in motor learning with practice (except components model for PT01 and PT10). Timing of change was specific to the individual but centred around Sessions 4, 5, and 6, e.g. technique changes were captured at Session 4 for PT07 and PT08 for the components model (Robertson & Halverson, 1984) and Bernstein's (1967) ROM. This occurred in the session before coupling of CoM-wrist (Session 5). Technique change occurred at the same session for PT03 (Session 6) and PT06 (Session 5) for three approaches.

Changes in 'step' action (PT02, PT04, PT05, PT06) and 'trunk' action (PT03, PT05, PT07, PT08, PT09) (Table 3.3) occurred at the same session as changes in lower limb

ROM (Fig 3.2) for all participants who changed this action level. Six of 10 participants did not change ‘step’ action level from level 3 onwards as a function of practice, while a significant increase in lower limb ROM was observed (Fig 3.2).

Change in ‘humerus’ action (PT03, PT04, PT07, PT08, PT09) and ‘forearm’ action (PT03, PT04, PT05, PT07, PT08, PT09) (Table 3.3) occurred at the same session as changes in upper limb ROM for all participants who changed this action. Four of 10 participants did not change ‘humerus’ or ‘forearm’ action (Table 3.3) level with practice, either due to being classified at the highest action level from Session 1 (PT01 and PT06) or, remained at action level 2 (PT02 and PT10). Significant increase in shoulder ROM was present for these participants (Fig 3.3). PT01, PT02 and PT10 significantly decreased elbow and wrist ROM. PT06 significantly increased ROM at all upper limb joints measured.

Coupling of CoM-wrist (vector coding) (Fig 3.1) changed at the same time as the components model (Robertson & Halverson, 1984) (PT01 and PT03) and ROM (PT01, PT03, PT06 and PT10). Changes in coupling angle for remaining participants occurred at a different session to the components model (Robertson & Halverson, 1984) and ROM (PT02, Session 4; PT05, Session 8; PT07 and PT08, Session 5; PT04 and PT09, Session 7).

3.5 Discussion

The aim of this Chapter was to investigate the evolution of changes in technique of the non-dominant overarm throw over practice with respect to three different but

potentially complementary approaches to qualitative and quantitative change of movement dynamics; Newell's (1985) stages of coordination, control and skill: the components model of overarm throwing (Robertson & Halverson, 1984); and Bernstein's (1967) hypothesis of freezing and freeing redundant mechanical degrees of freedom.

A common single pathway of change in throwing technique with practice was not present across participants. However, for individuals, the findings from the three approaches did complement each other in revealing related aspects of the skill progression. There were periods across the multiple practice sessions (4, 5, and 6) where each approach revealed marked changes in the technique of the participants. Additionally, participants fell into certain subgroups in relation to particular characteristics of technique change which is not an uncommon finding in the learning of whole-body motor skills (Williams et al., 2015; Teulier & Delignieres, 2007; Haibach, Daniels, & Newell, 2004) and is likely to be due to differences in individual constraints and intrinsic dynamics.

3.5.1 Newell's (1985) Learning Stages of Coordination, Control and Skill

A collective variable is defined as a high order, low dimension space variable that is representative of multiple joints at the muscular-articular level and provides information of the overarching macroscopic organisation the system. It should be noted that this thesis is not claiming that CoM and wrist are the collective variables for overarm throwing, but instead acted as a first attempt to investigate the problem of

the relationship between candidate postural variables (CoM) and candidate ball release property variable (wrist).

The CoM represents a high order, low dimension global space variable representative of the collective system at the muscular-articular level (Haken, 1983). In this view, a collective variable provides information of the macroscopic organization of coordination of the system (Ko, Challis & Newell, 2014) particularly in relation to postural control (CoM) and the end effector during throwing (wrist motion). The coordination between CoM and wrist displacement was quantified using vector coding and provided an insight into coupling and coupling variability changes with practice.

Two key coupling relations were observed between CoM and wrist over practice. At the beginning of practice. All participants demonstrated in-phase coupling at the start of the propulsive phase of the throw, where the CoM and wrist both travelled forwards together, towards zero at ball release (Fig. 1). With practice, 7 of 10 participants began to incorporate differentiated movement of the CoM and wrist, where coupling began at 180° before progressing to 0° at release. This latter strategy is representative of initial wrist-led coupling where backwards movement of wrist is the predominant influencer on the kinematic chain. Coupling progressed through anti-phase (forward movement of the CoM and backwards movement of the wrist) and CoM-led coupling (forward movement of the CoM) before in-phase coupling and forward wrist-led coupling at ball release (Fig. 3.1). This later strategy is in-line with dominant arm throws and provides evidence for the freeing of dynamical degrees of freedom (Newell & Vaillancourt, 200; Verhoeven & Newell, 2016; Ko, Han, & Newell, 2018). Specifically, the macroscopic organisation of the system has become more complex,

utilising a broader range of phase relations associated with the arm kinematic chain. While this macroscopic variable does not describe the nuances of an individual's technique, it was able to capture a transition in system organisation despite individual differences that influenced joint space organisation.

From a dynamical system theory perspective, variability is not inherently good or bad, but reflects the flexibility of the system to explore new coordination patterns during learning to consistently meet task demands (Haken, Kelso & Bunz, 1985; Schöner & Kelso, 1988). In terms of Newell's (1985) learning stages, 3 of the 10 participants significantly decreased coupling variability with practice, suggesting they had reached the control stage of learning (Newell, 1985), while the remaining 7 of the 10 participants significantly increased coordination variability with practice suggesting they remained in the coordination stage (Table 3.2). With practice, the coupling variability for 7 of the 10 participants became more similar to that of the dominant arm throws through either an increase or decrease in coupling variability. A paradox is then set since it might be assumed that variability across dominant arm throws is exploiting redundancy, whereas the variability across non-dominant arm throws is used for exploring new coordination strategies in the process of learning (Wilson et al., 2008; Verhoeven & Newell, 2016). Interestingly, Verhoeven and Newell (2016) found increased adaptive control shown through a more stable CoM at point of release to be a contributing factor to successful free throw shooting in basketball.

To understand the kinematics underpinning the collective dynamics, technique changes were examined using the components model (Robertson & Halverson, 1984) and Bernstein's (1967) observations of freezing and freeing the redundant mechanical

degrees of freedom. Both these approaches provide a description of the movement pattern, and enhance an understanding of the mechanisms for changes demonstrated in CoM-wrist coupling following practice.

3.5.2 Components Model of Overarm Throwing (Robertson & Halverson, 1984)

To the authors knowledge this is the first study to apply Robertson and Halverson's (1984) components model to non-dominant arm throwing. In agreement with the components model (Robertson & Halverson, 1984) adult participants in this study moved through the outlined developmental action levels following a 3-week period of non-dominant overarm throwing practice (Table 3.3).

As a foundation, the participants did not start practice like children with a throwing technique at action level 1 (L1). Instead, individuals advanced up the developmental action levels from L2 – L3 (PT02) and action levels L3 – L4 (PT04, PT05, PT06) for 'step' component, and action L2 – L3 for 'trunk' (PT05, PT07), 'humerus' (PT07) and 'forearm' (PT03, PT07) components. All other components for the individual remained at L3 for the study's duration. These findings are consistent with the expectations of motor learning and transfer (Adams, 1987) where a previously learnt skill positively influences the learning of a new skill or a skill performed with the other side of the body, as demonstrated by Aune et al. (2017) who reported motor learning transfer from the dominant arm to the non-dominant arm during a computer simulated tracking task.

With older adults who were similar to those reported by Halverson et al. (1982), William et al. (1998) reported low-to-intermediate level categorisation of ‘trunk’, ‘humerus’ and ‘forearm’ actions. Stodden et al. (2006*a,b*) reported the mean age of children categorised into the highest action level: ‘step’ (11.9 years), ‘trunk’ (12.9 years), ‘humerus’ (12.5 years), ‘forearm’ (12.9 years). These results show similarity to the results reported in this study expect for the ‘step’ component which was categorised as a level 3 for the majority of participants in the study. The number of individuals that transition between action levels was small. This is in contrast to Langendorfer & Robertson (2002).

The findings showed that an advanced action level in one component did not combine with lesser action levels in another component because the advancement of one component drives forward the development of another component (Langendorfer & Robertson, 2002). This can be illustrated by taking a contralateral step which places the body in a position that progresses trunk and arm components (Stodden et al., 2006*a*). Indeed, by the end of practice (Table 3.3) the throwing movement patterns were similar to those reported by Stodden et al. (2006*a,b*) who used a cross-sectional design to explore developmental changes in dominant arm throwing in children. The participants used by Stodden et al. (2006*a,b*) were more advanced than those studied by Halverson et al. (1982) and William et al. (1998) who examined longitudinal developmental changes in children and older adults, respectively. The results of this study show that the participants started non-dominant arm practice with an intermediate developmental profile particularly for the movement of the ‘humerus’ and ‘forearm’ (Table 3.3).

Based on previous literature (Langendorfer & Robertson, 2002) it was expected that the more advanced action level 3 or 4 of one component would not be combined with less advanced action levels in another component, since the advancement of one component drives the development of another component forward. An example of this would be that the contralateral ‘step’ places the body in a more anatomically advantageous position that facilitates the development of trunk and arm components (Stodden et al., 2006a). In agreement with the components model (Robertson & Halverson, 1984) participants moved through the outlined developmental action levels with practice (Table 3.3) indicating improved overarm throwing action. By the end of practice, developmental profiles of this study (Table 3.3) were similar to the findings of Stodden et al. (2006a,b) who studied cross-sectional kinematic and developmental changes in dominant arm throwing in children between 3 and 15 years of age. The current findings were more advanced than developmental profiles reported by Halverson et al. (1982) and William et al. (1998) who examined longitudinal developmental changes in children and older adults, respectively using the components model approach. Results suggest that the adult participants in this study started practice with an intermediate developmental profile for non-dominant arm throws, specifically for the ‘humerus’ and ‘forearm’ component of the model (Table 3.3).

At the end of practice, 7 of 10 participants had not reached the highest action level in the ‘step’ component. It was evident that while technique changes were elicited during non-dominant overarm throwing practice, further practice was required for non-dominant overarm throwing action skill level to be consistent with dominant overarm throwing skill level. The highest action level dominant arm throws were categorised

by 6 of 10 participants for the ‘step’, 9 of 10 participants for the ‘trunk’ and ‘humerus’, and 8 of 10 participants for the ‘forearm’ component (Table 3.3). The advanced developmental profiles for the majority of participants suggests that the dominant arm throws can be directly compared to non-dominant arm throws. Furthermore, it is expected that if there was a longer period of non-dominant arm practice participants would have continued to advance up the action levels of components. Changes at the components level, particularly in the ‘step’ action, were in line with the key change in CoM-wrist coupling, and thus suggest that further organisation changes at the level of components are still occurring at session 9.

3.5.3 Bernstein’s (1967) Joint Range of Motion

In line with freeing mechanical degrees of freedom, 7 of 10 participants produced an increase in lower limb and shoulder joint ROM with practice (Fig. 3.3). Specifically, a significant increase in ROM at the lower extremities and CoM occurred along with the more advanced ‘step’ action (Table 3.3; Fig. 3.2). Increased ROM of the lower extremities facilitated increased displacement of the CoM, which provides evidence for increased weight transfer in the act of throwing (Knudson & Morrison, 1996). The development of this fundamental aspect of throwing technique provides evidence for freeing of the mechanical degrees of freedom at the lower limbs, consistent with Bernstein’s (1967) hypothesis. This enables the storage of elastic energy which in turn will increase throwing ability by overcoming the limited power production of the upper extremities (Roach et al., 2013).

Interestingly, ROM of the elbow and wrist significantly decreased for the majority of participants with practice (Fig. 3.3). In parallel, the majority of participants were categorised in advanced action (Table 3.3) of 'humerus' and 'forearm' from the beginning of practice. While no other research has analysed ROM for non-dominant arm throwing, Southard (2006) reported that instructional cues positively influenced segmental distal lag, specifically the hand relative to the forearm. The results suggest that participants had initially freed the elbow and wrist joint at the start of practice and then reducing ROM or freezing of the elbow and wrist was a common strategy adopted. This finding provides support for the proposition of Hong and Newell (2006) that freezing or freeing degrees of freedom is task specific, rather than a universal directional rule for skill learning, and furthers the proposition by suggesting that different limb segments (arms or legs) may follow different patterns of change.

At the whole-body level, all participants showed significant change in joint ROM of three or more joints during one single session. This session seemed to represent a point of transition in technique that was captured in multiple single joints. A drawback of using freeing of individual degrees of mechanical degrees of freedom to describe technique change is its inability to explore coordination. Interestingly, since the timing and the combinations of joints involved in this change were individual specific, it would be of interest to explore whether a measure of coordination could better capture the key characteristics of technique change in spite of individual differences. In this view, the coupling between the CoM and wrist motion was examined.

In summary, the application of Bernstein's (1967) hypothesis to the data of this study has shown that as a general trend individuals experienced an increase in joint range of

motion to a greater extent than a decrease. However, the timings and freeing of joints was unique for each individual. The complexity of this problem should not be overlooked as there have been some suggestions that alternating between reducing and increasing degree of freedom could be an ideal strategy for investigating change during skill acquisition (Berthouze & Lungarella, 2004). Newell and Vaillancourt (2001) proposed that the directional change in the degrees of freedom and coordination is dependent on task constraints, specifically the change in relevant task intrinsic dynamics required to meet the new task demands. These demands will be different for each individual. This explanation clarifies why there was an absence of a general learning strategies across the participants.

3.5.4 Integrating frameworks to the acquisition of overarm throwing

Exploring different levels of the system is related to different theoretical propositions on motor control (Schöner & Kelso, 1988; Hong & Newell, 2006; Gray et al., 2006). Emphasising a macroscopic variable is based on the theoretical proposition that motor control is organized with overall system dynamics rather than the control of individual degrees of freedom (Kelso, 1995). Arguably, the components model (Robertson & Halverson, 1984) relates to the macroscopic variable through four components of coordinated sub-segments, however, this model is skill specific and cannot be generalised across movement tasks.

In supporting these different emphases on system organisation, the current findings suggest that a more complex CoM-wrist coupling is achieved by taking a contralateral step in the throwing action that is associated with greater ROM of the lower

extremities. Thus, in increasing the complexity of the collective dynamics, participants followed the sequence of components change in the Robertson and Halverson's (1984) components model (Table 3.3), while Bernstein's (1967) hypothesis of freeing mechanical degrees of freedom was limb specific (Fig 3.3).

Founded on Newell's (1985) stages of learning model the collective dynamic did change; however, variability of this collective dynamic was not clearly directional. Overall, a higher order variable was better able to identify commonalities in technique change across individuals than single joint motions, and therefore, might be key to understanding the dynamics of technique change across different task and organismic constraints from a dynamical systems theory perspective.

From an applied perspective, the integration of the three approaches provides a comprehensive view of technique changes during overarm throwing action because each approach explores a different aspect of the dynamic system: Newell (1985) macroscopic properties, Robertson and Halverson (1984) sub degrees of segmental change, Bernstein (1967) individual degrees of freedom. The dynamical systems theory used here brings together different properties of the movement dynamics that are usually studied individually, particularly in the throwing literature. This study has revealed experimental evidence of the progression of individual technique changes through the practice of non-dominant overarm throwing. The findings highlight that postural control is critical for facilitating the development of upper extremities in what is usually characterised as an upper extremity action; specifically, the ability to take a contralateral step to facilitate greater ROM (releasing) of the lower extremities and CoM movement in weight transfer. Large individual differences and varying time-

scales were present among participants and emphasised that technique changes are not linear. Despite 3-weeks of non-dominant overarm throwing, subsequent practice is required for non-dominant overarm action to be in line with dominant overarm throwing action. Future work could explore in more detail the coordination between multiple joint segments during learning and would be required to explore the extent to which these three complementary approaches characterise technique development in overarm throwing across childhood.

3.6 Conclusion

The aim of this chapter was to investigate the evolution of changes in technique of the non-dominant overarm throw with practice with respect to three complementary approaches to qualitative and quantitative change of movement dynamics: Newell's (1985) learning stages of coordination, control and skill, the components model of overarm throwing (Robertson & Halverson, 1984) and Bernstein's (1967) hypothesis of freezing and freeing redundant mechanical degrees of freedom.

Exploring different levels of the system is related to different theoretical propositions on motor control. Emphasising a collective variable is based on the theoretical proposition that motor control (Schöner & Kelso, 1988; Hong & Newell, 2006; Gray et al., 2006) is associated with overall system dynamics rather than the control of individual degrees of freedom (Ko et al., 2014; Wang et al. 2014; Dutt-Mazumder, Challis and Newell, 2016), contrasting the variables explored by Bernstein's (1967). Arguably, the components model (Robertson & Halverson 1984) provides collective variables through the hypothesis of four components, however this model is skill specific and cannot be generalised across movement tasks. In supporting these

different emphases on system organisation, our findings suggest that a more complex CoM-wrist coupling is achieved by taking a contralateral ‘step’ in the throwing action which is associated with greater ROM of the lower extremities. Thus, in increasing the complexity of the collective dynamics, participants did follow the sequence of components change in the Robertson and Halverson (1984) components model, while Bernstein’s (1967) postulation of freeing mechanical degrees of freedom was limb specific. Founded on Newell’s (1985) stage of learning the collective dynamics did change, however variability of this collective dynamic were not clearly directional. Overall, a higher order variable was better able to identify commonalities in technique change across individuals, and therefore, might be key to understanding the dynamics of technique change across different tasks and organismic constraints.

From an applied perspective, the three approaches provide a comprehensive view of technique changes during overarm throwing action because each approach explores a different aspect of the system organization that can be practically relevant. This study has revealed experimental evidence of the progression of individual technique changes during non-dominant overarm throwing. The findings highlight the importance of the lower extremities and dynamic postural control in what is usually characterised as an upper extremity action. Specifically, the ability to take a contralateral ‘step’ to facilitate greater ROM of the lower extremities and CoM movement in weight transfer. In summary, understanding qualitative and quantitative change of the system provides information about the progressive influence of practice effects on movement organization.

3.7 Chapter Summary

This chapter has examined how adults learnt the fundamental motor skill of overarm throwing action with the non-dominant arm. The aim of this chapter was to examine the evolution of changes in technique of the non-dominant overarm throw with practice with respect to three complementary approaches to qualitative and quantitative change of movement dynamics: Newell's (1985) learning stages of coordination, control and skill, the components model of overarm throwing (Robertson & Halverson, 1984), Bernstein's (1967) hypothesis of freezing and freeing redundant mechanical degrees of freedom. Section 3.2 outlined the three research questions for this chapter.

- **'With practice does the collective variable CoM-wrist show technique changes consistent with Newell's (1985) learning stages of coordination, control and skill?'**

Over the period of practice, two coupling profiles were identified. Initially, CoM and wrist movement coupling were characterised by in-phase coupling moving to wrist-led coupling during the propulsive phase. With practice, 7 of 10 participants demonstrated more complex coupling of the CoM and wrist (Fig 3.1). The remaining 3 of 10 participants continued to display in-phase coupling followed by wrist-led phase coupling at ball release for the duration of practice. With practice, 7 of 10 participants experienced significant increase in coordination variability between the CoM and wrist coupling (Table 3.2) suggesting that these participants remained in the coordination stage of learning (Newell, 1985). A significant decrease in coordination variability was present for 3 participants, suggesting that they might have reached the control stage of learning (Newell, 1985). The use of CoM and wrist collective

variables was able to capture a key change in system organisation despite individual constraints to action. Moreover a high order variable was able to identify commonality in technique change and therefore might be key to understanding the dynamics of technique change across different tasks of the organismic constraints.

➤ **‘With practice how do changes in components occur in-line with the components model of overarm throwing (Robertson & Halverson, 1984)?’**

Overall, the components model (Robertson & Halverson, 1984) provides practitioners with a framework to assess and progress technique changes. During non-dominant arm practice, adult participants started practice with an intermediate developmental profile for non-dominant arm throws, specifically for the ‘humerus’ and ‘forearm’ component (Table 3.3). Participants increased up the action levels of the components model (Robertson & Halverson, 1984) indicating an increase in overarm throwing action proficiency with practice. Dominant arm profiles were more advanced than those of the non-dominant arm. By the end of practice 7 of 10 participants did not reach the highest action level in the ‘step’ suggesting non-dominant overarm throwing action was not fully developed by the end of three-week practice period.

➤ **‘With practice, do changes in ROM occur in-line with Bernstein’s observation of freezing and freeing redundant degrees of freedom?’**

In order to address this question ROM of individual joints was analysed. Participants increased ROM of the lower extremities and shoulder. At the elbow and wrist ROM became more restricted with practice. Analysis of key kinematic variables provided a valuable insight into the techniques adopted with practice, however, further analysis is required to understand how these movement pathways were achieved and explain

why certain characteristics of technique related to improved performance. In line with Bernstein's (1967) observations of freeing and freezing redundant degrees of mechanical freedom, participants released degrees of freedom of the lower extremities prior to the upper extremities demonstrated through an increase in ROM. The results of this initial study indicate that the release of joints occurred in a distal to proximal fashion with increased 'freeing' as demonstrated by increased ROM of the lower extremities. However, the opposite was observed in the upper extremities where ROM reduced in the elbow and wrist with practice. This knowledge provides additional support to Vereijken et al. (1992) and Williams et al. (2015) who suggested that the order of freeing and freezing is task specific rather than the universal rule for technique change.

Chapter 3 has provided knowledge of technique changes in non-dominant throwing arm from three complementary though distinct approaches of motor learning. Practical applications of the current results are that during the initial stage of learning it is important to focus on the positioning of the feet, movement of the knee and rotation of the hip. In terms of the basic science of motor control, the findings of this study suggest that there may be a requirement to master the dynamic stability of postural control before the learner is able to master the throwing action with the upper limbs. These findings underpin Chapter 4 which will examine qualitative and quantitative changes in dominant arm throwing at 6, 10 and 14 years of age in an attempt to further understand the technique and pathways are used during childhood and adolescence to establish if there are any similarity to technique changes in adults.

CHAPTER 4: Movement Form and Scaling Properties of the Overarm Throw for Children at 6, 10 and 14 Years of Age

4.1 Introduction

Chapter 3 explored technique changes during practice for adults learning to throw with their non-dominant hand. The strengths of this chapter were the longitudinal approach. Key findings were that the application of three approaches to motor learning provided a comprehensive view of technique change during non-dominant overarm throwing. The findings highlighted that overall a high order variable was better able to identify commonalities in technique change across individuals. However, chapter 3 cannot provide evidence about whether children at different developmental stages show the same differences in technique as skilled and less skilled adults performing non dominant arm throwing. Therefore, chapter 4 builds upon chapter 3 by examining cross-sectional development of technique changes in dominant overarm throwing action across childhood and adolescence. This is in order to see if the current stages of learning models can capture changes at different ages during childhood when overarm throwing action is initially being learnt and to establish if changes are similar to those shown in chapter 3.

Keller et al. (2011) examined coordination of overarm throwing in children aged from 3 to 18 years of age. Keller et al. (2011) suggested that overarm throwing action is characterised by instability during childhood and adolescence with movement instability being associated with persistent changes in bodily factors impacting motor skill during childhood; body size and increases in strength have a significant impact

on segmental coordination during throwing. The aim of chapter 4 was to establish firstly if current approaches to motor learning are able to adequately describe technique changes at 6, 10 and 14 years of age during overarm throwing. The purpose was to establish if during the development of overarm throwing a three different developmental stages are present at 6, 10 and 14 years of age, and to understand if pathways of technique change across age are consistent with the learning of non-dominant overarm throw in adulthood (as demonstrated in chapter 3).

In order to address this aim, dominant arm throwing action were examined at 6, 10 and 14 years of age from the perspective of three distinct though potentially complementary approaches to motor skill acquisition that examine different aspects of the system: Newell's (1985) learning stages of coordination, control and skill; the components model of overarm throwing (Robertson & Halverson, 1984); and Bernstein's (1967) hypothesis of freezing and freeing the redundant mechanical degrees of freedom.

In order to understand how overarm throwing technique progresses with age in children, a number of qualitative and quantitative characteristics of movement need to be examined. Robertson & Halverson (1984) developed the components model of overarm throwing following a 7-year longitudinal study of 39 children. As the only specific overarm throwing model of technique changes, the components model has subsequently been applied to examine technique changes in both children (Robertson & Konczak, 2001; Langendorfer & Robertson, 2002; Stodden et al., 2006*a,b*; Keller et al., 2011) and adults (Williams et al., 1998) learning to throw. It is apparent that individual patterns of progression through the levels of the components occur

(Langendorfer & Robertson, 2002), and taking a contralateral step which places the body in a more advantageous position to adapt motions of the trunk and arm components (Stodden et al. 2006a) are key variables of change drawn from this body of work.

Quantifying the segmental lag between the extension of the torso and arm joints is an alternative method to understand technique in throwing by capturing the transfer of energy along the kinetic chain from heavier proximal segments to lighter more distal segments (Southard, 2006). Yan, Payne & Thomas (2000) found that children at 6 years of age maximised ball velocity through trunk rotation, forearm lag and elbow extension, while younger children at 3 and 4 years of age primarily used trunk flexion. These findings have provided support for the pathways of progression of children through stages of the components model with age.

Overall, these studies have identified that for children learning to throw, the key technique characteristics are likely to be associated with changes in the lower extremities through inclusion of a contralateral step and trunk rotation with advanced overarm throwing action developing around 13 years of age (Stodden et al., 2006a,b). Halverson, Williams & Langendorfer (1980) have found, however, that children at 13 years of age still do not demonstrate a fully developed overarm throwing technique. The majority of previous studies have reported single joint measures and applied of the components model (Robertson & Halverson, 1984).

From a dynamical systems theory perspective however, ‘coordination’ and ‘coordination variability’ between the joints and segments is the key to understanding

technique changes during learning. ‘Coordination’ and ‘coordination variability’ is emphasised by the generic motor learning models of Bernstein (1967) and Newell (1985). Bernstein’s (1967) hypothesis of freezing and freeing the redundant degrees of freedom captures properties of qualitative and quantitative technique changes with the direction of change has been suggested to be task specific (Hong & Newell, 2006). Newell’s (1985) stage of learning provides a functional distinction between the constructs of coordination, control and skill.

In chapter 3 it was reported that practice induced changes in the collective posture-ball release dynamics were supported by individual strategies at the joint ROM level. This high order, low dimensional variable CoM and wrist joint was able to capture a common transition in the macroscopic organisation of the overall system dynamics, despite being constrained by individual differences at the joint level. It is of interest to determine if CoM-wrist coupling is also able to identify common changes in overarm throwing action as a function of developmental age, and whether individual strategies exist at the joint space level.

4.2 Chapter Aim and Research Questions

The aim of this chapter was to investigate the differences in technique over childhood and adolescence for dominant overarm throwing with respect to the three different though potentially complementary approaches to qualitative and quantitative change of movement dynamics during learning: Newell’s (1985) learning stages of coordination, control and skill; the components model of overarm throwing (Robertson & Halverson, 1984); and Bernstein’s (1967) observations of freezing and freeing

redundant mechanical degrees of freedom. In this study the overarm throwing action of a cross-section of ages of children related to distinct developmental periods was examined (Robertson & Halverson, 1984; Hirabayashi & Iwasaki, 1995; Roncesvalles, Woollacott & Jensen, 2001; Meister et al., 2003; Stodden et al., 2006a,b; Nolan et al., 2005; Mickle, Munro & Steele, 2011). The purpose was to: (i) establish if current approaches to motor learning are able to adequately describe technique differences at 6, 10 and 14 years of age (ii) suggest if differences in technique across age are consistent with changes that occur during learning the non-dominant overarm throw in adulthood.

It was expected that an index of the macroscopic dynamics that linked the postural and limb effector motions could capture generalizable age-related changes in technique during learning. Furthermore, that quantitative changes in individual joint rotations and CoM motions are embedded within the sequential qualitative changes in trunk/arm relative motion during learning to throw with the non-dominant arm. This chapter therefore investigates technique changes in overarm throwing action as a function of a child's age using three different complementary approaches that each focus on a different aspect of the dynamical system.

In order to address the aim of this chapter, the following specific research questions were addressed:

- With age, does the collective variable CoM-wrist become more complex and less variable in line with Newell's (1985) learning stages of coordination, control and skill?

- With age, how do changes in technique occur in line with the components model of overarm throwing (Robertson & Halverson, 1984)?
- With age, how do changes in ROM occur in-line with Bernstein's (1967) observations of freezing and freeing redundant mechanical degrees of freedom?

4.3 Methods

4.3.1 Participants

Chapter 3 detailed the collection of kinematic data during overarm throwing action in adult learners (sections 3.3.1 to 3.3.3). Chapter 4 used similar kinematic data collection methods that were slightly altered for the current study with child participants. Ethical approval was granted from the departmental research ethics panel (DREP-15-031) Anglia Ruskin University Ethics Committee prior to study initiation. Analysis was performed on 18 children (Table 4.1). All participants provided assent alongside parent/guardian written informed consent. Parent/guardians also completed a pre-exercise health questionnaire (PAR-Q) on behalf of their child and the Edinburgh handedness inventory (Oldfield, 1971) was undertaken to establish if the child had a dominant hand. Inclusion criteria at recruitment were as follows: participants were not competing in a throwing-based activity, had a dominant hand, and were free from musculoskeletal injury. Participants were fairly homogenous with respect to size, weight and height (Table 4.1).

Table 4.1 Characteristics of participants in 6, 10 and 14 year age groups

Characteristic	6 years	10 years	14 years
Sex	5 (female)	4 (female)	4 (female)
	1 (male)	2 (male)	2 (male)
Age (years)	6.56 \pm 0.30	10.32 \pm 0.33	14.22 \pm 0.48
Stature (m)	1.22 \pm 0.05	1.47 \pm 0.10	1.64 \pm 0.11
Mass (kg)	23.88 \pm 5.02	39.29 \pm 3.26	61.02 \pm 6.97

The components model (Robertson & Halverson, 1984) collected longitudinal data with children from 6 to 13 years of age and concluded that overarm throwing was not fully developed by 13 years of age. As Robertson and Halverson's (1984) model is the only throwing specific model it was of interest to examine children within a similar age range. While the time constraints of a PhD thesis limits the ability to collect longitudinal data with children, the age range used by Robertson and Halverson (1984) was used as a guideline to inform age groups of children in this thesis.

Therefore, the age groups were based on two factors: ages that previous research has identified where key changes in throwing occur and academic school year groups. The first age group (6 years of age) was chosen as all children will have received a minimum of one school year of physical education as stated by the national curriculum. This will have helped to level the playing field as all children will have

been formally introduced to throwing. The second (10 years of age) and third age group (14 years of age) were informed by research. Literature suggested that by 10 years of age healthy children have developed advanced postural stability similar to adults (Taguchi & Tada, 1988; Faigenbaum et al., 2014). While Robertson and Halverson (1984) suggested a mature level of overarm throwing had not been developed by 13 years of age, Stodden et al. (2006) collected cross-sectional data with children between 3 to 15 years of age and reported that children of 12 years of age had developed a mature throw. It is of interest to explore if the application of stages of learning models along with novel methods could provide a greater understanding of cross-sectional changes in overarm throwing across childhood.

Participants' anthropometric measurements were as follows: stature (1.22 ± 0.05 ; 1.47 ± 0.10 ; 1.64 ± 0.11) and mass (23.88 ± 5.02 ; 39.29 ± 3.26 ; 61.02 ± 6.97). The standard deviation within a group for stature was similar at each age. For standard deviation within a group for mass, greater differences were found with the greatest standard deviation present within the 6 year old age group. This point raises one of the major issues of cross-sectional data collection which cannot be controlled between individuals of a group.

4.3.2 Procedure

Each participant attended a single data collection session. Kinematic data was collected for 5 overarm throws performed with the dominant arm. Overarm throws were completed from a standing position with each participant free to choose their preferred stance. Participants were given the aim of hitting 0.4 m target located 14 m

in front of them by throwing a standard issue tennis ball (Slazenger) ball as hard as possible. The target height was adjusted to each participant's standing eye level using a tape measure and 14 m was chosen as a distance to encourage the children to throw as far as they could. Participants were not blinded from knowledge of the results and verbal encouragement was provided using phrases that included the words: 'nice', 'well done' and 'good job'. The target placement and task instructions promoted forceful and accurate throws from the participants.

4.3.3 Data Collection

Kinematic data was collected at 200Hz using an automated 3D motion capture system (CODAmotion, Charnwood Dynamics Ltd, UK). Three CX1 scanners provided a 360-degree field of view around the participant and were synchronized to two Kistler Force Platforms (9865, UK) flush to the floor. Active markers were placed on the estimated joint centre of rotation using a lateral full body marker set. Specifically, the anatomical points were: 3rd metacarpal, ulnar styloid process, forearm, lateral epicondyle of the elbow, shoulder, xiphoid process, greater trochanter, thigh, femoral condyle, lateral malleolus, calcaneus and 2nd metatarsal. Whole-body CoM was defined based on the average mass and position of the individual segment CoM. Specifically, this was both hands, forearms, upper arms, shank, feet with the head and torso considered as a single segment (Plagenhoef, Evans & Abdelnour, 1983). Following a residual analysis of the shoulder, elbow and wrist markers, a fourth-order Butterworth filter was applied to raw marker data with a cut-off frequency of 6 Hz (Winter, 2005). Data was analysed during the propulsive phase of the throw which was defined as from the instance of forward and continuous motion of the markers in the direction of the throw until the frame of ball release. Data was analysed and presented as a percentage of the total

propulsive phase of the throw and normalised to 100%.

4.3.4 Variables

4.3.4.1 Newell's (1985) Stages of Coordination, Control and Skill

Coordination and variability of the CoM and wrist coupling in the anterior-posterior direction was quantified using a modified vector coding (Sparrow et al., 1987; Chang, Van Emmerik & Hamill, 2008; Needham, Naemi & Chockalingam, 2014). VC angles were defined using four key coordination patterns: (1) anti-phase coupling ($112.5 \leq \gamma < 157.5^\circ$, $292.5 \leq \gamma < 337.5^\circ$) where variables are moving in opposite direction; (2) in-phase coupling ($22.5 \leq \gamma < 67.5^\circ$, $202.5 \leq \gamma < 247.5^\circ$) where variables are moving in the same direction; (3) wrist-led phase coupling ($0 \leq \gamma < 22.5^\circ$, $157.5 \leq \gamma < 202.5^\circ$, $337.5 \leq \gamma < 360^\circ$) where wrist movement is dominant variable; and (4) CoM-led phase coupling ($67.5 \leq \gamma < 112.5^\circ$, $247.5 \leq \gamma < 292.5^\circ$) where CoM movement is more dominant. In order to quantify changes in the CoM-wrist coupling ROM during the propulsive phase of the throw was calculated. Average standard deviation across VC profiles of an individual were used to determine variability.

4.3.4.2 Components Model (Robertson & Halverson, 1984)

Action of the 'step', 'trunk', 'humerus' and 'forearm' were qualitatively classified by the principal investigator for all trials for all participants in line with the model description. A classification of 1 was representative of the least skilled action level and action level 3 or 4 was representative of skilled action of that component

(Robertson & Halverson, 1984; Table 4.2). If a participant's technique was split across two action levels for a component across the five throws, the action level with the highest number of trials was recorded.

Table 4.2 **Action level for components of overarm throwing action (Robertson & Halverson, 1984)**

Action level for components
Step component
Level 1: No step
Level 2: Ipsilateral step
Level 3: Contralateral short step
Level 4: Contralateral long step
Trunk component
Level 1: No trunk action
Level 2: Upper trunk rotation
Level 3: Differentiated trunk rotation
Humerus component
Level 1: Humerus oblique
Level 2: Humerus aligned by independent
Level 3: Humerus lag
Forearm component
Level 1: No forearm lag
Level 2: Forearm lag
Level 3: Delayed forearm lag

4.3.4.3 **Bernstein's (1967) Joint Range of Motion**

To capture the freeing of degrees of freedom, joint ROM during the propulsive phase of the throw was calculated. The ankle joint was defined from the 2nd metatarsal, lateral malleolus and calcaneus; knee joint from lateral malleolus, femoral condyle and greater trochanter; hip joint from femoral condyle, greater trochanter and xiphoid process; shoulder joint from shoulder joint centre of rotation, xiphoid process and lateral epicondyle of the elbow; elbow joint from shoulder joint centre of rotation, lateral epicondyle of the elbow, styloid process of ulna; and the wrist joint was defined from the 3rd metacarpal, styloid process of ulna and lateral epicondyle of the elbow. Average ROM across the 5 trials was calculated for each participant. The mean was then determined for each age group. Angles were defined in 3D where an angle of 180° represented maximum extension, while 0° would represent minimal flexion.

4.3.5 **Statistical Analysis**

Data were assessed for normality using a Shapiro-Wilks test. Once confirmed, a repeated measures analysis of variance (ANOVA) was conducted based on a single subject design ($p < 0.05$). Each dependent variable was run individually for each participant. Mauchly's test was used to determine the sphericity assumption within the data; where sphericity was violated, a Greenhouse-Geisser correction was applied. Comparisons of vector coding coordination variability were examined between age groups. Bonferroni post hoc correction was used as needed for multiple comparisons.

4.4 Results

4.4.1 Newell's (1985) Learning Stages of Coordination, Control and Skill

Fig 4.1a

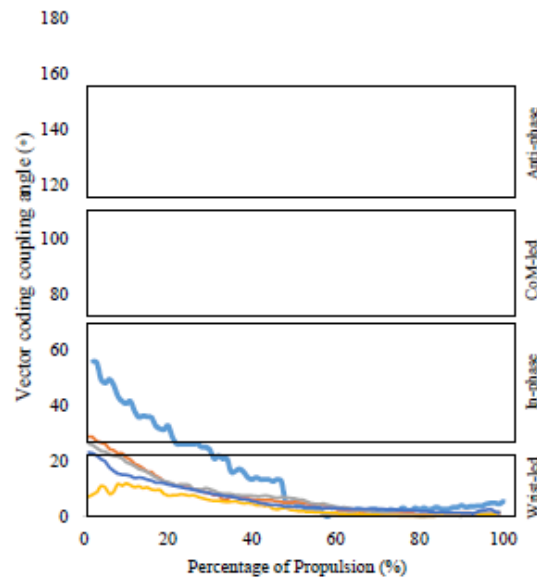


Fig 4.1b

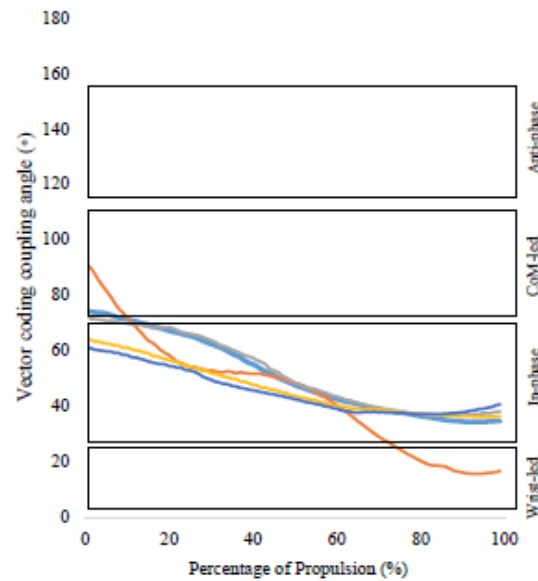


Fig 4.1c

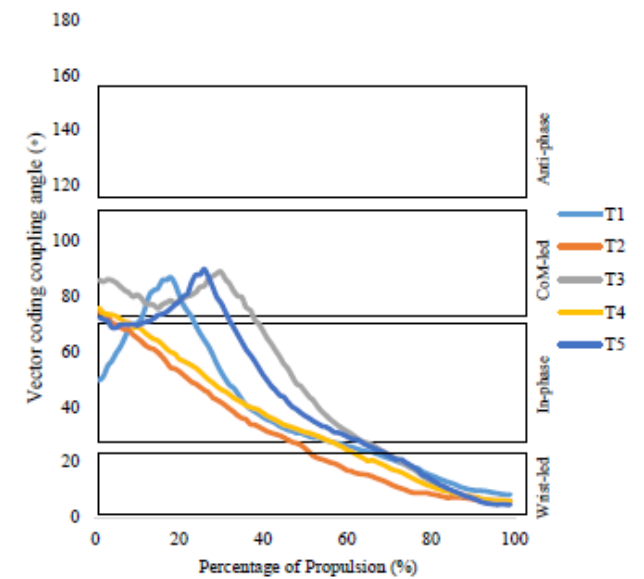


Fig 4.1 **Vector Coding Angle between Centre of Mass-Wrist Coupling for 5 Trials**

(Fig 4.1a, representative 6-year old; Fig 4.1b, representative 10-year old; and Fig 4.1c representative 14-year old).

Three CoM-wrist coupling modes were identified across the three age groups. Six year olds tended towards in-phase coupling of the CoM-wrist at the start of the propulsive phase of the throw, where the CoM and wrist were moving forward together. While in this age group the majority of the propulsive phase, wrist-led coupling dominated at around 20% and continued towards ball release ($0 \leq \gamma < 22.5^\circ$) (Fig 4.1a).

In line with Figure 4.1b, 10 and 14 year olds used CoM-led coupling at the start of the propulsive phase, progressing to in-phase coupling (at around 20%) finishing with wrist-led phase coupling at ball release (Fig 4.1b). Only 3 of the 6, 14 year olds exhibited CoM-led coupling at the start of the propulsive phase of the throw, which moved further into CoM-led coupling before progressing to wrist-led coupling at release (Fig 4.1c).

Significant age differences were found in ROM of the CoM-wrist coupling. Children at 6 years of age ($p = 0.007$) and 10 years of age ($p = 0.036$) had a significantly smaller ROM than 14 year olds. No significant differences was present in ROM of the CoM-wrist coupling between 6 and 10 years of age ($p = 0.342$).

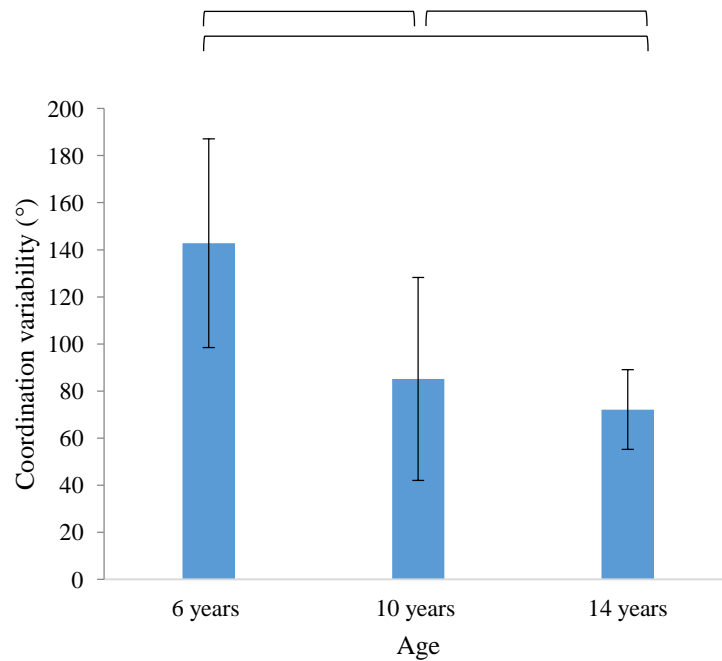


Fig 4.2 **Standard deviation between subjects during 5 trials of the centre of mass-wrist coupling in the anterior posterior direction for dominant arm overarm throws at 6, 10 and 14 years of age**

Significant differences were present in CoM-wrist coordination variability for dominant arm throws between 6, 10 and 14 years of age. Coordination variability at 6 year olds was significantly greater than 10 ($p = 0.001$; $d = 0.67$) and 14-year olds ($p = 0.001$; $d = 1.72$). Coordination variability at 10-years of age was significantly greater than the 14-year old group ($p = 0.04$; $d = 0.14$).

4.4.2 Components Model of Overarm Throwing (Robertson & Halverson, 1984)

Table 4.3 Action level at ages 6, 10 and 14 years

Segment	Action level	Dominant arm throws		
		6-yrs	10-yrs	14-yrs
Step	1	3		
	2	1		
	3	2	6	6
	4			
Trunk	1	1		
	2	5	6	6
	3			
Humerus	1	6		
	2		6	6
	3			
Forearm	1	6		
	2		6	6
	3			

Participants at 6, 10 and 14 years of age progressed through action levels of the components model (Table 4.3). Six years olds' overarm throws were characterised by humerus and forearm action that were classified at action level 1. For the majority, trunk was characterised at action level 2, and step

action distributed between levels 1 to 3.

At 10 and 14 years overarm throws were characterised by more advanced action levels, but only the penultimate action level for each component. By 14 years of age participants had not reached the highest action level of the components model for the ‘step’ component but had achieved this for the ‘trunk’, ‘humerus’ and ‘forearm’.

4.4.3 Bernstein’s (1967) Joint Range of Motion

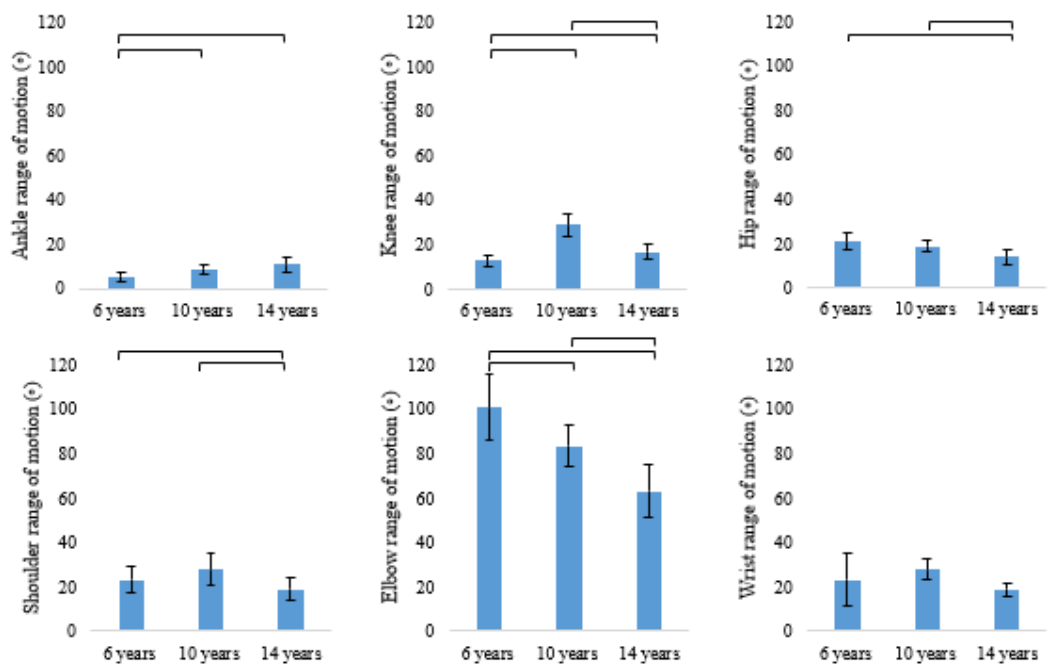


Fig 4.3 Joint range of motion at the ankle, knee, hip and shoulder, elbow and wrist at 6, 10 and 14 years of age

Significant age differences were found in ROM in the majority of joints. Six-year olds ankle ROM was significantly smaller than 10-year olds (ankle, $p = 0.003$) and 14-year olds ($p = 0.001$). Knee ROM at 6-years was significantly

smaller than 10- ($p = 0.002$) to 14-years ($p = 0.01$), however, greater at 10-years compared to 14-years ($p = 0.003$). Hip ROM were significantly greater at 6-year old age group compared to 10-years ($p = 0.01$) and 14-years ($p = 0.007$). Shoulder ROM at 14-years was significantly smaller than at 6- ($p = 0.02$) and 10-years ($p = 0.03$). Elbow ROM were significantly greater at 6-year olds compared to 10-years (elbow, $p = 0.001$) and 14-years ($p = 0.001$). The 6-year olds wrist ROM significantly smaller than to 10- ($p = 0.04$) and greater than 14-year olds ($p = 0.03$), where 10-year olds were significantly greater compared to 14-year olds ($p = 0.02$).

4.5 Discussion

The aim of this chapter was to investigate the differences in technique over childhood and adolescence during dominant overarm throwing with respect to the three different, though potentially complementary, approaches to qualitative and quantitative change of movement dynamics during learning: Newell's (1985) learning stages of coordination, control and skill, the components model of overarm throwing (Robertson & Halverson, 1984) and Bernstein's (1967) observations of the progression of freezing and freeing the redundant mechanical degrees of freedom. These models were used to examine technique changes during childhood and to see if the same changes in technique were present in children and adults alike during overarm throwing action. Combining the three approaches helps enhance understanding about how different levels of the system changes are different ages.

4.5.1 Newell's (1985) Learning Stages of Coordination, Control and Skill

In order to investigate the development of the overarching macroscopic properties of change in the coordination of the dynamic system during childhood, the collective variable CoM (postural variable) and wrist (end effector) were quantified using vector coding analysis. The transition to a stable coordination can be demonstrated through in-phase coupling ($22.5 \leq \gamma < 67.5^\circ$, positive coupling or $202.5 \leq \gamma < 247.5^\circ$, negative coupling). It was anticipated that older children in this study would be more developed at overarm throwing. The strategy of CoM-wrist coupling used at 10 and 14 years of age provides support for freeing of the dynamical degrees of freedom (Newell & Vaillancourt, 2001). Specifically, the macroscopic organisation of the system has become more complex with age, utilising a broader range of phase relations associated with the kinematic chain of the whole arm. Across all groups, and related to age, three key coupling modes were observed between the CoM and wrist. Six year olds displayed the most primitive CoM-wrist coupling which was characterised by in-phase coupling at the start of the throw, where the CoM and wrist both travelled forward together, and prior to wrist-led coupling up until ball release (Fig 4.1a). CoM-wrist coupling at 10 and 14 years of age was more complex (Fig 4.1b) and was characterised by CoM-led coupling initially, where forward movement of the CoM is the predominant influencer on the movement. Coupling then progressed through in-phase, and on towards wrist-led coupling at ball release (Fig 4.1b). Finally,

three of the 14 years olds exhibited CoM-led coupling at the start of the propulsive phase, with greater time with CoM-led coupling relative to the younger age groups, before progressing through to in-phase coupling, and eventually wrist-led coupling at ball release (Fig 4.1c). The use of a high order variable, CoM and wrist has captured sequential throwing motion across age groups.

It was shown in chapter 3 that CoM-wrist coupling captured robust characteristics of technique change across participants during non-dominant arm practice. In children, more complex modes of CoM-wrist coupling with the progression of age (from 6, 10, and 14 years) can be seen. Specifically, coupling mode 1 and 2 (Fig 4.1a; 4.1b) displayed a similar but simpler profile than previously reported in chapter 3. As the children spent less time in in-phase coupling (mode 1; Fig 4.1a) and CoM-wrist led coupling (mode 2; Fig 4.1b). Coupling mode 3 (Fig 4.1c) was similar to the coupling reported in chapter 3, while the progression of coupling angle further into the CoM-led coupling was a progression not present for adult participants. These differences in findings could be due to differences in dynamical degrees of freedom and potentially different postural control of the CoM or the aim, or their combination, in children compared to adults learning to throw. Taken collectively, both studies provide support for global macroscopic variables being associated with common inter-individual changes during learning which are not seen at the joint space levels of technique changes. This raises an important distinction regarding the level of the dynamical system that might capture fundamental characteristics of technique change during learning. This

stands as an epistemological shift from the joint space level of analysis in previous research (Bernstein, 1967; Newell et al., 1989; Vereijken et al., 1992; Chow et al., 2008).

Intra-individual coupling variability showed a decrease with the progression of age from 6 to 14 years which suggests that children at 10 years of age were able to produce a more consistent CoM-wrist coupling patterns than children at 6 years of age. Three participants at 14 years of age displayed a more advanced coupling. A consistent pattern emerged in this collective variable with age which could be generalizable to motor learning of all complex skills. This is consistent with findings reported by Wagner et al. (2012) who examined movement variability during a handball standing throw for individual of varying skill level. Findings reported that movement variability decreased with skill level in the standing throw. This finding was associated with skilled players having the ability to compensate for any increases in movement variability.

To understand the kinematics underpinning the collective dynamic, technique changes were further examined using the components model (Robertson & Halverson, 1984) and Bernstein's (1967) hypothesis of freezing and freeing the redundant mechanical degrees of freedom. Both these approaches provide a distinct description of the movement pattern, and a distinct perspective on the mechanisms underpinning changes demonstrated in CoM-wrist coupling following practice.

4.5.2 The Components Model of Overarm Throwing (Robertson & Halverson, 1984)

Cross sectional data showed that participants at 6, 10 and 14 years of age progressed through the outlined action levels of the components model (Robertson & Halverson, 1984) (Table 4.3). Six year olds were the least skilled at overarm throwing as categorised by the components model (Robertson & Halverson, 1984). They also displayed the greatest range of step action configurations for any of the three age groups (Table 4.3), including no step and ipsilateral step configurations. These configurations both create a closed body position and place constraints on the body that limit progression of the ‘humerus’ and ‘forearm’ components beyond level 1, through restricting the rotation of the trunk and preventing the production of angular velocity (Stodden et al., 2006a). Findings from this chapter are consistent with Branta, Haubenstricker & Seefeldt (1984) who reported that the greatest change in motor development occurred during the primary school aged indicating that children are most responsive to technique development during these years. Ten and 14 year olds all displayed a contralateral, short step (Table 4.3). However, no further qualitative technique changes were found between 10 and 14 years of age. A contralateral step (level 3) creates a more open position of the body (Stodden et al., 2006a,b) which affords the trunk to then be free to rotate to a more open position. These findings highlight the fundamental importance of step action for overarm throwing.

The development of distal to proximal sequence is developed later in motor development (Halverson et al. 1980). This is consistent with findings from the current study (Table 3.2) where children at 10 and 14 years of age demonstrated more proficient use of the mechanical capability of the body, namely through increased involvement of more distal segments than that of the 6 year olds. The results of this study provided some support for this, with 10 and 14 year olds both being categorised as level 2 for the trunk, humerus and forearm for dominant arms. Meanwhile, 6 year olds were categorised as level 1 ($n = 1$) and level 2 ($n = 5$) for the trunk and they were all classed at action level 1 for the humerus and forearm action. While the trunk and arm segments are highlighted as invaluable contributors to overarm throwing action (Robertson & Konczak, 2001; Nelson, Thomas & Nelson, 1991; Nelson et al., 1986), it might be that movements related to the step are currently more critical to the development of technique than other key biomechanical parameters such as segmental lag and the kinematic chain between torso and arm segments. Moreover, Yan et al. (2000) suggested that motor pattern of overarm throwing action is improved following greater involvement of the trunk (Urbin et al., 2013).

The findings support the notion that the basic organisation of degrees of freedom is not yet developed in overarm throwing, even by the age of 14 years of age. As no participants displayed a long contralateral step (level 4) or the most advanced trunk action, this suggests that the overarm throwing action is not necessarily fully developed by 14 years of age. This is in line with Halverson et al. (1980) who reported that by 13 years of age their participants were far from having ‘mastered’ or ‘developed proficiency’ in overarm

throwing and that instruction is still required in secondary level education to achieve advanced levels of the throw. Furthermore, the participants in the current study were slightly less advanced at throwing than those reported in Stodden et al. (2006a,b), who examined cross-sectional kinematic variables in dominant arm throwing in children between 3 and 15 years of age. Stodden et al. (2006a,b) reported a developmental level at 6 years of age to be in line with current findings. However, children between 11 and 13 years of age displayed more advanced developmental action levels (level 3 and level 4).

In comparison to the findings reported in chapter 3 (Table 3.2), no adult participants were categorised at the initial action level 1. It is suggested that adult non-dominant arm throws were supported by motor learning and transfer (Adams, 1987) where knowledge of dominant arm throwing positively influenced the learning of non-dominant arm throwing. Consistent with chapter 3, children and adult participants both progressed up the continuum of action levels of the components model rather than regressing down the continuum.

4.5.3 Bernstein's (1967) Joint Range of Motion

In line with Bernstein's hypothesis (1967) ROM of the ankle and knee joint increased with age (Fig 4.3) and occurred along with a more advanced 'step' action (Table 4.3; Fig 4.2). Interestingly ROM of the hip and elbow decreased with age from 6 to 14 years of age (Fig 4.3). In parallel, children at 10 and 14 years of age were categorised in advanced action levels for the 'humerus' and 'forearm' of the components model (Robertson & Halverson, 1984).

The findings lead to the suggestion that increased ROM of the ankle, hip and elbow specifically, might distinguish between child throwers at these developmental ages, and might be a key coaching point for the skill. However, the context to these increased ROM's is likely captured in the Robertson and Halverson (1984) components model which outlines coaching points. While Gray et al. (2006) reported kinematic differences between dominant and non-dominant arm throws to be attributed to the ability of the two arms to control interaction and exploit the interaction torques at the elbow and wrist in skilled recreational baseball players.

4.5.4 Integrating frameworks to the acquisition of overarm throwing

Emphasising a CoM-wrist coupling as a macroscopic collective variable which is controlled over that of individual degrees of freedom is based on the theoretical proposition that motor learning is associated with change in the overall system dynamics (Ko, Challis & Newell, 2014; Wang et al., 2014; Dutt-Mazumder, Challis & Newell, 2016). When using the components model (Robertson & Halverson, 1984) which examines changes in qualitative technique, no distinct differences were found beyond 10 years of age. Arguably, CoM-wrist coupling, the collective dynamic, is underpinned by the technique changes in the components model (Robertson & Halverson, 1984) which provided qualitative coordination variables through the four key components. In supporting these different emphases on system organisation, the findings suggest that a more complex CoM-wrist coupling is achieved

during progression throughout childhood by taking a contralateral step during throwing, which is associated with an increased ROM of the lower extremities. Therefore, by increasing the complexity of the collective dynamics, participants followed the sequence of components change in the Robertson and Halverson (1984) model, while Bernstein's (1967) postulation of freeing mechanical degrees of freedom was limb specific.

The application of all three approaches provides a comprehensive analysis of technique during overarm throwing action at 6, 10 and 14 years of age: Newell's (1985) macroscopic properties; Robertson and Halverson's (1984) sub degrees of segmental change; Bernstein's (1967), individual degree of freedom. This approach provides an in-depth holistic overview of changes in technique throughout childhood and developing adolescents that are practically relevant. Overall, the macroscopic variable was better able to distinguish changes in overarm throwing technique among the three age groups than across single joint motions, and therefore, might be key to understanding the dynamics of technique change across different task and organismic constraints from a dynamical systems theory perspective.

The findings of this chapter support the theoretical proposition that motor control is organized with overall system dynamics rather than the control of individual degrees of freedom (Kelso, 1995; Newell, 1985). Moreover, the findings highlight the importance of the lower extremities and dynamic postural control in what is usually characterised as an upper extremity action. Specifically, the presence of a contralateral step to facilitate greater ROM of

the lower extremities and CoM movement in weight transfer is related to the release of the individual joint space motion.

4.6 Conclusion

The aim of chapter 4 was to investigate the changes in technique over childhood and adolescence during dominant overarm throwing. This was related to three distinct though potentially complementary approaches to qualitative and quantitative change of movement dynamics during learning: Newell's (1985) learning stages of coordination, control and skill; the components model of overarm throwing (Robertson & Halverson, 1984); and Bernstein's (1967) observations of freezing and freeing redundant mechanical degrees of freedom.

This study has revealed experimental evidence of the progression of individual technique changes in dominant overarm throwing at 6, 10 and 14 years of age. The findings highlight that postural control is critical for facilitating the development of upper extremities in what is usually characterised as an upper extremity action. Specifically, this is the ability to take a contralateral step to facilitate greater ROM (releasing) of the lower extremities and CoM movement in weight transfer. Changes in technique occurred in line with the components model (Robertson & Halverson, 1984) while joint ROM was limb specific (Bernstein, 1967).

The use of the global variable (CoM and the wrist as an end effector) to examine the dynamics of the system provides an invaluable overview of overarching macroscopic technique changes in terms of complexity of postural control dynamics of the system. The application of a biomechanically relevant coupling strategy (CoM-wrist) is underpinned by the technique changes in the ‘step’ action level of the components model (Robertson & Halverson, 1984) and increased ROM of the lower extremities consistent with Bernstein hypothesis (1967). In part, the process of change to advance the developmental ‘step’ action with an increase in ankle and knee ROM facilitates increased weight transfer from back leg to front leg (Knudson & Morrison, 1996). Meanwhile the components model for overarm throwing (Robertson & Halverson 1984) and Bernstein’s (1967) hypothesis are unable to provide an understanding of the technique changes in the complexity of the system relative to movement of the whole system, and less clearly distinguishes between technique at 6, 10 and 14 years of age.

From a theoretical perspective, the use of collective variables to study Newell’s (1985) constructs of learning model is supported by the components model (Robertson & Halverson 1984) and Bernstein’s (1967) hypothesis. Newell’s (1985) stage of learning model is associated with the overall system dynamics rather than more traditional view of control of single units proposed by computational approaches (Adam, 1971; Schmidt, 1975).

From an applied perspective, the application of all three approaches provides a comprehensive overview of technique changes during overarm throwing

action at 6, 10 and 14 years of age. Each of the three approaches views a different level of the system, providing in-depth picture of changes in technique over childhood and adolescence. Key differences between ages can be used as feedback to inform skill development. The findings highlight that postural control is critical for facilitating the development of the upper extremities in what is usually characterised as an upper extremity action. Therefore, specific coaching points would be for children to adopt a contralateral step which would help to facilitate greater ROM of the lower extremities and CoM movement in weight transfer.

Overall, this study has shown how current theories of motor learning can be used to describe technique development in the overarm throw action throughout childhood and adolescence. If researchers can understand movement development during childhood and adolescence, it can aid sport practitioners, sports coaches and teachers of the key area that need developing and how it is possible to fast track movement development. Future work could explore in more detail the coordination between multiple joint segments during learning to throw.

4.7 Chapter Summary

This chapter has examined how technique of overarm throwing action with the dominant arm changed between groups of participants aged 6, 10 and 14 years. The aim of chapter 4 was to investigate the changes in technique over childhood and adolescence during dominant overarm throwing with respect to

three distinct though potentially complementary approaches to qualitative and quantitative change of movement dynamics during learning: Newell's (1985) learning stages of coordination, control and skill, the components model of overarm throwing (Robertson & Halverson, 1984) and Bernstein's (1967) observations of freezing and freeing redundant mechanical degrees of freedom. Section 4.2 outlined the 3 research questions for this chapter.

- **'With age, does the collective variable CoM-wrist become more complex and less variable in line with Newell's (1985) learning stages of coordination, control and skill?'**

As a function of age, three coupling profiles were identified. Children at 6 years of age displayed the least advanced coupling pattern which was characterised by in-phase coupling moving to wrist-led coupling during the propulsive phase (Fig 4.1a). Children at 10 years of age and 14 years of age demonstrated more advanced coupling patterns between the CoM and wrist (Fig 4.1b; Fig 4.1c). Specifically, coupling at 10 and 14 years of age was characterised by initial CoM-led coupling followed by in-phase and wrist-led coupling at ball release.

Coordination variability of CoM-wrist was highest at 6 years of age. A significant decrease in coordination variability was present between all three age groups (Fig 4.2). This is consistent with Newell's (1985) stage of learning model. Specifically, that that initial stage of learning, coordination, is characterised by high variability as the child searches for appropriate movement strategies in the constraint to action. The use of CoM and wrist

coupling as a collective variable enabled capture of a key change in system organisation despite individual constraints to action. Moreover this high order variable was able to identify commonality in technique change and therefore might be key to understanding the dynamics of technique change across different tasks of the organismic constraints.

➤ **‘With age, how do changes in technique occur in-line with the components model of overarm throwing (Robertson & Halverson, 1984)?’**

Overall, the components model (Robertson & Halverson, 1984) provides practitioners with a throwing specific framework to assess technique changes. During dominant limb overarm throws children at 6 years of age displayed the least advanced developmental action (Robertson and Halverson, 1984). By 10 years of age participants had reached advanced developmental profiles, however, not all participants had reached the highest action level by 14 years of age suggesting that overarm throwing action is still being developed at 14 years of age and further instruction is required. The results of the current study were consistent with previous findings (Halverson et al., 1980; William et al., 1998). Moreover, the components model (Robertson and Halverson, 1984) provides practitioners with a useful framework to access developmental changes in overarm throwing action during childhood and adolescence.

➤ **‘With age, how do changes in ROM occur in-line with Bernstein’s (1967) observations of freeing and freeing redundant mechanical degrees of freedom?’**

In order to address this question ROM of children at 6, 10 and 14 years was analysed. An increase in ROM of the ankle and knee joint was found with age. In contrast, ROM at the elbow and wrist ROM became more restricted with age. This finding was consistent with previous research (Button et al., 2003; Newell et al., 1989). In addition, ROM at the elbow was highlighted at a key variable of overarm throwing action. Examining the technique has provided valuable knowledge of how kinematic variables change over childhood and adolescence. Analysis of key kinematic variables provided an important insight into the technique adopted at different ages during childhood. In line with Bernstein’s (1967) observations of freeing and freezing the redundant degrees of mechanical freedom, children released the degrees of freedom of the ankle and knee joint prior to the upper extremities which was demonstrated through an increase in ROM. The findings from this chapter provide support to the notion that the order of freeing and freezing is task specific rather than the universal rule for technique change (Vereijken et al., 1992; Williams et al., 2015).

Chapter 4 has provided knowledge of technique changes in dominant overarm throwing action from three complementary though distinct approaches of motor learning across childhood. From a practical perspective it has provided a greater insight into the developmental technique changes during overarm throwing with the dominant arm, which is specifically the positioning of the

feet and taking a contralateral step. In terms of the basic science of motor control, the findings of this study suggest that there may be a requirement to master the dynamic stability of postural control before the learner is able to master the throwing action with the upper limbs. In an attempt to further understand the technique and pathways which individuals use to organise whole body movement to develop technique during overarm throwing Cluster Phase analysis of throwing movement was performed in chapter 5. Chapter 5 will build upon the application of the three approaches to technique change used in chapter 3 and chapter 4 to provide a greater understanding of the synchronization that underlies technique changes in the upper limb during overarm throwing in adults and children, which did not progress as expected.

CHAPTER 5: Age and Practice Related Changes in Upper Limb Tri-joint

Synchrony in Learning to Throw

5.1 Introduction

Chapter 3 and 4 used current stages of learning models to examine technique changes during overarm throwing action in adults and children. Chapters 3 and 4 provided knowledge and understanding of the qualitative and quantitative changes during overarm throwing by using three distinct approaches to motor skill acquisition (Newell, 1985; Robertson & Halverson, 1984; Bernstein, 1967). Specifically, chapter 3 examined the longitudinal evolution of movement technique of adults during non-dominant overarm throwing practice over 9 sessions. Chapter 4 used a cross-sectional study design to investigate technique in dominant overarm throwing as a function of age at 6, 10 and 14 years. Chapters 3 and 4 provided support for the use of a macroscopic coupling variable. Coupling of the CoM-wrist was able to more clearly identify commonalities in technique change between individuals than single joint motion. However, future work is required to explore in more detail the coordination between multiple joint segments during learning.

In order to build upon the work conducted in chapters 3 and 4, it is of interest to gain a more in-depth understanding of the coordination of the upper limb segment through the application of a multivariate method. The reason for this is that ROM of the upper limb joints did not increase with practice or age as hypothesised by Bernstein (1967) in chapter 3 or 4. This finding was surprising as overarm throwing action is typically thought of as an upper body movement with the majority of research focusing on

action of the arm. It is hoped that chapter 5 can address these points by using a multivariate method to study how coordination of the shoulder, elbow and wrist changes with practice in the non-dominant arm, or across ages in childhood.

Motor learning is the development of coordination and control. Bernstein (1967) provided a hypothesis to explain how complex systems are able to compress high dimensional states into controllable lower dimensional states called synergy. Once a synergy has been developed the multiple degrees of freedom are able to be self-organised (Bernstein, 1967; Kugler, Kelso & Turvey, 1980). This makes the study of movement coordination and synchronisation essential features of human movement and development (Thelen, 1995).

Coordination does not refer only to the spatial and temporal order but also to the varying degrees of functional order among interacting parts of the system and processes which occur in space and time. The study of coordination refers to methods and concepts used to describe, explain and predict the development of coordination and how it evolves and changes over time by identifying these patterns of coordination in relation to dynamical system theory.

The issue researchers face is developing robust methods can capture coordination of a complex system in a relevant and meaningful way. The application of multivariate methods provides the potential to study coordination beyond two oscillators, which is particularly relevant during early practice as an individual assembles the multiple degrees of freedom into a movement strategy to satisfy task demands within the coordination stage of learning (Newell, 1985).

The learning of a new movement pattern involves the assembly of spatial and temporal organisation of multiple joint and segment actions into a controllable dynamic system (Kugler, Kelso & Turvey, 1980). Thus, movement coordination and synchronisation are essential features to the study of human movement and its development in action (Thelen, 1995). Specifically, Bernstein (1967) and Newell (1985) suggested models that captured the nature of acquiring new movement patterns from a dynamical systems theory perspective. For Bernstein (1967) the key to understanding coordination was the process of mastering the redundant mechanical degrees of freedom, while Newell's (1985) model of coordination, control and skill provided a functional distinction between the three constructs in line with stages of learning. Newell (1985) suggested that a reduction in the variability of relevant coordination was a key characteristic of development between initial and more advanced stages of learning. Theoretically, this is consistent with the idea that exploration of coordination decreases as an individual finds the most appropriate movement strategies within their perceptual-motor workspace (Kelso, 1995; Hamill et al., 1999; Williams et al., 2015; Busquets et al. 2016). The current study aims to establish if Cluster Phase can adequately describe changes in upper limb coordination over a period of practice.

The majority of studies examining coordination in human movement have considered motion at two joints or segments (e.g. Haken, Kelso, & Bunz, 1985; Kelso, 1984; Schmidt, Shaw & Turvey, 1993). However, since the majority of human movement tasks engage limb motions involving three key joints (e.g. shoulder, elbow and wrist in throwing). This suggests the need to apply multivariate methods to further understand the coordination involved in whole-body tasks. Multivariate methods such

as principal component analysis have been used to search for coordinative patterns within the many degrees of freedom in human movement (Daffertshofer et al., 2004; Chow et al., 2006; Hong & Newell, 2006; Chow et al., 2008; Ko, Challis & Newell, 2013; Ko, Han & Newell, 2017) by extracting a small sample of relevant variables that best capture the entire data set (Daffertshofer et al., 2004). This is illustrated by Ko et al. (2017) who investigated the effect of skill level on the organisation of the postural control system during a pistol-aiming task. Novice participants required 3 components to accommodate for variance as opposed to 2 components for the skilled group. The findings of Ko et al. (2017) supports the proposition that skill acquisition reduces the kinematic variables into a lower collective dimension. In addition, Ko et al. (2013) explored the impact of rhythmical dynamics on a supporting surface on the organization of postural coordination patterns. A higher platform velocity led to a reduction in the number of principal components. Hong and Newell (2006) reported that the number of principal components did not change during a ski-simulator task with learners, although the contribution of each principal component to the movement pattern did change. Taken together, these studies suggest that in a more coordinated action, synchrony of the joint motions is higher.

Cluster Phase is a multivariate method that allows for multiple degrees of freedom to be examined at the same time (Frank & Richardson, 2010). Cluster Phase analysis provides a synchrony value which refers to the relative timing of each of the variables inputted. It is hoped that Cluster Phase analysis will provide understanding of coordination of the throwing arm (shoulder, elbow and wrist). The technique is based on the Kuramoto order parameter (Kuramoto, 1984; 1989) which has been applied to the study of fireflies flashing (Hanson, 1978), synchronisation of crickets chirping

(Walker, 1969), and audience clapping (Néda et al., 2000a,b). The basic algorithm was refined by Richardson et al. (2007) to work for a smaller number of oscillators as demonstrated by capturing the synchrony between 6 rocking chairs (Richardson et al., 2007; Richardson et al., 2012), and subsequently players on a football pitch (Duarte et al., 2013; Silva et al., 2016). The approach used here has been adapted by Frank and Richardson (2010) in order to study simultaneous synchrony between three joints. Diss et al. (2019) have used the Cluster Phase method to examine the tri-joint synchrony between hip, knee and ankle joints during the stance phase of running. Specifically, they examined how this synchrony changed over a 7 year period of ageing in a longitudinal study. Results suggested that the motions of the three joints became more synchronised from 50 to 57 years of age. The authors suggested that this could be due to a loss of independence and complexity between the three joints, which are controlled by mono and bi articular muscles. This work provided evidence that Cluster Phase can capture important characteristics of the temporal coordination between the three joints that make up a limb with changes in the biological system. In this chapter, Cluster Phase analysis will be used to examine the synchrony between the shoulders, elbow and wrist motion during the learning of a throwing action.

Overarm throwing movement is a fundamental motor skill that provides a rich motor dynamic to explore the temporal and spatial constraints of whole-body movements as individuals learn a motor skill. To date, researchers have examined how technique changes across age groups of children (Stodden et al., 2006a,b; Yan, Payne & Thomas, 2000), and also during periods of learning with the non-dominant arm in adults (Kernodle & Carlton, 1992; Hore et al., 1996; Williams et al., 1998; Gray et al., 2006; Southard, 2006).

Key analyses used to capture technique during overarm throwing include the Robertson and Halverson (1984) components model and measures of segmental lag. The components model (Robertson & Halverson, 1984) of overarm throwing was developed following a 7 year longitudinal study of a single cohort of 39 children from age 6 to 13 years. As the only overarm throwing specific model, it has subsequently been used to examine technique changes in both children learning to throw (Robertson & Konczak, 2001, Langendorfer & Robertson, 2002, Stodden et al., 2006*a,b*) and throwing in older adults ranging in age from 61 to 82 years (Williams et al., 1998). Validating this model via quantitative kinematics, Stodden et al. (2006*a,b*) explored the association between component levels of the Robertson and Halverson (1984) model and kinematic parameters, finding that kinematic parameters of the upper and lower body distinguished the developmental sequences in children.

Segmental lag is a key technique characteristic in the development of overarm throwing from a biomechanical perspective. Kernodle and Carlton (1992) reported that for adults learning with the non-dominant arm, the key cues for performance change were related to the lag of the upper arm and elbow with respect to the shoulder. Furthermore, Southard (2006) showed an increase in the number of upper limb segments experiencing positive segmental lag following 5 weeks of non-dominant overarm throwing practice in adults. At higher skill levels with the dominant arm, kinematic differences between dominant and non-dominant arm throws are attributed to the ability to utilise interaction torques at the elbow and wrist in skilled recreational baseball players (Gray et al., 2006). However, while segmental lag has been shown to change during learning in adults and for more skilled participants, studies have

suggested that during the initial stages of learning, segmental lag is subordinate to assimilating the general action of throwing (Meister et al., 2003; Langendorfer & Robertson, 2002). Therefore, Cluster Phase may provide a method to analyse the change in the movement coordination dynamics in the early stages of overarm throwing. A central question was whether the synchrony of the tri-joint arm motion in learning to throw was similarly enhanced with practice in both children (dominant arm) and adults (non-dominant arm).

In order to further understand technique changes in whole-body movement skills, the application of multivariate methods to assess coordination is important from a dynamical systems theory perspective (Newell, 1985; Nourrit et al., 2003; Diss et al., 2019; Silva et al., 2016; Alderisio et al., 2017). While some interpretations of Bernstein's (1967) hypothesis examined the mechanical degrees of freedom at the joint space level of the system, previous multivariate analysis research (Daffertshofer et al., 2004; Chow et al., 2006; Hong & Newell, 2006; Chow et al., 2008; Ko et al., 2013; Ko et al., 2017) has captured the macroscopic view of the degrees of freedom, as an individual assembles the multiple joints into some configuration to satisfy task demands within the 'coordination' stage of learning (Newell, 1985). It is suggested that these macroscopic variables might be sensitive enough to capture the initial organisation of the dynamic system during the primitive stage of learning, without being too sensitive to inter- and intra-individual specific variation in the organisation of the dynamic system that joint space degrees of freedom fall foul of. From this perspective Cluster Phase was used to understand the macroscopic view of the three degrees of freedom of the throwing arm in terms of their synchrony.

The use of the Cluster Phase technique in this joint movement context is novel. Applying this type of analysis to a particular study design might pose more questions on the efficacy of such measures for capturing relevant variables of technique change than it answers. Therefore, in this study Cluster Phase was used to contrast the changes that occur in tri-joint synchrony of the arm to a cross-section of ages across childhood that relate to distinct developmental periods (Ulrich, 2000; Roncesvalles, Woollacott & Jensen, 2001; Mickle, Munro & Steele, 2011; Meister et al., 2003), and during a longitudinal period of learning to throw with the non-dominant arm in adults.

5.2 Chapter Aim and Research Questions

The aim of this chapter was to apply Cluster Phase analysis to examine technique changes of upper limb coordination across age in childhood for dominant overarm throwing, and over a period of non-dominant overarm throwing practice in adults. In the application of a multivariate method to understand technique changes across childhood and adulthood when performing a complex gross whole-body motor skill, this chapter holds theoretical and applied relevance to motor control and learning. This approach with a longitudinal and cross sectional data collection included within a single study seems valid and useful since the methods of analysis are novel.

The central purpose of this chapter was to investigate if differences in coordination between children aged 6, 10 and 14 years of age throwing with the dominant arm were similar to changes that occur for adults learning to throw overarm with their non-dominant arm. This study adds to work in chapter 3 and chapter 4 in order to contribute to models of motor learning and technique change during practice. Based on the

previous findings using multivariate measures to examine coordination, it is hypothesised that tri-joint synchrony in the throwing arm will increase as a function of increased age in childhood and with practice in adults (Ko et al., 2013; Ko et al., 2017). In addition, in line with Newell's (1985) stages of learning, it is hypothesised that variability in tri-joint synchrony will decrease with an increase in childhood age and with practice in adults (chapter 3).

To satisfy the aim of this chapter, the following specific research questions were addressed:

- What differences were observed in the tri-joint synchrony at 6, 10 and 14 years of age compared to adults following a 3-week period of practice?
- What differences were observed in the individual joint synchrony at 6, 10 and 14 years of age compared to adults following a 3-week period of practice?
- What differences were observed in the synchrony variability of the upper arm at 6, 10 and 14 years of age compared to adults following a 3-week period of practice?

5.3 **Methods**

5.3.1 **Participants**

Written ethical approval was gained from the FREP (16-645) and DREP (15-031) Anglia Ruskin University Ethics Committee prior to study initiation. Inclusion criteria were as follows: participants were not participating in a throwing-based activity, had a dominant hand (as determined by Oldfield (1971) Edinburgh handedness inventory), and were free from musculoskeletal injury. Ten adult participants, with no specific

experiences with non-dominant arm throwing, gave written voluntary informed consent and completed a pre-exercise health questionnaire (PAR-Q). Eighteen child participants gave voluntary verbal assent, while their parent/guardian provided written voluntary informed consent and completed a pre-exercise health questionnaire (PAR-Q) on behalf of their child (see Table 5.1 for relevant demographic information).

Table 5.1 **Anthropometric measurements of participants in each age group: adults and children aged 6, 10 and 14 years**

Characteristic	Adults	6 years	10 years	14 years
Sex	4 (females)	5 (female)	4 (female)	4 (female)
	6 (males)	1 (male)	2 (male)	2 (male)
Age (years)	22 \pm 2	6.56 \pm 0.30	10.32 \pm 0.33	14.22 \pm 0.48
Stature (m)	1.71 \pm 0.60	1.22 \pm 0.05	1.47 \pm 0.10	1.64 \pm 0.11
Mass (kg)	73.01 \pm 14	23.88 \pm 5.02	39.29 \pm 3.26	61.02 \pm 6.97

5.3.2 Procedure

For the adult participants a longitudinal period of practice took place three times per week (Monday, Wednesday and Friday) for 3 consecutive weeks. The same testing procedures were conducted for each session. Between testing sessions participants were instructed not to practice throwing with either their dominant or non-dominant

arm. Data was collected for each participant during 10 overarm throwing movements with their non-dominant arm during the first and last sessions, and for the dominant arm dominant during the last session. Children attended a single data collection session where data were collected for each participant during 5 overarm throwing movements with their dominant arm.

A standard issue tennis ball (Slazenger) was used for all throwing trials with the adults and children as it had familiar properties (mass, size and shape). All participants were given the ongoing aim of hitting a 0.4 m target located 14m in front of them. Target height was adjusted to each participant's eye level. The target placement necessitated a forceful and accurate throw from the participant and was best realised with a near horizontal trajectory of the ball to the target. Knowledge of results from the target and verbal encouragement were provided using phrases which included: "nice", "well done" and "good job".

5.3.3 Data Collection

Kinematic data (200 Hz) was collected using a 3D motion capture system (CODAmotion, Charnwood Dynamics Ltd, UK). Three CX1 scanners provided a 360° field of view around the participant. Centre of rotation for each joint was estimated and active makers were located on the right and left lateral side of 3rd metacarpal, ulnar styloid process, forearm, lateral epicondyle of the elbow, shoulder joint at the centre of rotation, xiphoid process, greater trochanter, femoral condyle, lateral malleolus, calcaneus and 2nd metatarsal. The same researcher marked up each participant for each session and data was collected for every trial performed by the

participant. The throwing trials were also recorded using a two-dimensional camera (Fastcam high speed video camera, Ultima 512 Photron, Model 32K) placed perpendicular to the sagittal plane of the participant.

5.3.4 Data Processing

Data was analysed during the propulsive phase of the throw which was defined as the instance that any marker started moving in the direction of the throw until the instance of ball release. Raw marker data were obtained from CODA and analysis took place using Matrix Laboratory (MATLAB, R2017b). Based on a residual analysis of the following markers: shoulder, elbow and wrist, a Butterworth low-pass fourth-order filter was applied to the kinematic data at a cut-off frequency of 6 Hz (Winter, 2009). Analysis of data took place during the propulsive phase of the throw. Angles were defined in 3D where an angle of 180° would represent maximum extension, while 0° would represent minimum flexion of the joint. The shoulder joint was defined as being from the lateral epicondyle of the elbow to shoulder joint at the centre of rotation and xiphoid process. The elbow joint was defined as being from the shoulder joint at the centre of rotation to the lateral epicondyle of the elbow ulnar and styloid process. The wrist joint was defined as being from the 3rd metacarpal to the ulnar and styloid process and lateral epicondyle of the elbow.

Cluster Phase is a method proposed by Frank and Richardson (2010) and is an adaptation of the Kuramoto order parameter approach (Kuramoto & Nishikawa, 1987) which was used to assess the synchrony between the shoulder, elbow and wrist joints of the throwing arm. For each of the three joints time-series, $x_{shoulder}(t_i)$, $x_{elbow}(t_i)$,

$x_{wrist}(t_i)$, where t_i , $i = 1, \dots, N$ are the time steps, the phase time-series in radians $[-\pi, \pi]$ for $\theta_{shoulder}, \theta_{elbow}, \theta_{wrist}$ was calculated, using the Hilbert transform (Kuramoto & Nishikawa, 1987; Strogatz, 2000). Then, from the phase time-series the Cluster Phase was calculated as follows:

$$\dot{q}(t_i) = \frac{1}{3} \sum_{i=1}^N (\exp(i\theta_{shoulder}(t_i)) + \exp(i\theta_{elbow}(t_i)) + \exp(i\theta_{wrist}(t_i))) \quad \text{Equation 5.1}$$

And

$$q(t_i) = \text{atan2}(\dot{q}(t_i)) \quad \text{Equation 5.2}$$

Where $i = \sqrt{-1}$ (when not used as a time step index), and $\dot{q}(t_i)$ and $q(t_i)$ are the resulting group or Cluster Phase in complex and radian $[-\pi, \pi]$ forms, respectively.

The Cluster Phase calculated is a description of the global synchrony of the three joints. Based on the global Cluster Phase $q(t_i)$, the relative phases for the individual joints, $\phi_{shoulder}(t_i)$, $\phi_{elbow}(t_i)$, $\phi_{wrist}(t_i)$, can be calculated as:

$$\phi_{shoulder,elbow,wrist}(t_i) = \theta_{shoulder,elbow,wrist}(t_i) - q(t_i) \quad \text{Equation 5.3}$$

As a next step, mean relative phase $\bar{\phi}$ and the degree of synchrony ρ for every joint with respect to the cluster (group) behaviour are calculated from:

$$\bar{\phi}_{shoulder} = \frac{1}{N} \sum_{i=1}^N \exp(i\phi_{shoulder}(t_i)) \quad \text{Equation 5.4}$$

$$\bar{\phi}_{elbow} = \frac{1}{N} \sum_{i=1}^N \exp(i\phi_{elbow}(t_i)) \quad \text{Equation 5.6}$$

$$\overline{\phi_{wrist}} = \frac{1}{N} \sum_{i=1}^N \exp(i\phi_{wrist}(t_i))$$

And

$$\overline{\phi_{shoulder,elbow,wrist}} = \text{atan2}(\overline{\phi_{shoulder,elbow,wrist}}) \quad \text{Equation 5.7}$$

$$\rho_{shoulder,elbow,wrist} = |\overline{\phi_{shoulder,elbow,wrist}}| \quad \text{Equation 5.8}$$

Where $\overline{\phi}$ and $\overline{\phi}$ is the mean relative phase in complex and radian $[-\pi, \pi]$ forms, and $\rho \in [0,1]$.

If $\rho=1$ the movement is in complete synchrony with the group (i.e. the phase of the movement at any time step is equivalent to the group phase shifted by a constant phase) (Richardson et al., 2010). If $\rho=0$ the movement is completely unsynchronized to the group.

Finally, the degree of synchrony of the three joints group as a whole ρ_{group} at every time step t_i is defined by:

$$\rho_{group,i} = \frac{1}{3} \sum_{i=1}^N (\exp(i(\phi_{shoulder}(t_i) - \overline{\phi_{shoulder}})) + \exp(i(\phi_{elbow}(t_i) - \overline{\phi_{elbow}})) + \exp(i(\phi_{wrist}(t_i) - \overline{\phi_{wrist}}))) \quad \text{Equation 5.9}$$

It is worth noting that $\rho_{\text{group},i}$ provides a continuous measurement (i is the time index) of the group synchrony. In addition, $\rho_{\text{group},i} \in [0,1]$ and from this the average degree to group synchrony was calculated as:

$$\rho_{\text{group}} = \frac{1}{N} \sum_{i=1}^N \rho_{\text{group},i} \quad \textbf{Equation 5.10}$$

Note that ρ_{group} provides a single measure of group synchrony for the experiment (behavioural period or trial) and, again, the closer to 1 the value of $\rho_{\text{group},i}$ and ρ_{group} larger the degree of group synchrony.

5.3.5 Variables

Group synchronization is the average synchrony ρ_{group} of the shoulder, elbow and wrist and quantifies the degree of synchrony between the three joints. Individual joint synchrony $\rho_{\text{shoulder,elbow,wrist}}$ measures the average degree to which each individual joint was synchronised to the movement as a whole. Coordination variability of upper limb tri-joint synchrony was measured to determine degrees of repeatability.

5.3.6 Statistical Analysis

After testing for normality of data using Shapiro-Wilks test, repeated measures analyses of variance (ANOVA) were run for each participant for each dependent variable. The level of statistical significance was set prior ($p < 0.05$) and Bonferroni post hoc correction was used for multiple comparison tests. Mauchly's test was used to determine the sphericity assumption within the data; and where sphericity was

violated, probability was corrected according to the Greenhouse-Geisser procedure. Coordination variability values were compared before practice and after practice for non-dominant arm baseline trials with dominant arm. Effect size was determined using Cohen's d (1992) for all significant data to establish the standardised difference of synchrony before and after practice. Effect size was ranked as follows: large effect size ($d = 0.8$), medium effect size ($d = 0.5$) and small effect size ($d = 0.2$).

$$d = \frac{M_1 - M_2}{SD_{pooled}} \quad \text{Equation 5.11}$$

5.4 Results

5.4.1 Upper Limb Tri-joint Synchrony

For adults learning to throw with their non-dominant arm, synchrony changed in one of three ways following practice (see Fig 5.1). Four of the 10 participants (PT05 $p = 0.01$; $d = 0.64$, PT06 $p = 0.01$; $d = 1.27$, PT07 $p = 0.04$; $d = 1.28$ and PT08 $p = 0.01$; $d = 0.94$) decreased tri-joint synchrony of the non-dominant arm after practice. Five of the 10 participants (PT01 $p = 0.04$; $d = 0.84$, PT02 $p = 0.03$; $d = 1.25$, PT03 $p = 0.04$; $d = 1.12$, PT04 $p = 0.01$; $d = 0.68$ and PT10 $p = 0.01$; $d = 0.05$) increased tri-joint synchrony with practice. PT09 ($p = 0.09$; $d = 0.03$) showed no significant change in tri-synchrony with practice. Dominant arm tri-joint synchrony was not significantly different to non-dominant arm post practice in eight participants (PT01 $p = 0.14$, PT02 $p = 0.82$, PT03 $p = 0.42$, PT05 $p = 0.64$, PT07 $p = 0.83$, PT08 $p = 0.94$, PT10 $p = 0.72$), but was significantly lower than non-dominant arm post practice in two participants (PT04 $p = 0.01$, PT09 $p = 0.004$). Effect size was determined by Cohen's

d (1992), results showed that a large effect was present when comparing synchrony of 6 year olds to 10 year olds size ($d = 0.87$), 10 year olds to 14 year olds ($d = 0.88$) and 6 year olds to 14 year olds ($d = 0.91$).

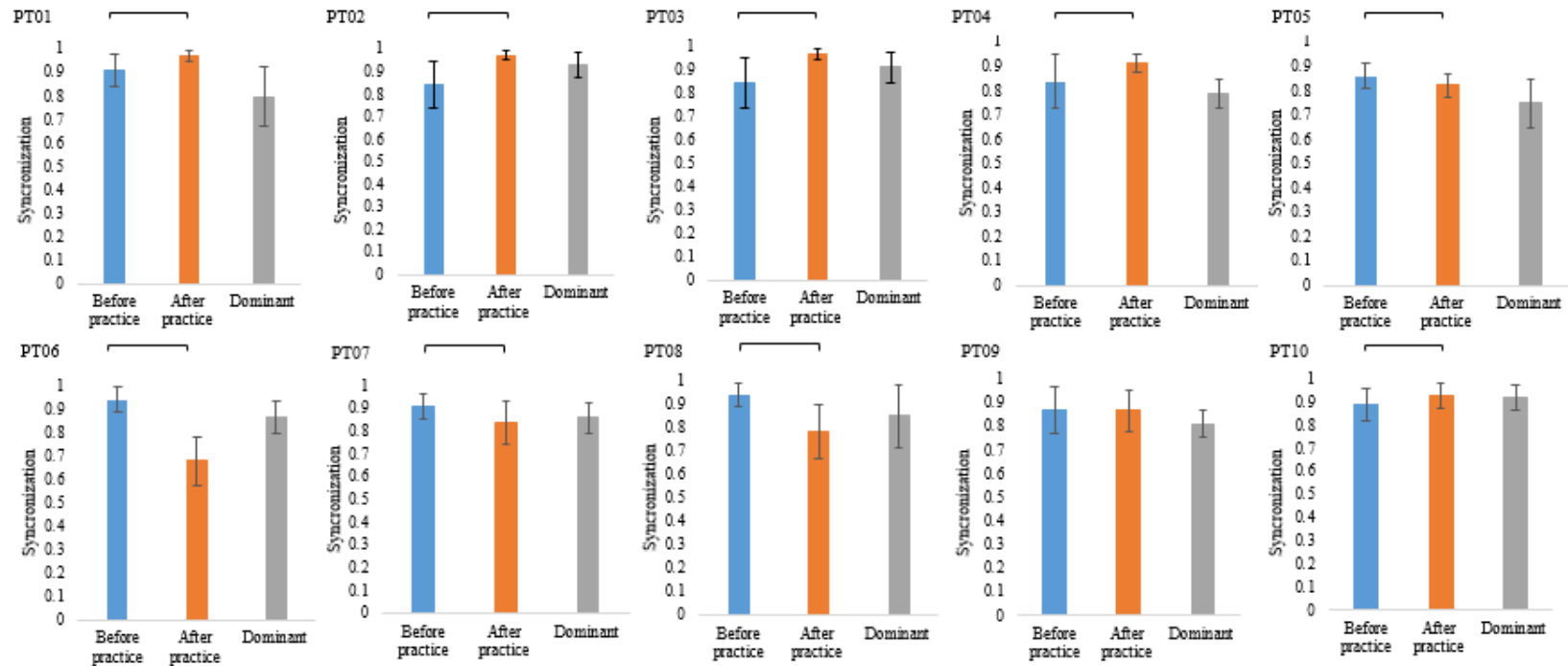


Fig 5.1 **Tri-joint synchrony of the throwing arm during overarm throws before practice (BP) and after practice (AP) with the non-dominant arm and the dominant arm**

Significant differences ($p < 0.05$) are shown between the bars.

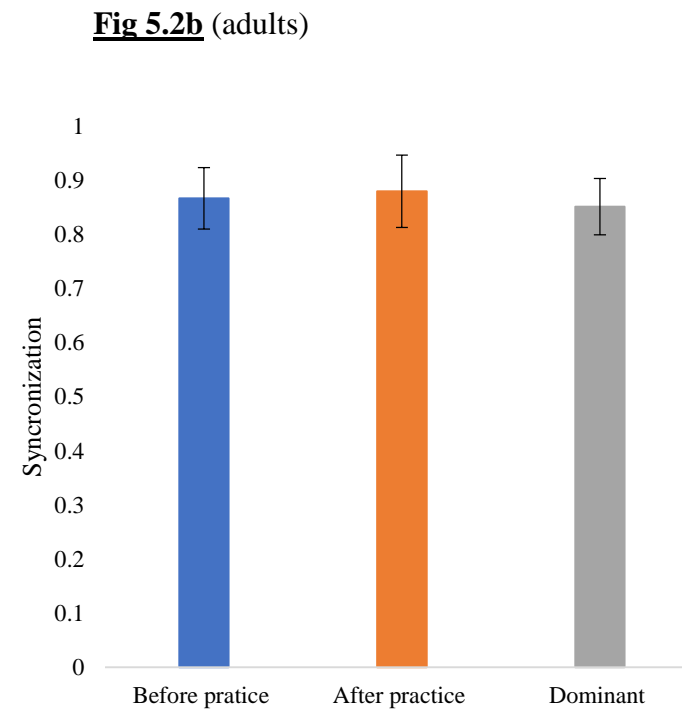
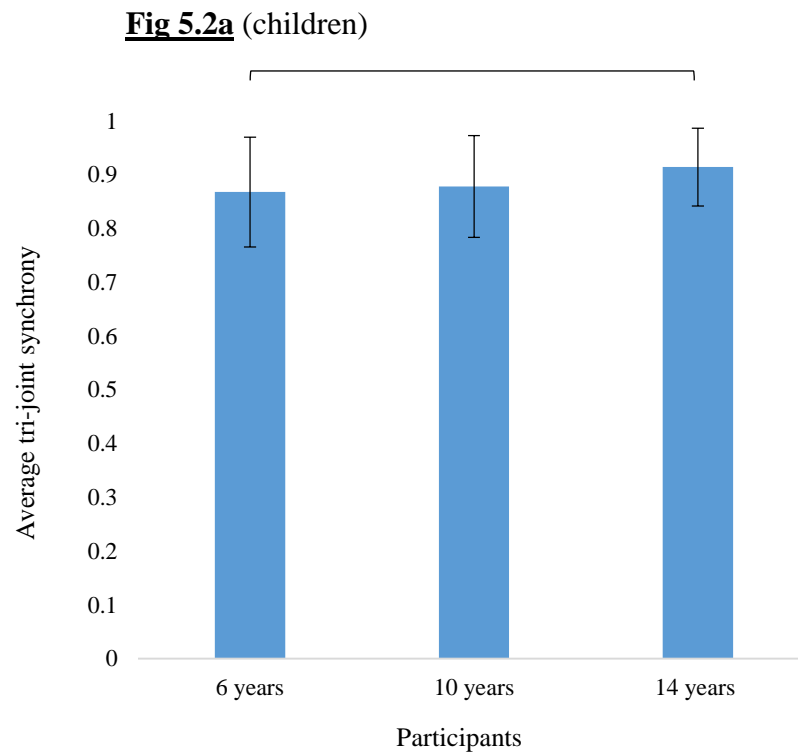


Fig 5.2 **Group tri-joint synchronization of the upper limb for (a) children at 6, 10 and 14 years (b) adults with the non-dominant arm before practice (BP), after practice (AP) and with their dominant arm**

Significant differences ($p < 0.05$) are shown between the bars. The group results showed no significant differences between pre and post and dominant tri-synchrony (before practice and after practice $p = 0.09$ before practice and dominant arm $p = 0.10$ and after practice and dominant arm $p = 0.07$) (Fig 5.2b). Group results for adult participants showed an increase in the average degree of tri-joint synchrony. No significant differences were present for group synchrony as a function of practice with the non-dominant arm (Fig 5.2b). Dominant arm throws were not significantly different from tri-joint synchronization of the non-dominant arm before or after practice in adult learners (Fig 5.2b).

For children, the older age group had higher upper limb tri-joint synchrony compared to the younger age group (Fig 5.2a). Significant differences in tri-joint synchrony between 6 and 14 years of age (Fig 5.2a; $p = 0.03$) with a large effect size ($d = 0.91$) were observed. No significance difference existed between 6 and 10 years of age ($p = 0.50$; $d = 0.87$), or 10 to 14-years ($p = 0.12$; $d = 0.88$) (Fig 5.2a). Fourteen year old age group displayed the greatest tri-joint synchrony of the throwing arm.

5.4.2 Individual Synchrony of the Upper Limb

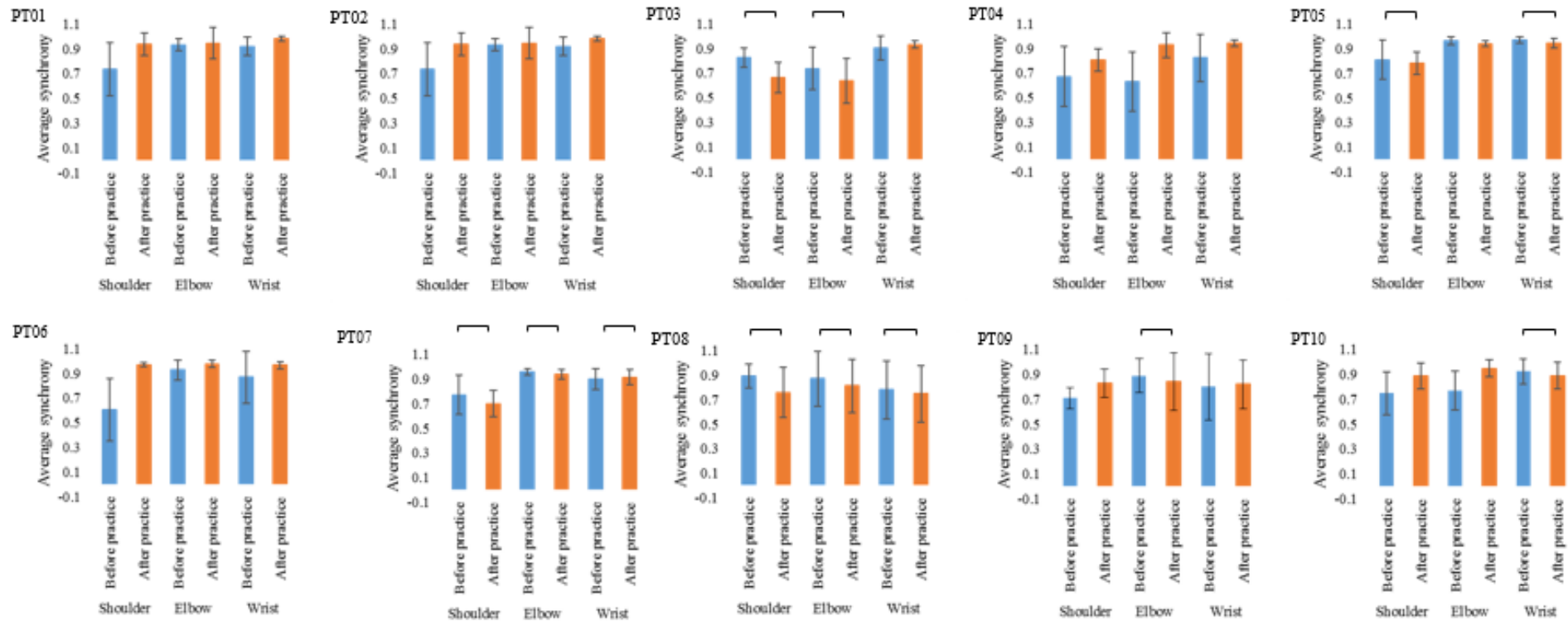


Fig 5.3 Individual joint synchrony of adults before practice (BP) and after practice (AP) at the shoulder, elbow and wrist joint for

non-dominant arm throws

Significant differences between joints ($p < 0.05$) are indicated between the horizontal bars.

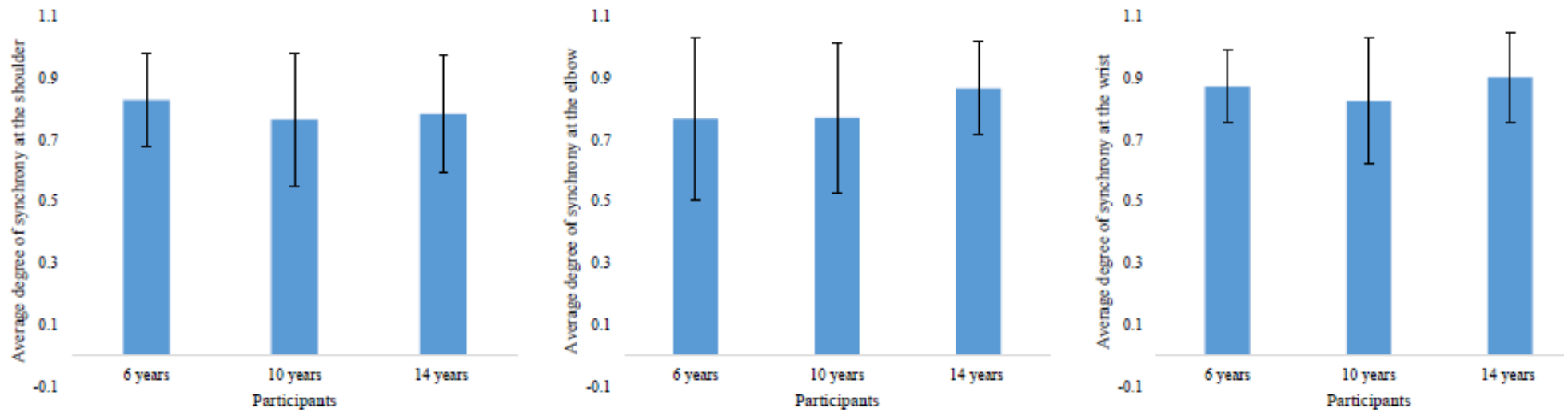


Fig 5.4 **Age group analysis at the shoulder, elbow and wrist joint at 6, 10 and 14 years of age**

No significant differences were found between 6, 10, 14 years for the shoulder, elbow or wrist joint ($p < 0.05$).

For adults, 2 of 10 participants demonstrated a significant decreased in shoulder synchrony (PT03 $p = 0.04$; PT05 $p = 0.01$; Fig 5.3) and 4 of 10 significantly showed increased synchrony of the shoulder joint following non-dominant overarm throwing practice (PT02 $p = 0.02$; PT09 $p = 0.01$; PT10 $p = 0.04$; Fig 5.3). Two of 10 participants significantly decreased synchrony of the elbow with practice (PT03 $p = 0.01$; PT08 $p = 0.04$; Fig 5.3) and 2 participants significantly increased in elbow synchrony (PT01 $p = 0.01$; PT04 $p = 0.04$; Fig 5.3). Three of 10 participants significantly increased synchrony of the wrist with practice (PT01 $p = 0.003$; PT03 $p = 0.03$; PT04 $p = 0.03$; Fig 5.3). For children, no significant differences were found between 6, 10, 14 years of age for the synchrony of the shoulder, elbow or wrist (all $p > 0.05$).

5.4.3 Dysfunctional Variability

Fig 5.5a Children

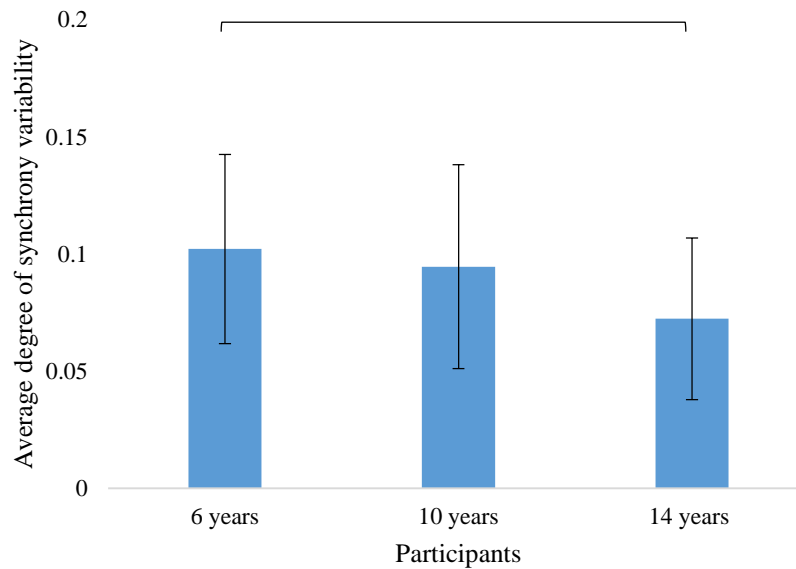


Fig 5.5b Adults

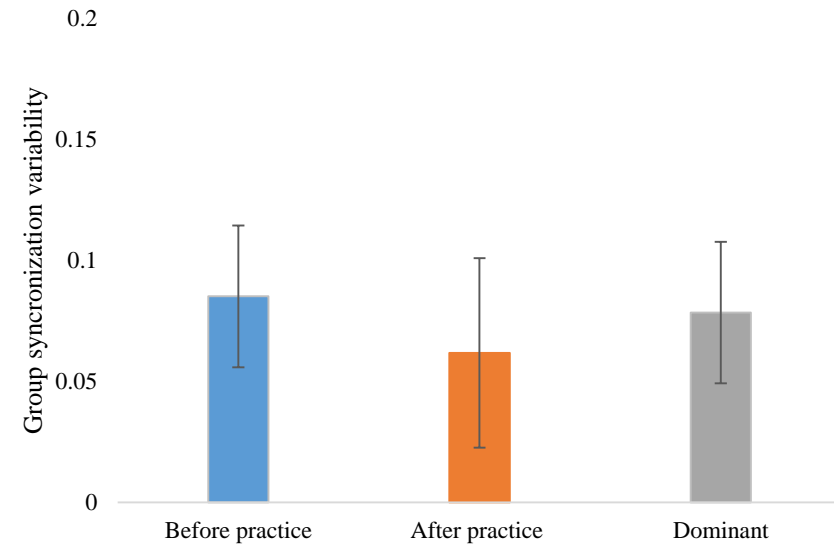


Fig 5.5 **Variability in tri-joint synchrony of upper limb segment during overarm throwing for (a) children at 6, 10 and 14 years of age (b) adults with the non-dominant arm before practice (BP), after practice (AP) and with their dominant arm**

Significant differences ($p < 0.05$) are shown between the bars.

Variability in tri-joint synchrony was significantly lower at 14 years of age compared to 6 years of age ($p = 0.02$). No significant difference was seen between 6 and 10 years or 10 and 14 years of age ($p = 0.50$; $p = 0.12$, respectively) (Fig 5.5a). While 8 of 10 adult participants decreased synchronization variability following practice with non-dominant arm (Fig 5.5b), the group analysis revealed no significant differences before and after practice ($p = 0.16$) or before practice and the dominant arm ($p = 0.56$). Tri-joint synchrony for adults was significantly less for non-dominant arm throws post practice than dominant arm throwing ($p = 0.03$; Fig 5.5b). Tri-joint synchrony of the dominant arm was greater for all adult participants than non-dominant arm after practice (except PT08; Fig 5.5b).

5.5 Discussion

The aim of this study was to investigate if the same pattern of coordination change occurs during development of overarm throwing between children aged 6, 10 and 14 years of age, as in adults learning overarm throwing with the non-dominant arm. It was hypothesised that tri-joint synchrony in the throwing arm would increase as a function of age in childhood and with practice in adults. For children, 14 year olds showed significantly higher upper limb tri-joint synchrony compared to the younger age group (Fig 2a) while no common pattern of change was present following non-dominant arm throwing practice in adults (Fig 5.1). Consistent with the hypothesis and in line with Newell's (1985) stages of learning, variability of tri joint synchrony significantly decreased with age in children (Fig 5.5a) and for 8 of 10 individual adults post practice, however, no significant group differences were found pre- and post-practice in adults (Fig 5.5b).

5.5.1 Tri-joint Synchrony

The findings were not in line with the hypothesis that tri-joint synchrony in the throwing arm would increase as a function of practice in adults. For adults throwing with the non-dominant arm, no common pattern of change occurred in tri-joint synchrony after practice (Fig 5.1). These results indicate that individual-specific changes in tri-joint synchrony of the upper limb during non-dominant overarm throwing occurred with practice. Consistent with the current findings, Palmer et al. (2018; Appendix A) reported that non-dominant overarm throwing practice induced more common changes in the collective posture-ball release dynamics that were supported by individual strategies at the joint range of motion (ROM) level. The study reported here using Cluster Phase as a measure of synchrony in joint motions has shown that individual strategies are also evident at the level of joint coordination. Therefore, common patterns of change for individuals might be more evident in global variables that capture whole body dynamics such as the CoM–wrist relation (Appendix A) and some components of the Robertson and Halverson model (1984), rather than changes in the individual joint ROM, segmental lag (Meister et al., 2003; Langendorfer & Robertson, 2002) or synchrony of arm joint motions.

It is likely that individual specific changes in joint synchrony occur due to self-organisation within individual constraints to action and relative to the intrinsic dynamics that are realised (Newell, 1986). More optimal solutions, therefore, arise through individual specific changes in the coordination pattern. The importance of

this finding concerns the definition of ‘successful technique’ and the drive for technique change that might be best un-prescribed and left to the individual to realise at certain stages of learning.

With practice 6 of 10 adult participant’s degree of synchrony became more similar to that of the dominant arm through either an increase or decrease in tri-joint synchrony (Fig 5.1). Therefore, it seems that the intrinsic dynamics and individual constraints dictate whether synchrony in a less skilled throw action (the non-dominant arm) will increase or decrease in line with a more optimal solution (the dominant arm). Cluster Phase provided a novel multivariate method to understand the coordinated action of the arm. Overall, however, the results show that synchrony is not linearly associated with practice or skill level, but instead based on individual constraints. Furthermore, the upper limb joint synchrony is not a candidate for a collective variable (Newell, 1985) that could help predict the development of technique with practice, but rather a variable that is self-organised based on individual constraints.

Analysing the adult participants as a group, there was an increase in tri-joint synchrony as a function of practice (Fig 5.2), though this increase was not significant. This reflects the implication of averaging data across a group of participants, creating a ‘mythical average’ that does not capture the individual patterns of change (Bates, 1996).

In line with the hypothesis, upper limb tri-joint synchrony of the shoulder, elbow and wrist was significantly greater in 14 year old age group compared to 6 year old age group (Fig 5.2a). This finding suggests that increased tri-joint synchrony is associated with a more advanced throwing technique in children. Meister et al. (2003) used a cross sectional design to examine elevation, internal rotation at 90° of abduction, and external rotation at 90° of abduction of the dominant and non-dominant shoulders for 294 Little League baseball players between 8 to 16 years of age. Findings showed that shoulder ROM decreased with age with the greatest differences reported between 13 to 14 years of age. This change was associated with adaption of the bone and soft tissue (Meister et al., 2003). This is consistent with the current findings with children at 14 years of age displaying the greatest synchrony indicating that the shoulder, elbow and wrist were moving as a rigid segment with the timings of each joint becoming more similar to each other, to a greater extent than children at 6 and 10 years of age.

5.5.2 Individual Synchrony of the Upper Limb

Synchrony of individual joints to the mean value were examined. Once again, there was an individual specific strategy of change among the adults (Fig 5.3). Participants who decreased tri-joint synchrony also showed a decrease in synchrony of the elbow and wrist joint to the group (Fig 5.3). This finding suggests that from a dynamical systems theory perspective, organisation progresses based on intrinsic dynamics and individual constraints, and since no joint dominated change, self-organisation should be considered a key point for coaching. Chapter 3 provided support for the notion that Bernstein's hypothesis (1967) of freezing

and freeing is task specific rather than a general rule for directional change during a period of non-dominant overarm throwing practice. Southard (2006) reported an increase in the number of upper limb segments experiencing positive segmental lag which refers to the transfer energy from the heavier proximal segment to lighter distal segments. While it is understood that elite throwing performance follows biomechanical principles, it seems that during earlier stages of learning the coordination and organisation of joint actions is harder to define (Langendorfer & Robertson, 2002).

Age was not found to alter synchrony of specific joints of the upper limb at 6, 10 or 14 years of age during the dominant arm throwing arm due to individual differences within each age group (Fig 5.4). Keller et al. (2011) suggested that during the development of motor control discontinuity can be seen across childhood and is often characterised by peaks and troughs as children explore for the most appropriate movement strategies in light of the constraints to action. Langendorfer & Robertson (2002) examined longitudinal pathways of technique changes in a single cohort of children using Robertson & Halverson's (1984) components model of overarm throwing. Findings showed that some developmental pathways were more 'attractive' to the children than others, while the differences between individuals were too great for a single developmental sequence to be identified. It might be that this same pattern would be found in the Cluster Phase variables in a longitudinal study of children, however, both papers emphasise individual differences.

5.5.3 **Variability in Tri-joint Synchrony**

In line with the second hypothesis, 8 of 10 adult participants decreased synchronization variability following practice with the non-dominant arm, however no group based effect was found (Fig 5.5b). Based on this idea and the work by Hamill and colleagues (Hamill et al., 1999; Wilson et al., 2008; Hamill, Palmer & Van Emmerik, 2012), the current findings are consistent with Newell's (1985) postulation of decreased dysfunctional variability with practice on an individual basis (Chow et al., 2008; Williams et al., 2015; Busquets et al., 2016). Theoretically, this is consistent with the idea of exploration decreasing as individuals find the most appropriate movement strategies within their motor-perceptual workspace (Kelso, 1995; Hamill et al., 1999; Williams et al., 2015; Busquets et al., 2016). It should be noted however, that there was not a significant decrease in variability at the group level for adults learning this skill. Based on the data (Fig 5.5b) intra-individual variability is high, masking the dominant change for individuals which is an important point for motor learning researchers to consider when exploring changes in coordination variability.

For adult participants, variability of the dominant arm was greater than variability of the non-dominant arm post practice (except PT06) (Fig 5.5b). This finding highlights the complex nature of change in variability with learning and skill development. It has been proposed that coordination variability has different functional roles during skill acquisition and refinement (Wilson et al., 2008; Davids et al., 2003; Newell, 1985). This can be illustrated by techniques to explore the functional nature of variability which could be applied to answer the question

of ‘good’ and ‘bad’ variability at these points in skill development. In addition, it is interesting to consider the question of variability and handedness and laterality. Changes in tri-joint synchrony variability with practice in adult participants in the current study can be paralleled with tri-joint synchrony variability with during childhood at 6, 10 and 14 years of age.

In line with the second hypothesis, synchronization variability at 6 years of age was significantly greater than at 14 years of age (Fig 5.5a). This suggests that 6 year olds were in the initial coordination stage of learning (Newell, 1985) which is characterised by learners trying to establish appropriate movement strategies by finding basic relationships between components to meet the constraints to action. Fourteen year olds had significantly lower variability in upper limb tri-joint synchrony which suggests that they have progressed to the control stage of learning (Fig 5.5a) characterised by the appropriate parameters being assigned to the coordination mode (Newell, 1985).

Coordination variability within movement is present in adults and children alike and provides pathways in which movement can successfully be carried out within ever changing constraints. Throughout the lifespan individuals are able to achieve new task performance goals through acquiring functional coordination patterns over time through a process of refining these acquired skills so advancing levels of learning. The current findings are consistent with the literature that has examined variability within gymnastics (Farana et al. 2014; Busquests et al., 2016; Vicinanza et al., 2018) and overarm throwing action (Palmer et al., 2018; Appendix A). Taken together with the results of tri-joint synchrony, this paper supports self-

organisation of arm coordination with a reduction in coordination variability during learning and during development in childhood.

5.6 Conclusion

This study has provided insight into upper limb tri-joint synchrony over practice in adults and across age in children during overarm throwing action. Findings provided support for the idea that patterns of synchronization are dependent upon individual constraints to action shown. A key characteristic of learning overarm throwing in both adult and child learners was a decrease in variability of the throwing arm synchrony. However, the change in the movement dynamics of adults learning to throw with the non-dominant arm showed greater individual variation to those of children learning to throw with the dominant arm in the direction of the progressive change of the tri-joint synchrony. From a dynamical system theory perspective, there are important implications associated with using a multivariate method to study coordination development of multiple moving segments during childhood (Robertson & Halverson, 1984; Yan et al., 2000; Stodden et al., 2006) and adulthood (Williams et al., 1998; Southard, 2006). Due to the infancy of this method within biomechanics and motor control, future research could look to expand upon the work conducted here to include a larger sample and the ability of the methods used to explain synchronization in other movements and sport skills.

5.7 Chapter Summary

The aim of this paper was to apply Cluster Phase analysis to examine technique changes of upper limb coordination during motor development of dominant arm overarm throwing action during childhood and over a period of non-dominant overarm throwing practice in adults. In the application of a multivariate method to understand technique changes across childhood and adulthood when performing a complex gross whole-body motor skill this paper holds theoretical and applied relevance to motor control and learning. In order to answer the aim of this study, three-research questions were presented in section 5.2.

- **‘What differences were observed in the tri-joint synchrony at 6, 10 and 14 years of age compared to adults following a 3-week period of practice?’**

Findings showed that tri-joint synchrony was greatest at 14 years of age in comparison to that of children at 6 and 10 years of age. This indicates that movement of the shoulder, elbow and wrist joint become more coherent with age. Coordination variability of the upper limb joint decreased with age with 14 year olds demonstrating significantly less coordination variability than 6 year olds. This is consistent with Newell’s (1985) stage of learning model, which suggests that a reduction in dysfunctional variability is associated with more advanced movement patterns. Findings from the current study were in line with changes in upper limb tri-joint synchrony in adults. Increased joint synchrony is associated with more advanced overarm throwing action. Findings from the Cluster Phase analysis showed there was no common pattern of change in tri-joint synchrony across

individuals. This suggests that changes in synchronization are individual specific. An increase in synchronization of the shoulder, elbow and wrist joint, during non-dominant arm trials showed that the timing of the joints were more closely coupled as three joints are behaving more as a single segment. Individuals might have adapted this movement pattern in order to reduce the kinematic chain making the act of overarm throwing easier to achieve. A decrease in the average degree of synchronization of the shoulder, elbow and wrist joint during non-dominant arm trials shows that the timing of the joints is less tightly coupled meaning the three joints are acting independently of each other. This allows the kinetic chain principle to be exploited.

➤ **‘What differences were observed in the individual joint synchrony at 6, 10 and 14 years of age compared to adults following a 3-week period of practice’**

In this current study 4 of 10 adult participants decreased synchrony at the shoulder joint, 4 of 10 adult participant’s decreased synchronization at the elbow joint, and 4 of 10 adult participants decreased synchronization at the wrist joint as a function of practice. This finding suggests that from a dynamical systems theory perspective, organisation progresses based on intrinsic dynamics and individual constraints, and since no joint dominated change, self-organisation should be considered a key point for coaching. In the current study no significant difference was present between upper limb synchrony at 6, 10 or 14 years of age. Indicating that individual joint synchrony to the group did not change with as a function of age during childhood.

➤ **‘What differences were observed in the dysfunctional coordination variability of the upper arm at 6, 10 and 14 years of age compared to adults following a 3-week period of practice’**

With adult participants a decrease in synchronization variability was present for 8 of 10 participants following a 3-week period practice with non-dominant arm. This is consistent with findings at 6, 10 and 14 years of age. Specifically, as age increased synchronization variability decreased, indicating that 14 year olds were able to more consistently produce similar tri-joint synchronization of the shoulder, elbow and wrist joint. Theoretically, this is in line with exploration, a functional idea of variability (Kelso, 1995; Hamill et al., 1999; Davids et al., 2003; Chow et al., 2008). The emergence of a new movement pattern may contribute to the organisation of a system in such a way that the attractor is more stable and likely to be maintained. The system interpretation of the imposed constraints is subject specific leading to an alternative pattern of coordination for the same task (Glazier & Davids, 2009). Current findings suggest that Cluster Phase analysis can identify biological constraints in upper limb coordination during overarm throwing action at different age during childhood and adolescence.

The work undertaken in chapter 5 has provided a contribution to knowledge through the use of a novel analysis technique, Cluster Phase. Findings suggest that between 6, 10 and 14 years, changes in technique were consistent with changes in technique during a period of learning non-dominant overarm throwing in adults. More skilled overarm throwing action was associated with greater tri-joint synchrony of the upper limb in adults and children. Future work is required to explore the use of Cluster Phase analysis in the identification of key characteristics

of biomechanical and motor learning technique changes as a function of age. Findings from chapter 4 and chapter 5 will inform and underpin chapter 6 which will examine changes in centre of pressure (CoP) motion during the development of overarm throwing action. CoP motion seems relevant since in previous chapters it is shown that collective dynamics are better able to capture common changes in technique across individuals. In addition, CoP could provide a more practical method of data collection to inform coaching than the time and equipment heavy methods involved in quantitative kinematic analysis.

CHAPTER 6: Centre of Pressure Pathway during Overarm Throwing

Action at 6, 10 and 14 Years of Age

6.1 Introduction

Chapter 3 and chapter 4 provided knowledge and understanding of the qualitative and quantitative changes during overarm throwing by using three distinct approaches to motor skill acquisition that examine different aspects of the system (Newell, 1985; Roberton & Halverson, 1984; Bernstein, 1967). Specifically, chapter 3 examined the longitudinal evolution of movement technique in adults during a period of non-dominant overarm throwing over 9 practice sessions in relation to three distinct approaches to motor skill acquisition (Newell, 1985; Roberton & Halverson, 1984; Bernstein, 1967). Chapter 4 used a cross-sectional approach to explore the evolution of movement technique (Newell, 1985; Roberton & Halverson, 1984; Bernstein, 1967) to understand the different aspects of technique changes across childhood. Chapter 3 and chapter 4 considered the aptness of the three models for capturing changes in throwing technique and provided information that can be practically relevant. Chapter 4 highlighted that movement at the lower extremities is critical in facilitating movement of the CoM, in what is usually characterised as an upper extremity action. Specifically, the ability to take a contralateral step facilitates greater ROM of the lower extremities and CoM movement in weight transfer. This finding was consistent with those from chapter 3.

In relation to variables that showed robust change across age and practice the use of a macroscopic variable linking CoM motion to that of the wrist (end effector) was key. Specifically, the findings from chapter 3 and chapter 4 reported that the CoM-wrist coupling became more complex with practice in both adults and age in children. In chapter 3 two key coupling relations were observed between CoM and wrist over practice in adults (chapter 3: Fig 3.1). At the beginning of practice, all adult participants demonstrated in-phase coupling at the start of the propulsive phase of the throw, where the CoM and wrist both travelled forwards together, towards zero at ball release (Fig 3.1). With practice, 7 of the 10 participants began to incorporate differentiated movement of the CoM and wrist, where coupling began at 180° before progressing to 0° at release. This latter strategy is representative of initial wrist-led coupling where backwards movement of the wrist is the predominant influencer on the kinematic chain. In children (chapter 4) three CoM-wrist coupling modes were identified across the three age groups. Specifically, coupling mode 1 and 2 (Fig 4.1a: 4.1b) displayed a similar but simpler profile than previously reported in chapter 3 (Fig 3.1). All the children at 6 years of age spent less time in in-phase coupling (mode 1: Fig 4.1a). All the children at 10 years of age demonstrated CoM-wrist led coupling (mode 2: Fig 4.1b) compared to adult participants (Fig 3.1). However, within the group of 14 year olds, three of them performed like 10 year olds while three displayed (mode 3: Fig 4.1c) a similar CoM-wrist coupling mode at the end of practice compared to the adult participants (Fig 3.1). In the adult group the progression of the coupling angle further into the CoM-led coupling was a progression not present. These differences in findings could be related to differences in the dynamical degrees of freedom and potentially different postural control of the CoM or the aim, or their

combination, in children compared to adults learning to throw. Taken collectively, both chapter 3 and chapter 4 provide support for global macroscopic variables being associated with common inter-individual changes during learning which are not seen at the joint space levels of technique changes.

Building upon chapters 3 and 4, chapter 5 used Cluster Phase analysis as a novel multivariate approach to examine the changes in synchrony between upper limb joints during both dominant arm throwing action at different childhood ages, and over a period of non-dominant overarm throwing practice in adults. The findings provided support for the idea that patterns of synchronization between the shoulder, elbow and wrist joints are dependent upon individual-specific constraints to action (Newell, 1986). Importantly, tri-joint synchrony of the upper limb became more closely coupled with increased age across childhood during dominant overarm throwing and over a period of non-dominant overarm throwing practice in adults. Since key changes in technique seem to go beyond the action of the upper limb, and the macroscopic CoM-wrist coupling captured technique change across age, it was imperative to explore higher order variables associated with weight transfer and the action of the whole body. Since the CoM and CoP are inherently linked, with the CoP being a projection of the CoM (Winter, 1995), CoP could provide a more practical method of data collection than CoM but still capture relevant change in the global dynamics of the system. Therefore, chapter 6 is underpinned by the knowledge established in previous chapters of this thesis by using a higher order variable to try and provide a time and cost effective method to establish cross-sectional differences in overarm throwing action.

In addition collecting CoP is a more powerful and time efficient tool to inform coaching than the time and equipment-heavy methods involved in quantitative kinematic analysis. Therefore, CoP movement measured via a force plate could be a quantitative and practical tool to inform and guide skill learning.

Chapter 6 builds upon this previous work by examining changes in the centre of pressure (CoP) motion during the development of overarm throwing action across childhood. Motion of the CoP seems relevant since the findings from previous chapters have shown that overall, the use of a macroscopic variable linking CoM motion to that of the wrist (end effector) was better able to distinguish children's age-related technique characteristics.

In understanding CoP it is important to consider postural stability. The dynamic system is unstable and is shaped by the environment, task and organismic constraints (Newell, 1985), therefore, balance should be studied at different ages across childhood. A better understanding of postural stability and the development of postural control during dynamic actions, such as throwing, is important as it will provide a valuable insight into how the perceptual-motor system is re-organised to meet the spatial and temporal constraints of the environment. It also allows for balance and coordination to be viewed as the same problem, providing an ecologically valid insight into motor control. Moreover, it has the potential to detect atypical postural development in children earlier and improve the interventions for children with pathological balance impairments through providing a better understanding and appreciation of the intra and inter differences

seen between children (Davids et al., 2000). Therefore, chapter 6 focuses on studying CoP pathway during a dynamic movement skill over childhood.

Postural control is the ability to resist forces of gravity whilst maintaining mechanical support during static and dynamic movements (Karlsson & Frykberg, 2000). This ability to maintain upright posture during dynamic movements is dependent upon the biomechanical properties of the system and the execution of the postural control programmes available to an individual (Lebiedowska & Syczewsk, 2000). During childhood, the development of proficient postural control occurs as a child progresses through stages of motor development and is shaped by the child's interaction with their environment (Newell, 1986; Roncesvalles, Woollacott & Jensen, 2001).

With balance inherently linked to motor learning and fundamental movement skills (Fisher et al., 2005), the first decade of a child's life is vital in the development of coordinated and controlled movement, with children beginning to display basic motor control skills between 5 and 8 years of age. This is demonstrated by displacement of CoP during standing on a moving platform (Shumway-Cook & Woollacott, 1985), single leg stance (Olivier et al., 2007), static balance (Rival, Ceyte & Olivier, 2005) and dual limb stance (Mickle, Munro & Steele, 2011; Ferdjallah et al., 2002; Roncesvalles et al., 2001). Motor control skills are subsequently refined and improved over the coming years as children find the most suitable movement solutions (Newell, 1986). By 10 years of age children have generally developed more efficient movement strategies and greater muscle strength, enabling them to consistently reproduce dynamic movement that

may lead to more consistent measures of postural control than younger children and more closely resemble the postural control of adults (Taguchi & Tada, 1988; Faigenbaum et al., 2014). This is illustrated by Taguchi and Tada (1988) who reported that children aged between 9 and 12 years of age presented similar postural control performance to adults in an eyes open condition during quiet stance. In contrast, Hirabayashi & Iwasaki, (1995) reported that during an eye closed condition only children aged between 12 and 15 years of age were similar to adults. However, there is the suggestion that adult-like postural control in children is task-dependent and influenced by sensory manipulation and muscle strength (Faigenbaum, et al., 2014).

Studies have examined postural control during stance in pre-adolescents, but to the authors knowledge postural control has not being examined in fundamental dynamic movement actions (Mickle et al., 2011; Bucci, Ajrezo & Wiener-Vacher, 2015; Chang et al., 2010; Condon & Cremin 2004; Cuisinier et al., 2011). Research has reported age-related differences in postural control of healthy children. Cuisinier et al. (2011) reported improvement in postural stability in children from 7 to 10 years of age compared to a group of young adults (mean age 25 years) during a semi-tandem position with the right foot in front of the left. Moreover, Barozzi et al. (2014) compared postural stability of 289 healthy children (children were spilt into two age groups: 6 to 10 years of age and 11 to 14 years of age) to healthy adults. Barozzi et al. (2014) reported an improvement in postural stability with age which was independent of the test condition during quiet standing; in addition, results suggested that children age 13 to 14 years of age still had not achieved adult levels of postural stability. Overall this study postulated that the

central and peripheral structure responsible for the development of postural control is still being developed at 14 years of age.

Physiologically, development in postural control is maintained through the maturation of the visual, neurological and proprioceptive system and environmental influences, which are still developing at 14 to 15 years of age (Hirabayashi & Iwasaki, 1995; Steindl et al., 2006). Steindl et al. (2006) reported that while proprioceptive function seemed to be mature at 3 to 4 years of age, visual and vestibular function became mature at 15 to 16 years of age. Meanwhile Gouleme et al. (2014) reported that during postural control tasks under different conditions, proprioceptive function and vestibular information are not fully developed in younger children and continues to develop into adulthood (Gouleme et al., 2014). In addition, it is also important to consider factors related to somatotype which is related to the development of muscle tissue and bones lengthening effecting the child's stature and physical activity level (Mickle et al., 2001).

The development of postural stance can be represented by the CoP pathways and demonstrates the mastery of the redundant degrees of freedom in order to produce coordinated and controlled movement (Fujinaga, 2008). Examining the CoP movement during overarm throwing provides a new variable to describe throwing performance, which has biomechanical, theoretical and practical relevance. Biomechanically, the CoP provides a measure of the weighted average of all the pressures distributed over the surface area in contact with the ground (Winter, 1995). Emphasising a collective variable such as CoP is based on the theoretical

proposition that motor control is organized with overall system dynamics rather than the control of individual degrees of freedom (Kelso, 1995). From a practical view point, the CoP movement is measured via a force plate and could therefore be a quantitative and practical tool to inform and guide skill learning.

A better understanding of postural stability and the development of postural control during dynamical movements, such as throwing, is important for many reasons. Specifically, this will provide a valuable insight into how the perceptual-motor system is re-organised to meet the spatial and temporal constraints of the environment and allows for balance and coordination to be viewed in the same problem, providing an ecologically valid insight into motor control.

6.2 Chapter Aim and Research Questions

The aim of this chapter was to examine CoP pathway during dominant overarm throwing action in children at 6, 10 and 14 years of age. A better understanding of postural stability and the development of postural control during childhood is important. Specifically, this will provide valuable insight into how the perceptual-motor system is re-organised to meet the spatial and temporal constraints of the environment and allows for balance and coordination to be viewed in the same problem, providing an ecologically valid insight into motor control. This study adds to work from previous chapters which highlighted postural control as a key technique change in overarm throwing action. The purpose of this research was to establish if CoP could capture robust changes in postural control of healthy children to describe throwing performance during dominant overarm throwing.

In order to address the aim of this chapter, the following specific research questions were addressed:

- What is the difference in displacement of the centre of pressure during overarm throwing action at 6, 10 and 14 years of age?
- What is the difference in velocity of the centre of pressure during overarm throwing action at 6, 10 and 14 years of age?
- What is the difference in acceleration of the centre of pressure motion during overarm throwing action at 6, 10 and 14 years of age?
- What is the difference in centre of pressure path length at 6, 10 and 14 years of age?

6.3 **Methods**

6.3.1 **Participants and Data Collection**

Written ethical approval was gained from the host University's DREP (15-031) committee prior to study initiation. Analysis was performed on 18 children (Table 6.1). All participants gave assent and the parent/guardian provided informed consent and completed an exercise health questionnaire (PAR-Q) on behalf of their child. Participants attended a single data collection session where five baseline data trials were collected for each participant during overarm throwing action with their dominant arm using a standard issue tennis ball (Slazenger). Kinetic data (1000 Hz) was collected using two Kistler Force Platforms (9865, UK) flush to the floor. Data was collected for every trial performed by each participant. Participants

were given the ongoing aim of hitting a 4m target located 14m in front of them whilst throwing a standard issue tennis ball as fast as possible. The target height was adjusted in line with each participant's eye level. Participants were not blinded from knowledge of results and verbal encouragement was provided with phrases including the words: 'nice', 'well done' and 'good job'.

Table 6.1 Anthropometric measurements of participants at 6, 10 and 14 years of age

Characteristic	6 years	10 years	14 years
Sex	5 (female)	4 (female)	4 (female)
	1 (male)	2 (male)	2 (male)
Age (years)	6.56 ± 0.30	10.32 ± 0.33	14.22 ± 0.48
Stature (m)	1.22 ± 0.05	1.47 ± 0.10	1.64 ± 0.11
Mass (kg)	23.88 ± 5.02	39.29 ± 3.26	61.02 ± 6.97

6.3.2 Data Processing and Analysis

Following a residual analysis, a fourth-order Butterworth filter was applied to raw marker data with a cut-off frequency of 6 Hz (Winter, 2009). Data was analysed during the propulsive phase of the throw which was defined as from the moment of forward and continuous motion in the direction of the throw until the frame of ball release. Data was normalized to the participant's individual body mass and

analysed and presented as a percentage of the total propulsive phase of the throw and normalised to 100%. The CoP is defined as the point of location of the vertical ground reaction force vector and provided a representation of the weighted average of all the pressures over the surface of the area in contact with the support surface (Winter, 1995).

The following dependent measures were derived from the force platform: anterior-posterior displacement of the centre of pressure, medial-lateral displacement of the centre of pressure, maximum anterior-posterior velocity of the centre of pressure, maximum medial-lateral velocity of the centre of pressure, maximum anterior-posterior acceleration of the centre of pressure, maximum medial-lateral acceleration of the centre of pressure and path length in the anterior-posterior direction and medial-lateral direction. Displacement of the CoP was defined as the total distance travelled during the propulsive phase of the throw and was calculated in the anterior-posterior direction and medial-lateral direction. Maximum velocity of the CoP was defined as the rate of change in displacement of the body with respect to time and was calculated in the anterior-posterior direction and medial lateral direction. CoP path length was defined as the length of the CoP displacement trajectory and is independent of direction (Winter, 1995). Maximum acceleration of the CoP was defined as the rate of change of velocity of the CoP with respect to time and was calculated in the anterior-posterior direction and medial lateral direction. Path length of the CoP was calculated in the anterior-posterior direction and medial-lateral direction. Raw force data was treated using Equations 6.1 to 6.9 in order to calculate CoP for the two force plates before being exported.

To calculate the location of the CoP, moments around the plate's internal x and y axes were determined:

$$M_x = b \times (f_{z_1} + f_{z_2} - f_{z_3} - f_{z_4}) \quad \text{Equation 6.1}$$

M_x = moment about x axis

b = y distance from centre of plate to centre of sensors

$f_{z_{1-4}}$ = force in z direction measured by sensors 1 to 4

$$M_y = a \times (-f_{z_1} + f_{z_2} + f_{z_3} - f_{z_4}) \quad \text{Equation 6.2}$$

M_y = moment about y axis

a = x distance from centre of plate to centre of sensors

$f_{z_{1-4}}$ = force in z direction measured by sensors 1 to 4

Moments about the plate's internal axes were calculated next:

$$M_{x'} = M_x + (f_y \times az_0) \quad \text{Equation 6.3}$$

$M_{x'}$ = x moment about track surface

M_x = moment about x axis of plate

F_y = force in y direction

az_0 = track surface offset from centre of plate

$$M_{y'} = M_y + (f_x \times az_0) \quad \text{Equation 6.4}$$

My' = y moment about track surface

My = moment about y axis of plate

F_x = force in x direction

az_o = track surface offset from centre of plate

$$ax = -My' / F_z \quad \textbf{Equation 6.5}$$

ax = x location of CoP measured from centre of plate

My' = y moment about top surface

F_z = force in z direction

$$ay = -Mx' / F_z \quad \textbf{Equation 6.6}$$

ay = y location of CoP measured from centre of plate

Mx' = x moment about top surface

F_z = force in z direction

Component force magnitudes were calculated next by calculating the force measured by each of the force plates:

$$F_x = F_{x_a} + F_{x_b} \quad \textbf{Equation 6.7}$$

F_x = total force in x direction

F_{x_a} = force in x direction measured by Plate A

F_{x_b} = force in x direction measured by Plate B

$$F_y = F_{y_a} + F_{y_b}$$

Equation 6.8

F_y = total force in y direction

F_{y_a} = force in y direction measured by Plate A

F_{y_b} = force in y direction measured by Plate B

$$F_z = F_{z_a} + F_{z_b}$$

Equation 6.9

F_z = total force in z direction

F_{z_a} = force in z direction measured by Plate A

F_{z_b} = force in z direction measured by Plate B

For trials when the CoP was loaded on two force plates equations 6.10 to 6.11 were used by weighting the CoP on each plate based on the relative force that was applied to that plate:

$$Pa = Fz_a + Fz$$

Equation 6.10

Pa = Plate A weighting

Fz_a = vertical force measured by Plate A

Fz = total vertical force measured by both plates

$$Pb = Fz_b + Fz$$

Equation 6.11

P_b = Plate B weighting

Fz_b = vertical force measured by Plate B

Fz = total vertical force measured by both plates

The total CoP location in the x and y directions was calculated next through combining the data from both force plates: Raw force data were treated using Equations 6.12 to 6.13 in order to calculate CoP for the two force plates before being exported:

$$ax = (a_x \times P_a) + (a_{x_b} \times P_b)$$

Equation 6.12

ax = global x location of CoP

ax_a = x location of CoP measured by Plate A

ax_b = x location of CoP measured by Plate B

P_a = Plate A weighting

P_b = Plate B weighting

ay = global y location of CoP

$$ay = (a_y \times P_a) + (ay_b \times P_b)$$

Equation 6.13

ay_a = y location of CoP measured by Plate A

ay_b = y location of CoP measured by Plate B

P_a = Plate A weighting

P_b = Plate B weighting

6.3.3 Statistical Analysis

Data were assessed for normality using a Shapiro-Wilks test. Once confirmed, a repeated measures analysis of variance (ANOVA) was conducted based on a single subject design ($p < 0.05$) with each dependent variable being run individually for each participant. Mauchly's test was used to determine the sphericity assumption within the data; where sphericity was violated, a Greenhouse-Geisser correction was applied. Comparisons of vector coding coordination variability were examined between age groups. Bonferroni post hoc correction was used as needed for multiple comparisons. Effect size was calculated using Cohen's d equation for all significant data, effect size was ranked as follows: large effect size ($d = 0.80$), medium effect size ($d = 0.50$) and small effect size ($d = 0.20$) (Cohen, 1998).

6.4 Results

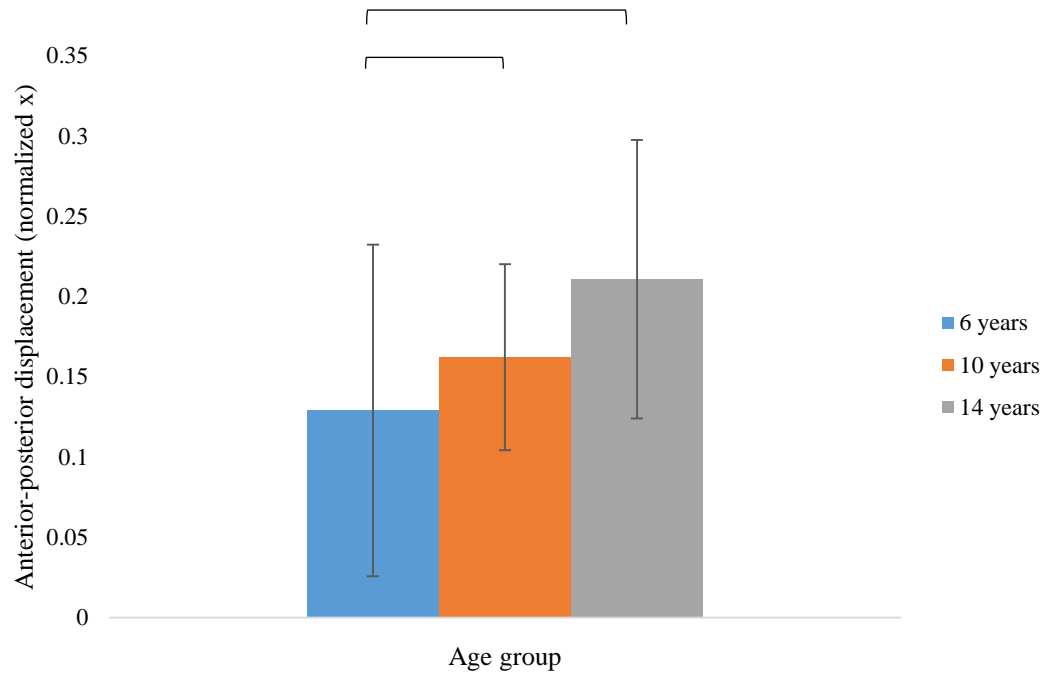


Fig 6.1 **Anterior posterior displacement of the centre of pressure for dominant overarm throws at 6, 10 and 14 years of age normalized to stature**

Anterior-posterior displacement of the centre of pressure was significantly greater at 10 ($p = 0.01$) and 14 ($p = 0.02$) years of age compared to 6 years of age. No significant difference was found between 10 and 14 year olds ($p = 0.44$).

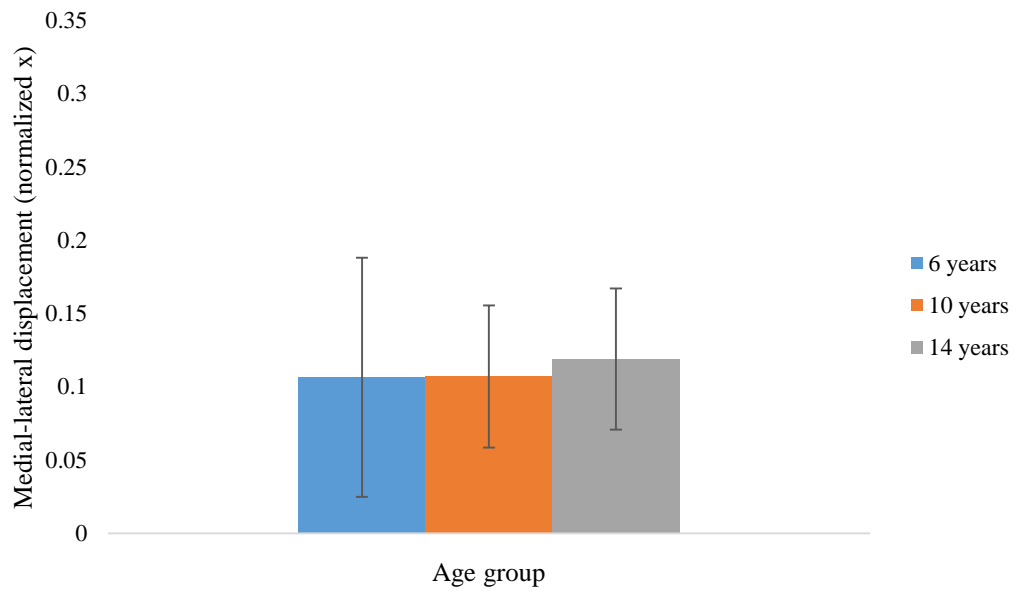


Fig 6.2 **Medial lateral displacement of the centre of pressure for dominant overarm throws at 6, 10 and 14 years of age normalized to stature**

Medial lateral displacement of the centre of pressure did not significantly change with age (6 to 10 years, $p = 0.99$; 6 to 14 years, $p = 0.78$; 10 to 14 years, $p = 0.66$).

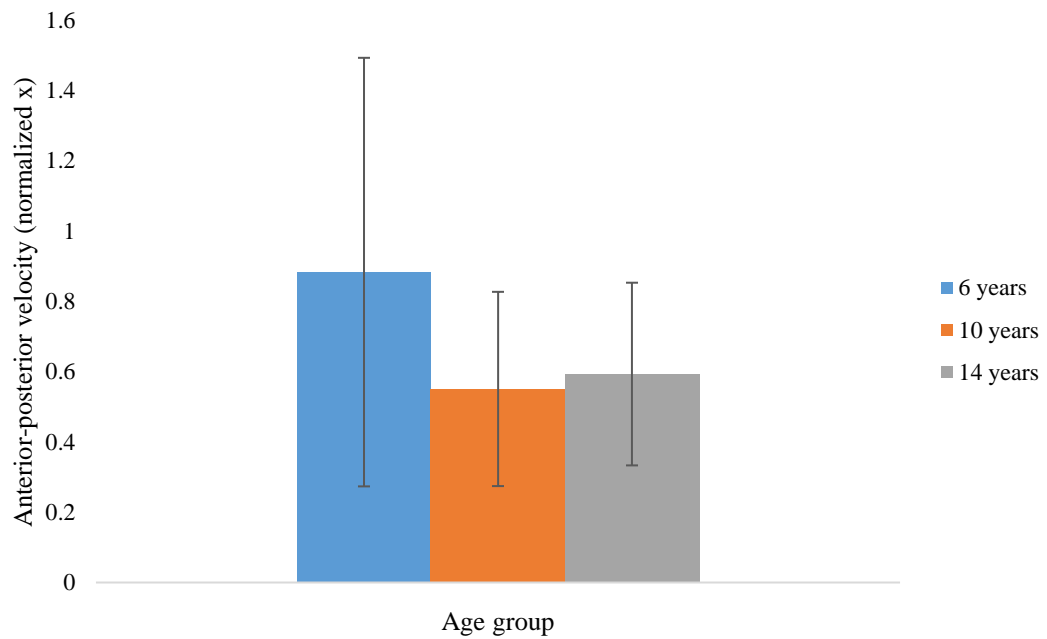


Fig 6.3 **Maximum velocity of the centre of pressure in anterior posterior direction for dominant overarm throws at 6, 10 and 14 years of age normalized to stature**

Anterior posterior velocity of the centre of pressure was not significantly different between children aged 6, 10 and 14 years of age (6 to 10 years, $p = 0.10$; 6 to 14 years, $p = 0.09$; 10 to 14 years, $p = 0.15$).

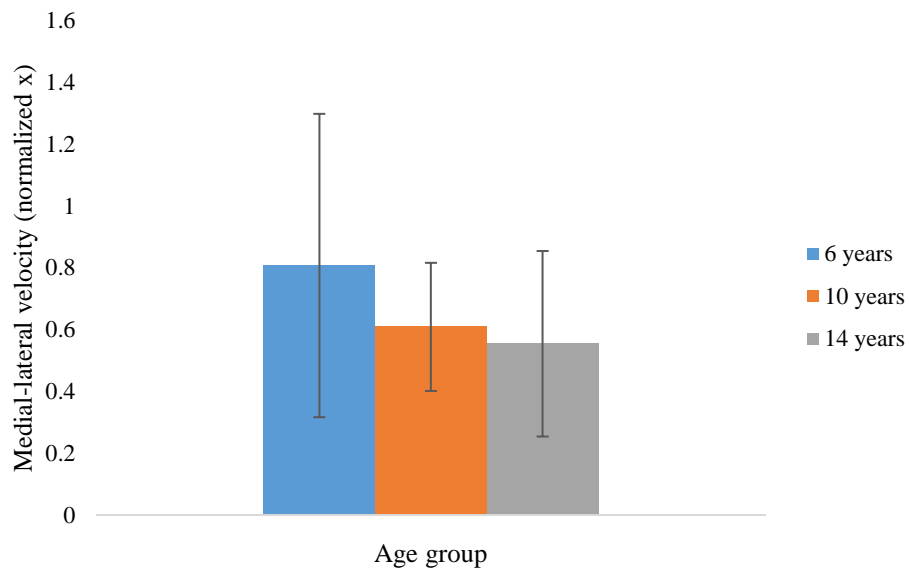


Fig 6.4 **Maximum velocity of the centre of pressure in medial lateral direction for dominant overarm throws at 6, 10 and 14 years of age normalized to stature**

Medial lateral velocity of the centre of pressure was not significantly different between children aged 6, 10 and 14 years of age (6 to 10 years, $p = 0.99$; 6 to 14 years, $p = 0.70$; 10 to 14 years, $p = 0.50$).

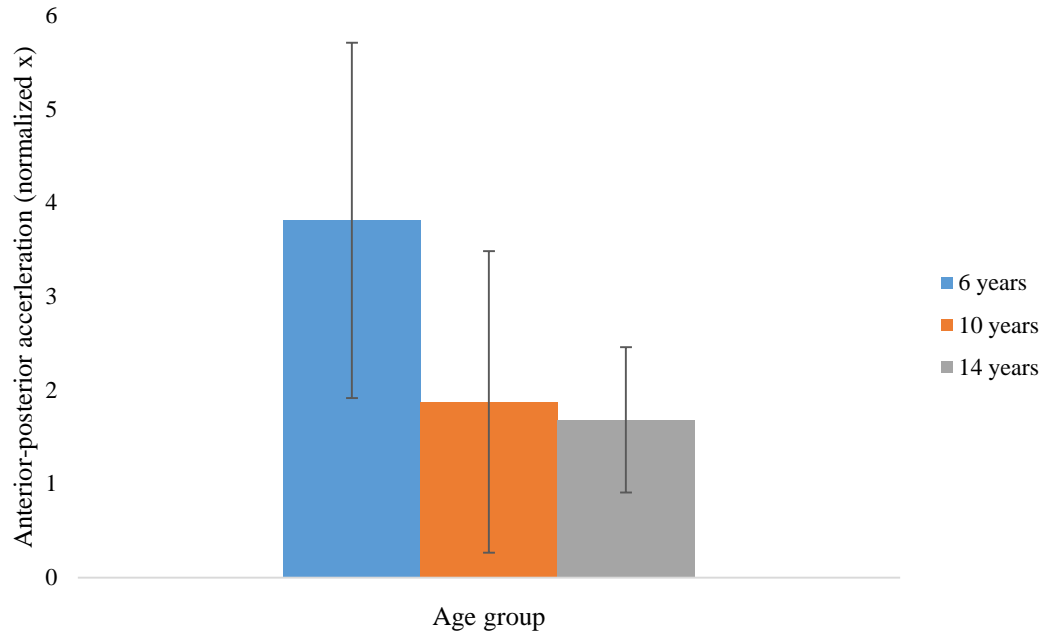


Fig 6.5 **Maximum acceleration of the centre of pressure in anterior posterior direction for dominant overarm throws at 6, 10 and 14 years of age normalized to stature**

Anterior posterior acceleration of the centre of pressure was not significantly different between children aged 6, 10 and 14 years of age (6 to 10 years, $p = 0.50$; 6 to 14 years, $p = 0.22$; 10 to 14 years, $p = 0.56$).

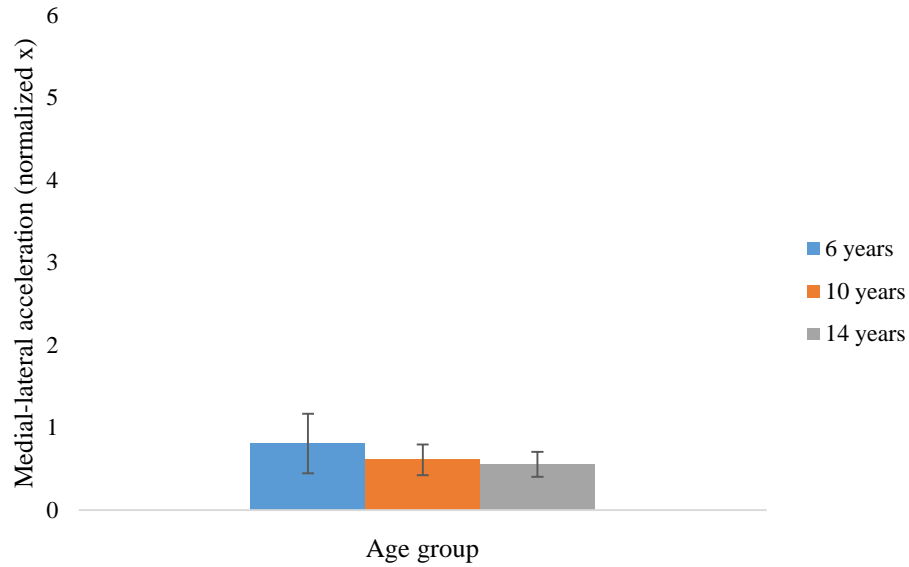


Fig 6.6 **Maximum acceleration of the centre of pressure in medial lateral direction for dominant overarm throws at 6, 10 and 14 years of age normalized to stature**

Medial lateral acceleration of the centre of pressure was not significantly different between children aged 6, 10 and 14 years of age (6 to 10 years, $p = 0.94$; 6 to 14 years, $p = 0.70$; 10 to 14 years, $p = 0.44$).

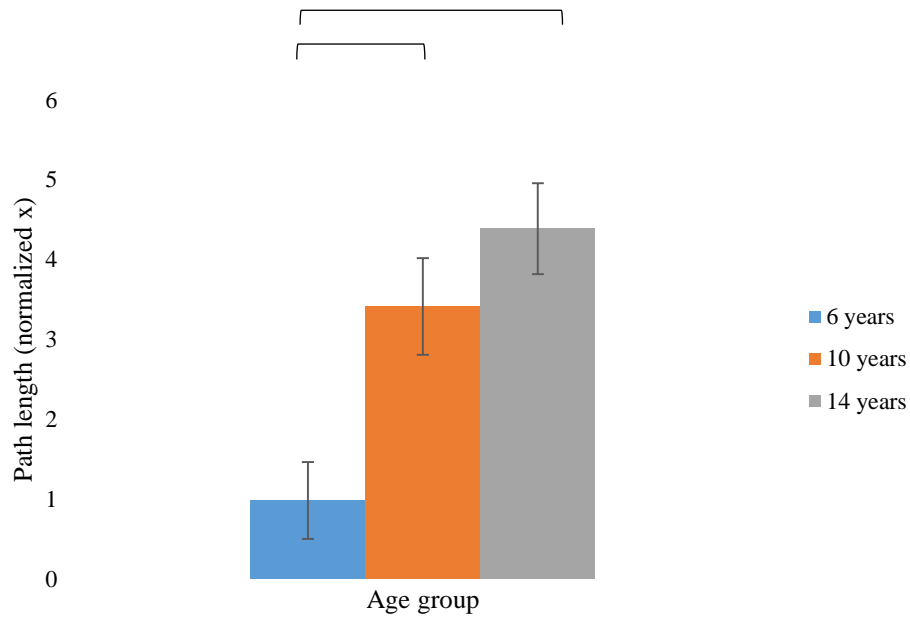


Fig 6.7 **Total path length of centre of pressure during dominant overarm throws at 6, 10 and 14 years of age normalized to stature**

Total CoP path length of the 6 year olds was significantly less to path length at 10 ($p = 0.01$) and 14 years old ($p = 0.001$). No significant difference was present between total path length of children at 10 and 14 years of age ($p = 0.25$).

6.5 **Discussion**

The CoP was examined during dominant overarm throwing action across childhood in order to provide a better understanding of the postural stability and dynamics during the overarm throwing performed at different ages. Further insight was gained into how the perceptual-motor system is re-organised to meet the spatial and temporal constraints of the environment and allows for balance and coordination to be viewed in the same problem. Specifically, the aim of chapter 6 was to examine cross-sectional development of CoP in healthy children at 6, 10 and 14 years of age during dominant overarm throwing action. To the author's knowledge this is the first paper to study CoP during dominant overarm throwing action in children. The main findings were twofold: firstly anterior-posterior displacement of the CoP (Fig 6.1) and total path length (Fig 6.7) were significantly greater at 10 and 14 years of age compared to children at 6 years of age. Secondly, age was found to have no significant effect for any medial-lateral variable measured. These findings are now discussed along with the other findings of this thesis and current literature.

6.5.1 **Displacement of the Centre of Pressure**

The CoP was examined to provide spatial information of postural dynamics during dominant overarm throwing action (Haas et al., 1989). Children at 6 years of age displayed significantly smaller anterior-posterior displacement of the CoP during overarm throwing action compared to children at 10 and 14 years of age (Fig 6.1). No significant difference was present between children at 10 and 14 years of age (Fig 6.1). The CoP profile reported here can be explained in line with the findings from chapter

4. Chapter 4 used the components model (Robertson & Halverson, 1984) to examine qualitative technique changes in overarm throwing action at 6, 10 and 14 years of age. As categorised by the components model (Robertson & Halverson, 1984; see Table 2.1), step action changed with age (Table 4.2). Children at 10 and 14 years of age all displayed a short contralateral step (level 3) during overarm throwing action compared to children at 6 years of age who used no step (3 of 6 participants), ipsilateral step (1 of 6 participants) and contralateral, short step (2 of 6 participants). The presence of a short contralateral step, where participants step forward with the opposite foot to their throwing arm creates a more open position of the body which would enable greater anterior-posterior displacement of the CoP (Stodden et al., 2006a). Participants aged 6 years of age displayed the greatest range of step action configuration of any age group, including, no step (3 of 6 participants), ipsilateral step (1 of 6 participants) and contralateral, short step (2 of 6 participants). The presence of no step (level 1) and ipsilateral step (level 2) creates a closed body position, which limits the degrees of anterior-posterior displacement.

Consistent with the current findings, studies have indicated that the development of the basic structures responsible for postural control are generally established between 5 and 8 years of age: during a standing moving platform (Shumway-Cook & Woollacott, 1985), static balance (Rival et al., 2005) and dual limb stance (Mickle et al., 2011; Ferdjallah et al., 2002; Roncesvalles et al., 2001). Mickle et al. (2011) studied postural stability in dynamic and static postural tasks where the findings suggested that proficient postural control was present at around 9 years of age for dual limb task; however, further time was required for more single leg tasks. Mickle et al. (2011) reported no further development in balance tasks occurred beyond 10 years of

age. This is supported by Geldhof et al. (2006) who suggested that no further development occurred between 9 to 10 years of age during a dual limb balance task. This improvement can be paralleled with sensory feedback through maturation of the visual, vestibular and proprioceptive systems, improved neural control (Burton & Davis, 1992) and external factors that can influence postural control including: motivation, concentration and fatigue (Geldhof et al., 2006). This is consistent with the findings of the current studies where changes in anterior-posterior displacement at 6 years of age was significantly smaller than at 10 or 14 years of age (Fig 6.1). No significant difference was found between 10 and 14 years of age suggesting that proficient postural control was obtained for anterior-posterior displacement by 10 years of age during dynamic movement task (Fig 6.1).

Maximum medial-lateral displacement of the CoP was similar between children at 6, 10 and 14 years of age (Fig 6.2). Overarm throwing action is characterised by the forward propulsion of the body, therefore, due to the task constraint the body would generally move in an anterior-posterior direction with large values of medial lateral-displacement associated with a lack of ability in overarm throwing action (Nolan et al., 2005). This lack of significant difference in medial lateral displacement at 6, 10 and 14 years of age during overarm throwing action is not overly surprising as participants were throwing towards a target located in front of them promoting anteroposterior displacement of the CoP to a greater extent than medial-lateral displacement of the CoP. Wolff et al. (1998) reported that for mixed sex group of children aged between 5 and 18 years of age, amplitude in the medial-lateral direction decreased by 25% from the youngest to oldest participants during quiet standing trials with eyes open. This is in contrast to current findings where age was found to not

impact on the medial-lateral displacement of the CoP during dominant overarm throwing; however, this could be due to task constraint associated with overarm throwing action which requires the forward propulsion of the body.

6.5.2 Velocity of the Centre of Pressure

Investigating the velocity of the CoP gives an indication of the momentum being produced during overarm throwing via a transfer of weight from the back leg to the forward positioned leg. During the propulsion phase of the throw maximum velocity of the CoP was examined in the anterior-posterior direction (Fig 6.3) and medial-lateral direction (Fig 6.4). As a function of age, no statistical difference was present for maximum anterior-posterior velocity or maximum medial-lateral velocity of the CoP. A reduction in medial-lateral velocity of the CoP is an indicator of mature postural stability (Nolan et al., 2005) and is associated with effective kinematic strategies, namely at the ankle joint to help attenuate forces and stabilise movement (Seroyer et al., 2010). These findings indicate that by 6 years of age individuals have learnt to utilise the components of the body as demonstrated by an increase in balance forces. Therefore, there is little change in the medial-lateral direction and similar activation strategies for postural control have been implemented by all age groups (Dillman, Fleisig & Andrews, 1993; Cook & Strike, 2000; Hutchinson & Wynn, 2004; Van den Tillaar, 2005).

High postural velocity is associated with the ability to make fast ballistic corrections to the CoP (Kirshenbaum, Riach & Starkes, 2001) which is linked with open-loop postural control. Younger children who have yet to develop a ‘mature sense of

balance' are reported to use an open-loop high-velocity postural strategy (Riach & Starkes 1994; Kirshenbaum et al., 2001). Research has suggested that between the age of 7 and 9 years children progress towards an integrated open-loop and closed-loop strategy where more precise and controlled correction of the CoP can be made (Riach & Starkes 1994; Kirshenbaum et al., 2001). However, males may progress towards an integrated open- and closed-loop strategy a little later than females (Riach & Starkes 1994; Kirshenbaum et al., 2001). This difference has been attributed to the vestibular system still developing in males at 9 to 10 years of age.

One study has reported no age-related relationship to sway parameters during a static dual stance in a group mixed sex group of children (Lebiedowska & Syczewski, 2000). It was concluded that the majority of balance parameters remain unchanged in children between 6 to 18 years of age with the same postural strategy implemented at 6, 10 and 14 years of age. This is consistent with the current findings where age was not found to impact on medial-lateral velocity of the CoP. Overarm throwing action is a dynamic task in which an individual is required to displace the CoM and in turn the CoP.

6.5.3 Acceleration of the Centre of Pressure

Maximum acceleration of the CoP in the anterior-posterior (Fig 6.5) direction and medial lateral direction (Fig 6.6) were examined and findings showed that no significant difference was present for either variable between age groups. Adjustment to movement through activation of the muscles leads to changes of the acceleration of the CoP in different directions which impacts on movement outcome (Day et al., 1993). Therefore, the rate of movement of the CoP is dependent upon the build-up of

muscular force and is achieved partly by passive elastic forces. These forces develop partly through the stretching of the tissues during movement and partly by changes in muscle activity. The current findings suggest that by 6 years of age children have developed effective muscle activation skills during dynamic movement tasks.

6.5.4 Path Length of the Centre of Pressure

Path length was significantly greater at 10 and 14 years of age compared to children at 6 years of age (Fig 6.7). The organisation of the body segments resulted in greater anterior-posterior displacement of the CoP during the throw with age (Fig 6.1). The CoP provides insight into the overall system and postural control dynamics. Findings suggest that children at 10 and 14 years of age were using more dynamic strategies in throwing. Moving of their CoP and CoM (chapter 4; Fig 4.1) increased during the process and they are therefore demonstrating a ‘freer’ action than children at 6 years of age.

6.6 Conclusion

The aim of chapter 6 was to examine cross-sectional development of CoP during a dynamical movement task in healthy children at 6, 10 and 14 years of age. The dynamic movement skill used was a dominant overarm throw towards a target located 14m in front of the child at standing eye height.

Analysis of postural control during dominant overarm throwing action at 6, 10 and 14 years of age showed that 6 year old age group displayed significantly smaller anterior-

posterior displacement of the CoP (Fig 6.1) and total path length (Fig 6.7) of the CoP compared to children at 10 and 14 years of age. Small anterior-posterior displacement suggested that this element of postural control is established by 10 years of age during dynamic movements such as throwing. Combining these findings, and in line with chapter 4, children at 10 and 14 years of age displayed a more advanced step action (Table 4.2) and greater ROM of the lower extremities (Fig 4.3) than children at 6 years of age. In terms of biomechanics of throwing, increased CoP displacement and path length in older children indicates better weight transfer which is a fundamental part of the overarm throwing action. It could be that the CoP is a practical proxy for this kinematic characteristic of technique.

Adaptation to movement will continue during childhood and into adulthood but these adjustments are likely to be on a much smaller scale, as demonstrated in chapter 4. The practical implications of this chapter are the importance of activity encouraging a contralateral step allowing for effective weight transfer during development of overarm throwing in childhood providing a key area for the movement practitioner to direct their focus.

6.7 Chapter Summary

This chapter has examined how postural control changed during a fundamental motor skill of the overarm throwing action with the dominant arm at 6, 10 and 14 years of age. Providing a quantitative insight into the development of coordinated and controlled movement is useful to teachers and health care professionals. The aim of chapter 6 was to examine the cross-sectional development of CoP in healthy children

at 6, 10 and 14 years of age during dominant overarm throwing action. Section 6.2 outlined three research questions in order to address the aim.

➤ **‘What is the difference in displacement of the centre of pressure during overarm throwing action at 6, 10 and 14 years of age?’**

Overall the findings showed that children at 6 years of age had significantly smaller maximum anterior-posterior displacement of the CoP during overarm throwing action (Fig 6.1) while no significant differences were present in children of 10 and 14 years. For all ages, no significant difference was present for maximum medial lateral displacement of the CoP (Fig 6.2). This suggests that 6 year olds are able to display similar medial-lateral displacement of the CoP as children aged 10 and 14 years of age (Fig 6.1). Further postural control development is required for anterior-posterior displacement of the CoP with current findings indicating this occurs between 6 and 10 years of age. Inclusion of a greater age range of children would be required to explore this further.

➤ **‘What is the difference in velocity of the centre of pressure during overarm throwing action at 6, 10 and 14 years of age?’**

The findings showed no age-related statistical difference for maximum anterior-posterior velocity or maximum medial-lateral velocity of the CoP. Suggesting that adequate movement strategies had been developed to control the velocity of the CoP in the anterior-posterior and medial-lateral direction by the time a child was 6 years of age. Therefore, there is little change in the medial-lateral direction and similar activation strategies for postural control have been implemented by all age groups

(Dillman, Fleisig & Andrews, 1993; Cook & Strike, 2000; Hutchinson & Wynn, 2004; van den Tillaar, 2005).

➤ **‘What is the difference in acceleration of the centre of pressure motion during overarm throwing action at 6, 10 and 14 years of age?’**

The findings showed that no significant difference was present for either variable between age groups with the maximum acceleration of the CoP dependent on muscular activation leading to a build-up of force. This suggests that by 6 years of age children have developed effective muscle activation skills during dynamic movement tasks to create acceleration, or that acceleration is not a relevant.

➤ **‘What is the difference in centre of pressure path length at 6, 10 and 14 years of age?’**

Children at 6 years of age displayed a significantly smaller CoP path length than children at 10 and 14 years (Fig 6.7). The increased CoP pathway suggests better weight transfer in 10 and 14 year olds compared to 6 year olds. Findings suggest that children at 10 and 14 years of age were using more dynamic strategies in throwing, moving their CoP and CoM (chapter 4; Fig 4.1) to a greater extent during the process and are therefore demonstrating a ‘freer’ action than children at 6 years of age. Current findings suggest that CoP pathways during dominant overarm throwing action at 10 and 14 years of age are similar suggesting that a mature level of postural control has been acquired by the time a child, Lopez, is 10 years old during dynamic movement tasks. This is consistent with findings of the other studies (Shumway-Cook & Woollacott, 1985; Forssberg et al., 2005; Mickle et al., 2011). Specifically in the

findings of Mickle et al. (2011) where it is suggested that proficient postural control during dual limb task was present around 9 years of age.

The data presented in this chapter has provided an insight into the characteristic of CoP during a fundamental movement skill at ages 6, 10 and 14 years during dominant arm throwing building upon the work presented in chapters 3 to 5. This adds to a comprehensive view of technique changes during a fundamental whole body movement. In a summary of the key findings, anterior-posterior displacement and total path length of the CoP were significantly smaller at 6 years of age compared to children at 10 and 14 years of age. This was associated with weight transfer which was facilitated by children at 10 and 14 years of age taking a contralateral step (chapter 4; Table 4.3). The findings of chapter 6 suggest that the majority of postural control variables, with the exception of anterior-posterior displacement and total path length of the CoP, remain unchanged between 6, 10 and 14 years of age. These findings are consistent with studies examining balance during static and dynamic balance tasks (Roncesvalles, Woollacott & Jensen, 2001; Ferdjallah et al., 2002; Mickle, Munro & Steele, 2011). Practical applications of the current results are that it is important to focus on anterior-posterior displacement of the CoP with children at 6 years of age and this can be facilitated by encouraging children to take a contralateral step (chapter 4). By 10 years of age participants are proficient in postural control variables of dominant overarm throwing. In terms of the basic science of motor control, findings from chapter 3 suggested there may be a requirement to master the dynamic stability of postural control before the learner is able to master the throwing action with the upper limbs. Current findings from chapter 6 postulate that postural control is proficient from 10 years of age during dynamic movement tasks. Measuring the CoP

using a force platform provides a quantitative, practical and time efficient method to inform coaches of postural control and guide skill learning.

CHAPTER 7: General Discussion

7.1 Introduction

Considerable research has focused on identifying the series of stable states in technique that occur when practising complex motor tasks. From an applied perspective, forming a model of motor learning in this way informs interventions to elicit the most efficient and effective practice. From a theoretical perspective, models of motor learning provide insight into qualitative and quantitative states that reflect how movement is controlled.

To explore technique changes, the overarm throw for force was chosen as the vehicle for this research as it provides a discrete complex whole-body movement skill. Moreover, it allows for balance and coordination to be viewed in the same problem. Since overarm throwing action is a fundamental movement task that develops during childhood it allows for the observation of skill across the lifespan. In addition, it allows for exploration of greater and lesser ability levels within the same participant by observing dominant and non-dominant arm actions.

The overarm throw for force is an example of a motor action that has received substantial study and its own model of technique change. The components model (Robertson & Halverson, 1984) for overarm throwing consists of a series of stable states related to four key components of the body involved in overarm throwing action. However, from a dynamical systems theory perspective (Newell, 1986) components (arms, legs) do not operate independently of each other. Changing the operation of one

component will drive the system to subsequently self-organise to compensate by altering another component to maintain a consistent performance (Southard, 2006). Thus, this thesis further explored technique changes in line with notions of dynamical systems as well as the pre-existing model of Robertson & Halverson (1984). The application of a dynamical systems theory perspective to movement development provides a way to explain the complex and ever-changing perturbations that occur at multiple levels of the system through the process of self-organisation of the task, environment and organismic constraints (Newell, 1986).

Chapter 2 presented a critical review of literature where gaps within current motor learning and biomechanics knowledge were highlighted. Motor control researchers are still working towards an appropriate theory of motor learning that can adequately describe changes in technique without oversimplifying the complexity of the system (Newell, 1986). Biomechanics literature is characterised by kinematic and kinetic technique changes in throwing action and provides the key characteristics of technique change associated with optimal throwing action in a range of throwing styles (Kernodle & Carlton, 1992; Southard, 2006; Fleisig et al., 1996; Plummer & Oliver, 2015).

Informed by current literature, the overall aim of this thesis was to increase understanding of the key processes of motor learning and biomechanical variables involved in learning a complex movement skill. A number of research questions were developed in order to answer the overall aim of the thesis and were addressed and analysed in chapters 3 to 6. In order to achieve this, two experimental studies were undertaken to observe technique changes during the overarm throwing action in adults

and children. In the first data collection, full body kinematic data was collected over a longitudinal 3-week period of overarm throwing practice for adults with their non-dominant arm. For the second data collection, full body kinematic and force plate data was collected during cross-sectional study of technique during dominant overarm throws at 6, 10, and 14 years of age. Chapter 7 discusses the individual research questions that contribute to addressing the overall aim of this thesis:

1. Provide a template of a motor learning analysis framework during skill acquisitions underpinned by the dynamical system theory in adults over a period of practice and children at difference chronological ages.

Major contributions to knowledge resulting from this thesis include the powerful nature of exploring different levels of the system to understand the process of technique change, control and coordination in the multidimensional system. This is particularly relevant since there is still no consensus on the ‘typical’ characteristics of technique change during learning that can be applied across different movement tasks, thus it is suggested that there is strength in the research being carried out by using comparative methods in the same study. By viewing changes at different levels of the system this thesis has provided an understanding of the complementary nature of qualitative and quantitative methods which are underpinned by theory and are practically relevant to motor learning. A more specific finding is that of the macroscopic collective variables being able to capture common characteristics of technique change across individuals, despite individual-specific changes occurring at the joint space level. Since however, it is acknowledged that these macroscopic variables may not easily facilitate feedback information (or the effectiveness of this

still needs to be explored), the key characteristics of technique change were also identified, in this case the contralateral step, as drivers for improvement.

2. Conduct and provide research that is ecologically valid, therefore, providing evidence towards a general theoretical approach to understand technique change that characterises motor learning in adults and children or support for current motor learning approaches.

With throwing studies conducted in an ecologically valid environment, the CoM-wrist coupling pattern was a key finding of this research. The use of a postural control variable and the end effector of movement patterns was an important approach that was able to clearly identify technique changes among adults and children. The application of macroscopic variables was not limited by individual degrees of freedom but instead was able to provide an overarching view of dynamical changes of the system in adults and children. Changes in ROM were found to be individual specific among adults and children with no clear direction of change related to practice or age. This evidence underpins general theoretical approaches to understand technique change in whole body motor skills and is particularly powerful since changes in the learning of a novel task in adults was examined, as well as across age groups in children.

3. Provide evidence-based advice to sport practitioners and educators in informing skill development in overarm throwing.

Based on point 2 above, the coupling of the CoM-wrist provided a really powerful representation of technique changes with practice in adults and age-related changes in children. From a practical perspective however, the use of a macroscopic variable cannot be easily translated to underpin strategies adopted by practitioners and educators. The multimodal application of qualitative and quantitative approaches provided additional theoretically and practical knowledge. Specifically, the components model (Robertson & Halverson, 1984) consists of four key components related to qualitative technique of overarm throwing action that are visual and easy to communicate to coaches and learners. The components model was followed to a large extent by the participants, and thus can provide a tool that can be applied by health practitioners and educators to facilitate and fast track movement development. It was highlighted however, that the step action included in the components model was a particularly dominant predictor of practice or age-related changes, and in line with previous literature, constrained the progression of other actions. Therefore, step action and anterior-posterior displacement of the CoM are largely adequate to describe and facilitate technique progression in the early stages of learning to throw.

7.2 Overall Thesis Synthesis

This thesis is underpinned by the dynamical system theory approach to motor learning and the associated stages of learning models (Bernstein, 1967; Newell, 1985) and throwing specific models (Robertson & Halverson, 1984) to understand the

investigation of technique changes in a fundamental movement skill that is ecologically valid. Furthermore, the use of novel analysis methods was investigated in order to find a method that can adequately explain technique changes within children and adults. Overarm throwing action was examined in adults and children and was chosen as the vehicle due to it being a fundamental and complex movement skill that requires the coordination of the whole body (Van den Tillaar & Ettema, 2007). In addition it allows for throwing action to be viewed from a greater and lesser skill level by observing dominant and non-dominant overarm throws of the same individual. Technique changes in non-dominant overarm throwing over a 3 week period of practice in 10 adult participants was examined. Cross-sectional technique changes were observed at 6, 10 and 14 years of age during dominant overarm throwing. Longitudinal and cross sectional data was collected to determine if the development of overarm throwing action and associated movement strategies in children occurred in a similar manner as technique changes induced over practice in adults.

The development of non-dominant overarm throwing technique for ten adult participants was explained through the use of three approaches of motor learning that describe qualitative and quantitative changes over a three-week period of practice. The aim of chapter 3 was to investigate the evolution of changes in technique of the non-dominant overarm throw over practice with respect to three different, but potentially complementary, approaches to qualitative and quantitative change of movement dynamics: Newell's (1985) learning stages of coordination, control and skill, the components model of overarm throwing (Robertson & Halverson, 1984), and Bernstein's (1967) hypothesis of freezing and freeing redundant mechanical degrees of freedom. Common practice induced changes in the collective posture-ball release

dynamics and were supported by individual strategies at the joint ROM level revealing the complementary nature of the three approaches and their key dependent variables to the analysis of learning to throw.

In a novel approach, vector coding was conducted with the collective variables CoM and wrist coupling to investigate dynamic changes in technique (Newell, 1985). This was an initial attempt at investigating the relationship between candidate collective variables for postural support (CoM motion) and end effector (wrist motion) during overarm throwing action. At the start of a 3 week period of practice all adult participants demonstrated in-phase coupling of the CoM-wrist at the beginning of the propulsive phase moving to wrist-led phase coupling at ball release (Fig 3.1). Following a 3 week period of practice 3 of the 10 participants continued to demonstrate this coupling style (Fig 3.1). Seven of the 10 participants began to demonstrate a broader range of differentiated phase relations coupling of CoM-wrist (Fig 3.1). This later strategy was in line with dominant overarm throws and provided evidence for freeing the dynamical degrees of freedom, specifically, greater involvement of the CoM with a 3 week period of practice. In line with Newell's (1985) learning stage coordination, variability significantly decreased ($p < 0.05$) for 3 of the 10 participants with practice suggesting that they might have progressed to the second stage of learning which is 'control' (Newell, 1985) (Table 3.1). The remaining 7 of 10 participants significantly increased ($p < 0.05$) coupling variability suggesting they had remained in the initial stage of learning which is 'coordination' (Newell, 1985; Table 3.1).

Changes in the action level of the components were consistent with those outlined in the components model (Robertson & Halverson, 1984) (Table 3.2). During non-dominant arm throws changes in the action level of the 'step' and 'trunk' coincided with an associated increased ROM of the lower extremities and CoM in line with Bernstein's (1967) hypothesis. Action of the 'humerus' and 'forearm' components during non-dominant arm throws started at advanced actions levels from study initiation suggesting that some level of cross transfer had occurred (Adams, 1987). The highest action levels were not achieved in the step/torso/arm for all participants. This may indicate that although 3 weeks of non-dominant arm throwing practice elicited technique change, further practice would be required for non-dominant arm throws to be categorised at the same action level as dominant arm throws (Table 3.2). Overall, the components model (Robertson & Halverson, 1984) provides practitioners with a framework to assess and progress technique changes in adults.

During a period of non-dominant overarm throwing practice, changes in lower limb and shoulder ROM occurred in-line with Bernstein's (1967) hypothesis of freezing and freeing redundant mechanical degrees of freedom (Fig 3.3). This in turn enabled a greater displacement of the CoM as was demonstrated by the CoM and wrist coupling and the components model (Robertson & Halverson, 1984). Interestingly, ROM of the elbow and wrist did not occur in-line with Bernstein's (1967) observations of freezing and freeing redundant mechanical degrees of freedom with the majority of participants decreasing ROM of the elbow and wrist joint with practice. This provides support for the suggestion that the process of freezing and freeing (Bernstein, 1967) is perhaps task specific rather than a universal rule of change (Hong & Newell, 2006).

The analysis of key kinematic variables in chapter 3 provided an insight into the techniques adopted with practice of a fundamental whole body movement. Support was provided for the use of a high order, low dimensional variable to explain technique changes of the dynamics system. Postural control was a key component of more advanced throwing technique as demonstrated by a broader range of CoM-wrist coupling (Newell, 1984), higher step action level (Robertson & Halverson, 1984) and greater ROM of the lower extremities (Bernstein, 1967). The three different approaches used here examined different levels of the system which provided a complementary overview of technique changes.

Building upon chapter 3, cross-sectional data was collected with children at 6, 10 and 14 years of age. This was undertaken to firstly examine technique changes in a more ecologically valid research population and secondly to establish if changes in technique across childhood were in line with technique changes in adults. Therefore, the aim of chapter 4 was to investigate the differences in technique over childhood and adolescence for dominant overarm throwing via the same approaches to qualitative and quantitative change of movement dynamics during learning as Chapter 3: Newell's (1985) learning stages of coordination, control and skill, the components model of overarm throwing (Robertson & Halverson, 1984) and Bernstein's (1967) observations of freezing and freeing redundant mechanical degrees of freedom.

In terms of Newell's (1985) stages of learning model, CoM-wrist coupling angle became more complex as a function of age with a greater range of phase relations implemented. During dominant arm throws, 6 year old age group displayed in-phase coupling at the start of the propulsive phase and which was followed by wrist-led

coupling at ball release (Fig 4.1a), much like the adults at the start of non-dominant arm practice discussed in chapter 3 (Fig 3.1). Ten year olds and 14 year olds displayed CoM-led coupling at initiation of the throw before progressing to in-phase coupling at 20% of the propulsive phase and further progressing to wrist-led coupling at ball release, similar to the adults at the end of practice of non-dominant arm throwing (Fig 4.1b and Fig 4.1c). Therefore, the vector coding analysis provided a method in which to highlight key characteristics of technique change in adults and children during overarm throwing action (Fig 3.1 and Fig 4.1). From a practical perspective, it is important to have knowledge of how technique changes over practice and during learning, and the level of the system at which this is particularly evident.

Significant changes were present for coordination variability between 6, 10 and 14 years of age during dominant arm throws (Fig 4.2). Coordination variability of the coupling angle was high for each age group, particularly at 6 years of age. This indicates that 6 year old participants were in the coordination stage of Newell's (1985) learning model. By 10 and 14 years of age variability had decreased in the coupling angle which suggests that by 10 years of age children had established a more stable dynamic between the CoM and wrist (Fig 4.2).

The findings from chapter 4 demonstrated that changes in technique occurred in line with the components model (Table 4.2 and Robertson & Halverson, 1984). Six year olds displayed primitive and intermediate developmental action levels (Table 4.2) while 10 and 14 year olds showed advanced action level (Table 4.2). However, all 14 year olds had still not reached the highest action level for step but were similar to non-dominant arm developmental profiles reported in chapter 3 (Table 3.2).

Kinematic data varied at individual joints. ROM of the ankle and knee increased in a linear direction with age with 6 year olds having the most restricted ROM at the ankle and knee (Fig 4.3). ROM of the hip was significantly greater at 6 and 10 years of age compared to 14 years of age (Fig 4.3). ROM at the shoulder at 6 years and 10 years of age was significantly greater to that of 14 years of age. This is consistent with Meister, et al. (2003) who reported that shoulder ROM decreased as age increased suggesting that this was due to maturational bone and soft tissue adaptations. ROM of the elbow and wrist joint was most restricted at 14 years of age (Fig 4.3). Chapter 4 provided an understanding that a global variable is able to give an invaluable overview of the overarching macroscopic technique changes in terms of complexity of a postural dynamic system. The use of CoM and wrist as the collective variables was underpinned by qualitative changes in 'step' (Robertson & Halverson, 1984) and quantitative changes in lower limb ROM (Bernstein, 1967).

Chapter 3 and chapter 4 provided an understanding of technique changes in non-dominant overarm throwing action in adults and dominant overarm throwing action in children using current motor control approaches. The approaches were chosen as each of them explores a different level of the system to help explain kinematics of overarm throwing action from a dynamical system theory perspective. Overall, the use of a macroscopic variable linking CoM motion to that of the end effector, wrist, was more able to identify the technique changes related to practice of adults and age-related changes in children. Combining the three analysis approaches affords an integration of the system changes as a function of practice in adults and age in children.

In children three key coupling modes were identified which became more complex with the progression of age from 6, 10, and 14 years of age (chapter 4; Fig 4.1). Specifically, coupling mode 1 and 2 (Fig 4.1a; 4.1b) displayed a similar but simpler profile than previously reported by adults (chapter 3; Fig 3.1) as the children spent less time in in-phase coupling (mode 1; Fig 4.1a) and CoM-wrist led coupling (mode 2; Fig 4.1b). Coupling mode 3 (Fig 4.1c) was similar to the coupling reported in chapter 3, while the progression of coupling angle further into the CoM-led coupling was a progression not present for adult participants. These differences in findings could be due to differences in dynamical degrees of freedom and potentially different postural control of the CoM or the target aim, or their combination, in children compared to adults learning to throw. Taken collectively, both studies provide support for global macroscopic variables being associated with common inter-individual changes during learning which are not seen at the joint space levels of technique changes. This raises an important distinction regarding the level of the dynamical system that might capture fundamental characteristics of technique change during learning. This stands as an epistemological shift from the joint space level of analysis in previous research (Bernstein, 1967; Newell et al., 1989; Vereijken, Whiting, & Beek, 1992; Chow et al., 2008).

To further understand and explain technique changes and explore in more depth why the action of upper extremities ‘froze’ with practice and age, chapter 5 examined synchrony of the upper limb joint using a novel multivariate analysis method. The aim of chapter 5 was to apply Cluster Phase analysis to explore technique changes of upper limb coordination during motor development of dominant overarm throwing action during childhood and over a period of non-dominant overarm throwing practice in

adults. Traditionally due to mathematical limitations, coordination in human movement has been viewed as the motion of two joints and segments (e.g. Haken, Kelso, & Bunz, 1985; Kelso, 1984; Schmidt, Shaw & Turvey, 1993). However, the majority of human movement requires the application of more than two joints. It was therefore of interest to apply a multivariate method (Cluster Phase) that allows more than two variables to be examined at one time.

To investigate changes in the individual joint synchrony at 6, 10 and 14 years of age, a comparison was made to adults who had undergone a 3 week period of practice. The results revealed that joint synchrony was significantly greater while its intra-individual variability was significantly lower at 14 years of age compared to 6 years of age. However, the direction of change in joint synchrony was specific for individual adults after a period of non-dominant overarm throwing practice (Fig 5.1). A reduction in tri-joint synchrony variability was a characteristic of both older children, compared to younger children, and adults learning to throw with their non-dominant arm. Overall, while evidence of increased tri-joint synchrony with age was found, individual constraints of the intrinsic dynamics of an individual dictates if more or less synchrony is present suggesting that synchrony is not associated with practice in adult participants. Therefore, upper limb joint synchrony is not a candidate for a collective variable (Newell, 1985) due to variation in the development of the average degree of synchrony with practice. These findings are consistent with decreased ROM of the upper extremities in chapter 3 for non-dominant overarm throwing in adults (Fig 3.3) and findings from chapter 4 showed that 14 year olds had the lowest ROM at the shoulder, elbow and wrist joint compared with children at 6 and 10 years of age during dominant overarm throws (Fig 4.3).

When analysing longitudinal changes in tri-joint synchrony of adults practising with the non-dominant arm, results showed that 4 of the 10 participants demonstrated decreased synchrony at the shoulder joint, 5 of the 10 participants exhibited decreased synchronization at the elbow joint, and 4 of the 10 participants had decreased synchronization at the wrist joint as a function of practice (Fig 5.3). These results allude to the idea that the elbow joint might be a possible indicator for changes in overarm throwing practice. Participants who decreased tri-joint synchrony also showed a decrease in synchrony of the elbow and wrist joint (chapter 3; Fig 3.3). No significant difference was present between individual synchrony of the shoulder, elbow or wrist joint for children at 6, 10 or 14 years of age (Fig 5.4). This suggests that individual joint synchrony to the group did not significantly change as a function of increased age during childhood which could be due to individuals within an age group developing individual specific solutions to overcome the constraints in action (Newell, 1986) which impacts on the overall group data.

In summary chapter 5 used a novel multivariate method to explore dynamics and provided an insight into upper limb tri-joint synchrony over practice in adults and across age in children during the overarm throwing action. Chapter 5 provided support for the idea that patterns of synchronization are dependent upon the individual constraints to action shown. It seems that the intrinsic dynamics and individual constraints dictate whether synchrony in a less skilled throw action (the non-dominant arm) will increase or decrease in line with a more optimal solution (the dominant arm). Overall, however, the results show that synchrony is not linearly associated with practice or skill level, but instead based on individual constraints. Therefore, the

synchrony of the upper limb is not a candidate for a collective variable (Newell, 1985) that could help predict the development of technique during overarm throwing action. However, from a theoretical perspective, the application of multivariate methods to the study of coordination and development is important as it has the ability to provide information on multiple components involved within a motor task.

A clear understanding has been provided thus far of the qualitative and quantitative kinematic technique changes during overarm throwing using existing approaches of motor learning and novel methods of analyses (vector coding: chapter 3 and chapter 4; Cluster Phase: chapter 5). These different, although complementary, approaches of motor learning provided information of different layers of the system to give an overview of technique changes and an understanding of technique change from a dynamical system theory perspective (Newell, 1985; Newell, 2003; Mayer-Kress et al., 2006; Hong & Newell, 2006).

Chapter 6 builds upon the previous chapters by examining changes in the CoP motion during the development of overarm throwing action across childhood. Motion of the CoP seemed relevant since the findings from previous chapters 3 and 4 have shown that overall, the use of a macroscopic variable linking CoM motion to that of the effector wrist was more able to identify children's age-related technique changes in movement form and capture the impact of posture-ball release dynamics. The aim of chapter 6 was to examine the CoP pathway during dominant overarm throwing action in children at 6, 10 and 14 years of age.

Overall the findings showed that children at 6 years of age had the significantly smallest maximum anterior-posterior displacement of the CoP during overarm throwing action (Fig 6.1), while no significant differences were present between children at 10 and 14 years of age. The anterior-posterior CoP profile can be explained in line with the findings from chapter 4. As categorised by the components model (Robertson & Halverson, 1984; Table 2.1), step action changed with age (Table 4.2). Children at 10 and 14 years of age all displayed a short contralateral step (level 3) during overarm throwing action compared to children at 6 years of age who used no step (3 of 6 participants), ipsilateral step (1 of 6 participants) and contralateral, short step (2 of 6 participants).

No significant difference was present for the maximum medial lateral displacement of the CoP (Fig 6.2) suggesting that 6 year olds are able to display similar medial-lateral displacement of the CoP as children aged 10 and 14 years of age (Fig 6.2). Further postural control development is required for anterior-posterior displacement of the CoP with current findings indicating this occurs between 6 and 10 years of age. Inclusion of a greater age range of children would be required to explore this further. Age did not show a significant change in velocity of the CoP in the anterior-posterior direction or medial-lateral direction which implies that adequate movement strategies had been developed to control the velocity of the CoP in the medial-lateral direction by the time a child was 6 years of age. Similarly, no significant difference was present in maximum acceleration between age groups. With the maximum acceleration of the CoP dependent on muscular activation leading to a build-up of force, it suggests that by 6 years of age children have developed effective muscle activation skills during overarm throwing action. Lastly, for CoP pathway length, significant differences were

present between 6 year olds compared to 10 and 14 year olds. Findings suggest that children at 10 and 14 years of age were using more dynamic strategies in throwing by increased movement of their CoP (chapter 6; Fig 6.1) and CoM (chapter 4; Fig 4.1) during the process and therefore demonstrating a 'freer' action than children at 6 years of age.

The data presented in chapter 6 has provided an insight into the characteristic of CoP during a fundamental movement skill at age 6, 10 and 14 years of age during dominant arm throwing building upon the work presented in chapters 3 to 5, so giving a comprehensive view of technique changes during a fundamental whole body movement. In conclusion, the findings of chapter 6 suggest that the majority of postural control variables, with the exception of anterior-posterior displacement of the CoP, remain unchanged between 6, 10 and 14 years of age. These findings are consistent with studies examining static and dynamic balance tasks (Roncesvalles, Woollacott & Jensen, 2001; Ferdjallah et al., 2002; Mickle, Munro & Steele, 2011).

Measuring the CoP using a force platform provides a quantitative, practical and time efficient method to inform coaches of postural control and guide skill learning. Practical applications of the current results are that it is important to focus on anterior-posterior displacement of the CoP of children at 6 years of age which can be facilitated by encouraging children to take a contralateral step. By 10 years of age participants are proficient in postural control variables of dominant overarm throwing. In terms of the basic science of motor control, the findings from chapter 3 suggest that there may be a requirement to master the dynamic stability of postural control before the learner is able to master the throwing action with the upper limbs.

7.3 Contribution of Knowledge

7.3.1 Framework for Single Joint Analysis

The analysis undertaken in this thesis provides a possible outline for coupling biomechanical investigation with motor control, theoretically underpinned by a dynamical system theory perspective of motor learning. Two multi-subject design experimental studies were used: a longitudinal 3 week period of non-dominant arm throwing in adults and a cross-sectional dominant arm throwing at different ages across childhood. These studies provided a rich data set to examine technique changes in line with constraints to action from a dynamical system theory approach (Newell, 1986). The longitudinal and cross-sectional multiple single-subject design elicited the necessary data to examine technique changes during the development of a fundamental skill during childhood and over practice in adulthood. Specifically, analysis was able to identify a key characteristic of technique change in overarm throwing action in adults and children. Using biomechanical analysis to describe and explain overarm throwing highlighted key technique changes that were assisted with a more advanced throwing action, namely weight transfer of the CoM. This was facilitated through increased ROM of the lower extremities shown with practice in the adults (chapter 3) and increased age in children (chapter 4), which in turn increased displacement of the CoM. Biomechanical analysis techniques were able to explain technique changes in overarm throwing action and why some individuals adopted one style of technique change while others did not.

In order to examine Bernstein's (1967) observation of freezing and freeing the redundant degrees of mechanical freedom, biomechanical analysis of ROM was used to provide information about changes in technique at individual units. This allowed explanation of the characteristics associated with technique change in throwing action in adults and children and to examine changes in technique adopted by different individuals. Identifying and describing biomechanical technique changes enabled the identification of constraints that were associated with a more advanced throwing action.

In chapter 3 the key biomechanical constraints to action for adults were ROM of the lower limb and the shoulder which experienced an increase in ROM with practice; this is consistent with a more advanced step action and greater ROM of the CoM in the anterior-posterior direction. From a biomechanical perspective, increased ROM of the lower extremities facilitated increased displacement of the CoM which provides evidence for increased weight transfer (Knudson & Morrison, 1996). The development of this fundamental aspect of throwing technique demonstrates freeing of the mechanical degrees of freedom at the lower limbs consistent with Bernstein's (1967) postulation. For the majority of participants, the same pattern of change did not occur for ROM of the elbow and wrist as they demonstrated a significant decrease with practice (Fig 3.2). In parallel, the majority of participants were categorised in advanced action of 'humerus' and 'forearm' from initiation of practice (Table 3.2). While no other research has reported ROM for non-dominant arm throwing, Southard (2006) reported instruction positively influenced segmental distal lag, specifically the hand relative to the forearm. When viewed in conjunction with the components model (Robertson & Halverson, 1984), the ROM results suggest that participants had the

ability to effectively use the elbow and wrist joint at the start of practice, and reducing ROM was a common strategy to adopt. This finding provides support for the proposition of Hong & Newell (2006) who postulated that freezing or freeing degrees of freedom is task specific rather than a universal rule for skill learning.

The key constraints to action in chapter 4 across childhood and adolescence were changes in ROM which did not occur in a linear direction as a function of age. Children at 14 years of age displayed the greatest ROM at the ankle joint. This suggests that by 14 years of age children have developed the ability to adapt the ROM at the ankle joint to match the continuously changing perturbations that the body experiences to help attenuate the forces more successfully. The results for the ROM at the knee joint showed that 10 year olds displayed the greatest ROM which was significantly higher than ankle ROM displayed at 6 years of age, but not at 14 years of age. From this it may be proposed that the ankle, hip and elbow specifically, could distinguish between child throwers at these developmental ages and might be a key coaching point for the skill. However, the context to these increased ROMs are captured by the components outlined by Robertson & Halverson (1984). Pathways of technique change were associated with individual-specific pathways of change related to an individual's to ability to interact within their own biomechanical constraints.

7.3.2 Implications to Motor Learning Research

This thesis has provided novel and ecologically valid evidence towards technique changes theoretically underpinned by a dynamical system theory approach to motor learning. A key finding included the use of CoM and wrist motion as collective variables (chapter 3 and chapter 4). In turn this provides evidence for the overarching macroscopic properties of the CoM-wrist coupling to become more complex with practice in adults (chapter 3) and with increased chronological age in children (chapter 4). This was seen through a broader range of phase relations. The use of the collective variables CoM and wrist during overarm throwing action was able to provide information of the overall system dynamics. The collective variables CoM and wrist were chosen as an initial attempt to understand the constructs of learning in overarm throwing.

In order to explore this further a multivariate method was applied to understand coordination of the upper limb using Cluster Phase analysis (chapter 5). Cluster Phase analysis enabled an understanding of the kinematic arm chain as more than two variables were able to be run simultaneously. This allowed the synchrony between the shoulder, elbow and wrist joint to be examined. The presence of longitudinal data for adult participants and cross-sectional data at different developmental ages in chapter 5 provided a backdrop to explore Cluster Phase. The comparison of different populations (adults and children) enabled a greater understanding of Cluster Phase as a method to analyse technique changes in overarm throwing action. The use of Cluster Phase provides a novel contribution to knowledge through the application of analysis to upper limb joints during overarm throwing action. Moreover, it has contributed to

knowledge of the synchronization pattern of the shoulder, elbow and wrist joint over a period of non-dominant overarm throwing practice in adult learners. The findings highlight the individual-specific nature of technique changes in both adult and child participants. This thesis delivered evidence that understanding the system dynamics is facilitated by an understanding of the biomechanical dynamics. The full body approach was imperative, however, as evidence by CoM-wrist coupling and identification of the step action being more associated with technique change than arm movements alone. This finding moves beyond the majority of throwing literature that has focussed on the movement of the upper limb segments only.

7.3.3 Implications for Complex Skill Development

Overarm throwing action has been examined over a period of practice with adult learners and across childhood and adolescence. The findings of this thesis have highlighted key indicators for technique change during overarm throwing action which could subsequently be used as key coaching points and to help fast track learning. Chapters 3 to 6 have identified key motor learning and biomechanical constraints to action during overarm throwing action.

Findings have shown that good dynamic stability is critical for facilitating the development of overarm throwing action. A specific coaching point would be for children to initially adopt a wide base of support with their feet parallel to the target during the overarm throw. Next children could practice transferring weight from their heel to their toe by gently rocking back and forward with their feet still parallel. Building upon this a small step should be taken and over time this will develop into a

contralateral step which would help facilitate greater ROM of the lower extremities and CoM displacement.

Moreover, the findings of this thesis have provided evidence that moves beyond the action levels of the components model (Robertson & Halverson, 1984). Specifically, to show that the use of a collective variable was able to capture robust overarching changes at the dynamic level of the system. In contrast, the findings of this thesis were captured within the action levels identified by Robertson and Halverson (1984) components model. The participants moved through the components model (Robertson & Halverson, 1984) in individual-specific ways, limiting the general information that would be relevant when coaching. From a coaching view point, this highlights that postural control is a key factor associated with advanced throwing action and therefore should be a key coaching point.

Chapter 3 and chapter 4 provided novel experimental evidence of technique changes during overarm throwing and highlighted the importance of the lower extremities in what seems an upper extremity action. Specifically, this is the ability to take a contralateral step to facilitate greater ROM of the lower extremities and CoM movement. Practical applications of the current results are that it is initially important to focus on the positioning of the feet, movement of the knee and rotation of the hip. In terms of the basic science of motor control, the findings of this study suggest that there may be a requirement to master the dynamic stability of postural control before the learner is able to master the throwing action with the upper limbs.

Chapter 5 provided an in-depth analysis of the upper limb tri-joint synchrony. Findings demonstrated the individual specific nature of upper limb tri-joint synchrony due to individual constraints to action. Tri-joint synchrony of the upper limb increased with age with 14 year olds showing the greatest tri-joint synchrony during overarm throwing action. With the more skilled throwing action associated with greater upper limb joint synchrony, this finding is consistent with changes in upper limb synchrony in the adult population. Specifically, with practice upper limb tri-joint synchrony evolved in one of three ways: decreased tri-joint synchrony of the non-dominant arm after practice, increased upper limb tri-joint synchrony with practice or no change in synchrony with practice.

7.4 Methodological Approaches

7.4.1 Ecological Validity and the Skill used as a Vehicle

It is important that the application of dynamical system theory to motor learning is applied to ecologically valid research. This study has provided a novel understanding of technique changes during a fundamental complex whole-body movement skill. From a dynamical system theory perspective of motor learning, changes in technique occur through self-organisation of the system in light of the constraints to action (Newell, 1986).

Overarm throwing action is a fundamental movement skill that is taught from an early age as it provides the basis for many other movements involved in team sports. This movement requires coordination of the whole body providing an insight which enables

an understanding of how adults and children set about self-organising the dynamics system in light of the constraints to action (Newell, 1986) to produce a coordinated and controlled action. In addition, overarm throwing allows for a greater and lesser skill level to be examined within the same individual by studying dominant and non-dominant overarm throws of the same individuals (chapter 3 and chapter 5). Overarm throwing with the non-dominant arm action generally has less advanced movement organization than the dominant arm (Hore et al. 1996; Kernodle & Carlton, 1992; Southard, 2006). The biomechanics behind successful overarm throwing action is well understood within the literature (Bartlett, 2007; Grimshaw et al., 2007) providing a basis to theoretically explore skill acquisition from a dynamical system theory perspective. Therefore, the application of overarm throwing as the vehicle to explore technique changes in adults and children provided a useful action set to examine skill acquisition from a motor control view point. Previous research has tried to elicit changes in technique through altering the task constraints, such as altering the weight of the ball (Southard, 1998). Southard (1998) changed the task constraint of overarm throwing action by altering the mass and velocity of the upper limb segment during throwing action and found an increase in the velocity of segmental lag through trunk rotation in less skilled throwers. Alternatively, researchers have provided cues to help facilitate non-dominant overarm throwing action and improve overarm throwing technique (Southard, 2006; Kernodle & Carlton, 1992). Southard (2006) reported an increase in the number of upper limb segments experiencing positive segmental lag which refers to the transfer of energy from the heavier proximal segment to lighter distal segments. Meanwhile, Kernodle and Carlton (1992) showed evidence that the key cues to performance change related to the lag of the upper arm and elbow with respect to the shoulder as opposed to transitional cues. Interestingly, whilst segmental

lag provides a biomechanically relevant technique parameter, models of motor learning emphasise the whole body contribution to the skill. A drawback of using freeing of individual degrees of freedom to describe technique change is its inability to explore coordination; specifically, a significant change in ROM of three or more joints during one single session was observed.

In this particular study accuracy of the throw was not analysed, as this body of work focused on understanding technique change with practice as opposed to the outcome measure. The potential effect of an inaccurate throw on the interpretation of results relates to the potential masking of specific technique or focusing on technique that does not foster improved overarm throwing performance. While it is understood that even at the elite level individuals are unable to reproduce identical movement patterns (Davids et al., 2003) due to the role of functional variability within the kinematics (Newell & Corcos, 1993; Wilson et al., 2008; Ko et al., 2017). The technique used to execute overarm throwing action through the positioning and timing of joints will directly impact the three release parameter: release angle, release speed and release height. Technique variability within the coordination pattern can provide flexibility to the system so that the optimal movement strategies can be found. Whereas high variability of the outcome measure is an indicator of a reduction in task performance (Arutyunya et al. 1969; Morasso, 1981). The inclusion of inaccurate throws in analysis would inhibit the ability to state the relevant dynamics required to throw for distance and accuracy in order to intercept a target.

It would be of interest for future work to explore the technique differences between accurate and inaccurate throws to gain a deeper understanding of the defining

technique changes between accurate and inaccurate throws. Throwing for distance and/or accuracy is a key feature of many sporting activities while the biomechanics of the action are well understood. A greater understanding is required of the perception-action control mechanism that provide the information of the biomechanical outcomes (Urbini, 2012). In addition it is understood that the inclusion of an outcome measure would have provided additional relevant information to this thesis.

This work is the first to study overarm throwing from a dynamical system theory perspective, and based on the rationale above is a good vehicle for studying development in children and learning in adults.

7.4.2 The Measure of System Dynamics

In order to measure system dynamics, more than one variable needs to be analysed simultaneously which was achieved using vector coding (chapter 3 and chapter 4). Vector coding provides an insight into the overarching macroscopic change to the dynamics system. CoM and wrist were the two variables chosen as an initial attempt at using vector coding to explore changes in technique. It is not claimed that the CoM-wrist coupling is the collective variable for throwing, but rather as a first attempt to understand the problem by investigating the relationship between a candidate's postural collective variable (CoM) and a candidate's ball release property (wrist motion). The CoM was chosen as it provides information of the overall coordination of the system whilst the wrist was chosen as it is the end effector of the overarm throwing action. The use of the CoM and wrist provided an insight into technique changes during overarm throwing action in both adults and children. Founded on

Newell's (1985) stages of learning model, the collective dynamic did change; however, variability of this collective dynamic was not clearly directional. Overall, a higher order variable was better able to identify commonalities in technique change across individuals than single joint motions, and therefore, might be key to understanding the dynamics of technique change across different tasks and organismic constraints from a dynamical systems theory perspective.

A novel multivariate method was used in chapter 5 to further explore synchronization of the upper limb joint. Cluster Phase analysis enabled coordination between more than two variables to be analysed at the same time. The action of the shoulder, elbow and wrist joint could be analysed simultaneously providing a value of how synchronized these 3 joints were to the group and individually. The measure of synchronization was considered to provide an insight into the dynamical degrees of freedom with practice in adults and age-related change in children. This indicates if the joints were progressing forward to ball release as a single stiff unit or if differentiated action of the shoulder, elbow and wrist occurred with practice or increased age in children. Future research might consider using a broader number of variables to gain greater insight into synchronization of the upper and lower extremities or consider using Cluster Phase as a diagnostic tool for health care professionals or coaches which would allow individual specific feedback enabling more specific recommendations to improve techniques.

7.4.3 Biomechanical Analysis

Examining ROM provided information about how an individual's joint changed as a function of practice in adults (chapter 3) and increased age in children (chapter 4) highlighting the importance of lower extremities and freeing of the CoM in overarm throwing action. A drawback of using freeing of individual degrees of freedom to describe technique change is its inability to explore coordination. Though provokingly, since the timing and the combination of joints involved in change were individual specific, it was of interest to explore whether a measure of coordination could better capture the key characteristics of technique change in spite of individual differences. In this view, the CoM and wrist coupling were examined which moved away from purely biomechanical analysis. At the whole body level, all participants showed transition in technique that was captured in multiple single joints. Specifically, a significant change in ROM of three or more joints during one single session was observed. A drawback of exploring changes in individual degrees of freedom during learning is the inability to explore the coordinated nature of joint actions.

Chapter 3 and chapter 4 both used full body three dimensional kinematic analysis to explore the macroscopic level of the system by examining phase relation of the CoM and wrist during the propulsive phase of the throw. The use of CoM-wrist showed robust change across age and practice in chapter 3 and chapter 4. However, collecting full body three-dimensional data is not an easily portable system and is time consuming for the participants. The full body approach was imperative, however, as evidenced by CoM-wrist coupling and identification of the step action was more associated with technique change than arm movements alone. This finding moves

beyond the majority of throwing literature that has focussed on the movement of the upper limb segments only.

Since the CoM and CoP are inherently linked, the CoP had the potential to provide a more practically relevant and time efficient method of data collection than CoM while still capturing relevant change in the global dynamics of the system. Chapter 6 builds upon this previous work by examining changes in the CoP motion during the development of overarm throwing action across childhood. Findings showed that children at 6 years of age displayed lower values of anterior-posterior displacement and total path length compared to 10 and 14 year olds which had similar values.

Using the CoP as a measure of change enabled a practically relevant variable to capture age-related change at the dynamic level of the system. The use of force plates to measure postural control provided a time efficient method that could allow researchers, health professionals and sports practitioners with immediate feedback. However, CoP variables are not easily translated into key coaching points that will be meaningful to the participants unlike action levels which are more insightful as seen in the components model (Table 2.1).

7.5 Chapter Conclusion

The aim of this thesis was to increase the understanding of the key processes of motor learning during learning a complex movement skill. The methods, data collection and conclusion were underpinned by motor learning models and theory along with biomechanics. Specifically, the methods were informed by a dynamical system theory

(Newell, 1986) used beside two novel analysis methods of vector coding and Cluster Phase which aimed to build a deeper understanding of technique changes. These were observed through qualitative and quantitative methods and were used to further understand how technique changes occur in adults and children.

Qualitative and quantitative kinematic analysis was used to describe technique changes in adults and children at the mechanical and dynamical level of the system. Kinetic analysis was conducted to understand a practical proxy for kinematic technique changes in children. Analysis of the mechanical degrees of freedom provided support for the proposition of Hong & Newell (2006) that freezing or freeing degrees of freedom is task specific, rather than a universal directional rule for skill learning, and furthers the proposition by suggesting that different limb segments (arms or legs) may follow different patterns of change.

In order to explore the dynamical degrees of freedom a collective variable was used to examine the overarching macroscopic change of the dynamic system (chapter 3 and chapter 4). Building upon this, Cluster Phase was used to measure the synchrony of the upper limb to provide an insight into the individual specific nature of technique change (chapter 5). The use of a multifaceted framework to explore technique changes in this research has delivered experimental evidence for the complementary nature of existing approaches of motor learning to facilitating skill acquisition. It might be however, that collective macroscopic variables are better able to capture common changes in technique across individuals compared to single joint measures that appear to change in an individual specific manner.

This research has increased the empirical understanding of technique changes of overarm throwing action from a dynamical system theory perspective in practice-related changes in adults and age-related changes across childhood during skill development. It has been possible to highlight key areas of research design, current and novel analysis and interpretation that allow motor control and biomechanical analysis to add to the existing theoretical and practical understanding of skill acquisition of a fundamental movement from a dynamical system theory perspective.

The studies undertaken have provided ecologically valid support for the notion that Bernstein's (1976) hypothesis of freezing the mechanical degrees of freedom before freeing the redundant degrees of freedom is task and limb specific rather than a directional rule for technique change (Hone & Newell, 2006). Furthermore, the biomechanical reason behind this is associated with individual constraints to action of the task, organism and environment (Newell, 1986) with Newell's (1985) stages of learning model highlighting reduced variability as a key indicator of skill learning. This idea was in line with the findings of the research undertaken in this thesis. From this perspective, it was concluded that Newell's (1985) stages of learning provides a valuable framework in which to investigate technique changes during learning.

Variability has been a running theme in this research. A surprising finding was the change/difference in variability when different analyses were applied to the data. Specifically, chapter 3 used the collective variable CoM-wrist coupling to explore the overarching macroscopic properties of the system and the global movement pattern arising from the interaction of muscles, joints and segments during action (Haken, 1983; Kelso, 1995). Variability of the CoM-wrist coupling increased over a period of

non-dominant overarm throwing practice (Table 3.2) which is in contrast to children of different ages who demonstrated a decrease in CoM-wrist coupling variability with age. This is in line with chapter 5 which used Cluster Phase to determine synchrony of the upper limb joint during overarm throwing action. Upper limb variability decreased over a period of non-dominant overarm throwing practice for 8 of the 10 participants (Fig 5.5b) and with an increase in age of children throwing with the dominant arm, which is in line with Newell's (1985) stage of learning model. The variability measured in chapter 3 was associated with coupling of a postural variable and end effector in overarm throwing action. Meanwhile chapter 5 did not include a postural variable, but explored coordination of the shoulder, elbow and wrist joint. This work therefore suggests that variability in coordination reduces with age in children, independent of the level of the system being explored. However for adults learning to throw with the non-dominant hand, it can still increase at the collective dynamic level.

Knowledge of the key technique changes associated with a more skilful overarm throw was enhanced. The ability to identify technique changes at different levels of the system enabled a deeper understanding of these changes and the complementary nature of analysis methods from a biomechanical and motor control perspective. Individual constraints acted to influence the participant in their movement strategy which lead to different time scales of change. Future work is required to underpin a general model of motor learning, but this body of work suggests that macroscopic collective variables might be key in this endeavour.

Informed by current literature, the overall aim of this thesis to increase understanding of the key processes of motor control and biomechanical variables during learning a complex movement skill has been achieved. Moreover, the work conducted provided a contribution to knowledge through novel exploratory analysis techniques to examine motor control from a dynamical system theory perspective helping achieve the purpose of this research.

The use of the CoM-wrist coupling as a collective variable for overarm throwing action was able to identify an overarching macroscopic change in overarm throwing action as a function of practice in adults (chapter 3) and age-related changes in children (chapter 4). This was enhanced by the use of a collective variables that were able to give a bird's eye view which was not limited by individual constraints. The combination of a postural control variable (CoM) and end effector (wrist) provided a novel application of a collective variable to explore dynamic changes in the system which seemed to change in a robust manner with practice and age.

The application of Cluster Phase to the analysis of joint synchronisation provided a different method to explore the coordination between multiple degrees of freedoms at the same time. From a dynamical system theory perspective, Cluster Phase allowed the use of a really interesting multivariate method to study coordination of the throwing arm with three joints that make up the segment (shoulder, elbow and wrist). Findings provided support for the idea that patterns of synchronization are dependent upon individual constraints to action. A key characteristic of learning overarm throwing in both adult and child learners was a decrease in variability of the throwing arm synchrony. However, the change in the movement dynamics of adults learning to

throw with the non-dominant arm showed greater individual variation to those of children learning to throw with the dominant arm in the direction of the progressive change of the tri-joint synchrony.

Exploring CoP movement as a proxy for learning in the overarm throw delivered information of changes in postural control across childhood. Analysis of postural control during dominant overarm throwing action at 6, 10 and 14 years of age showed that 6 year old age group displayed significantly smaller anterior-posterior displacement of the CoP (Fig 6.1) and total path length (Fig 6.7) of the CoP compared to children at 10 and 14 years. Small anterior-posterior displacement suggested that this element of postural control is established by 10 years of age during dynamic movements such as throwing. Combining these findings, and in line with chapter 4, children at 10 and 14 years of age displayed a more advanced step action (Table 4.2) and greater ROM of the lower extremities (Fig 4.3) than children at 6 years of age. In terms of the biomechanics of throwing, increased CoP displacement and path length in older children indicates better weight transfer which is a fundamental aspect of the overarm throwing action. It could be that the CoP is a practical proxy for this kinematic characteristic of technique.

7.6 Future Investigations

Advancement in overarm throwing action was demonstrated by increased ROM of the lower extremities and increased anterior-posterior displacement of the CoM. Interestingly, the upper extremities tended to be constrained in individuals who displayed a more advanced overarm throwing technique. Furthermore, the application

of a multi-faceted approach to the study of technique changes provides a complementary overview of mechanical, dynamical and macroscopic information related to each participant. Thus, this information could form the foundation for providing individual specific information of technique changes with the aim of enhancing the effectiveness of practice in a school or health care environment, although this would need to be supported by future work.

A single model from a dynamical system theory perspective is yet to be established by motor learning researchers. Two stages of learning models are proposed from a dynamical system theory perspective in existing literature: Newell's (1985) stages of learning coordination, control and skill and Bernstein's (1967) observation of freezing and freeing the redundant mechanical degrees of freedom. Overall, the use of a macroscopic variable linking CoM motion to that of the effector wrist was more effectively able to identify changes in technique in adults (practice-related) and in children (age-related) whilst capturing the impact of posture-ball release dynamics. The process of freezing and freeing the redundant degrees of mechanical freedom during learning has been suggested to be task specific and dependent on the level of analysis during learning (Newell & Vaillancourt, 2001; Hong & Newell, 2006).

This research has provided support for the notion of freezing and freeing to be task specific rather than a universal directional rule for technique change (Hong & Newell, 2006). Therefore, based on the work of this thesis, future work needs to add to the body of evidence for how freeing and freezing occurs in limb motion for a wide range of different skills. This will allow determination of what and if there are fundamental patterns of change associated with specific task constraints. Furthermore, or ideally in

addition to, future work needs to explore the macroscopic collective variables and how they evolve during learning for different skills in order to ascertain whether this level of the system is robustly associated with stages of learning, as was found here. This work will drive an epistemological shift in the variables used to underpin motor learning studies. Specifically, macroscopic collective variables could be more fruitful than current methods embedded in single joint biomechanics and bivariate coordination studies.

This thesis made two attempts at using a collective variable to explore macroscopic organisation of the system: CoM-wrist coupling in chapter 3 and chapter 4 and Cluster Phase analysis of the upper limb in chapter 5. While the application of CoM-wrist showed robust changes with practice in adults and cross-sectional changes in childhood Cluster Phase analysis did not. This thesis does not claim CoM and wrist to be the only collective variables for overarm throwing, but instead was an initial attempt to examine the relationship between candidate postural and ball release property variables. Therefore, future research could explore different variables to gain understanding of the macroscopic change to the system organisation.

In order to explore coordination of the system further, Cluster Phase analysis was conducted to try and establish the synchrony of the shoulder, elbow and wrist joint. Findings from chapter 5 added to the idea of individual-specific changes in technique over non-dominant overarm throwing practice in adults and at different developmental levels in children. Due to the infancy of this method within biomechanics and motor control, future research could look to expand upon the current study to include a larger sample and the ability of the method to explain synchronization in other movements.

Chapter 6 provided an insight into the characteristics of CoP during a dynamic fundamental movement skill at 6, 10 and 14 years of age. This built upon the work presented in chapters 3 to 5 to provide a comprehensive view of technique changes during a fundamental whole-body movement. These findings suggest that the majority of postural control variables with the exception of maximum anterior-posterior displacement and path length of the CoP remain unchanged between 6, 10 and 14 years of age. These findings are associated with the position of the feet. Children at 6 years of age should be encouraged to take a contralateral step. By 10 years of age participants were proficient in postural control variables of dominant overarm throwing. In order to test this theory, future work should concentrate on an intervention study where movement is examined based on the three complementary approaches presented here to explore which one facilitates more effective and efficient improvement in technique and performance.

Overall, the philosophy and framework of this research can be applied to other ecologically valid movement skills in order to develop theoretically grounded evidence for a multi-disciplinary approach to technique changes, which might allow a move closer to a generalised model of motor learning.

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APPENDICES

Appendix A

QUALITATIVE AND QUANTITATIVE CHANGE IN THE KINEMATICS OF LEARNING A NON-DOMINANT OVERARM THROW

Qualitative and Quantitative Change in the Kinematics of Learning a Non-Dominant Overarm Throw

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05/07/18

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Abstract

This study investigates changes in non-dominant arm throw technique over a 3-week period of practice with respect to three complementary approaches to motor skill acquisition. Ten participants (mean \pm SD age 22 \pm 2yrs, stature 1.71 \pm 0.60m, mass 73 \pm 14kg) practiced for nine sessions, during which kinematic data were collected. In line with Newell's (1985) learning stages of coordination, control and skill, coupling between the Centre of Mass (CoM) and wrist movement were explored. During initial practice, coupling began in-phase moving to wrist-led coupling. With further practice a more complex backwards wrist-led coupling that progressed to forward wrist-led coupling was observed. The components model of overarm throwing (Robertson & Halverson, 1984) and Bernstein's (1967) hypothesis of freezing and freeing redundant mechanical degrees of freedom were used to understand technique changes underpinning changes in the collective dynamic. Participants began in mid to high action levels for the torso/arm components, while the step component progressed to higher action levels with practice. A significant increase in joint angle range of motion (ROM) at the lower limb joints and shoulder and a significant decrease in elbow and wrist ROM coincided with the time course of changes in the components model. Key aspects of technique change were taking a contralateral step which was associated with greater ROM of the lower extremities and CoM, and underpinned a more complex CoM-wrist coupling. In identifying stages of learning, commonalities in changes in the collective dynamic were supported by individual strategies at the joint space level.

Word count: 241

Keywords: motor control, motor learning, biomechanics, throwing

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Knowledge of the characteristics of technique change during motor learning can provide insight into how the demands of a task influence the process of motor skill acquisition. In this study, non-dominant overarm throwing action was the motor skill used to explore technique changes during learning. The overarm throw is a fundamental discrete motor skill (Knudson, 2007) that requires the formation of qualitative kinematic properties in the organization of the limb segments that constrain the quantitative change in movement technique and task outcome (Kernodle & Carlton, 1992; Robertson & Halverson, 1984; Southard, 2006).

Overarm throwing is a skill for which the non-dominant arm action generally has less advanced movement organization than the dominant arm (Kernodle & Carlton, 1992; Southard, 2006). Two studies have investigated the effect of instruction and feedback on the development of non-dominant overarm throwing in adults (Kernodle & Carlton, 1992; Southard, 2006). Southard (2006) reported an increase in the arm and trunk segments experiencing positive segmental lag, while Kernodle and Carlton (1992) showed that the key cues to technique change related to the lag of the upper arm and elbow with respect to the shoulder. Interestingly, whilst segmental lag provides a biomechanically relevant technique parameter, it is not emphasised in the stages of learning models proposed in motor control literature.

Three complementary approaches for quantifying technique changes in human movement were used in the study; Newell's (1985) learning stages of coordination, control and skill and Bernstein's (1967) hypothesis of freezing and freeing the redundant mechanical degrees of freedom are generalised models for the development of motor skills, underpinned by a dynamical systems theory perspective. The component model of overarm throwing (Robertson & Halverson, 1984) is a model

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developed specifically for throwing actions. Firstly, Newell (1985) provided a functional distinction between the constructs coordination, control and skill. In Newell's (1985) framework variables that describe technique and directions of change were purposefully not defined, since it was hypothesised that both were task specific. More recent work has used collective variables to assess the constructs of the learning stages (Ko, Challis & Newell, 2014; Wang, Ko, Challis & Newell, 2014; Dutt-Mazumder, Challis & Newell, 2016; Dutt-Mazumder & Newell, 2017). The assumption is that the collective variable provides the fundamental organization of the system's macroscopic coordination patterns (Ko et al. 2014). A collective variable or order parameter is defined as a high order, low dimension space variable that is representative of multiple joints at the muscular-articular level (Haken, 1983; Mitra, Amazeen & Turvey, 1998). It has been shown in learning projectile tasks that the collective movements of the body (indexed by CoM) and the end effector during throwing (wrist motion) become more strongly coupled (Verhoeven & Newell, 2016).

Bernstein's (1967) hypothesis of freezing and freeing the redundant mechanical degrees of freedom captures properties of qualitative and quantitative technique changes. In this view Bernstein (1967) defined coordination as the process of mastering redundant mechanical degrees of freedom (DF), suggesting that movement is coordinated through a three-stage embedded approach of freezing and freeing the joint space DFs, and finally exploiting the reactive forces. Changes in joint angle range of motion (ROM) (Newell, Kugler, Van Emmerik & McDonald, 1989; Vereijken, Whiting & Beek, 1992; Chow, Davids, Button & Rein, 2008) and coordination variables (Ko, Challis, & Newell, 2003; Verhoeven & Newell, 2016) during novel tasks have been investigated in line with the notion of freezing before freeing during motor

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learning. The postulation of Bernstein (1967) has since been proposed to be task specific and dependent on the level of analysis during learning (Hong & Newell, 2006; Newell & Vaillancourt, 2001). This paper investigates changes in the ROM of the mechanical degrees of freedom with practice in learning the overarm throw.

Lastly, the components model of overarm throwing (Robertson & Halverson, 1984) tracks qualitative technique changes through relative changes in four segmental components: ‘step’, ‘trunk’, ‘humerus’ and ‘forearm’. The components model has been examined extensively in children learning to throw (Robertson & Halverson, 1984; Robertson & Konczak, 2001; Langendorfer & Robertson, 2002; Stodden, Langendorfer, Fleisig & Andrews, 2006*a,b*) and older adults ranging in age from 61 – 82 years (Williams, Haywood & VanSant, 1998). The model was the product of years of longitudinal study in children up to 13-years of age but has yet to be applied to technique changes for young adults or for non-dominant arm throws. It is important to have an understanding of the mechanics of qualitative developmental changes in the fundamental skills to establish if young adult technique changes in line with that of children and older adults.

This paper examines the pathways of change in the movement organization that provide structure to the formation of a new task relevant movement coordination mode for the overarm throw with the non-dominant arm. The aim of this research was to investigate the evolution of changes in technique of the non-dominant overarm throw over practice with respect to three complementary approaches to qualitative and quantitative change of movement dynamics: Newell’s (1985) stages of coordination, control and skill, Bernstein’s (1967) hypothesis of freezing and freeing redundant mechanical degrees of freedom, and the components model of overarm throwing

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(Robertson & Halverson, 1984). We expect that collective dynamics capture common changes in technique during learning. It was expected that quantitative changes in joint rotations and Centre of Mass (CoM) movements are embedded in sequential qualitative changes in ‘trunk’/arm relative motion during learning to throw with the non-dominant. The approach focuses on the qualitative and quantitative kinematic changes at the individual participant level as a function of practice to reveal the individual pathways of change that are likely to be evident when not masked by averaging procedures.

Method

Participants

Written ethical approval was gained from the host University’s Ethics Committee (Faculty Research Ethics Panel, Anglia Ruskin University) prior to study initiation. Ten participants (PT) (4 female, 6 males; age 22 ± 2 yrs, stature 1.71 ± 0.60 m, and mass 73 ± 14 kg), all of whom had no specific experiences with non-dominant arm throwing, gave written voluntary informed consent and successfully completed a health questionnaire. Inclusion criteria were as follows: participants were not participating in a throwing-based activity, had a dominant hand (as determined by Oldfield (1971) Edinburgh handedness inventory), and were free from musculoskeletal injury.

Procedures

The longitudinal practice took place three times per week (Monday, Wednesday and Friday) for 3 consecutive weeks. The same procedures were conducted for each session. Between testing sessions participants were instructed not to practice throwing with either their dominant or non-dominant arm. Baseline data were collected for each

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participant during 10 overarm throwing movements, with their dominant arm and non-dominant arm. A standard issue tennis ball (Slazenger) was used. Participants were given the ongoing aim of hitting a 0.4m target located 14m in front of them. Target height was adjusted to each participant's eye level. Knowledge of results from the target and verbal encouragement were provided, phrases included: "nice", "well done" and "good job". The target placement necessitated a forceful and accurate throw from the participant and was best realized with a near horizontal trajectory of the ball to the target.

Data collection

Kinematic data (200 Hz) were collected using 3D motion capture system (CODAmotion, Charnwood Dynamics Ltd, UK). Three CX1 scanners provided a 360° field of view around the participant. Centre of rotation for each joint was estimated and active markers were located on the right and left lateral side of: 3rd metacarpal, ulnar styloid process, lateral epicondyle of the elbow, shoulder joint at the centre of rotation, xiphoid process, greater trochanter, thigh, femoral condyle, tibia, lateral malleolus, calcaneus and 2nd metatarsal. The same researcher marked up each participant each week. Data were collected for every trial performed by the participant. The throwing trials were recorded using a two-dimensional camera (Fastcam high speed video camera, Ultima 512 Photron, Model 32K) placed perpendicular to the sagittal plane of the participant.

Raw marker data in the horizontal and vertical direction were identified from the three-dimensional CODA output. A Butterworth low-pass fourth-order filter was applied to the kinematic data at a cut-off frequency of 6 Hz (Winter, 2005). Data were

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analysed during the propulsive phase of the throw, defined from the instance that a marker started moving in the direction of the throw until the instance of ball release.

Variables

Newell's (1985) learning stages of coordination, control and skill: Vector coding (VC) was performed on the displacement of the CoM and wrist in the anterior posterior direction (Sparrow, Donovan, Van Emmerik & Barry, 1987). Based on Chang, van Emmerik and Hamill (2008) four key coordination patterns can be defined for vector coding: (1) anti-phase coupling ($112.5\text{--}157.5^\circ$ or $292.5\text{--}337.5^\circ$), variables are moving in opposite direction; (2) in-phase coupling ($22.5\text{--}67.5^\circ$ and $202.5\text{--}247.5^\circ$) variables are moving in the same direction; (3) wrist-led phase coupling ($0\text{--}22.5^\circ$ $157.5\text{--}202.5^\circ$ or $337.5\text{--}360^\circ$), wrist is a more predominant variable; and (4) CoM-led phase coupling ($67.5\text{--}112.5^\circ$ $247.5\text{--}292.5^\circ$), CoM is the more predominant variable. Average standard deviation of the within-session VC profiles was used to determine variability of the movement coordination pattern as a function of practice.

Components Model (Robertson and Halverson, 1984): 'step' 'trunk', 'humerus' and 'forearm' were classified by the principal investigator and were verified by another author for all trials for all participants in line with the components model (Robertson & Halverson, 1984).

Bernstein (1967) joint range of motion: Ankle joint was defined from the 2nd metatarsal, lateral malleolus and calcaneus. The knee joint was defined from lateral malleolus, femoral condyle and greater trochanter. The hip joint was defined from femoral condyle, greater trochanter and xiphoid process. Shoulder joint was defined from lateral epicondyle of the elbow, shoulder joint at the centre of rotation and xiphoid

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process. Elbow joint was defined from shoulder joint at the centre of rotation, lateral epicondyle of the elbow ulnar and styloid process. The wrist joint was defined from the 3rd metacarpal, ulnar and styloid process and lateral epicondyle of the elbow.

Angles were defined in 3D where an angle of 180° would represent maximum extension, while 0° would represent minimal flexion. ROM of CoM in the anterior-posterior direction was also calculated, where CoM was defined as the average mass of each segment midpoint of all the segments. To estimate the position of total body CoM with 3D trajectories of the 16 active markers, CoM of individual segments were calculated based on the anthropometric data provided by Dempster (1955). Then the total body CoM position was derived from the combined individual CoM to provide weighted summation of individual segment CoM positions (Ko et al. 2014; Winter 1995).

Statistical analysis

IBM 24 Statistical Package for the Social Sciences (SPSS Inc.) was used to determine statistically significant differences between discrete variables: joint ROM of the ankle, knee, hip, shoulder, elbow and wrist, CoM and the coupling variability of CoM-wrist across testing sessions using repeated measures analysis of variance (ANOVA), based on a single subject design ($p < 0.05$). Bonferroni post hoc correction was used for multiple comparison test. Mauchly's test was used to determine the sphericity assumption within the data; where sphericity was violated, probability was corrected according to the Greenhouse-Geisser procedure.

Results

Newell's (1985) learning stages of coordination, control and skill

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Fig 1. CoM-wrist coupling for single trial per session for PT06 (representative of PT03, PT04, PT05, PT08, PT09 and PT10) and PT07 (representative of PT01 and PT02).

Two key profiles of this vector-coding angle were identified with practice. The first profile started the propulsive phase with in-phase coupling ($22.5\text{--}67.5^\circ$) and progressed to wrist-led coupling ($0\text{--}22.5^\circ$) at ball release (Fig 1) where the wrist is moving forward and the CoM is nearing stationary (zero degrees). At the start of practice, all participants demonstrated this coupling relation. The second profile started with wrist-led coupling ($157.5\text{--}202.5^\circ$) where the wrist moved backwards and progressed through the following couplings; anti-phase coupling ($112.5\text{--}157.5^\circ$) where the CoM is progressing forward as the wrist moves backwards, CoM-led coupling ($67.5\text{--}112.5^\circ$) followed and is associated with the forwards movement of the CoM. Past 60% of the propulsive phase, coupling angle passes through in-phase characterised by forward progression of CoM-wrist towards wrist-led phase coupling at ball release (Fig 1). With practice, 7 of the 10 (PT03, PT04, PT05, PT06, PT08, PT09 and PT10) participants demonstrated the second profile. The remaining 3 of 10 participants (PT01, PT02 and PT07) continued to display in-phase coupling followed by wrist-led phase coupling at ball release for the duration of practice (Fig 1). Changes in CoM-wrist coupling (Fig 1) occurred at the same session as components model (Robertson & Halverson, 1984) (PT01 and PT03) and ROM (PT01, PT03, PT06 and PT10).

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By the end of practice non-dominant arm throws were more closely representative of dominant arm throws for the majority of the participants. Seven of 10 participants (PT03, PT04, PT05, PT06, PT08, PT09 and PT10) were characterised by wrist-led coupling moving towards zero at ball release. Three of 10 participants (PT01, PT02 and PT07) dominant arm throws were characterised by in-phase coupling progressing to wrist-led phase at ball release.

Table 2. Coupling variability with practice for CoM-wrist.

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With practice, 7 of 10 participants (PT01, PT03, PT04, PT05, PT06, PT08, and PT09) significantly increased ($p < 0.05$) CoM-wrist coordination variability (Table 2). Three of 10 participants (PT02, PT07, and PT10) significantly decreased ($p < 0.05$) coordination variability with practice. Seven of 10 participants (PT02, PT03, PT05, PT06, PT07, PT08, and PT09) more closely resembled dominant arm baseline trials with practice (Table 2).

Components model (Robertson & Halverson, 1984)

----- insert Table 1 around here -----

Table 1. Developmental action level with practice.

No participants were categorised as action level 1 or over practice regressed down the skill action levels. Most participants progressed up an action level, participants PT01 and PT10 did not progress or retreat with practice. Specifically, from Session 6 onwards, 7 of the 10 participants were categorised as action level 3 for the

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‘step’ and 3 of 10 participants at level 4 for ‘step’. For the ‘trunk’ 2 of 10 participants were categorised as action level 2 and 8 of 10 participants were categorised as action level 3. For ‘humerus’ and ‘forearm’ 3 of 10 participants were categorised as action level 2 and 7 of 10 participants were categorised as action level 3. Key changes occurred at Session 2 (PT05), Session 4 (PT02, PT04, PT07), and Session 6 (PT03, PT06). Dominant arm throw configurations were characterised in higher levels (Table 1).

Bernstein (1967) joint range of motion

----- insert Figure 2 around here -----

Fig 2. Representation of group changes in range of motion of the joints and centre of mass over 3-weeks of practice.

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Fig 3. Group ROM development at the right ankle, knee, hip, left shoulder, elbow and wrist joint as a function of practice. There was a significant increase in ROM of the lower limb joints and shoulder with practice (9 of 10 participants at the ankle and 8 of 10 participants at the knee, hip and shoulder) ($p < 0.05$). Six of 10 participants significantly decreased ROM at the elbow and 7 of 10 participants at the wrist ($p < 0.05$). Eight of 10 participants significantly increased ROM of the CoM in the anterior-posterior direction ($p < 0.05$) (Fig 2).

Changes in ‘step’ (PT02, PT04, PT05, PT06), ‘trunk’ (PT03, PT05, PT07, PT08, PT09), ‘humerus’ (PT03, PT04, PT07, PT08, PT09) and ‘forearm’ action (PT03, PT04, PT05, PT07, PT08, PT09) (Table 1) occurred at the same session as ROM for all participants that changed action level. Six of 10 participants did not change ‘step’ action from level 3 but did significantly increase lower limb ROM (Fig 3).

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Discussion

The aim of this research was to investigate the evolution of changes in technique of the non-dominant overarm throw over practice with respect to three complementary approaches to qualitative and quantitative change of movement dynamics: Newell's (1985) stages of coordination, control and skill, the components model of overarm throwing (Robertson & Halverson, 1984), and Bernstein's (1967) hypothesis of freezing and freeing redundant mechanical degrees of freedom. A common single pathway of change in technique with practice was not present across participants. However, for individuals, the findings from the three measurement approaches did complement each other in revealing aspects of the skill progression. There were periods across the multiple practice sessions (4, 5, and 6) where each approach revealed distinct changes in the technique of the participants. Additionally, participants fell into certain subgroups in relation to particular characteristics of technique change, not an uncommon finding in the learning of whole-body motor skills (Williams, Irwin, Kerwin, & Newell, 2015; Teulier & Delignières, 2007; Haibach, Daniels & Newell, 2004); that are likely due to differences in individual constraints and intrinsic dynamics.

Newell's (1985) learning stages of coordination, control and skill

Dynamical systems approaches to motor skill acquisition seek a macroscopic variable(s) that captures the essential properties of the structure and integrity of the movement pattern in action (Kelso, 1995; Mitra et al., 2002). The CoM represents a higher order, low dimensional global space variable that results from the muscle joint actions at the muscular-articular level (Haken, 1983). In this view, the relation between the movement of the CoM and the wrist as the end effector provides information of the

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macroscopic organization of the system in this throwing task and the link between postural support and instrumental limb action (Verhoeven & Newell, 2016).

Two key coupling relations were observed. At the beginning of practice, all participants demonstrated in-phase coupling at the start of the propulsive phase of the throw, where the CoM and wrist both travelled forwards together, towards zero at ball release (Fig 1). With practice, 7 of the 10 participants began to incorporate differentiated movement of the CoM and wrist, where coupling began at 180° before progressing to 0° at release. The strategy is representative of initial wrist-led coupling where backwards movement of wrist is the predominant influencer on the kinematic chain. Coupling progressed through anti-phase (forward movement of the CoM and backwards movement of the wrist) and CoM-led coupling (forward movement of the CoM) before in-phase coupling and forward wrist-led coupling at ball release (Fig 1).

This later strategy is in-line with dominant arm throws (Verhoeven & Newell, 2016; Ko, Han & Newell, 2018) and provides evidence for the freeing of dynamical degree of freedom (Newell & Vaillancourt, 2001). Specifically, the macroscopic organisation of the system has become more complex, utilising a broader range of phase relations associated with the arm kinematic chain. While this macroscopic variable does not describe the nuances of an individual's technique, it was able to capture a transition in system organisation despite individual differences in organismic constraints that effect joint space organisation.

In terms of Newell's (1985) learning stages, 3 of the 10 participants significantly decreased coupling variability with practice, suggesting they had reached the control stage of learning (Newell, 1985), while the remaining 7 participants significantly increased coordination variability with practice suggesting they remained in the

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coordination stage (Table 2). With practice the coupling variability of 7 of the 10 participants became more similar to that of the dominant arm throws, through either an increase or decrease in coupling variability. A paradox is then set since we can assume variability across dominant arm throws is facilitating functional changes and exploiting redundancy, whereas the variability in the non-dominant arm was used for exploring new coupling strategies in the process of learning (Wilson, Simpson, Richard, Van Emmerick & Hamill 2008; Verhoeven & Newell 2016).

To understand the kinematics underpinning the collective dynamic, technique changes were examined using the components model (Robertson & Halverson, 1984) and Bernstein's (1967) observations of freezing and freeing the redundant mechanical degrees of freedom. Both these approaches provide a distinct description of the movement pattern, and the findings provide support for changes demonstrated in CoM-wrist coupling following practice.

Components Model (Robertson and Halverson, 1984)

To our knowledge this is the first paper to apply Robertson and Halverson (1984) components model to non-dominant arm throwing in adults. As a foundation, the participants did not start practice with a throwing technique at action level 1. This is consistent with the expectations of motor learning and transfer (Adams, 1987), where a previously learnt skill positively influences the learning of a new skill or a skill performed with the other side of the body. For example, this finding is in line with those of Aune, Aune, Ingvaldsen, and Vereijken (2017) who reported motor learning transfer from the dominant arm to the non-dominant arm during a computer simulated tracking task. More generally, our findings are consistent with the pattern of findings on cross-

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education of upper limb performance (Hore, Watts, Tweed, & Miller, 1996; Sainburg & Kalakanis, 2000).

The findings showed that an advanced action level in one component did not combine with lesser action levels in another component, arguably because the advancement of one component drives forward the development of another component (Langendorfer & Robertson, 2002). For example, taking a contralateral step places the body in a position that progresses trunk and arm components (Stodden et al. 2006a). Indeed, by the end of practice (Table 1) the throwing movement patterns were similar to those reported by Stodden et al. (2006a,b) who used a cross sectional design to explore developmental changes in dominant arm throwing in children. Stodden et al.'s (2006a,b) participants were more advanced than those studied in Halverson et al. (1982) and William et al. (1998), who examined longitudinal developmental changes in children and older adults, respectively. Our results show that participants started non-dominant arm practice with an intermediate developmental profile particularly for the 'humerus' and 'forearm' (Table 1).

At the end of practice, 7 of the 10 participants had not reached the highest 'step' action level, suggesting the skill was not fully developed. The highest action level for dominant arm throws was categorised by 6 of 10 participants for the 'step', 9 of 10 participants for the 'trunk' and 'humerus', and 8 of 10 participants for the 'forearm' (Table 1). The advanced developmental profiles for the dominant arm suggest that non-dominant arm throws can be directly compared to those of adults performing the overarm throwing skill. Moreover, we would expect that if there was a longer period of non-dominant arm practice participants would have continued to advance up the action levels of components. As discussed later, these changes did, however, underpin

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the key change in CoM-wrist coupling described above but suggest that further organisation changes at the level of components are still occurring at session 9.

Bernstein (1967) joint range of motion

In line with freeing mechanical degrees of freedom, seven of the 10 participants produced an increase in lower limb and shoulder joint ROM with practice (Fig 3). Specifically, a significant increase in ROM at the lower extremities and CoM occurred along with the more advanced ‘step’ action (Table 1; Fig 2). Increased ROM of the lower extremities facilitated increased displacement of the CoM, which provides evidence for increased weight transfer in the act of throwing (Knudson & Morrison, 1996). The development of this fundamental aspect of throwing technique provides evidence for freeing of the mechanical degrees of freedom at the lower limbs, consistent with Bernstein’s (1967) postulation.

Interestingly, ROM of the elbow and wrist significantly decreased for the majority of participants with practice (Fig 3). In parallel, the majority of participants were categorised in advanced action (Table 1) of ‘humerus’ and ‘forearm’ from the beginning of practice. While no other research has analysed ROM for non-dominant arm throwing, Southard (2006) reported that instructional cues positively influenced segmental distal lag, specifically the hand relative to the forearm. When viewed in conjunction with the components model (Robertson & Halverson, 1984) the ROM results suggest that participants had the ability to effectively use the elbow and wrist joint at the start of practice, and reducing ROM was a common strategy to adopt. This finding provides support for the proposition of Hong and Newell (2006) that freezing or freeing degrees of freedom is task specific, rather than a universal directional rule

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for skill learning, and furthers the proposition by suggesting that different limb segments (arms or legs) may follow different patterns of change.

At the whole-body level, all participants showed a transition in technique that was captured by a significant change in ROM of three or more joints during one single session. However, the combination of joints involved was individual specific, not an uncommon finding in motor learning literature (Williams, Irwin, Kerwin, & Newell, 2015; Teulier & Delignières, 2007; Haibach, Daniels & Newell, 2004). A drawback of describing technique change through individual degrees of freedom is the inability to explore how these joints are coordinated. Since the timing and the combinations of joints involved in change were individual specific, it is of interest to investigate whether a measure of inter-joint coordination would capture common characteristics of technique change in spite individual constraints and intrinsic dynamics.

Integrating Frameworks to the Acquisition of Overarm Throwing

Exploring different levels of the system is related to different theoretical propositions on motor control (Schoner & Kelso, 1988; Hong & Newell, 2004; Gray, Watts, Debicki, & Hore, 2006). Emphasising a collective variable is based on the theoretical proposition that motor control is associated with overall system dynamics rather than the control of individual degrees of freedom (Ko et al., 2014; Wang et al. 2014; Dutt-Mazumder et al. 2016). Arguably, the components model (Robertson & Halverson 1984) provides collective variables through the hypothesis of four components, however, this model is skill specific and cannot be generalised across movement tasks. In supporting these different emphases on system organisation, our findings suggest that a more complex CoM-wrist coupling is achieved by taking a contralateral step in the throwing action which is associated with greater ROM of the

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lower extremities. Thus, in increasing the complexity of the collective dynamics, participants followed the sequence of components change in the Robertson and Halverson (1984) components model, while Bernstein's (1967) postulation of freeing mechanical degrees of freedom was limb specific. Founded on Newell's (1985) stage of learning collective dynamics did change, however variability of this collective dynamic was not clearly directional. Overall, a higher order variable was better able to identify commonalities in technique change across individuals than single joint motions, and therefore, might be key to understanding the dynamics of technique change across different task and organismic constraints from a dynamical systems theory perspective.

From an applied perspective, the integration of the three approaches provide a comprehensive view of technique changes during overarm throwing action because each approach explores a different aspect of the system organization that can be practically relevant. This study has revealed experimental evidence of the progression of individual technique changes during non-dominant overarm throwing. The findings highlight the importance of the lower extremities and dynamic postural control in what is usually characterised as an upper extremity action. Specifically, the ability to take a contralateral step to facilitate greater ROM of the lower extremities and CoM movement in weight transfer.

Future work could explore the coordination between multiple joint segments during learning. In addition, future work is required to explore the extent to which these three complimentary approaches characterise technique development in overarm throwing across childhood.

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List of Figure and Table Headings

Figure 1. CoM-wrist coupling for single trial per session for PT06 (representative of PT03, PT04, PT05, PT08, PT09 and PT10) and PT07 (representative of PT01 and PT02).

Figure 2. Representation of group changes in range of motion of the joints and centre of mass during 3-weeks of practice.

Figure 3. Group ROM development at the right ankle, knee, hip, left shoulder, elbow and wrist joint during practice. A general trend showed significant increase in ROM of the lower limb joints and shoulder with practice (9 of 10 participants at the ankle and 8 of 10 participants at the knee, hip and shoulder) ($p < 0.05$). Six of 10 participants significantly decreased ROM at the elbow and 7 of 10 participants at the wrist ($p < 0.05$). Eight of 10 participants significantly increased ROM of the CoM in the anterior-posterior direction ($p < 0.05$) (Fig 1.).

Changes in 'step' (PT02, PT04, PT05, PT06), 'trunk' (PT03, PT05, PT07, PT08, PT09), 'humerus' (PT03, PT04, PT07, PT08, PT09) and 'forearm' action (PT03, PT04, PT05, PT07, PT08, PT09) (Table 1.) occurred at the same session as ROM for all participants that changed action level. Six of 10 participants did not change 'step' action from level 3 but did significantly increase lower limb ROM (Fig 2.).

Table 1. Developmental action level with practice.

Table 2. Coupling variability with practice for CoM-wrist.