BIOMECHANICAL AND NEUROMUSCULAR ASSESSMENT OF CHANGE OF DIRECTION PERFORMANCE IN MALE UNIVERSITY SOCCER PLAYERS

by

Ken Morrison

BScKin, University of New Brunswick, 2011

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

Master of Science in Exercise Sport Science

in the Graduate Academic Unit of Kinesiology

Co-Supervisors:	Wayne Albert, PhD, Faculty of Kinesiology Usha Kuruganti, PhD, Faculty of Kinesiology
Examining Board:	Ken Seaman, PhD, Faculty of Kinesiology Scott Landry, PhD, Acadia University
	Jeremy Noble, PhD, Kinesiology, Chair

This thesis is accepted by the Dean of Graduate Studies

THE UNIVERSITY OF NEW BRUNSWICK

September 2014

© Ken Morrison, 2014

Abstract

The purpose of this study was to identify biomechanical and neuromuscular variables that distinguish change of direction performance in a well-trained athletic population. Twenty athletes from the University of New Brunswick's varsity men's soccer team were recruited for the study. Vicon motion capture, force plate data, and electromyography (EMG) were collected simultaneously during the plant phase of the 505 agility test. The median time to complete the agility task was used to divide the athletes into a "fast" group (n=10) and a "slow" group (n=10). An ANOVA with an alpha level of 0.05 was used to compare group's kinematic, kinetic, and neuromuscular data. Athletes in the fast group were found to have shorter overall contact time ($p=0.011$) and relative time spent in transition ($p=0.001$) when compared to the slow group. The fast group also produced more relative horizontal to vertical ground reaction force during weight acceptance ($p=0.03$) and push off ($p=0.002$). Kinematic analysis revealed that during weight acceptance faster athletes displayed a lower centre of mass ($p=0.003$), greater torso lateral lean ($p=0.018$), and greater pelvis rotation ($p=0.004$) than slower athletes. During transition the fast group had greater torso lateral lean ($p=0.004$), less spine rotation range of motion ($p=0.035$), and less hip adduction/abduction range of motion ($p=0.02$). Finally, the fast group was found to maintain greater torso lateral lean ($p=0.015$) throughout push off and a lower centre of mass at toe off ($p=0.015$). EMG analysis did not reveal many significant differences between groups, however, future studies should look to perform a more in-depth EMG

analysis including trunk musculature during change of direction. The major findings of this study suggest that faster athletes adopt different technical strategies during change of direction than slower athletes. Professionals working to improve athletic performance can use the results from this study to improve athletes' change of direction performance.

Acknowledgement

This thesis could not have been completed without the help and guidance of many individuals. Thank you to Miles Pinsent and the UNB Men's Soccer team for volunteering to participate in the research conducted for this thesis. Thank you to Dr. Wayne Albert and Dr. Usha Kuruganti for taking me on as a graduate student and providing support and guidance throughout this process. Your time, patience and expertise has made this experience a rewarding one. Thank you to my supervisory committee, Dr. Jim Croll and Dr. Tim McGarry for providing your time to help make a stronger thesis. Thank you to Dr. Scott Landry for sitting on my examining committee and bringing your expertise in this area to provide quality constructive criticism. Thank you to Dr. Vicky Chester for taking the time on many occasions to help me with any issues that came up during my data collection. Thank you to Greg Dickinson for all of your help throughout my thesis and finally, thank you to Dr. Ken Seaman for sparking my interest in this area and your continued support throughout this project as well as my professional career.

Table of Contents

Abstract ii

Acknowledgement iv

List of Tables vii

List of Figures viii

List of Symbols, Nomenclature or Abbreviations ix

Chapter 1 1
Introduction 1

Chapter 2 4
Literature Review 4

2.1 Introduction 4

2.2 What is Agility? 4

2.3 Importance of Agility 7

2.4 What Correlates With Change of Direction Performance? 7

2.5 Training Agility 14

2.6 Biomechanics of Agility and Change of Direction 21

2.7 Muscle Activation 23

2.8 Conclusion 26

Chapter 3 30
Methodology 30

3.1 Participants 30

3.2 Change of Direction Performance Testing 30

3.3 Instrumentation 32

3.4 Protocol 33

3.5 Data Processing and Analysis 39

3.6 Statistical Analysis 44

Chapter 4 45
Results 45

4.1 Kinematics 45

4.2 Kinetics 48

4.3 Neuromuscular 49

4.4 Athlete Analysis 54

Chapter 5 60

Discussion 60
5.1 Kinetics 61

5.2 Kinematics 63

5.3 Neuromuscular Coordination 67

5.4 Limitations 72

5.5 Summary 75

References 77

Appendix A 83

Curriculum Vitae

List of Tables

Table 2.1: Correlational agility studies……9

Table 2.2: Training agility studies……..…15

Table 3.1: Participant's anthropometric measurements……..…33

Table 3.2: EMG electrode placement…….……38

Table 3.3: Variables measured by Vicon……..……..…39

Table 3.4: Kinematic data analysis……41

Table 3.5: Kinetic data analysis…….42

Table 4.1: Group descriptive statistics..…….……45

Table 4.2: Summary of kinematic statistical analysis……47

Table 4.3: Summary of kinetic statistical analysis…….……49

Table 4.4: Summary of EMG co-contraction statistical analysis…….…..50

List of Figures

Figure 2.1: Components of agility.……...5

Figure 3.1: 505 agility test……..31

Figure 3.2: Anterior view of marker placement…….36

Figure 3.3: Posterior view of marker placement……36

Figure 3.4: Sagittal view of marker placement……..37

Figure 4.1: Athlete's hamstring muscle activation pattern……51

Figure 4.2: Athlete's quadriceps muscle activation pattern……...52

Figure 4.3: Athlete's gluteus maximus muscle activation pattern…….53

Figure 4.4: Athlete's gluteus medius muscle activation pattern……54

Figure 4.5: Comparison between fast and slow athlete's centre of mass position……55

Figure 4.6: Comparison between fast and slow athlete's dominant hip angle data…...55

Figure 4.7: Comparison between fast and slow athlete's spine angle data……56

Figure 4.8: Comparison between fast and slow athlete's thorax angle data……..…57

Figure 4.9: Comparison between fast and slow athlete's pelvis angle data……..…58

Figure 4.10: Comparison between fast and slow athlete's ground reaction force...…..58

Figure 4.11: Comparison between fast and slow athlete's muscle activation timing…59

List of Symbols, Nomenclature or Abbreviations

5JT=Quintuple horizontal jump test

Acc=acceleration

BW=Body weight

COD=Change of direction

CMJ=Countermovement jump

Con=Concentric

D=Dominant

DJ=Drop jump

Ecc=Eccentric

EMG=Electromyography

Ext=Extension

Flex=Flexion

FS=Front squat

JS=Jump squat

LBM=Lean body mass

LJ=Lateral jump

ND-Non dominant

PF=Peak force

PL=Plyometric

PP=Peak power

RM=Repetition maximum

SJ=Squat jump

SL=Single leg

VJ=Vertical jump

VJH=Vertical jump height

Wk=Week

Chapter 1

Introduction

Strength and conditioning training plays a critical role in the development of elite athletes. Well implemented strength and conditioning programs have been shown to improve strength, speed, power, coordination, and ultimately performance (Thomas, French, & Hayes, 2009; Miller, Herniman, Ricard, Cheatham, & Michael, 2006; Myer, Ford, Palumbo, & Hewett, 2005). Well conducted academic research helps maximize the effectiveness of strength and conditioning programs by providing a platform of scientific information to guide program design and exercise prescription. This research is intended to advance the field of strength and conditioning by establishing a foundation of biomechanical information for athletic change of direction performance. Changing direction is a complex task that requires coordination of multiple joint segments to decelerate movement in one direction and accelerate in a new direction. Because of the complexity of movement coordination and force application required for effective cutting, it was hypothesized that athletes who demonstrate quicker changes in direction apply different biomechanical strategies than athletes who exhibit slower changes in direction.

Previous research focused on athletic performance has emphasized physiological properties and adaptation to various stimuli (Cronin & Hansen, 2005). While improving physiological capabilities of an athlete has distinct

performance advantages such as improved muscle function, it can be argued that without proper biomechanics these advantages are negated. For example, an athlete who possesses the physiological ability to contract muscles at high speeds may still be an ineffective athlete if these forces are not applied in the appropriate direction with proper timing and sequencing of the muscles involved. This example demonstrates the importance of biomechanics in athletic performance, yet research evaluating the relationship between biomechanics and agility performance is scarce. Agility has been shown to be a strong predictor of performance in sport (Reilly, Williams, Nevill & Franks, 2000; Kaplan, Erkmen & Taskin, 2009); therefore, establishing a foundation of scientific research that explains the relationship between biomechanics and agility performance can help athletes maximize athletic potential by improving quality of movement and force application.

The current study used force plates, electromyography, and motion capture to analyze various biomechanical variables involved in athletic change of direction. Force plates were used to monitor ground reaction force to determine direction and magnitude of force produced by the athletes while changing direction. Electromyography (EMG) was used to analyze different muscle activation strategies used by athletes. Motion capture was used to evaluate kinematics and how different joint positions and speeds effect force production and performance. The combination of data collected from force plates, electromyography and motion capture allowed for a complete analysis of the relationships between variables, and a comprehensive understanding of how these variables affect performance.

The purpose of this research was to analyze kinematic, kinetic, and neuromuscular differences between faster and slower athletes during maximal 180 degree change of direction tasks. Analysis was performed during the plant phase of the change of direction. The plant phase was broken into three sub-phases: weight acceptance, transition and push off based from each individual's ground reaction force. It was hypothesized that due to the complexity of a maximal 180 degree change of direction, athletes who change direction faster would:

1. Adopt different biomechanical strategies while changing direction.

2. Demonstrate different muscle coordination timing.

3. Adopt more effective biomechanical strategies that improve performance by enhancing control and force production while changing direction.

The current research is intended to provide a foundation of scientific information for further research in the field of sports biomechanics. The data collected from the current research provides a valuable analysis of multiple variables involved in athletic change of direction. This research has identified biomechanical variables that impact change of direction performance that can lead to further investigation and application to a variety of different athletic tasks. The major contribution of this research is providing strength and conditioning specialists, coaches, and athletes with scientifically sound knowledge of movement biomechanics that can help maximize performance.

Chapter 2

Literature Review

2.1 Introduction

This literature review summarizes relevant research concerning agility and change of direction performance to identify gaps that exist in agility performance research and direct future research reported to expand our knowledge on the topic. The present research establishes correlations between biomechanical factors that distinguish quicker and slower athletes performing an agility task. Because athletic change of direction is a complex task that involves coordination of multiple joint segments to decelerate movement in one direction and accelerate in another direction, it was hypothesized that athletes would adopt different technical strategies for changing direction. This research analyzed different technical strategies used by athletes to change direction to determine what technical strategies could potentially be more effective. Because of the complexity of the change of direction task, the literature review summarizes research in several fields to establish how numerous factors work interdependently to establish change of direction performance.

2.2 What is Agility?

Agility is a term that is used frequently in sport and performance, but can be used in many different contexts. Terms such as agility, change of direction, cutting

and quickness are often used interchangeably, yet can mean very different things. Different disciplines may view agility performance in different ways. For example, biomechanists focus on technical factors, while strength coaches focus on physical qualities, while motor control professionals focus on cognitive processes and factors affecting learning and retention of the task (Sheppard & Young, 2006). With these various different perspectives of agility, Sheppard and Young (2005) emphasized the need to establish clear definitions for agility tasks, especially in the sport community. To clarify the definition of agility, Sheppard and Young (2005) modified the work of Chelladurai (1976) to classify different agility tasks (Figure 1).

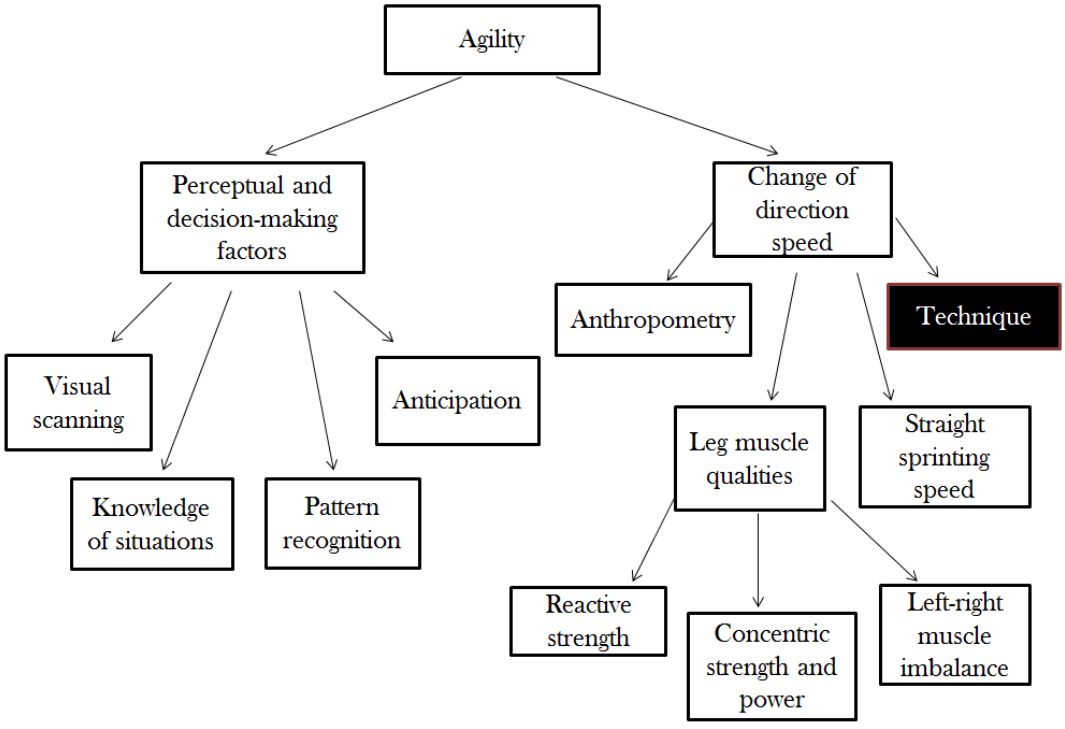

Figure 2.1. Components of agility (modified from Sheppard and Young, 2002)

Sheppard and Young (2006) proposed that agility be defined as "a rapid whole-body movement with change of velocity or direction in response to a stimulus." Pg. 918. This definition requires that the movement be an open skill that encompasses perceptual decision making factors as well as physical performance factors. Sheppard and Young (2006) also concluded that preplanned (closed skill) changes in direction can therefore be referred to as change of direction or change of direction speed. For the purpose of clarity, the current research will use these definitions to define agility and change of direction tasks.

It is also important to consider what context of agility or change of direction is being discussed when evaluating agility. For example, field and team sport athletes have adopted different strategies for running compared to professional sprinters (Cronin & Hansen, 2005). Team sport athletes run with a lower centre of gravity with more slouching and forward lean in the upper torso. They also have less knee flexion during leg recovery and knee lift (Young, James, & Montgomery, 2002). The sport being played may dictate the type of agility necessary as well. For example, a hockey player can maintain a relatively low centre of mass while changing direction because they must track the puck on the ice, while a net ball or volleyball player may have to perform a change of direction task in a more erect position in order to catch/intercept a pass or block a spike (Hewit, Cronin, Button, & Hume, 2010).

2.3 Importance of Agility

Agility plays a crucial role in sport and is often involved in pivotal moments of a competition where an athlete must avoid or track a competitor, or change direction to be first to a ball or gain position. These moments often result in the scoring or conceding of a goal or point which ultimately determines the outcome of the competition (Kaplan, Erkmen, & Taskin, 2009). Reilly et al. (2000) found that agility was one of the strongest predictors of talent amongst soccer players. This finding is supported by further research that has shown elite soccer players agility performance is higher than their amateur counterparts (Kaplan, Erkmen, & Taskin, 2009). It has also been shown that higher performing rugby players perform reactive agility tasks better than lower performing rugby players (Shepperd, Young, Doyle, Sheppard, & Newton, 2006). Unlike Kaplan et al. (2009), Sheppard et al. (2006) found that change of direction speed was not significantly different between talent groups when the reactionary or anticipatory factors were removed. Gabbett et al. (2008) found similar results to Sheppard et al. (2006), reporting that when comparing higher level and lower level rugby players, higher level rugby players had faster speed, movement time and decision times on reactive agility tasks but no differences were found between groups for change of direction speed.

2.4 What Correlates With Change of Direction Performance?

In order to understand any performance variable it is important to first gain an understanding of what factors correlate with the performance variable. Once

factors that are correlated with the performance variable are identified, these factors can be tested and trained to evaluate how changes in the correlated factors affect the performance variable (Brughelli, Cronin, Levin, & Chaouachi, 2008). Change of direction is a complex performance variable that is difficult to fully understand because it requires a combination of physiological, biomechanical and motor control factors. The interplay of these variables makes it difficult to interpret the exact contribution of each variable to agility performance. Several studies have sought to improve the understanding of the factors contributing to agility and change of direction using correlational research (table 1.1); however, these studies have used a number of different protocols to assess performance variables and change of direction performance which has resulted in varied results.

From a physiological standpoint, the majority of agility/change of direction correlational research has focused on strength, power, and reactive strength as predictors of performance (Table 1.1). A review of the research has revealed conflicting results that make it difficult to interpret the true determinants of change of direction performance. The issue when reviewing and comparing this research lies within the large variation in the techniques used to measure each variable. For example, agility and change of direction performance has been measured using numerous techniques including; t-test, 505 agility test, zigzag test, sprints with various change of direction angles, 3 cone drill, and custom agility tests. With such large variance in agility testing, it is difficult to understand how various performance factors relate to agility and change of direction performance.

Table 2.1 *Summary of studies related to different task's correlation with agility performance*

Study	Subjects (age)	Agility (time)	Component and correlation
Nimphius, McGuigan, and Newton (2010)	Competitive female softball (18.1 ± 1.6 yrs)	Longitudinal 505 agility test	Relative 1RM ND 505 (-0.75, -0.73, -0.85) Relative 1RM D 505 (-0.50, -0.75, -0.60) VJH ND 505 (-0.23, -0.45, -0.30) VJH D 505 (-0.35, -0.31, -0.48) 1stBase 10m ND 505 (0.76, 0.76, 0.96) 1stBase 10m D 505 (0.55, 0.81, 0.53) 1stBase Spint ND 505 (0.86, 0.76, 0.96) 1stBase Spint D 505 (0.66, 0.88, 0.55) 2ndBase Spint ND 505 (0.87, 0.89, 0.99) 2ndBase Sprint D 505 (0.58, 0.94, 0.59) BW ND 505 (0.93, 0.74, 0.82) BW D 505 (0.71, 0.71, 0.70) JS PF + PP correlate better with weight compared to BW
Little and Williams (2005)	106 professional male soccer players	zigzag test (5.34s) 3 CODs	10m sprint time (0.346) Flying 20m sprint time (0.458)

Study	Subjects (age)	Agility (time)	Component and correlation
Young et al. (2002)	15 male soccer, basketball, Australian football and tennis players (18-28 yrs)	7 x 8 m sprint with direction change at a variety of angles (1.65-2.85s)	Bilateral DJ (-0.35 to -0.65) Unilateral DJ (-0.23 to 0.71)
Vescovi and McGuigan (?)	83 female high school soccer players, 51 female college soccer players, and 79 female college lacrosse players.	Illinois (10.24s ± 0.42s, 10.24s ± 0.38s, 10.45s ± 0.57s) Pro agility (4.91 ± 0.22, 4.88 ± 0.20, 4.99 ± 0.24)	Illinois and pro agility correlations tended to improve as sprint distances increased and if sprints began from a flying start. CMJ correlated with both Illinois (0.551) and pro agility (0.613).
Hoffman et al. (2007)	62 national collegiate division 3 American football players (19.7 ± 1.4 yrs)	3 cone drill (-8s) 3 CODs	D Bilateral VJ (-0.34). ND Bilateral VJ (-0.39). D SL ND VJ (-0.36). ND SL ND VJ (-0.37).
Meylan et al. (2009)	44 male and 36 female recreationally active physical education students (20.9 ± 4.5 yrs)	COD test (7.5x5x7.5) D COD (5.38s) ND COD (5.41s)	ND COD correlated well with acceleration 10m for males (0.645) and females (0.572) but D COD did not show a significant correlation with acceleration 10m for males (0.208) and females (0.205). HJ had significant correlation for males (0.489) and

Study	Subjects (age)	Agility (time)	Component and correlation
			females (0.470) D COD and males (0.460) and females (0.590) ND COD. VJ had a significant correlation with all CODs for males and females except males D COD. Height and mass were not significantly correlated for any COD variable. LJ was not significantly correlated with any COD variables.
Chaouachi et al. (2009)	14 Tunisian national team basketball players (23.3 ± 2.7 yrs)	T Test (9.7 ± 0.2)	BM (0.58) and Body Fat % (0.80) were significantly correlated with agility. 5JT (-0.61) and VO2 max (-0.72) were significantly correlated with agility. Squat, Bench, CMJ, SJ and Sprints (5, 10 and 30m) were not significantly correlated with agility.
Jones, Bampoura, and Marrin (2009)	5 female 33 male (21.5 ± 3.8 yrs) university student with various	505	All variables (5m sprint, flying 5m, leg press, con ext, ecc ext, con flex, ecc flex, CMJ height) significantly

Study	Subjects (age)	Agility (time)	Component and correlation
	sporting background		correlated with 505 times excepts DJ height.
Hori et al. (2008)	29 male semi pro Australian rules football (21.3 ± 2.7 yrs)	5-5 COD (2.58 top 50%, 2.65 bottom 50%)	1RM FS (-0.51) and 20m sprint (0.52) showed the highest correlations while hang clean (-0.41), and CMJ (-0.42) also showed a significant correlation to agility performance. It is interesting to note that relative hang clean and FS showed lower correlations than their absolute counterparts.
Barnes et al. (2007)	29 female collegiate volleyball, div 1=9 (20.3 ± 1.5 yrs), div 2=11 (19.6 ±1.4 yrs) div 3=9 (20.0 ± 1.3 yrs)	4 x 5m custom agility test (div 1=5.93s, div 2=6.00s, div 3=6.1s)	CMJ height significantly correlated with agility performance (-0.580). DJ contact time (0.049) and DJ height (-0.320) did not correlate significantly with agility performance.
Meyhew et al. (1989)	53 college football players (20.3 ± 1.09 yrs)	Southeast Missouri agility run (10.92 ± 0.65)	LBM (0.40), % body fat (0.47) and weight (0.46) correlated significantly with agility performance.

Study	Subjects (age)	Agility (time)	Component and correlation
Peterson et al. (2006)	19 male and 36 female first year collegiate athletes (19.4 yrs)	t-test (m=9.89s, f=11.48s)	For males broad jump (-0.613), sprint acc (-0.491) and sprint velocity (-0.579) correlated with agility time. For females 1RM squat (-0.408) relative 1RM squat (-0.633), VJ (-0.713), broad jump (-0.788), sprint acc (-0.630) and sprint velocity (-0.693) correlated with agility.
Castillo-Rodriguez et al. (2012)	42 male physical education students	90 degree COD right (L run) COD 180 degrees (5x5m)	The study found that all jumping variables were significantly related to COD performance except left side CMJ. Right side CMJ was found to correlate best with 90 degree COD to the left while CMJ was found to be the best overall predictor of COD performance. DJ was significant but CMJ had higher correlation.

After reviewing the research, the consensus is that agility performance is affected by numerous factors that work in synchronization to optimize performance. One of the few factors that has consistently been shown to correlate

with agility tasks is BMI and % body fat. Longitudinal studies have also shown that female softball players' body mass correlates highly with agility performance throughout the run of a season (Nimphius, McGuigan, & Newton, 2010).

When looking at muscle power and reactive strength, Young and Montgomery (2002) found that even the highest correlations between unilateral reactive strength only accounted for 50% of the shared variance for change of direction speed. Since the agility tasks were closed skilled and did not require reactive agility, it seems likely to assume technical factors or other strength factors may also play a significant role in change of direction. Young and Montgomery suggested that individuals in their study adopted different strategies for changing direction and that a biomechanical evaluation of running with change of direction would provide a clearer picture of performance variables affecting performance. Little and Williams (2005) analyzed correlations between acceleration, sprinting, and change of direction. It was concluded that acceleration, speed and change of direction ability are task specific, possibly due to mechanical differences between tasks. Since straight sprinting mechanics are already well established, emphasis on establishing a better understanding of change of direction mechanics may improve our understanding of these relationships and enhance performance.

2.5 Training Agility

Training studies provide a more longitudinal cause and effect approach to understanding agility performance than correlational research. Much like the

correlational research that was reviewed, results of training studies vary; however, training studies do provide valuable insight into what factors may affect agility performance. A summary of training studies involving agility is provided in Table 2.2. Additional training studies that do not specifically involve agility have been included in the table if they provide relevant information for agility training and performance.

Table 2.2 *Summary of training studies related to agility performance*

Study	**Subjects**	**Frequency /duration of training**	**Type of training**	**Agility test**	**Results**
Porter et al. (2010)	14 male and 6 female undergraduate students		Instruction, ext focus = get to cone as fast as possible and push off ground as hard as possible, int = move legs as fast as possible and plant feet as firmly as possible. Control group	3 cone test (L run)	Ext = 6.10 Int = 6.45 Con = 6.36
Thomas, French, and Hayes (2009)	15 semi-professional male soccer (17.3 yrs)	2x/wk; 6 wk	Plyometric, DJ and CMJ group	505 agility	Both groups significantly improved agility times.

Study	Subjects	Frequency /duration of training	Type of training	Agility test	Results
Miller et al. (2006)	28 male and female recreational athletes	2x/wk; 6 wk	Plyometric group = horizontal, lateral, vertical hop, jumps and bounds Control group did not do any plyometric exercise	t-test Illinois agility test	PL = -5.5%. Control = no change PL = -2.9%. Control = no change
Young, McDowell, and Scarlett (2001)	36 males (24.0 ± 5.7 yrs)	2x/wk; 6wk	Sprint training group, agility training group, and control group	7 30m sprints with increasing amount and angle of change of direction	Control group did not improve. Agility group improved on test 2-7 but more so on the more demanding change of direction tasks (5-7). Sprint group improved straight sprint but improved less as test change of direction difficulty increased.

Study	Subjects	Frequency /duration of training	Type of training	Agility test	Results
Wojtys et al. (1996)	16 males, 16 females (25.4 yrs)	3x/wk; 6wk	Isokinetic group, isotonic group, agility training group, control group	Tibial translation test	Agility group was only group to improve spinal reflex times in response to tibial translation. Also the only group to improve cortical response time.
Myer et al. (2005)	53 female high school female athletes (15.3 ± 0.9 yrs)	3x/wk; 6wk	Control group and training group	Physical test along with three dimensional biomechanical testing	Training group improved knee range of motion during drop vertical jump and decreased varus/valgus toques to show training can improve biomechanics.
Twist and Benicky (1996)	Practical review of agility				Suggests that % body fat and lean mass will affect movement efficiency during agility.

Specificity of training appears to be the largest contributor to enhancing change of direction performance. Young et al. (2001) analyzed the effects of a six week training program on sprint performance with various degrees and amounts of change of direction. It was found that the straight sprint training group improved significantly in straight sprint performance but not sprints with change of direction.

Conversely, the agility training group did not improve straight sprint performance but improved performance on sprints with change of direction. Furthermore, the agility group showed greater improvements as the number and degree of changes of direction during the sprint task increased. The control group showed no improvement in either straight sprinting or sprints with changes of direction. These results are supported by the correlational research of Little et al. (2005) that concluded that acceleration, straight sprinting and agility were specific tasks. It is possible that agility specific training elicits motor control improvements that other training methods do not. Wojtys et al. (1996) found that when comparing agility, isometric and isotonic training groups only, the agility trained group significantly improved spinal reflex time and voluntary muscle contraction time. The agility group was also the only group that significantly improved cortical response time for the gastrocnemius, medial hamstrings and lateral quadriceps.

Another factor related to training studies is the type of force involved during training. Some authors have suggested that horizontal force plays a more important role than vertical force during running and change of direction tasks. Studies that have used training methods involving horizontal, or combined horizontal and vertical jump training have noted success at improving agility (Miller, Herniman, Ricard, Cheatham, & Michael, 2006). These results are somewhat contradictory to the results reported by Randell and colleagues (2010) who noted that vertical force was greater than horizontal force during constant velocity and acceleration running tasks. However, the ratio between vertical and horizontal forces was much closer during acceleration than constant velocity running. It is possible that the ratio

between horizontal and vertical force may be more important than the overall magnitude of the forces or that horizontal force plays a larger role in some athletic tasks even though the overall magnitude is not as high as vertical force. It has been suggested that vertical ground reaction force plays a greater role in increasing stride length. During acceleration, increased vertical GRF may decrease the amount of time spent in contact with the ground, which may decrease the amount of time that the athlete can influence their acceleration (Randell, Cronin, Keogh, & Gill, 2010). When comparing differences between fast and slow acceleration groups, Murphy et al. (2003) found no difference between groups' stride length or flight times, which are thought to be a result of vertical GRF. Fast and slow acceleration groups were found to have a significant difference in stride frequency and ground contact time.

Further research is needed before any substantial conclusions can be made regarding which and to what degree factors contribute to agility performance. Research has showed that training can improve athletic performance variables but the interplay between several variables makes it difficult to determine how manipulating a variable will affect overall performance. It has been relatively well accepted that training programs aimed at improving cutting movements and agility should progress from a closed environment to an open environment (Braechle & Earle, 2008). A closed environment allows athletes the opportunity to acquire the appropriate motor patterns and achieve consistent performance before attempting to perform unpredicted movements (Braechle & Earle, 2008). After consistent performance with proper movement mechanics is achieved the program must progress to an open environment so the athlete can be exposed to the stresses

involved when performing the task in an unpredictable environment. Unpredicted cutting movements produce greater stress on joints and must be practiced to reduce the risk of injury and enhance performance (Besier, Lloyd, Cochrane, & Ackland, 2000). Jeffreys (2011) suggests that after establishing a sound technical base it is important to challenge athletes in an open environment so they can learn to select an appropriate motor pattern before performing the task.

Despite the general consensus that agility training should develop a sound technical base before progressing, few research studies have analyzed what change of direction techniques maximize performance while reducing the risk of injury. Most studies concerning agility and change of direction performance have focused on manipulating physiological variables while neglecting to track biomechanical variables. A number of studies have acknowledged that athletes adopt different technical strategies for changing direction and that technique likely affects performance; however, very few studies have reviewed biomechanical factors during agility with an emphasis on performance. A review of the research that has analyzed biomechanics during agility and change of direction follows, but it is important to note that research providing a solid foundation of what biomechanical factors affect agility and change of direction performance is scarce.

2.6 Biomechanics of Agility and Change of Direction

Most research that has focused on biomechanics during agility and change of direction tasks have analyzed biomechanical differences between genders or between anticipated and unanticipated cutting tasks. The emphasis behind these research studies is generally injury prevention. Different sidestep cutting techniques have been shown to load the knee in different ways that may place it at risk of injury. It has been shown that wide foot placement, torso lean and/or rotation in the opposite direction of the cut increases internal rotation and valgus loads at the knee, which may place the ACL at risk of injury (Dempsey, et al., 2007). Establishing proper technique can help prevent these injuries while maximizing the efficiency and effectiveness of the change of direction.

Change of direction is one of the major causes of ACL injury, especially for female athletes (Dempsey, Lloyd, Elliott, Steele, Munro, & Russo, 2007). For this reason a number of studies have compared gender differences during agility and change of direction tasks to determine what mechanisms may be the source of these injuries. Biomechanical differences between sexes appear to be relatively consistent across studies. Females display less hip and knee flexion and greater valgus moments during cutting tasks than males (McLean, Walker, & Van Den Bogert, 2005). Females have also been found to produce a hip adductor moment during the stance phase of a crosscut, which would contribute to a knee valgus moment (Landry, McKean, Hubley-Kozey, Stanish, & Deluzio, 2007). Landry et al. (2007) also found that during an unanticipated crosscut, females displayed a knee extension moment during early stance (0-12%), while males produced a knee

flexion moment. This may be a serious cause for injury because ACL injuries have been shown to occur while the leg is in a more extended position. It is also concerning that valgus and extensor moments are being produced during this phase because tibial anterior translation and adduction place a high amount of stress on the ACL that could be a potential cause of injury. Research of gender differences during change of direction has shown that females demonstrate biomechanics that place them at a higher risk of injury than males. Unfortunately little research has shown how these injury mechanisms can be improved during change of direction tasks to reduce the risk of injury. Cochrane et al. (2010) did attempt to address this issue by assessing a number of different training modalities to examine their effect on knee kinematics during cutting maneuvers. Training modalities were shown to alter knee biomechanics after a training period of 12 weeks. Balance training was found to decrease knee varus and valgus moments during cutting, which may decrease the risk of injury and improve mechanical efficiency by allowing prime movers to perform more efficiently. Future research involving training interventions that could potentially improve biomechanics during change of direction may help better understand what types of training interventions improve biomechanics and how these interventions can impact performance.

Another research concern is the change in biomechanics due to anticipated and unanticipated cutting events. Research suggests that the biomechanical differences seen between anticipated and unanticipated change of direction are similar to the differences seen between sexes and with the presence of a defensive opponent. Besier et al. (2000) found that when comparing anticipated and

unanticipated changes of direction conditions, unanticipated change of direction resulted in greater knee valgus, and knee flexion. Analysis of sidestep cutting results also shows that the addition of a defensive opponent results in increased medial GRF, hip flexion, hip abduction, knee flexion and knee valgus for both genders (McLean, Lipfert, & Van Den Bogert, 2004)

2.7 Muscle Activation

In any athletic or voluntary movement, like an explosive change of direction, numerous cognitive, biomechanical and physiological processes must work in synergy to determine the efficiency and effectiveness of the movement. One of the major processes that can have a substantial impact on performance of a movement is the coordination of muscular activity, or muscle activation patterns. Muscle activation during movement serves two major purposes, the first is to stabilize a joint to protect it from injury or assist in transfer of force through that joint in the intended direction of movement. The second is to produce force and torque about a joint to generate movement. Research has suggested that during voluntary movement muscle activation and deactivation occurs in a chronological order and that the magnitude and duration of muscle activity increases as the task or movement becomes more difficult (Zattara & Bouisset, 1988). Muscle activation patterns in Zattara and Bouisset's (1988) study were found to be reproducible between trials and subjects, which suggest that these muscle activation patterns are foundational principles for all voluntary movement. Furthermore, stabilizers were

found to be active before the prime movers during voluntary movement but were not active during passive movement, which may also suggest that these activation patterns are a result of a motor program that anticipates postural adjustments.

As mentioned, one of the major roles of muscular activity or contraction is to stabilize a joint during movement to help prevent injury. During change of direction tasks, knee stabilization is a major concern for injury prevention due to the prevalence of ligament damage caused during change of direction. Numerous studies have used EMG to observe what muscles act to stabilize the knee under different conditions. In an early knee stabilization study, Hutson et al. (1996) used a tibial translation apparatus to test knee laxity and different knee stabilization strategies in males and females. The study found that females relied more on quads and gastrocnemius to resist anterior tibial translation while males used hamstrings for initial stabilization of the knee. It was also shown that women had great knee laxity and took significantly longer to reach peak hamstring torque than men even though no difference was found between males and females spinal and cortical reaction time. These results are supported by Lloyd and Buchanan (2001) who found that co-contraction of hamstrings and quadriceps was used to stabilize the knee during varus and valgus moments, while gracilis and tensor fascia latae muscle activation also increased with varus and valgus moments, respectively, to provide stability. The sartorius muscle was found to help support the knee during valgus moments.

Colby et al. (2000) had recreational collegiate athletes perform four different tasks (sidestep cut, crosscut, landing and stopping) to compare muscle

activation strategies between tasks. Quadriceps muscles reach the highest % MVC during all tasks with the largest peak occurring during the crosscut and stopping maneuvers. Quadriceps activity was found to increase after foot strike for all maneuvers while hamstring activity peaked before foot strike, then remained steady or decreased at foot strike in all activities except landing. The muscle activation strategies recorded during the study performed by Colby et al. (2000) appear to be logical. The hamstrings activate prior to foot contact to stabilize the knee and prevent anterior tibial translation, while the quadriceps become increasingly active after foot strike to extend the knee and propel the body in the intended direction of movement. Similar strategies were noted by Neptune et al. (1999) when recording EMG during a 45 degree sidestep change of direction. Biceps femoris and semimembranosis were active at impact to help stabilize the knee along with adductors, which were active prior to foot contact. Hip/knee extensors and abductors showed a gradual onset of activity with a peak occurring around mid-stance to develop torque to assist in movement. Hip/knee flexors are activated prior to toe off to assist in propulsion by increasing momentum in the intended direction of movement.

Few studies have analyzed muscle activation patterns of core, hip and knee musculature simultaneously during a dynamic task like an athletic change of direction. Considering the literature reviewed, it is possible that timing of trunk musculature may play an integral role in providing stabilization prior to movement, and assist in energy transfer in the intended movement direction during movement. Observing muscles that act on the hip may provide valuable information about what

muscles help stabilize the hip and knee during movement. For example, gluteus medius could potentially play a significant role in stabilizing the knee by abducting the leg at the hip. By analyzing musculature that acts on the trunk, hips, and knees simultaneously, a more complete understanding of muscle activation strategies used to provide stabilization and produce force during dynamic movements will be presented.

2.8 Conclusion

After reviewing the literature, it is clear that the biomechanics of agility and change of direction research has focused on injury prevention, biomechanical differences between sexes, and biomechanical differences between situations (i.e., anticipated vs. unanticipated, or presence of a defender vs. no defender). Although these studies have provided valuable insight into what circumstances may affect biomechanics during change of direction and how changes in biomechanics may predispose an athlete to injury, research focusing on biomechanics of change of direction performance is limited. Green et al. (2011) is one of the few studies interested in kinematic differences between rugby union starters and non-starters during a preplanned 45 degree change of direction. The study revealed that starters' knee extension began earlier and had shorter plant leg contact time during a dominant 45 degree cut than non-starters. It was suggested that non-starters required more time to decelerate during the plant phase and therefore began extension later than the starters. This study did not report whether or not the starters

and non-starters change of direction times were significantly different from each other. It is possible that some non-starters may be more effective at changing direction than starters, which could affect the results seen in this study.

Unlike the study performed by Green et al. (2011), Murphy et al. (2003) separated groups into "fast" and "slow" acceleration based on time to perform a straight acceleration task. Although their study was analyzing kinematics and acceleration performance, some of the results may help explain change of direction performance. No differences were found between groups' stride length or flight times; however, significant differences were found for ground contact time and stride frequency between the fast and slow acceleration group. The only kinematic variable found to be significantly different between groups was knee extension angle, with the fast group displaying significantly knee extension on their third acceleration step (only one side was analyzed). First step also approached significance with a p value of 0.07. This study emphasizes the need to develop stride frequency during acceleration. It appears that the fast group does this by producing less knee extension while maintaining flight time and hip extension. These variables could potentially play a role during the first few strides in the acceleration phase during change of direction.

Hewit et al. (2010) analyzed three types of 90 degree turn and sprint starts and applied biomechanical principles to evaluate the effectiveness and technical advantages that exist between techniques. The biomechanical principles that were considered as potential benefits to change of direction performance were lower centre of mass prior to turn, movement of centre of mass in the intended direction

of movement, arms and legs close to body while turning, centre of mass ahead of takeoff foot, full lateral extension of the takeoff leg, and driving action of the arms. Hewit et al. (2010) provide reasoning for these principles and conclude that the crossover cut meets these criteria better than the false-start pivot or forward-moving sidestep techniques.

Besier et al. (2007) were concerned with comparing unanticipated vs. anticipated changes of direction but found that half of their participants displayed a knee varus moment while the other half displayed a knee valgus moment. After analyzing further it was noted that the valgus group performed the 60 degree cutting task 0.25ms slower than the varus group and had more trouble achieving the desired cutting angle of 60 degrees than the varus group. These results indicate that a varus moment during change of direction tasks may help improve the effectiveness of the change of direction.

These studies provide information about how biomechanics affect change of direction performance, but a solid foundation of research that distinguishes biomechanical differences between faster and slower changes of direction has yet to be established. The current research project will establish biomechanical differences that exist between faster and slower athletes from the same population. Integrating data collected from force plates, surface electromyography, and motion capture will allow for a complete analysis of the variables involved in change of direction performance. Force plates will provide information about what magnitude and direction of ground reaction forces involved in faster changes of direction. Surface electromyography will be used to analyze different muscle activation

strategies and timing used by athletes to help determine what muscle activation patterns allow for more effective change of direction. Motion capture will be used to evaluate different joint positions and their effect on force production and performance. When integrated with force plate data, motion capture will also provide valuable information about what joint moments assist in effective change of direction. The combination of data collected from force plates, electromyography and motion capture will allow for a complete analysis of the relationships between variables, and a comprehensive understanding of how these variables affect performance by comparing faster and slower change of direction groups.

Chapter 3

Methodology

3.1 Participants

Twenty members of the University of New Brunswick men's soccer team participated in this study. All athletes were healthy and able to participate in full training sessions and games when they were tested for this study. Exclusion criteria included any athletes who were injured or unable to participate in full practices or games at the time of data collection. This study only included male participants because females have been shown to demonstrate different biomechanics and muscle activation patterns during change of direction than males. This project has been approved by the Research Ethics Board of the University of New Brunswick and is on file as REB 2013-024.

3.2 Change of Direction Performance Testing

All testing was done indoors at the Andrew and Marjorie McCain Human Performance Laboratory located in the Richard J. CURRIE CENTER at the University of New Brunswick. Participants were required to attend one testing session and were asked to wear athletic shorts and the training shoes that they use for their off field training sessions so they were comfortable while performing the change of direction task. Each participant completed the 505 agility test (Draper & Lancaster, 1985) to measure change of direction performance. Four trials of the

change of direction task were performed by each participant. All trials were performed on what the athlete determined as their dominant side for change of direction.

505 agility test (Figure 3.1): The 505 agility test began with the athlete positioned at the start line in a split stance position with the toe of their front foot in line with the start line. When the athlete was ready, they accelerated from the start line through a set of timing lights positioned 10 meters away (initiating the time for the agility task) to a cone positioned 15 meters from the start line. At the cone, the athlete changed direction 180 degrees and accelerated through the same timing lights 5 meters away to stop the time for the agility task.

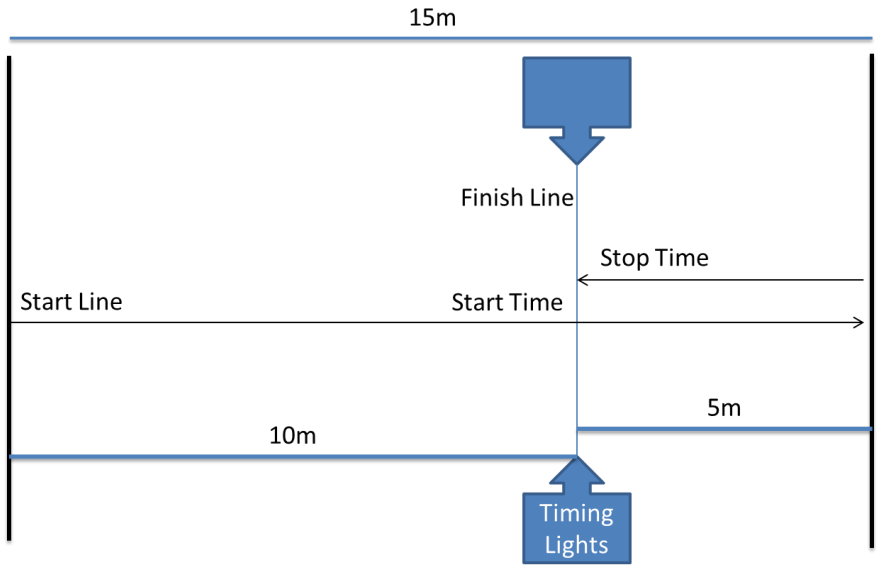

Figure 3.1. Schematic of the 505 agility test. Arrows indicate direction and distance of athlete's movement.

3.3 Instrumentation

Kinematics, kinetics and neuromuscular activity of the change of direction task were monitored using a Vicon motion capture system equipped with 12 T160 cameras recording at 200Hz, one Kistler force plate recording at 2000Hz (Kistler Instruments, Inc., Amherst, NY), and electromyography (Zerowire, Aurion, Inc.) recording at 2000 Hz. Timing lights (Test Center timing system, Brower Timing Systems, Draper, Utah) were used to record the time to complete the task and separate participants into "fast" and "slow" agility groups for analysis. Timing lights were placed at a height of 18 inches so that the light could only be broken by the legs and not an outstretched arm.

Vicon Plug-in Gait (Vicon, Oxford UK, www.vicon.com) was used to analyze the motion data collected from Vicon and the force plate during the change of direction task. Plug-in Gait is a tool developed by Vicon to assist in data capture and processing. Plug-in Gait is an application that is installed with Vicon Motion Capture Software based on the Newington-Helen Hayes gait model (Vicon Motion Systems, 2008). It is a user-friendly model that produces kinematic and kinetic outputs of data collected during a task based on a defined marker set and specific subject measurements. Plug-in Gait has been cited in several peer-reviewed publications (Vicon Motion Systems, 2008).

3.4 Protocol

Upon arrival for their testing session, participants' anthropometric measurements were taken as outlined in Table 3.1. Once the measurements were taken the participant ran through a preplanned warm up routine including 5 minutes of light jogging to increase blood flow, and 5 minutes dynamic stretching. They were then fitted with the electromyography electrodes and motion capture markers described in the following paragraph before performing sprints with change of direction increasing in intensity to mobilize joints and activate muscle groups in preparation for the agility trials.

Table 3.1 *List of participant's required anthropometric measurements*

Name	Description	Measurement left	Measurement right	
All				
Body mass	Patient mass			Kg
Height	Patient height			mm
Lower body				
Ankle width	The medio-lateral distance across the malleoli. Measure with patient standing, if possible.	mm		mm
ASIS-Trochanter distance	ASIS-ASIS distance is the distance between the left ASIS and right ASIS. This measurement is only needed when markers cannot be placed directly on the ASIS,	mm		mm

	for example, in obese patients.		
Inter-ASIS difference	ASIS-ASIS distance is the distance between the left ASIS and right ASIS. This measurement is only needed when markers cannot be placed directly on the ASIS, for example, in obese patients.	mm	mm
Knee width	The medio-lateral width of the knee across the line of the knee axis. Measure with patient standing, if possible.	mm	mm
Leg length	Full leg length, measured between the ASIS marker and the medial malleolus, via the knee joint. Measure with patient standing, if possible. If the patient is standing in the crouch position, this measurement is NOT the shortest distance between the ASIS and medial malleoli, but rather the measure of the skeletal leg length.	mm	mm
Sole thickness delta * [1]	The difference in the thickness of the sole at the toe and the heel. A positive sole delta indicates that the patient's heel is raised compared with the toe.	mm	mm
Upper body			
Elbow width	Width of elbow along flexion axis (roughly	mm	mm

	between the medial and lateral epicondyles of the humerus).		
Hand thickness	Anterior/Posterior thickness between the dorsum and palmar surfaces of the hand.	mm	mm
Shoulder offset	Vertical offset from the base of the acromion marker to shoulder joint centre.	mm	mm
Wrist width	Anterior/Posterior thickness of wrist at position where wrist marker bar is attached.	mm	mm

Following the dynamic stretching in the warm up protocol, 14mm retro-reflective markers were attached to each subject to allow for 3D motion capture of their change of direction tasks using the Vicon motion analysis system. Markers were attached directly to the skin to decrease the amount of marker displacement during the collection trials. The Plug-in Gait full body marker set was used in this study with a total of 39 retro-reflective markers. Markers were placed on both posterior superior iliac spines to define the pelvis as oppose to one sacral marker. The landmarks used for placement of the retro-reflective markers are outlined by Vicon Plug-in Gait (Vicon Motion Systems, 2008) and are shown in figure 3.2 to figure 3.4. Landmark palpation was used to ensure consistent marker placement between subjects. The orange marker options were not used in this study.

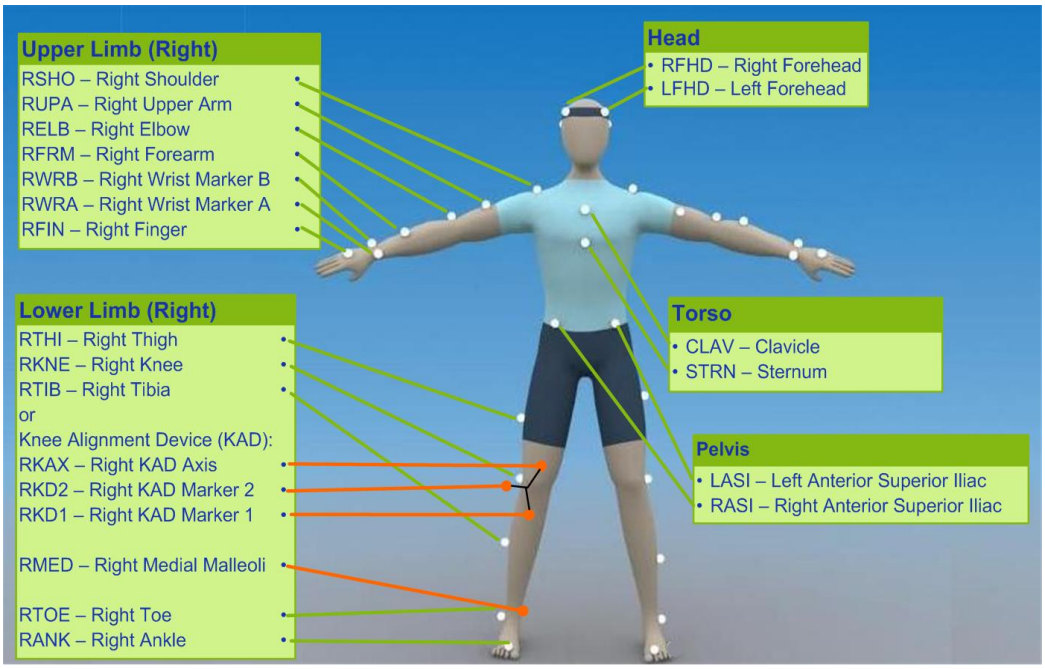

Figure 3.2 Anterior view of Vicon retro-reflective marker placement (Vicon Motion Systems, 2008)

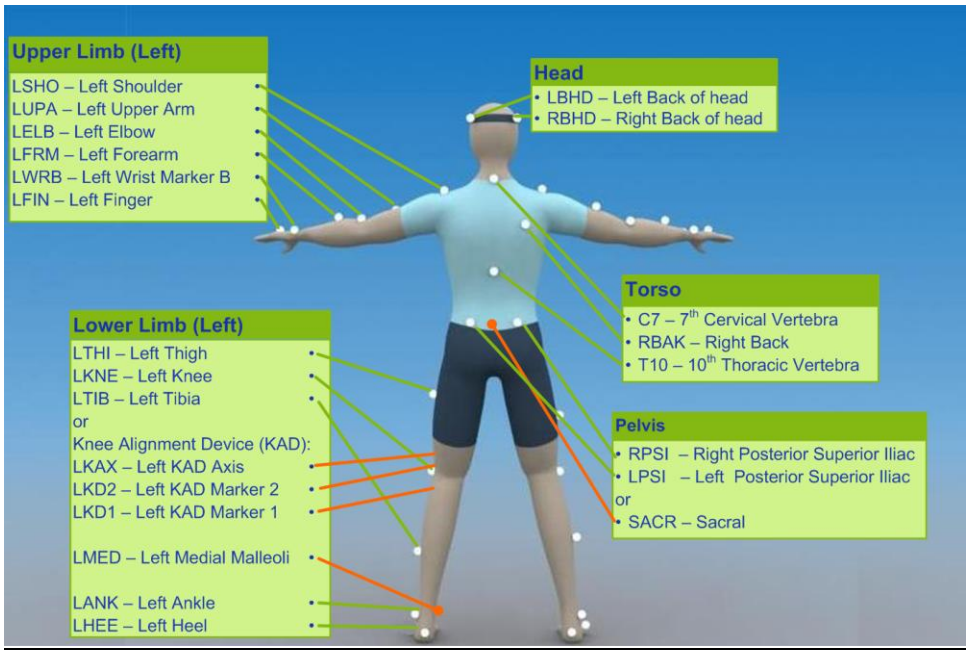

Figure 3.3 Posterior view of Vicon retro-reflective marker placement (Vicon Motion Systems, 2008)

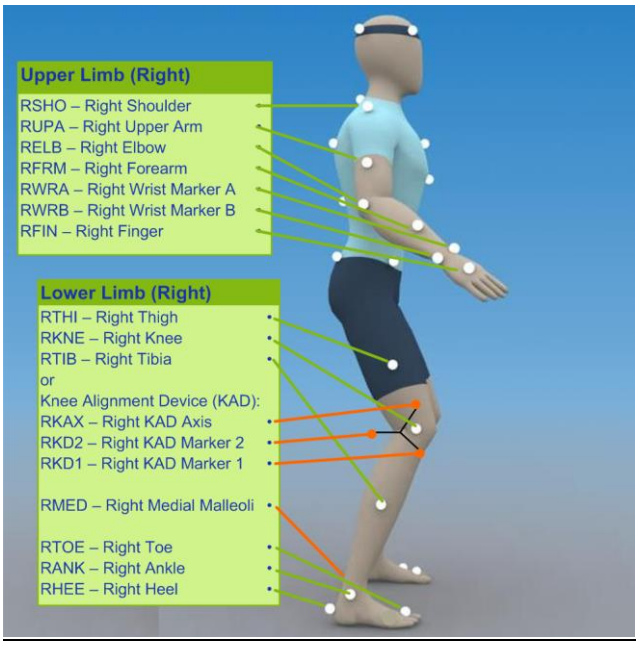

Figure 3.4 Sagittal view of Vicon retro-reflective marker placement (Vicon Motion Systems, 2008)

Subjects were also fitted with surface electromyography (EMG) electrodes to analyze muscle activity during their change of direction task. A 16-channel surface EMG system (Zerowire, Aurion, Inc.) was used to record muscle activity from the muscles listed in Table 3.2. These muscles were chosen to provide a general analysis of the neuromuscular coordination involved with the musculature acting on the trunk, hip and knee. Prior to electrode placement, the subject's skin was shaved and cleaned with alcohol wipes to ensure good quality electrical signals.

Table 3.2 *Table describing electrode placement for EMG analysis during agility tasks (Criswell, 2011)*

Muscle	Electrode Placement
External obliques	Electrodes placed directly above anterior superior iliac spine halfway between iliac crest and the ribs at slightly oblique angle.
Erector spinae	Electrodes placed parallel to the spine approximately 2cm laterally at the level of the iliac crest.
Gluteus maximus	Electrodes placed halfway between trochanter and sacral vertebrae on an oblique angle slightly above the level of the trochanter.
Gluteus medius	Electrodes placed between the iliac crest and trochanter, one third of the way down from the iliac crest. Electrodes placed parallel to the muscle fibers.
Rectus femoris	Electrodes placed parallel to the muscle fiber half the distance between the knee and iliac spine on the anterior surface of the thigh.
Hamstrings	Electrodes placed in the centre of the posterior thigh approximately half the distance between the gluteal fold and the back of the knee.

After subjects were fitted with the appropriate electrodes and retro-reflective markers, they were given clear instructions on how to perform the agility performance task (505 agility tests). Subjects performed one practice trial of the agility task for familiarization to ensure proper performance. Four captured trials of the agility task were then performed. The participant's fastest trial that had all the information needed available was used for further analysis.

3.5 Data Processing and Analysis

Motion capture, force plates and EMG were used to collect respective data for the plant phase of the change of direction task. The plant phase of the change of direction task took place such that the subjects lead plant leg contacted a force plate to allow for ground reaction forces to be analyzed. Vicon Plug-in Gait was used to process and analyze joint kinematics and centre of mass tracking throughout the stance phase. A Woltring filter (5^{th} order spline) was used by Plug-in Gait to smooth the data collected by Vicon. Joint angles analyzed by Plug-in Gait are outlined in table 3.3 (Vicon Motion Systems, 2008).

Table 3.3 *Description of Joint angles, forces, moments and powers analyzed using Vicon Plug in Gait*

Output	Description
Kinematics	
Angles	
AbsAnkleAngle	The angle between the AJC to KJC vector and the AJC to TOE vector
AnkleAngles	Relative. The angles between the shank and the foot
FootProgressAngles	Absolute. The angles between the foot and the global coordinate system
HipAngles	Relative. The angles between the pelvis and the thigh
KneeAngles	Relative. The angles between the thigh and the shank
PelvisAngles	Absolute. The angles between the pelvis and the laboratory coordinate system

The plant phase was separated into three sub-phases to provide a more complete analysis of the kinematics and kinetics present during the change of direction. The first phase was the "weight acceptance phase", beginning at foot strike and ending when the ground reaction forces stabilizes (vertical ground reaction force < ~2.5N/Kg). During the weight acceptance phase maximum and minimum joint angles, speeds and ranges of motion were analyzed to determine if any differences were evident between faster and slower athletes. Hip and knee joint speeds were also compared to determine if athletes predominantly use their hip or their knee to absorb the forces during the weight acceptance phase. Horizontal and vertical GRFs were evaluated to determine if all athletes used a similar ratio of horizontal and vertical forces or if differences in these ratios contributed to performance.

The second phase was the "transition" phase, beginning at the end of the weight acceptance phase and ending at the beginning of the "push off" phase. Vertical ground reaction force was used to determine the beginning and end of the transition phase. Transition began when the athlete's absolute vertical ground reaction force dropped below 2.5 newtons and ended when absolute ground reaction force rose above 2.5 newtons. One athlete's ground reaction force did not drop below 2.5 newtons and therefore their transition began when their vertical ground reaction force stabilized and ended when their vertical ground reaction force began to increase. Maximum and minimum joint angles and ranges were analyzed during this phase. Normalized GRF's were analyzed to determine if higher or lower GRF's during this phase affect performance.

The third phase was the "push off" phase, beginning when ground reaction forces increased during push off (>2.5 N/Kg), and ending at toe off. Maximum and minimum joint angles, speeds and ranges were analyzed during this phase to determine the amount of lower limb extension and direction of forces being applied during push off. Similar to the weight acceptance phase, hip and knee speed ratios and horizontal and vertical GRFs were analyzed during push off.

Maximum and minimum values and ranges were analyzed for centre of mass tracking, and spine and thorax angles throughout all phases to compare postural control between faster and slower athletes. Overall contact time was calculated and each sub-phase was represented as a percentage of overall contact time to determine if the amount of time spent in the individual plant phases affects performance. Kinematics and kinetics that were analyzed are represented in table 3.4 and 3.5.

Table 3.4 *Kinematic data analyzed during the three phases of the cutting tasks*

Kinematics	**Foot contact**	**Transition**	**Toe off**
Ankle angle	Ankle angle at foot contact	Peak ankle angle during transition	Ankle angle at toe off
Knee angle	Knee angle at foot contact	Peak ankle angle during transition	Knee angle at toe off
Hip angle	Hip angle at foot contact	Peak hip angle during transition	Hip angle at toe off
Spine angle	Spine angle at foot contact	Peak spine angle during transition	Spine angle at toe off
Thorax	Thorax	Thorax angle	Thorax

angle	angle at foot contact	during transition	angle at toe off
Centre of mass height	Centre of mass height at foot contact	Peak hip angle during transition	Centre of mass height at toe off
Centre of mass lean	Centre of mass lean at foot contact	Peak hip angle during transition	Centre of mass lean at toe off

Table 3.5 *Kinetic data analyzed during the three phases of the cutting tasks*

Kinetics	**Weight acceptance**	**Transition**	**Push off**
Contact time (%)	% contact time spent in weight acceptance	% contact time spent in transition phase	% contact time spent in push off
Horizontal vs. vertical GRF	Ratio of horizontal to vertical GRF during weight acceptance		Ratio of horizontal to vertical GRF during push off
Peak Normalized GRF	Peak GRF	Peak/Min GRF	Peak GRF
Hip to knee ratio	Ratio of hip to knee joint speed during weight acceptance		Ratio of hip to knee joint speed during push off

EMG was used to analyze muscle activation throughout the plant phase of the change of direction task. Average amplitudes were calculated and compared between groups using root mean square for the three major phases (acceptance, transition, and push off) as well as a pre contact phase of 200 frames of data. A co-contraction index was calculated for the hamstrings and quadriceps using the root mean square values during each of the three major phases and the pre contact phase to compare coordination strategies between groups. The co-contraction index was calculated by dividing the hamstring RMS by the quadriceps RMS for each phase.

EMG data was also used to perform timing analysis, comparing muscle onset, offset and duration between groups. Only the athlete's first and last muscle burst during the plant phase was analyzed for their quadriceps, hamstrings, gluteus maximus and gluteus medius muscles. A modified double threshold method was used to determine the onset/offset and duration of muscle activity for each muscle (Kamen & Gabriel, 2010). Average EMG values were taken by a 20ms window that moved at 10ms increments. If the average value surpassed the baseline value by two standard deviations from the mean, the muscle was considered "on". Baseline values were manually selected by taking the average of a manually set window over what was considered a resting EMG signal for that trial. Only the first and last muscle onset, offset and duration were used for analysis. This analysis allowed for differences in individual muscle activation timing and duration to be compared between faster and slower athletes.

3.6 Statistical Analysis

Participants were split evenly using the median time into a fast group (less time to complete the agility task) and a slow group (more time to complete the agility task) so a performance based statistical analysis could be completed. An Analysis of Variance (ANOVA) was performed to determine if differences between variables existed between groups. A Levene's test of homogeneity was used to ensure that groups were homogeneous and parametric statistical analysis was appropriate. An alpha level of 0.05 was used in this analysis.

Chapter 4

Results

The ANOVA performed on the data indicated that several variables were significantly different between the fast and slow groups. General group characteristics are presented in table 4.1. The two groups were not significantly different from one another when comparing playing experience, height, and weight.

Table 4.1 *Descriptive group characteristics*

Group	Experience (yrs)			Height (cm)			Weight (kg)		
	Mean	STD	p value	Mean	STD	p value	Mean	STD	p value
Fast	14.8	4.13	0.373	179.76	3.76	0.446	75.08	6.02	0.486
Slow	16.2	2.53		181.49	5.92		77.88	10.89	

4.1 Kinematics

Several kinematic differences were found between groups and a summary is provided in table 4.2. During the acceptance phase, the fast group demonstrated a lower centre of mass ($p=0.003$) at foot contact and more forward lean relative to the ground ($p=0.002$) than the slow group. The fast group also performed the task with more lateral lean relative to the ground during acceptance ($p=0.018$).

During the transition phase the fast group kept their centre of mass further in the direction of their intended change of direction ($p=0.003$). The fast group also had more lean relative to the ground in the direction of their intended movement throughout the transition phase (transition thorax max lateral lean $p=0.004$, and

transition thorax min lateral lean p=0.019). Spine and hip stability were found to be significantly different between groups with the fast group demonstrating less trunk rotation range (p=0.035) and less range of hip adduction/abduction during the transition phase (p=0.02).

During the push off phase, faster athletes kept their centre of mass lower and further towards the direction of their change of direction than slower athletes (push off centre of mass max height p=0.015, and centre of mass max displacement along line of travel p=0.033). The fast group was found to exhibit more lateral lean (p=0.015) but less lateral thorax range of motion during push off (p=0.01).

Athletes demonstrated significant group difference in pelvis positioning throughout all phases of the change of direction task. The fast group was found to maintain more forward rotation of their pelvis throughout the acceptance phase when compared to the slow group (acceptance pelvis max anterior/posterior tilt p=0.04, and acceptance pelvis min anterior/posterior tilt p=0.017). The fast group also rotated their hips further in the intended change of direction at foot contact (p=0.004) and displayed more lateral hip tilt towards their lead plant leg than the slow group during the acceptance phase (p=0.004). During transition the fast group maintained more lateral tilt of the pelvis towards their lead plant leg than the slow group (transition pelvis max lateral tilt p=0.002, and transition pelvis min lateral tilt p=0.027). Finally, the fast group maintained more lateral tilt of the pelvis throughout push off compared to the slow group (push off pelvis max lateral tilt p=0.038, and push off pelvis min lateral tilt p=0.008).

Table 4.2 *Summary of kinematic statistical analysis*

Variable	Group	N	Mean	SD	p value
Acceptance Centre of Mass	Fast	10	708.58	69.52	0.003
Height (mm)	Slow	9	800.12	37.53	
Acceptance Thorax Angle	Fast	10	40.24	9.51	0.002
Flexion (deg)	Slow	10	26.92	6.19	
Acceptance Thorax Angle	Fast	10	-19.53	11.55	0.018
Min Lateral Lean (deg)	Slow	10	-6.2	11.32	
Acceptance Pelvis Angle	Fast	10	30.31	6.81	0.04
Max Anterior/Posterior Tilt (deg)	Slow	10	24.28	5.22	
Acceptance Pelvis Angle	Fast	10	28.95	9.55	0.004
Max Rotation (deg)	Slow	10	43.12	9.68	
Acceptance Pelvis Angle	Fast	10	20.8	4.37	0.017
Min Anterior/Posterior Tilt (deg)	Slow	10	14.73	5.89	
Acceptance Pelvis Angle	Fast	10	-33.81	6.04	0.004
Min Lateral Tilt (deg)	Slow	10	-25.29	5.32	
Transition Centre of Mass Max	Fast	10	1830.92	106.21	0.003
Displacement Along Line of Travel (mm)	Slow	9	1626.29	135.14	
Transition Hip Angle	Fast	10	6.41	4.28	0.02
Range Lateral Tilt (deg)	Slow	10	10.86	3.49	
Transition Spine Angle	Fast	10	7.99	6.19	0.035
Range Rotation (deg)	Slow	9	14.74	6.65	
Transition Thorax Angle	Fast	10	-19.38	12.34	0.004
Max Lateral Lean (deg)	Slow	9	5.11	19.28	
Transition Thorax Angle	Fast	10	-32.63	12.35	0.019
Min Lateral Lean (deg)	Slow	9	-12.25	21.34	
Transition Pelvis Angle	Fast	10	-30.34	8.32	0.002
Max Latreral Tilt (deg)	Slow	10	-17.15	7.53	
Transition Pelvis Angle	Fast	10	-36.16	6.85	0.027
Min Lateral Tilt (deg)	Slow	10	-28.29	7.77	

Push Off Centre of Mass Max Displacement Along Line of Travel (mm)	Fast	10	2381.44	125.95	0.033
	Slow	9	2202.69	204.29	
Push Off Centre of Mass Max Height (mm)	Fast	10	790.27	45.52	0.015
	Slow	9	843.69	40.32	
Push Off Thorax Angle Max Lateral Lean (deg)	Fast	10	-32.33	11.81	0.015
	Slow	9	-12.06	20.22	
Push Off Thorax Angle Range Lateral Lean (deg)	Fast	10	14.34	9.15	0.01
	Slow	9	28.13	11.58	
Push Off Pelvis Angle Max Lateral Tilt (deg)	Fast	10	-35.66	6.97	0.038
	Slow	10	-28.41	7.48	
Push Off Pelvis Angle Min Lateral Tilt (deg)	Fast	10	-54.25	3.99	0.008
	Slow	10	-48.05	5.25	

4.2 Kinetics

The fast group demonstrated shorter foot contact time during the transition phase (p=0.001) and overall contact time (p=0.011) than the slow group. The fast group also had a higher horizontal to vertical ground reaction force ratio during the acceptance (P=0.03) and push off phases (p=0.002). A summary of the kinetic differences between groups is provided in table 4.3.

Table 4.3 *Summary of kinetic statistical analysis*

Variable	Group	N	Mean	STD	p value
Time to Complete Agility	Fast	10	2.31	0.042	0.000
Task (seconds)	Slow	10	2.51	0.076	
Contact Time (Seconds)	Fast	10	0.66	0.108	0.011
	Slow	10	0.80	0.115	
Acceptance GRF Ratio	Fast	9	0.89	0.12	0.030
(%/100)	Slow	10	0.78	0.08	
Transition Phase Contact	Fast	10	22.13	7.02	0.001
(%)	Slow	10	35.23	8.39	
Push Off GRF Ratio	Fast	9	0.78	0.06	0.002
(%/100)	Slow	10	0.68	0.05	

4.3 Neuromuscular

No differences were found between groups' average EMG amplitude values for any of the phases with the exception of the non-dominant hamstrings and erector spinae during the acceptance phase. The fast group displayed higher average EMG in both instances. No differences between groups were found for hamstring and quadriceps co-contraction indexes during any change of direction phases. A summary of the EMG co-contraction statistical analysis is presented in table 4.4.

Table 4.4 *Summary of EMG co-contraction statistical analysis*

Co-contraction Index (Ham/Quad)					
Phase	**Group**	**N**	**Mean**	**Standard Deviation**	**p value**
Dominant Pre-acceptance	1	9	0.289	0.158	0.057
	2	6	2.023	2.530	
Dominant Acceptance	1	9	0.592	0.481	0.128
	2	9	1.142	0.910	
Dominant Transition	1	9	2.240	0.937	0.413
	2	9	3.368	3.912	
Dominant Push Off	1	9	0.926	0.610	0.549
	2	9	1.171	1.034	
Nondominant Pre-acceptance	1	9	12.861	32.770	0.400
	2	6	1.055	1.547	
Nondominant Acceptance	1	9	13.048	31.065	0.260
	2	9	0.941	0.885	
Nondominant Transition	1	9	8.262	16.158	0.202
	2	9	1.071	1.366	
Nondominant Push Off	1	9	10.951	26.989	0.292
	2	9	1.148	0.676	

EMG timing analysis did not reveal any significant differences between groups. Figures 4.1 to 4.4 display each athlete's first and last muscle activation pattern from foot strike to toe off for their hamstrings, quadriceps, gluteus maximus, and gluteus medius. The coloured bars indicate when a muscle was

active. The fast group's muscle onsets/offsets are shown as dark bars while the slow group's muscle onsets/offsets are shown as shaded bars.

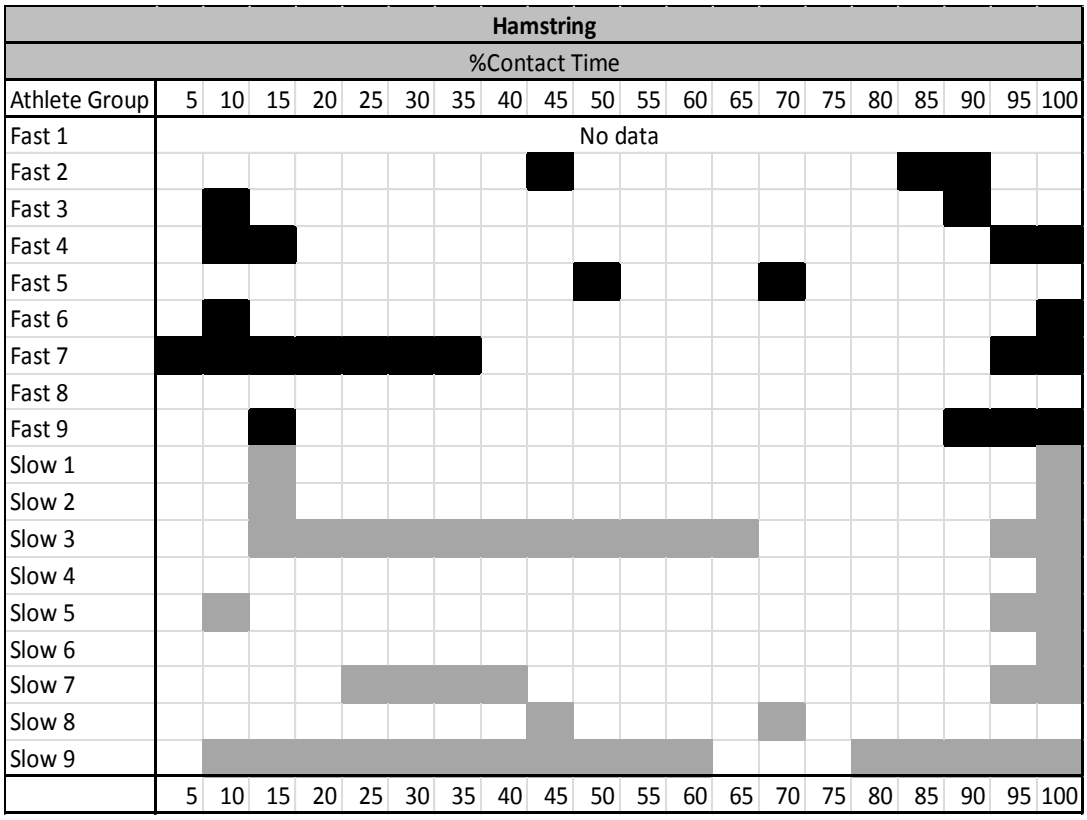

Figure 4.1 *Athlete's first and last muscle activation pattern from foot strike to toe off for their hamstring*

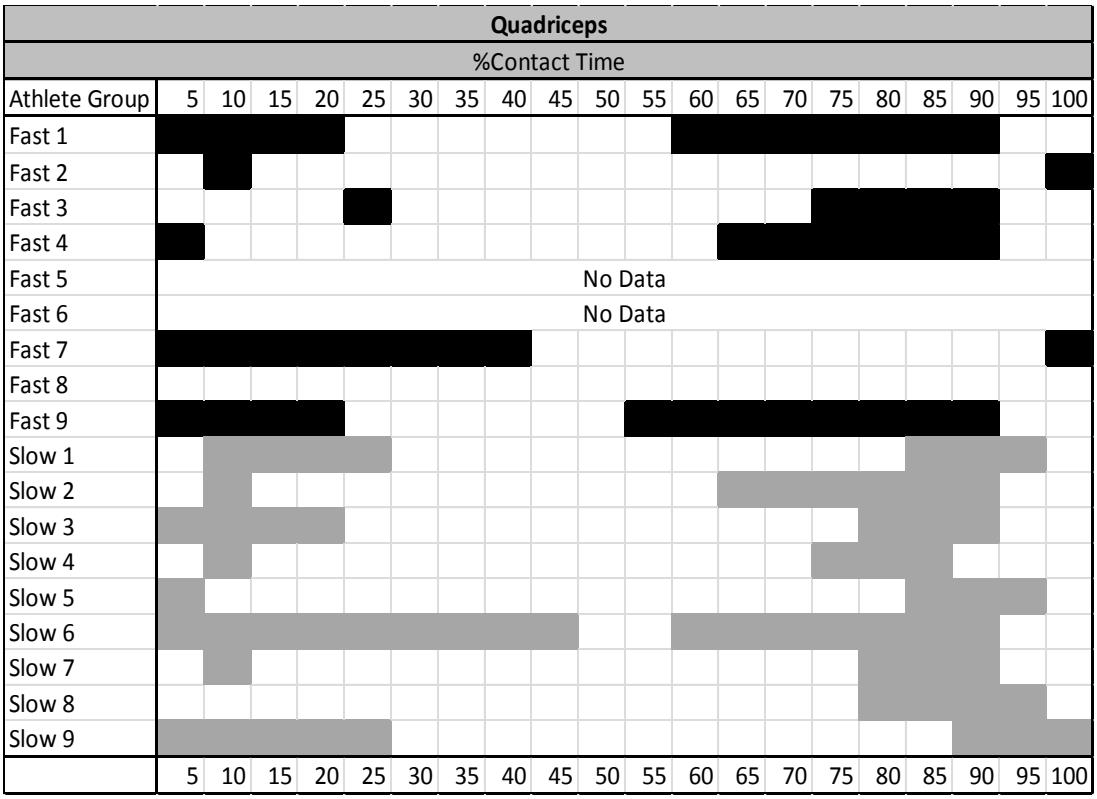

Figure 4.2 *Athlete's first and last muscle activation pattern from foot strike to toe off for their quadriceps*

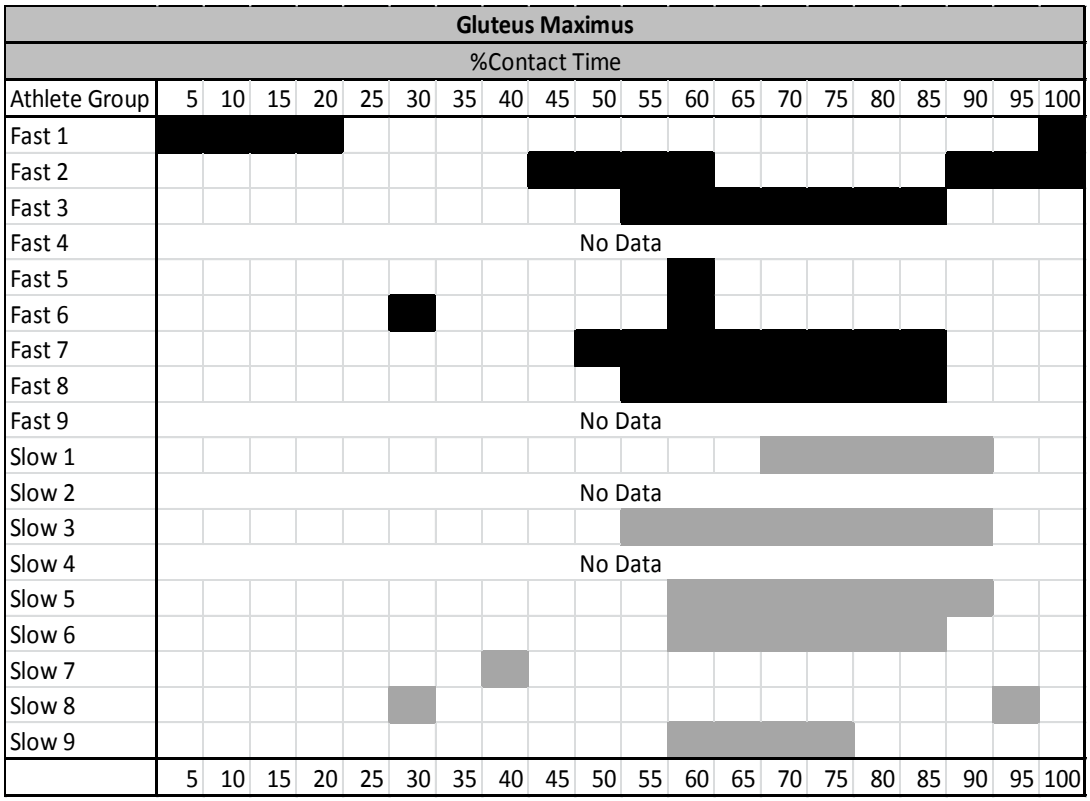

Figure 4.3 *Athlete's first and last muscle activation pattern from foot strike to toe off for their gluteus maximus*

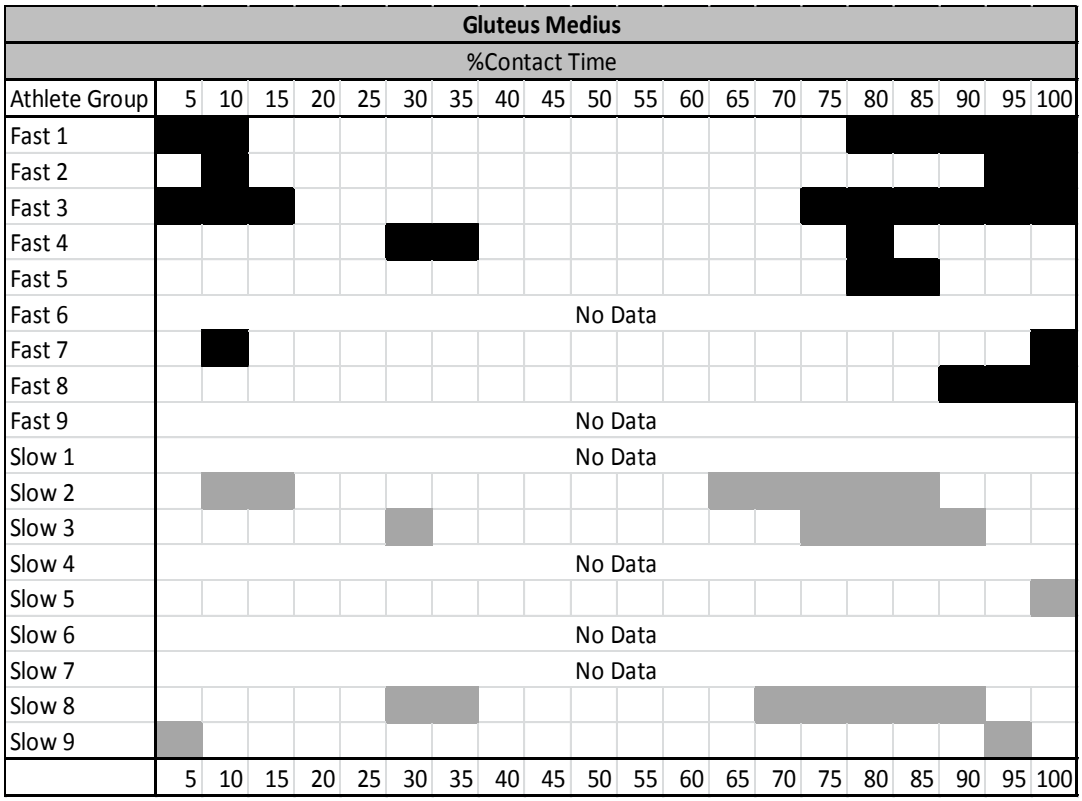

Figure 4.4 *Athlete's first and last muscle activation pattern from foot strike to toe off for their gluteus medius*

4.4 Athlete Analysis

To provide a visual of what a full athlete comparison looks like, a complete kinematic and kinetic analysis of one athlete from the fast group and one athlete from the slow group is shown in figures 4.5 to 4.10. Only the variables found to be different between groups are shown, with the fast group athlete's figures shown on the left side, and the slow group athlete's figures shown on the right side.

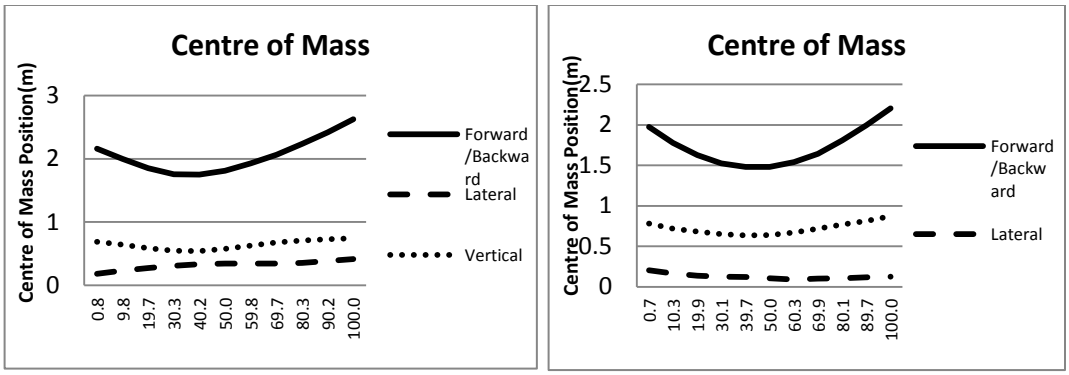

Figure 4.5 *Comparison between one fast group athlete's and one slow group athlete's centre of mass position. The fast group athlete's figure is on the left and the slow group athlete's figure on the right.*

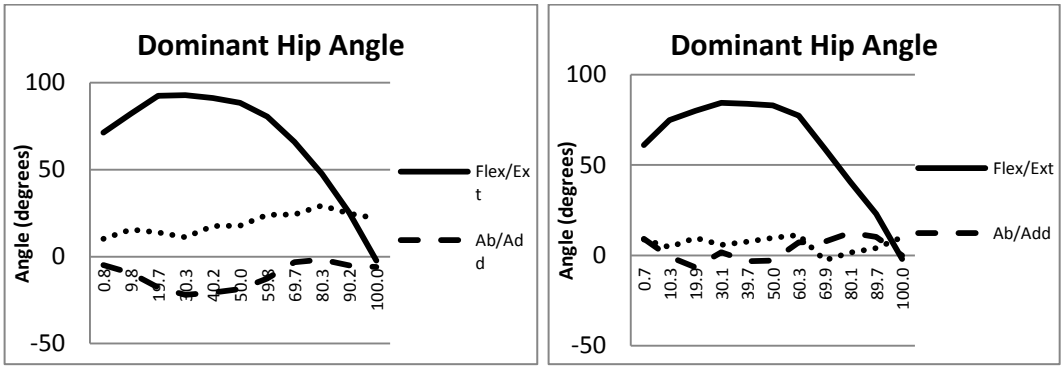

Figure 4.6 *Comparison between one fast group athlete's and one slow group athlete's Dominant Hip Angle Data. The fast group athlete's figure is on the left and the slow group athlete's figure on the right. Flexion, abduction, and internal rotation are positive while extension, adduction and external rotation are negative.*

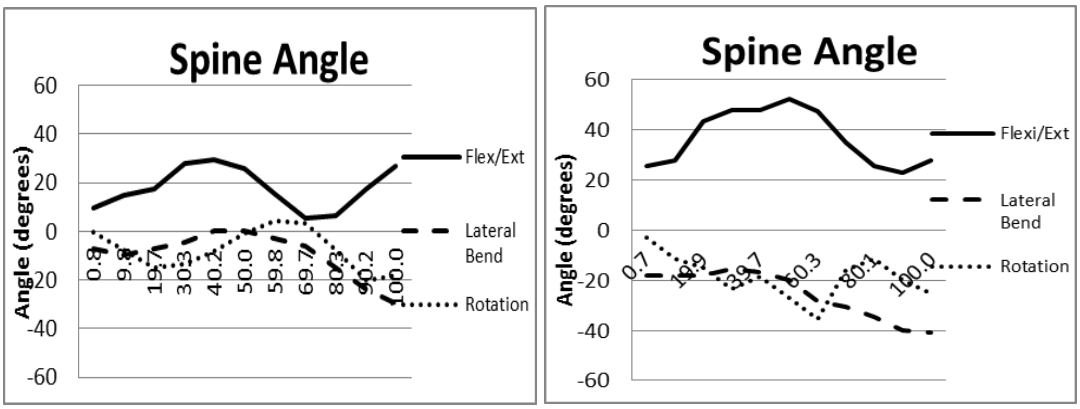

Figure 4.7 *Comparison between one fast group athlete's and one slow group athlete's Spine Angle Data. The fast group athlete's figure is on the left and the slow group athlete's figure on the right. Flexion, lateral bend towards non-dominant plant leg, and rotation toward non-dominant plant leg are positive, while extension, lateral bend towards dominant plant leg, and rotation towards dominant plant leg are negative.*

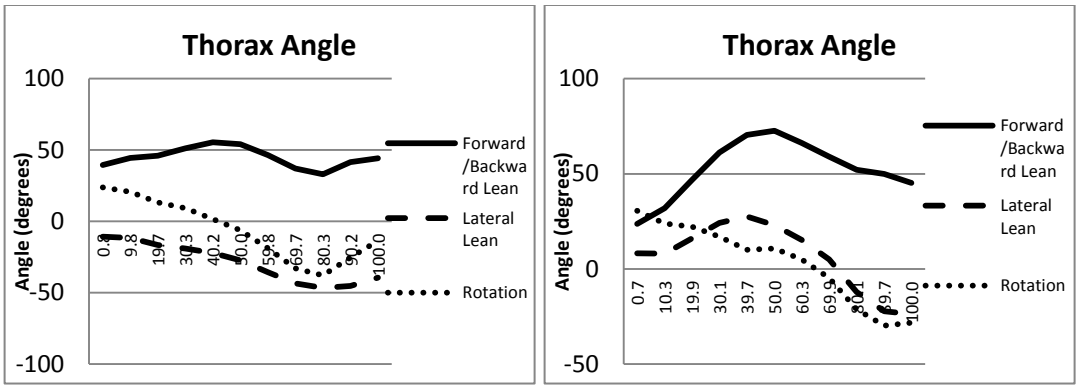

Figure 4.8 *Comparison between one fast group athlete's and one slow group athlete's Thorax Angle Data. The fast group athlete's figure is on the left and the slow group athlete's figure on the right. Forward lean, lateral lean towards non-dominant plant leg, and rotation towards non-dominant plant leg are positive while backward lean, lateral lean towards dominant plant leg and rotation toward dominant plant leg are negative.*

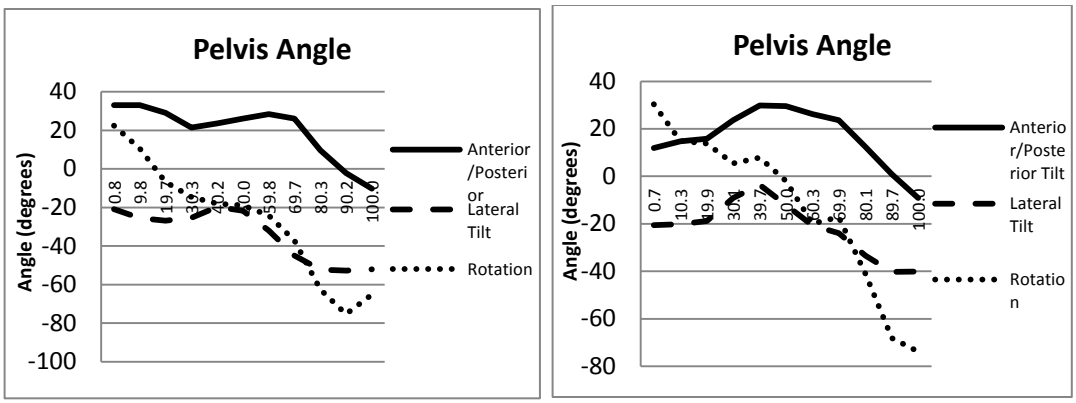

Figure 4.9 *Comparison between one fast group athlete's and one slow group athlete's Pelvis Angle Data. The fast group athlete's figure is on the left and the slow group athlete's figure on the right. Flexion, lateral tilt towards non-dominant plant leg, and rotation towards non-dominant plant leg are positive while backward lean, lateral tilt towards dominant plant leg and rotation toward dominant plant leg are negative.*

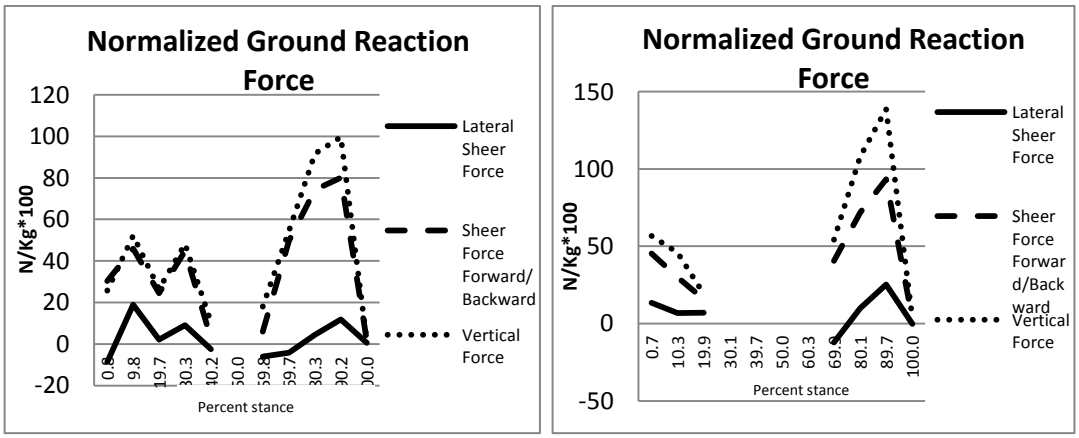

Figure 4.10 *Comparison between one fast group athlete's and one slow group athlete's normalized GRF The fast group athlete's figure is on the left and the slow group athlete's figure on the right.*

Figure 4.11 shows the EMG timing analysis for the same two athletes as the kinematic and kinetic figures above.

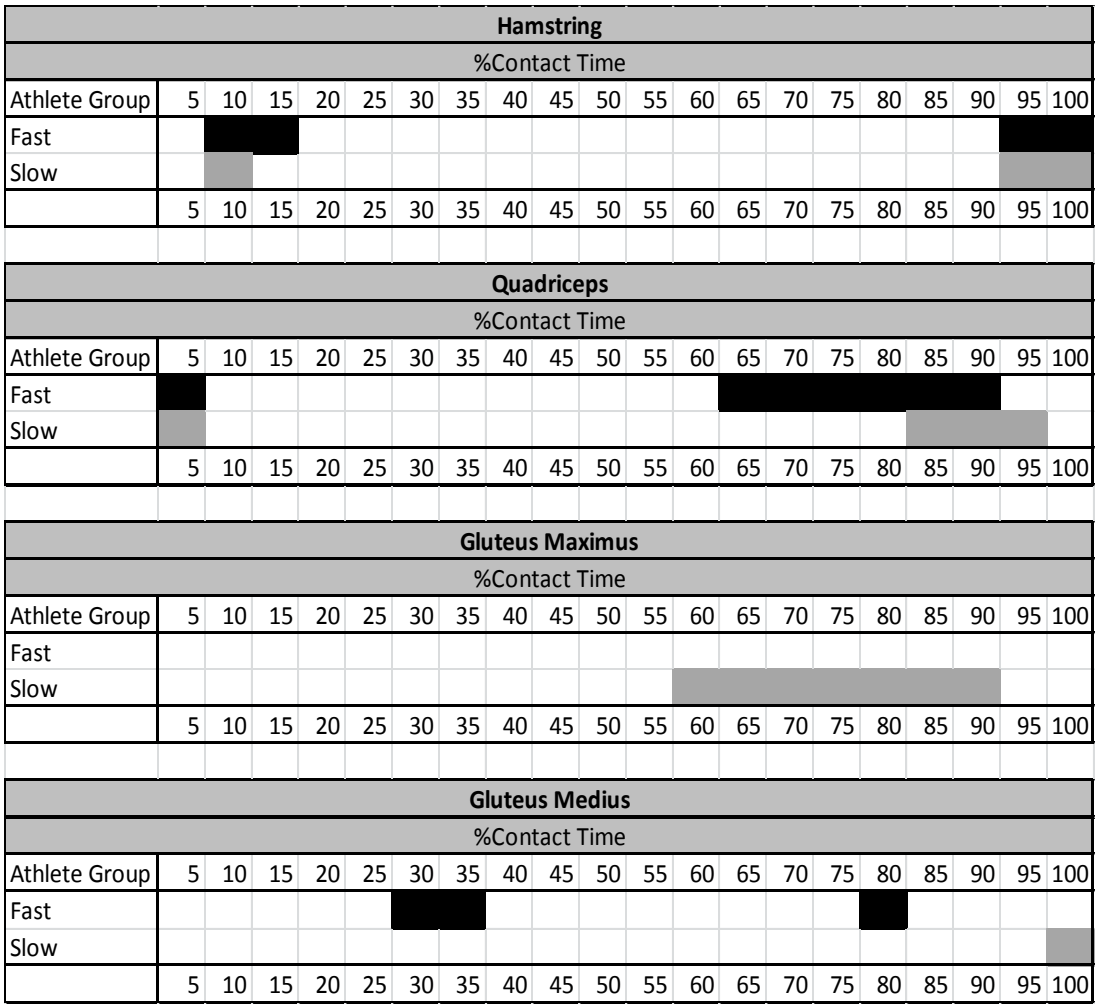

Figure 4.11 *EMG timing analysis of the hamstring, quadriceps, gluteus maximus and gluteus medius for one fast group athlete and one slow group athlete.*

Chapter 5

Discussion

The purpose of the present study was to identify biomechanical and neuromuscular coordination variables that distinguish change of direction performance between male collegiate soccer players. This research was exploratory in nature and the goal was to identify potential coordination and technical variables that contribute to agility performance. It is important to bear in mind that a change of direction has several distinct sub-phases that can all contribute to overall performance. As with muscle actions, a full 180 degree change of direction has what could be considered an eccentric phase while decelerating, an amortization phase while in transition between deceleration and acceleration, and a concentric phase while accelerating in the new direction of movement. This study only focused on the plant phase (amortization phase) of the change of direction, which was broken into three sub-phases (weight acceptance, transition, and push off) based on each individual's GRF. Future research will be required to analyze different deceleration and acceleration strategies during 180 degree change of direction.

5.1 Kinetics

Contact time has been shown to play a role in performance of several functional athletic tasks (Murphy, Lockie, & Coutts, 2003; Flanagan & Comyns, 2008). When considering change of direction performance, it is logical to think that if an athlete is able to transition from the plant phase to the acceleration phase in less time with equal efficiency then they will decrease their overall change of direction time. Faster athletes in this study were found to have shorter overall contact time than slower athletes, which supports this explanation and previous research (Murphy, Lockie, & Coutts, 2003; Flanagan & Comyns, 2008). While understanding overall contact time and its role in change of direction performance is important, it is also important to consider the different muscle actions and kinetics involved throughout contact to better understand what strategies athletes use to improve efficiency during contact. Some studies have suggested that fast eccentric muscle action and relative eccentric time during contact impacts performance of athletic tasks such as jumping (Laffaye, Wagner, & Tombleson, 2014). In the present study, when considering each athlete's relative time spent in each phase during contact, it was found that fast athletes spent less relative time in the transition phase of the change of direction. This finding suggests that more effective athletes were able to shift from eccentric to concentric muscle action faster than less effective athletes. The manner in which relative time spent in each phase was calculated in the present study was different than that used by Laffaye et al. (2014), which may help explain why the present study did not find any differences in relative time spent in the eccentric phase of contact. Another

potential explanation for the differences between the present study and that of Laffaye et al. (2014) is the task analyzed. Both countermovement jumping and change of direction require use of the stretch-shortening cycle, however, the stretch-shortening cycle of the countermovement jumps in the study performed by Laffaye et al. (2014) are shorter than those seen in the present study with change of direction. The differences in technique and the stretch-shortening cycles required for the two tasks may explain the differences between the two studies relative time spent in each phase during contact. When considering change of direction performance it appears that reducing amortization time during foot contact may be critical in separating faster and slower athletes.

It also appears that the direction of force applied to the ground by athletes plays a major role in performance. Results from this study suggest that the ratio of horizontal to vertical GRF during the acceptance and push off phases of the change of direction may play a critical role in performance. Many of the kinematic differences between groups discussed in the following paragraphs also appear to promote the ability to produce horizontal force while changing direction. This finding seems logical seeing that the goal of a change of direction is to displace the body horizontally along the ground or playing surface. The purpose of the acceptance phase is to decelerate momentum from the current direction of travel, while the goal of the push off phase is to accelerate and increase momentum in a new direction. Both of these tasks require a large amount of horizontal force with the primary plane of movement being in the horizontal direction. It seems logical that if an athlete is able to produce more force horizontally while maintaining

enough vertical force to maintain friction with the ground they will improve their ability to decelerate and accelerate during change of direction. Overall magnitude of ground reaction force in any direction did not differ between groups during any of the change of direction phases. This suggests that direction and timing of force production plays a more critical role in change of direction performance than overall magnitude.

5.2 Kinematics

Many of the kinematic findings suggest that postural positioning has a substantial impact on change of direction performance. During weight acceptance faster athletes were found to have a lower centre of mass which helps increase stability and create a more horizontal impulse to assist in deceleration. Faster athletes also demonstrate more forward and lateral lean of their thorax, which may assist athletes in lowering centre of mass during weight acceptance. The lateral lean of the thorax is also a postural adjustment that promotes the athlete's ability to apply horizontal force to the ground that was discussed earlier as potentially beneficial to change of direction performance. A lower centre of mass and more lateral lean also helps establish what Breachle and Earle (2008) term as a power line. Braechle and Earle (2008) emphasize the importance of establishing a power line during change of direction similar to that of a sprint start. Faster athletes may increase the lateral lean of their thorax to keep their centre of mass further in their intended movement direction, while allowing their legs to drive their centre of mass

from behind, much like a sprint start and the power line. It is important to note that faster athletes lowered their centre of mass and leaned further in their intended movement direction without bending or flexing their spine more than the slower athletes. This suggests that fast athletes accomplish these postures by positioning their whole body to achieve their low/leaned posture, not just their trunk and spine.

Faster athletes were also found to tilt their pelvis further toward their lead plant leg and rotate their pelvis further toward their intended change of direction at foot contact. The increased lateral tilt of the pelvis could potentially allow the fast athletes to push their base of support further from their centre of mass to increase horizontal force and power line angle, while the increased rotation of their pelvis would decrease the amount of rotational friction and torque placed on the ground and lower extremity joints which would increase efficiency while decreasing joint damage and injury risk.

The transition phase of the change of direction requires athletes to change from eccentric to concentric muscle action as fast as possible which requires a great deal of strength and stability. In the current study, faster athletes were found to have less range of motion, or what could be thought of as more stability, during the transition phase for spine rotation and hip abduction/adduction. Hip stability during change of direction has previously received some research attention, mostly to identify injury mechanisms during change of direction, in particular ACL injuries in females. Previous research has suggested that high hip adduction moments during change of direction can increase strain placed on the ACL (Imwalle, Myer, Ford, & Hewett, 2009). The current study did not analyze joint moments, however,

the only lower body kinematic difference found between groups was hip abduction/adduction range of motion during the transition phase. The slow group displayed greater hip abduction/adduction range of motion during transition, which could potentially cause an increased hip adduction moment. Previous research suggests that ACL injuries are most likely to occur near foot contact with the leg in a more extended position (Besier et al. 2000; Landry et al. 2007). Given that the slow group displayed greater hip abduction/adduction range of motion in the transition phase when the leg is in a more flexed position and has already undergone weight acceptance it is thought that the difference in hip range of motion observed in this study is more likely to impact performance than predispose athletes to injury. It is possible that if the fast group is able to maintain a more stable hip position during the transition phase then they will be able to transition from eccentric to concentric muscle action quicker. This could also partially explain why the fast group spends less relative time in transition compared to the slow group that ultimately decreases contact time and improves efficiency.

Besier et al. (2000) performed a study looking at potential ACL injury mechanisms during change of direction and found that athletes who completed the change of direction task faster tended to display a varus moment at the knee while slower athletes generally displayed valgus moments. Unfortunately, the current study did not analyze joint moments so it is unclear if this occurred in the present study but it does appear that hip and knee abduction/adduction moments and stability may play a role in distinguishing faster and slower change of direction performance. It is also important to note that Besier et al. (2000) analyzed a side

step cut which has similar principles to the crossover cut analyzed in this study but is ultimately a very different movement. Any comparisons made between the present study and the study done by Besier et. al (2000) should consider the different methodologies used in the two studies.

Less research has analyzed spine angles during change of direction so it is difficult to compare and interpret the greater spine rotation demonstrated by the slow group in the transition phase. One study did look at the impact of different postures on knee loading during side step cutting (Dempsey, Lloyd, Elliott, Steele, Munro, & Russo, 2007). Dempsey et al. (2007) concluded that torso lean or rotation in the opposite direction of the intended side step cut increased ACL stress. Therefore, maintaining a more stable torso and spine may decrease ACL stress during side step cutting. It is unknown whether or not the same principles apply to crossover cutting but it is certainly possible that torso and spine stability could affect stress placed on lower extremity joints such as the knee. In the current study maintaining a more stable spine may help the fast group preserve lower body stability and sustain their leaned posture throughout transition. This hypothesis is supported by the fact that much like the acceptance phase, the fast group displayed more lateral lean at the thorax and pelvis, suggesting that the fast group maintains a consistent and stable power line during change of direction. Finally, it is also interesting that the fast group was able to keep their centre of mass out further in the direction of their intended acceleration. This means that the fast athletes actually displace their centre of mass less along their line of travel than slower athletes even though their feet are required to travel the same distance in order to

contact the force plate. This is likely due to the lean that the faster athletes were able to establish which promoted less centre of mass displacement along the line of travel.

At push off the faster athletes already had their centre of mass further in their intended direction of acceleration as a result of the postural positions they adopted during weight acceptance and transition. Effectively, the fast group's postural decisions during weight acceptance and transition allowed them to establish a power line to accelerate from during push off. This is again supported by the fact that the fast group demonstrated a more lateral leaned posture at the thorax and pelvis with their centre of mass further in the direction of their intended movement during push off. It also appears that the fast group is able to maintain a stable leaned posture throughout push off, while the slow group displayed greater thorax lateral lean range of motion during push off. The fast group's ability to maintain their leaned posture could explain why they are able to produce more relative horizontal force than the slow group during push off.

5.3 Neuromuscular Coordination

Previous research has highlighted the importance of muscular coordination during human movement. For example, stabilizers have consistently been shown to be active prior to prime movers during voluntary movement (Zattara & Bouisset, 1988), while other studies have emphasized the role of muscular co-contraction during performance tasks (Osu, et al., 2002). It was hypothesized in the present

study that in order to perform a more efficient change of direction, fast athletes would activate their stabilizers earlier than slower athletes to provide a stable platform to produce force more effectively. No differences in muscle activation timing or duration were found between groups despite numerous kinematic and postural differences; however, timing analysis was only performed on the quadriceps, hamstrings, gluteus maximus, and gluteus medius muscles. Many of the kinematic differences between groups suggest that postural differences could potentially separate these groups rather than lower body kinematics, which may explain why no differences were found between groups' lower body muscular timing and duration. There were, however, differences between the groups hip abduction/adduction range of motion during the transition phase of the change of direction. Despite the fast group demonstrating significantly less hip abduction/adduction, no differences were found between timing, duration or magnitude of gluteus medius activation. This is interesting because gluteus medius is thought to play a major role in stabilizing the hip from internal/external rotation and hip abduction/adduction. It would seem reasonable to assume that gluteus medius could potentially play a role in the increased hip stability noted in the fast group during transition. It is possible that the fast group's increased hip stability during transition could be supported by a combination of several muscles' activity or perhaps even by the postural position acquired during transition.

Most of the kinematic differences found between groups in this study suggest that coordination and positioning of the trunk may be what separates faster and slower change of direction performances. Unfortunately, timing analysis was

not performed on the erector spinae and external oblique muscles, which may have provided more insight into what neuromuscular coordination factors could potentially drive these postural differences. It is suggested that future studies consider a more in-depth analysis of trunk musculature during change of direction. It should also be noted that it was difficult to obtain quality EMG signals of the trunk musculature during such an intense and dynamic task. Some EMG signals were lost due to poor signal quality in this study. Newer EMG technologies have emerged allowing for the capture of a greater number of electrode channels and the ability to map the muscle both temporally and spatially. Future studies should investigate activation and coordination using more advanced multichannel EMG systems in order to more accurately map the musculature.

It was also hypothesized that muscular co-contraction would play a role in change of direction performance. Some studies have suggested that co-contraction decreases as task motor learning progresses (Osu, et al., 2002). Osu et al. (2002) propose that co-contraction is used to stabilize joints to produce a more predictable and consistent movement while internal models develop to coordinate an efficient reproducible movement pattern. As internal models become more mature and accurate, co-contraction decreases in order to improve task efficiency and conserve energy. In the present study, it was hypothesized that the fast group would have developed a more efficient internal model for the change of direction movement and therefore demonstrate less co-contraction than the slow group. The statistical analysis revealed no differences between the groups' co-contraction of the hamstrings and quadriceps during any phase of the change of direction in this

study. It is interesting to note that the co-contraction of the dominant plant leg was lower for the fast group for all phases of the change of direction. Although none were significantly different, the mean co-contraction value of the fast group during the pre-acceptance phase was noticeably lower than the slow group and approached significance. The standard deviation of the slow group's dominant co-contraction indexes was quite high with many ranging higher than the means. This variance in the slow group's performance may explain why no statistically significant differences were found between dominant co-contraction indexes. Interestingly, the opposite trend was observed for the non-dominant co-contraction. The fast group displayed higher co-contraction means for all phases with standard deviations ranging higher than the means. It is difficult to conclude why these trends might exist in the present study. Future research focusing on a more in-depth analysis of muscular co-contraction during change of direction may prove valuable in understanding neuromuscular variables affecting performance.

The only EMG variables found to be statistically significant by the ANOVA in the present study were non-dominant erector spinae ($p<0.037$) and hamstring ($p<0.016$) RMS amplitude during the acceptance phase of the change of direction. This is a difficult variable to interpret because participants' maximal voluntary contractions were not collected and therefore normalization of the EMG amplitude was not possible. Interpretation of these results is further complicated because kinetics and kinematics were not analyzed on the non-dominant plant leg. The acceptance phase was determined by the kinetics of the dominant plant leg, which means the position of the non-dominant leg is difficult to determine during this

phase. While some athletes may have planted their non-dominant leg and initiated weight acceptance, others may still be reaching their non-dominant leg in a pre-acceptance phase. Without knowing the kinematics and kinetics it is difficult to be confident in any conclusions made about why non-dominant hamstring amplitude would differ between groups during the acceptance phase.

The significantly higher amplitude of the fast group's non-dominant erector spinae during weight acceptance could potentially be explained by some of the kinematic variance between groups. During weight acceptance, the fast group exhibited more forward and lateral lean of the thorax. It could be expected that this type of posture might increase erector spinae activity in order to stabilize the trunk in this position. Again without obtaining participants maximal voluntary contractions and normalizing the EMG amplitudes it is difficult to make any final conclusions from the amplitude data. It should also be noted again that it was difficult to collect quality EMG signals during such an intense dynamic task. Electrode attachment was challenging with some participants, in particular the erector spinae electrode attachment. Perspiration from the athlete along with the speed of the movement and impact on the ground made securing the electrode difficult for some participants.

5.4 Limitations

There were a number of limitations within the present study, mostly stemming from the large scope and exploratory nature of the study. The intention of this study was to identify technical variables that separate agility performance amongst athletes to provide direction for more detailed future research in this area. To analyse change of direction performance, participants needed to be evaluated to separate athletes into "fast" and "slow" groups for comparison. Time to perform the change of direction task was chosen as the performance variable to separate athletes. The median time was chosen to divide athletes into a fast and slow group respectively. This division can seriously impact the results of the analysis. The slowest athletes in the fast group and the fastest athletes in the slow group may have performance times that are quite similar, therefore, providing little separation between athletes that are already fairly analogous. Performing an analysis between the top and bottom quartile of athletes would provide a more distinct separation between groups and could identify variables affecting change of direction that were overlooked in the present study. Due to the small sample size in the present study it was decided to separate athletes based on the median time to perform the change of direction task.

Kinetic and lower body kinematic analysis was limited by the fact that athletes were only required to contact the force plate with their dominant plant leg. This issue was considered prior to data collection but it was decided not to attempt to have athletes contact separate force plates with each foot, risking altering their natural change of direction pattern. This decision has left a gap in the analysis of

the lower body kinetics and kinematics of change of direction performance. The lack of kinematic and kinetic data for the non-dominant plant leg also had implications for the EMG analysis. Without knowing the position of the non-dominant plant leg it is difficult to make any conclusion on the EMG data collected from that limb. A more in-depth analysis of the kinematics, kinetics, and neuromuscular activity of both lower limbs simultaneously during change of direction would provide a clearer picture of what lower body factors contribute to change of direction performance.

EMG analysis in this study was also limited. Due to time constraints and because the major focus of the neuromuscular analysis was timing and coordination, participants' maximal voluntary contractions were not measured prior to collecting the data, therefore EMG amplitude data could not be normalized which may have allowed for some valuable comparisons. EMG data was also limited to six general muscles bilaterally in an attempt to gain some insight as to what neuromuscular coordination factors could potentially contribute to change of direction performance. A more detailed EMG analysis may be required to fully understand what neuromuscular coordination strategies influence performance. In the present study one electrode on either side of the thigh was used to analyze general hamstring and quadriceps activity during the change of direction task. Future research may want to look at each of the quadriceps and hamstring muscles separately to provide a more complete analysis of the muscles that act on the hip and knee during change of direction. More advanced sensors and muscle mapping techniques would provide a more detailed analysis of the coordination involved

with the musculature acting on the hip and knee. It was also mentioned earlier that many of the kinematic differences noted in this study were postural, surrounding the trunk and thorax. Future studies may also want to perform a more in-depth analysis of the core musculature responsible for stabilizing the spine and thorax.

Prior to data collection, it was intended that joint moments would be analyzed in the present study. Due to an issue with the force plates and motion capture system the joint moment data for the present study was lost. Joint speeds were analyzed for the hip, knee, and ankle in an attempt to gain some understanding of lower body joint torques, however, no differences were found between group's lower body joint speeds during change of direction. It was hypothesized prior to data collection that the ratio, timing, and coordination of lower body joint moments would have an impact on performance. Future research directed at joint moment ratios, timing and coordination during change of direction will be necessary to better understand how joint torques affect change of direction performance.

There are an abundant amount of variables that could affect change of direction performance. This study attempted to provide a general overview of what variables might separate athlete's change of direction performance; however, there were several variables that were not considered in this study. Future research may want to consider variables such as: shank angle, stance width (distance between feet), foot angle (where is the toe pointed at plant), change in foot angle during plant (foot angle at plant minus foot angle at toe off), and arm contribution during change of direction to name a few. This study also only considered the plant phase

of the change of direction. Future research will be required to investigate deceleration and acceleration during change of direction. Ultimately the technical variables analyzed in the present study will need to be compared to other variables that contribute to change of direction performance such as strength and power, to determine the relationship between these variables and how they can be used together to maximize performance.

5.5 Summary

Very few research studies have analyzed change of direction performance from a technical perspective. The present study is one of the first studies to investigate change of direction performance while analyzing kinematics, kinetics, and neuromuscular activity simultaneously. This study has identified a number of variables that distinguish agility performance in an athletic population.

Key findings

1. Direction and ratio of GRF appear to play a more substantial role than the magnitude of GRF. Increased horizontal GRF during weight acceptance and push off separates fast and slow change of direction performance.
2. Decreased contact time and transition from acceptance to push off separates fast and slow change of direction performance.

3. Lower centre of mass during weight acceptance separates fast and slow change of direction performance.
4. Increased body lean throughout the foot contact separates fast and slow change of direction performance.
5. Increased hip and spine stability during transition separates fast and slow change of direction performance.
6. More advanced EMG analysis is required to analyze neuromuscular activity during change of direction within this population.
7. Future studies should be conscious that postural differences appear to play a substantial role in change of direction performance.

This study has provided a foundation of general knowledge regarding kinematics, kinetics, and neuromuscular activity during a 180 degree change of direction. Future research can use these findings to expand our knowledge of change of direction performance. Coaches and trainers can use these principles to help improve athlete's change of direction performance.

References

Barnes, J. L., Schilling, B. K., Falvo, M. J., Weiss, L. W., Creasy, A. K., & Fry, A. C. (2007). Relaionship of Jumping and Agility Performance in Female Volleyball Athletes. *Journal of Strength and Conditioning Research, 21*(4), 1192-1196.

Besier, T. F., Lloyd, D. G., Cochrane, J. L., & Ackland, T. R. (2000). External Loading of the Knee During Running and Cutting Maneuvers. *Medicine & Science in Sports & Exercise, 33*(7), 1168-1175.

Braechle, T. R., & Earle, R. W. (2008). *Essentials of Strength and Conditioning.* Omaha: Human Kinetics.

Brughelli, M., Cronin, J., Levin, G., & Chaouachi, A. (2008). Understanding Change of Direction Ability in Sport. *Sports Medicine, 38*(12), 1045-1063.

Castillo-Rodriguez, A., Fernandez-Garcia, J. C., Chinchilla-Minguet, J. L., & Alvarez Carnero, E. (2012). Relationship Between Muscular Strength and Sprints with Changes of Direction. *Journal of Strength and Conditioning Research, 26*(3), 725-732.

Chaouachi, A., Brughelli, M., Chamari, K., Levin, G. T., Abdelkrim, N. B., Laurencelle, L., et al. (2009). Lower Limb Maximal Dynamic Strength and Agility Determinants in Elite Basketball Players. *Journal of Strength and Conditioning Research, 23*(5), 1570-1577.

Ciccotti, M. G., Kerlan, R. K., Perry, J., & Pink, M. (1994). An Electromyographic Analysis of the Knee During Functional Activities. *The American Journal of Sports Medicine, 22*(5), 651-658.

Cochrane, J. L., Lloyd, D. G., Besier, T. F., Elliott, B. C., Doyle, T. L., & Ackland, T. R. (2010). Training Affects Knee Kinematics and Kinetics in Cutting Maneuvers in Sport. *Medicine & Science in Sports & Exercise, 42*(8), 1535.

Colby, S., Francisco, A., Bing, Y., Kirkendall, D., Finch, M., & Garrett, W. (2000). Electromyographic and Kinematic Analysis of Cutting Maneuvers. *The American Journal of Sports Medicine, 28*(2), 234-240.

Cronin, J. B., & Hansen, K. T. (2005). Strength and Power Predictors of Sport Speed. *Journal of Strength and Conditioning Research, 19*(2), 349-357.

Dempsey, A. R., Lloyd, D. G., Elliott, B. C., Steele, J. R., Munro, B. J., & Russo, K. A. (2007). The Effect of Technique Change on Knee Loads During Sidestep Cutting. *Medicine & Science in Sports & Exercise, 39*(10), 1765-1773.

Draper, J. A., & G, L. M. (1985). The 505 test: a test for agility in the horizontal plane. *Australian Journal of science and medicine in sport, 17*(1), 15-18.

Ebben, W. P., Fauth, M. L., Petushek, E. J., Garceau, L. R., Hsu, B. E., Lutsch, B. N., et al. (2010). Gender-based Analysis of Hamstring and Quadricep Muscle Activation During

Jump Landings and Cutting. *Journal of Strength and Conditioning Research, 24*(2), 408-415.

Flanagan, E. P., & Comyns, T. N. (2008). The use of contact time and the reactive strength index to optimize fast stretch-shortening cycle training. *Strength and Conditioning Journal, 30*(5), 32-38.

Gabbett, T. J., Kelly, J. N., & Sheppard, J. M. (2008). Speed, Change of Direction Speed, and Reactive Agility of Rugby League Players. *Journal of Strength and Conditioning Research, 22*(1), 174-181.

Green, B. S., Blake, C., & Caulfield, B. M. (2011). A Comparison of Cutting Technique Performance in Rugby Union Players. *Journal of Strength and Conditioning Research, 25*, 2668.

Harman, E. A., Rosenstein, M. T., Frykman, P. N., & Rosenstein, R. M. (1990). The Effects of Arm and Countermovement on Vertical Jumping. *Medicine and Science in Sports and Exercise, 22*(6), 825-833.

Hewit, J., Cronin, J., Button, C., & Hume, P. (2010). Understanding Change of Direction Performance Via the 90 Degree Turn and Sprint Test. *Strength and Conditioning Journal, 32*(6), 82-88.

Hoffman, J. R., Ratamess, N. A., Klatt, M., Faigenbaum, A. D., & Kang, J. (2007). Do Bilateral Power Deficits Influence Direction-Specific Movement Patterns? *Research in Sports Medicine, 15*, 125-132.

Hori, N., Newton, R. U., Andrews, W. A., Kawamori, N., McGuigan, M. R., & Nasaka, K. (2008). Does Performance of Hang Power Clean Differentiate Performance of Jumping, Sprinting, and Changing of Direction? *Journal of Strength and Conditioning Research, 22*(2), 412-418.

Huston, L. J., & Wojtys, E. M. (1996). Neuromuscular Performance Characteristics in Elite Female Athletes. *The American Journal of Sports Medicine, 24*(4), 427-436.

Imwalle, L. E., Myer, G. D., Ford, K. R., & Hewett, T. E. (2009). Relationship Between Hip and Knee Kinematics in Athletic Women During Cutting Maneuvers: A Possible Link to Noncontact Anterior Cruciate Ligament Injury and Prevention. *Journal of Strength and Conditioning Research, 23*(8), 2223-2230.

Jeffreys, I. (2006). Motor Learning - Applications for Agility, Part 1. *Strength and Conditioning Journal, 28*(5), 72-76.

Jeffreys, I. (2011). A Task-Based Approach to Developing Context-Specific Agility. *Strength and Conditioning Journal, 33*(4), 52-59.

Jones, P., Bampouras, T. M., & Marrin, K. (2009). An Investigation Into the Physical Determinants of Change of Direction Speed. *Journal of Sports Medicine and Physical Fitness, 49*(1), 97-104.

Jullien, H., Bisch, C., Largouet, N., Manouvrier, C., Carling, C. J., & Valerie, A. (2008). Does a Short Period of Lower Limb Strength Training Improve Performance in Field-Based

Tests of Running and Agility in young Proffesional Soccer Players. *Journal of Strength and Conditioning Research, 22*(2), 404-411.

Kamen, G., & Gabriel, D. A. (2010). *Essentials of Electromyography.* Champaign, IL: Human Kinetics.

Kaplan, T., Erkmen, N., & Taskin, H. (2009). The Evaluation of the Running Speed and Agility Performance in Professional and Amateur Soccer Players. *Journal of Strength and Conditioning Research, 23*(3), 774-778.

Kibler, B. W., Press, J., & Sciascia, A. (2006). The Role of Core Stability in Athletic Function. *Sports Medicine, 36*(3), 189-198.

Laffaye, G., Wagner, P. P., & Tombleson, T. I. (2014). Countermovement Jump Height: Gender and Sport-Specific Differences in the Force-Time Variables. *The Journal of Strength and Conditioning Research, 28*(4), 1096-1105.

Landry, S.C., McKean, K. A., Hubley-Kozey, C. L., Stanish, W. D., & Deluzio, K. J. (2007). Neuromuscular and Lower Limb Biomechanical Differences Exist Between Male and Female Elite Adolescent Soccer Players During an Unanticipated Run and Crosscut Maneuver. *The American Journal of Sports Medicine, 35*(11), 1901-1911.

Little, T., & Williams, A. G. (2005). Specificity of Acceleration, Maximum Speed, and Agility in Professional Soccer Players. *Journal of Strength and Conditioning Research, 19*(1), 76-78.

Lloyd, D. G., & Buchanan, T. S. (2001). Strategies of Muscular Support of Varus and Valgus Isometric Loads at the Human Knee. *Journal of Biomechanics, 34*, 1257-1267.

Mayhew, J. L., Piper, F. C., Schwegler, T. M., & Ball, T. E. (1989). Contributions of Speed Agility and Body Composition to Anaerobic Power Measurement in College Football Players. *Journal of Applied Sport Science Research, 3*(4), 101-106.

McGill, S. (2010). Core Training: Evidence Translating to Better Performance and Injury Prevention. *Strength and Conditioning Journal, 32*(3), 33-46.

McGill, S. M., Grenier, S., Kavcic, N., & Cholewicki, J. (2003). Coordination of Muscle Activity to Assure Statbility of the Lumbar Spine. *Journal of Electromyography and Kinesiology, 13*, 353-359.

McLean, S. G., Lipfert, S. W., & Van Den Bogert, A. J. (2004). Effect of Gender and Defensive Opponent on the Biomechanics of Sidestep Cutting. *Medicine & Science in Sports & Exercise, 36*, 1008-1016.

McLean, S. G., Walker, K. B., & Van Den Bogert, A. J. (2005). Effect of Gender on Lower Extremity Kinematics During Rapid Direction Changes: An Integrated Analysis of Three Sports Movements. *Journal of Science & Medicine in Sport, 8*(4), 411-422.

Miller, M. G., Herniman, J. J., Ricard, M. D., Cheatham, C. C., & Michael, T. J. (2006). The Effects of a 6-Week Plyometric Training Program on Agility. *Journal of Sport Science and Medicine, 5*, 459-465.

Mills, J. D., Taunton, J. E., & Mills, W. A. (2005). The effect of a 10-Week Training Regimen on Lumbo-pelvic Stability and Athletic Performance in Female Athletes: A Randomized-Controlled Trial. *Physical Therapy in Sport, 6*, 60-66.

Murphy, A. J., Lockie, R. G., & Coutts, A. J. (2003). Kinematic Determinants of Early Acceleration in Field Sport Athletes. *Journal of Sports Science and Medicine, 2*, 144-150.

Myer, G. D., Ford, K. R., Palumbo, J. P., & Hewett, T. E. (2005). Neuromuscular Training Improves Performance and Lower-Extremity Biomechanics in Female Athletes. *Journal of Strength and Conditioning Research, 19*(1), 51-60.

Neptune, R. R., Wright, I. C., & Van Den Bogert, A. J. (1999). Muscle Coordination and Function During Cutting Movements. *Medicine and Science in Sports and Exercise, 31*(2), 294-302.

Nesser, T. W., Huxel, K. C., Tincher, J. L., & Okada, T. (2008). The Relationship Between Core Stability and Performance in Devision 1 Football Players. *Journal of Strength and Conditioning Research, 22*(6), 1750-1754.

Nimphius, S., McGuigan, M. R., & Newton, R. U. (2010). Relationship Between Strength, Power, Speed, and Change of Direction Performance of Female Softball Players. *Journal of Strength and Conditioning Research, 24*(4), 885-895.

Nyland, J. A., Caborn, D. N., Shapiro, R., & Johnson, D. L. (1999). Crossover Cutting During Hamstring Fatigue Produces Transverse Plane Knee Control Deficits. *Journal of Athletic Training, 34*(2), 137-143.

Okada, T., Huxel, K. C., & Nesser, T. W. (2011). Relationship Between Core Stability, Functional Movement, and Performance. *Journal of Strength and Conditioning Research, 25*(1), 252-261.

Osu, R., Franklin, D. W., Kato, H., Gomi, H., Domen, K., Yoshioka, T., et al. (2002). Short- and Long-Term Changes in Joint Co-Contraction Associated with Motor Learning as Revealed From Surface EMG. *Journal of Neurophysiology, 88*, 991-1004.

Porter, J. M., Nolan, R. P., Ostrowski, E. J., & Wulf, G. (2010). Directing Attention Externally Enhances Agility Performance: A Qualitative and Quantitative Analysis of the Efficacy of Using Verbal Instructions to Focus Attention. *Frontiers in Psychology, 1*(216), 1-7.

Randell, A. D., Cronin, J. B., Keogh, J. W., & Gill, N. D. (2010). Transference of strength and power adaptation to sports performance-horizontal and vertical force production. *Strength and Conditioning Journal, 32*(4), 100-106.

Raven, P. B., Gettman, L. R., Pollock, M. L., & Cooper, K. H. (1976). A Physiological Evaluation of Professional Soccer Players. *British Journal of Sports Medicine, 10*, 209-216.

Reilly, T., Williams, A. M., Nevill, A., & Franks, A. (2000). A Multidisciplinary Approach to Talent Identification in Soccer. *Journal of Sport Science, 18*, 695-702.

Serpell, B. G., Ford, M., & Young, W. B. (2010). The Development of a New Test of Agility for Rugby League. *Journal of Strength and Conditioning Research, 24*(12), 3270-3277.

Sheppard, J. M., & Young, W. B. (2005). Agility literature review: Classifications, training and testing.

Sheppard, J. M., & Young, W. B. (2006). Agility literature review: Classifications, training and testing. *Journal of Sport Science, 24*(9), 915-928.

Sheppard, J. M., Young, W. B., A, D. T., Sheppard, T. A., & Newton, R. U. (2006). An Evaluation of a New Test of Reactive Agility and its Relationship to Sprint and Change of Direction Speed. *Journal of Science and Medicine in Sport, 9*, 342-349.

Shepperd, J. M., Young, W. B., Doyle, T. L., Sheppard, T. A., & Newton, R. U. (2006). An Evaluation of a New Test of Reactive Agility and its Relationship to Sprint Speed and Change of Direction Speed. *Journal of Science and Medicine in Sport, 9*, 342-349.

Shinkle, J., Nesser, T. W., Demchak, T. J., & McMannus, D. M. (2012). Effect of Core Strength on the Measure of Power in the Extremities. *Journal of Strength and Conditioning Research, 26*(2), 373-380.

Thomas, K., French, D., & Hayes, P. R. (2009). The Effect of Two Plyometric Training Techniques on Muscular Power and Agility in Youth Soccer Players. *Journal of Strength and Conditioning Research, 23*(1), 332-335.

Turner, A. N., & Jeffreys, I. (2010). The Stretch-Shortening Cycle: Proposed Mechanisms and Methods for Enhancement. *Strength and Conditioning Journal, 32*(4), 87-99.

Twist, P. W., & Benicky, D. (1996). Conditioning Leteral Movement for Multi-Sport athletes: Practical Strength and Quickness Drills. *Strength and Conditioning*, 10-19.

Vescovi, J. D., & Mcguigan, M. R. (2008). Relatioship between sprinting, agility, and jump ability in female athletes. *Journal of Sport Sciences, 26*(1), 97-107.

Wallmann, H. W., Gillis, C. B., & Martinez, N. J. (2008). The Effects of Different Stretching Techniques of the Quadriceps Muscle on Agility Performance in Female Collegiate Soccer Athletes: A Pilot Study. *North American Journal of Sports Physical Therapy, 3*(1), 41-47.

Wojtys, E. M., Hutson, L. J., Taylor, P. D., & Bastian, S. D. (1996). Neuromuscular Adaptations in Isokinetic, Isotonic, and Agility Training Programs. *The American Journal of Sports Medicine, 24*(2), 187-192.

Young, W. B., James, R., & Montgomery, I. (2002). Is Muscle Power Related to Running Speed With Changes of Direction. *Journal of Sports Medicine and Physical Fitness, 42*(3), 282-288.

Young, W. B., McDowell, M. H., & Scarlett, B. J. (2001). Specificity of Sprint and Agility Training Methods. *Journal of Strength and Conditioning Research, 15*(3), 315-319.

Zajac, F. E. (1993). Muscle Coordination of Movement: A Perspective. *Journal of Biomechanics, 26*, 109-124.

Zattara, M., & Bouisset, S. (1988). Posturo-kinetic Organization During the Early Phase of Voluntary Upper Limb Movement. 1 Normal Subjects. *Journal of Neurology, Neurosurgury, and Psychiatry, 51*, 956-965.

Zazulak, B. T., Hewett, T. E., Reeves, P. N., Goldberg, B., & Cholewicki, J. (2007). The Effects of Core Proprioception on Knee Injury. *The American Journal of Sports Medicine, 35*(3), 368-373.

Appendix A

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Contact Time	Equal variances assumed	.516	.482	-2.817	18	.011	-.141000	.050053	-.258933	-.023067
	Equal variances not assumed			-2.817	17.933	.011	-.141000	.050053	-.258971	-.023029

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
AGRF Ratio	Equal variances assumed	.004	.953	2.371	17	.030	.108649	.045829	.000124	.217175
	Equal variances not assumed			2.325	14.122	.035	.108649	.046723	-.004073	.221372

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
T Phase CT	Equal variances assumed	.321	.578	-3.787	18	.001	-13.095000	3.458312	-21.243405	-4.946595
	Equal variances not assumed			-3.787	17.454	.001	-13.095000	3.458312	-21.265179	-4.924821

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
PGRF Ratio	Equal variances assumed	.269	.611	3.584	17	.002	.091965	.025659	.031202	.152728
	Equal variances not assumed			3.551	15.803	.003	.091965	.025897	.030216	.153714

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
ACM Max Z	Equal variances assumed	3.695	.072	-3.510	17	.003	-91.544775	26.077707	-153.298215	-29.791336
	Equal variances not assumed			-3.619	14.109	.003	-91.544775	25.293562	-152.573549	-30.516002

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
ATA Min X	Equal variances assumed	2.072	.167	3.713	18	.002	13.321764	3.587910	4.868001	21.775527
	Equal variances not assumed			3.713	15.471	.002	13.321764	3.587910	4.748638	21.894890

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
ATA Min Y	Equal variances assumed	.017	.897	-2.607	18	.018	-13.330796	5.113735	-25.379676	-1.281916
	Equal variances not assumed			-2.607	17.993	.018	-13.330796	5.113735	-25.380074	-1.281518

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
APelMaxX	Equal variances assumed	.237	.632	2.220	18	.040	6.024954	2.714068	-.369877	12.419786
	Equal variances not assumed			2.220	16.865	.040	6.024954	2.714068	-.406769	12.456677

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
APelMaxZ	Equal variances assumed	.005	.946	-3.296	18	.004	-14.172304	4.299775	-24.303349	-4.041259
	Equal variances not assumed			-3.296	17.997	.004	-14.172304	4.299775	-24.303511	-4.041098

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
APelMinX	Equal variances assumed	.745	.400	2.619	18	.017	6.076303	2.320143	.609628	11.542978
	Equal variances not assumed			2.619	16.594	.018	6.076303	2.320143	.569858	11.582748

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
APelMinY	Equal variances assumed	.376	.548	-3.347	18	.004	-8.522902	2.546278	-14.522391	-2.523412
	Equal variances not assumed			-3.347	17.714	.004	-8.522902	2.546278	-14.530655	-2.515148

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
TCM Max X	Equal variances assumed	1.944	.181	3.415	17	.003	204.628773	59.922272	62.729552	346.527995
	Equal variances not assumed			3.349	14.080	.005	204.628773	61.105383	57.159687	352.097859

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
THA Range Y	Equal variances assumed	.312	.583	-2.549	18	.020	-4.453296	1.746899	-8.569305	-.337286
	Equal variances not assumed			-2.549	17.290	.021	-4.453296	1.746899	-8.583766	-.322825

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
TSA Range Z	Equal variances assumed	.087	.772	-2.292	17	.035	-6.750992	2.945615	-13.726370	.224387
	Equal variances not assumed			-2.283	16.453	.036	-6.750992	2.957312	-13.775257	.273274

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
TTA Max Y	Equal variances assumed	1.715	.208	-3.333	17	.004	-24.488103	7.347755	-41.887990	-7.088215
	Equal variances not assumed			-3.256	13.382	.006	-24.488103	7.521055	-42.744920	-6.231286

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
TTA Min Y	Equal variances assumed	1.745	.204	-2.581	17	.019	-20.371431	7.892397	-39.061059	-1.681803
	Equal variances not assumed			-2.510	12.537	.027	-20.371431	8.115004	-40.227236	-.515626

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
TPelMaxY	Equal variances assumed	.445	.513	-3.717	18	.002	-13.187671	3.547601	-21.546459	-4.828884
	Equal variances not assumed			-3.717	17.823	.002	-13.187671	3.547601	-21.553538	-4.821804

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
TPelMinY	Equal variances assumed	1.244	.279	-2.404	18	.027	-7.875129	3.275552	-15.592920	-.157339
	Equal variances not assumed			-2.404	17.718	.027	-7.875129	3.275552	-15.603390	-.146869

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
PCM Max X	Equal variances assumed	1.310	.268	2.323	17	.033	178.741582	76.934679	-3.443950	360.927115
	Equal variances not assumed			2.266	13.052	.041	178.741582	78.887922	-13.324472	370.807637

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
PCM Max Z	Equal variances assumed	.486	.495	-2.695	17	.015	-53.422737	19.825942	-100.371654	-6.473820
	Equal variances not assumed			-2.713	16.998	.015	-53.422737	19.692965	-100.057162	-6.788312

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
PTA Max Y	Equal variances assumed	1.815	.196	-2.704	17	.015	-20.270445	7.496100	-38.021621	-2.519269
	Equal variances not assumed			-2.631	12.609	.021	-20.270445	7.704563	-39.108387	-1.432503

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
PTA Range Y	Equal variances assumed	.301	.590	-2.894	17	.010	-13.782351	4.762929	-25.061228	-2.503473
	Equal variances not assumed			-2.857	15.244	.012	-13.782351	4.824634	-25.327869	-2.236833

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									97% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
PPelMaxY	Equal variances assumed	.912	.352	-2.242	18	.038	-7.248383	3.232578	-14.864918	.368152
	Equal variances not assumed			-2.242	17.911	.038	-7.248383	3.232578	-14.868141	.371374

Curriculum Vitae

Ken Morrison

University of New Brunswick (BScKin, 2011)