Changes in movement control and coordination

with increasing skill in females and males

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STATEMENT OF AUTHORSHIP

I, Michaela Rose Bruton, hereby declare that this submission is my own work and that it contains no material previously published or written by another person, except as indicated in the text. No material has been submitted previously, in whole or in part, for the award of any other academic award.
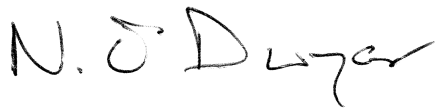
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SUPERVISORS STATEMENT

This is to certify that the thesis entitled 'Changes in movement control and coordination with increasing skill in males and females', submitted by Michaela Rose Bruton in fulfilment of the degree of Doctor of Philosophy, is her own work and is ready for submission.

A/Prof Nicholas O'Dwyer

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ABSTRACT

In studies that have compared females and males on movement tasks, the emphasis has been on performance outcome measures, with comparatively little focus upon the coordination process that underpins the performance. Coordinated motor skills are developed through practice; any differences in coordination and performance between the sexes may therefore reflect differences in the volume of prior practice or experience with a task. Investigating the changes in coordination that occur with practice also provides insight into the underlying processes of motor control, yet research in the field of motor control rarely considers novice performers, nor the comparison of the sexes.

There has been recent interest in the exploration of sex differences in movement that may occur during the performance of landing related tasks. It has been suggested that the inconsistency of findings may in part be accounted for by the confounding factor of prior practice or experience in the motor task. To further explore the role that experience plays in shaping movement kinematics, the study that comprises chapter three included both recreational and competitive surfers and compared their performance with non-surfers on a drop-landing task (surfers are exposed to incidental landing with an increasing frequency as they progress in the sport). Knee flexion and ankle dorsiflexion at initial ground contact were greater in male participants, independently of surfing experience. Body configuration at initial contact represents the neuromuscular strategy being used to land and absorb force; it was possible that males and females here used different movement strategies, to achieve the same performance outcome. In both females and males, range of motion at these joints was related to surfing experience, with experienced surfers using a greater range of motion. Recreational female surfers landed in a more extended ankle and knee posture than all other groups and had less ankle dorsiflexion at the end of landing. In conclusion, movement pattern during landing differed on the basis of both sex and level of expertise, with the sex difference most apparent in females with some but not a lot of surfing experience.

The results of the first study highlighted a need to consider the mediating factor of prior practice or experience when comparing movement and performance between females and males. Evidence from this and other landing research suggests that sex differences in movement can be accounted for at least in part by experience; the related question of whether females and males achieve similar performance improvement from an equal volume of practice has not been addressed. Chapter four explored this question using the slalom-skiing simulator task to compare performance and rate of learning between the sexes on a novel task. Whole body coordination and electromyography (EMG) were employed to provide a comprehensive account of movement kinematics and kinetics. Eight males and eight females performed five days of practice (25 x 1 min trials). There were no differences in rate of learning for any outcome variable. A male performance advantage was observed for the related outcome measures of platform oscillation frequency, cycle duration and work performed, but these differences were largely accounted for by the higher spring resistance settings of the apparatus for heavier male subjects, in accordance with manufacturer specifications. Most importantly, it was shown that both males and females were moving towards their optimal frequency with practice – performance and success at the task actually comparable. Some minimal differences observed in movement kinematics between the sexes also were attributable to height differences, interacting with the apparatus set up. The only kinematic difference not readily explained was that males employed greater maximum knee flexion throughout the movement cycle. In summary, minor differences in movement performance and kinematics were attributable to anthropometric differences between the sexes, but otherwise males and females showed similar initial and final performance outcomes and achieved similar gains from an equal volume of practice. The findings support the view that any sex differences observed in movement commonly may be accounted for by differences in prior experience.

The results from chapter four provided evidence for the idea that similar performance can be achieved via different movement patterns; otherwise understood as the redundancy problem. A fundamental concept in motor control is that complex movement is organised into a low dimensional control space and that this develops through practice. The basis of this coordination structure is the coupling and correlation between elements in the motor system. Principal component analysis (PCA) provides a

powerful tool for quantifying these relations and allows the reduction of complex movement datasets into a smaller number of variables. This can provide insight into the development of coordinated movement and has been applied to a limited number of studies investigating longitudinal changes with learning. Chapter six applied a recently developed technique in PCA, to provide further insight into the changes in coordination that occurred with practice on the skiing-simulator. Whereas traditional PCA uses Pearson's correlation coefficients (PCC) to quantify correlation between elements, the more recent technique employs linear systems analysis and a measure of overall coherence (COH) to quantify correlation in the frequency domain. We compared the changes in the dimensionality of both kinematic and IEMG signals over the course of practice to establish which technique could provide better insight into the underlying coordination structure for this movement. There were no differences between male and female performers for this measure of coordination, which again supported the idea that with equal practice, performance is similar, despite any differences in anthropmetrics. The variance accounted for by the first principal component increased with practice and was significantly greater using the COH method compared to the PCC. Fewer principal components were required to account for 90% of the variance using COH; the number also decreased significantly with practice only for this method. The loading of original variables onto the principal components revealed that all variables were loaded strongly onto the first principal component. Overall the results revealed whole body movement on the skiing-simulator could be defined in a low dimensional space and that the dimension was reduced further over the course of practice. More importantly, the hidden low dimensional structure was best revealed when PCA incorporating correlation in the frequency domain was employed.

PUBLICATIONS

The systematic review component of **Chapter 1** and **Appendix A** has been published –

Bruton MR, O'Dwyer N and Adams R. Sex differences in the kinematics and neuromuscular control of landing: Biological, environmental and sociocultural factors. Journal of Electromyography and Kinesiology 2013;23 (4):747-58

Parts of the thesis that are being prepared for submission to peer-reviewed journals include:

Chapter 2
Bruton MR, O'Dwyer N and Adams R. (Under preparation). Sex differences in landing are more apparent in recreational female surfers than in competitive surfers or non-surfers.

Chapter 4
Bruton MR, O'Dwyer N and Halaki M. (Under preparation). Absence of sex differences in performance a novel whole body movement task before and after an equal volume of practice

Chapter 6
Bruton MR, O'Dwyer N and Halaki M. (Under preparation). Changes in coordinative structure with practice.

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OUTLINE OF THESIS STRUCTURE

General summary

In this thesis, a comprehensive investigation of motor performance and movement coordination and their changes with practice in both males and females is sought. Owing to the fact that males are generally seen as more proficient than females in the physical domain, we were interested in establishing whether the sexes perform differently (for the task of landing) and whether they make differential gains from practice (when tasked with learning a novel slalom ski-simulator task). Literature from both the cognitive and motor domains presented suggests that practice and experience is an important mediator in any differences between males and females.

In an attempt to understand how coordination is organised in the successful execution of any given task, efforts have been directed towards quantifying the spatial and temporal relationships between body segments and muscles. Research in this vein has traditionally been split into two approaches that differ in what they ascribe as the basis of the organisation - information processing (that emphasises the role of the CNS) and dynamical systems (that emphasises the role of the environment). However despite this debate, it is generally accepted that coordination is achieved through a reduction in the number of independent elements that are under direct control. There has been comparatively little focus by any approach on movement during the early and later phases of skill development, and even less for tasks that involve the whole body. A handful of studies have investigated changes in the number of independent elements by incorporating PCA as a tool for uncovering hidden structure in coordination, with practice on tasks including a slalom skiing simulator.

Aims

The overall aim and focus of this thesis was twofold (this is reflected in the overall structure): to explore coordination as a function of motor skill in male and female participants, to reveal any differences or similarities that may be apparent between the sexes and to provide further insight into the organisation of skilled movement, as it develops with practice in both males and females. Specific questions to be addressed were as follows:

Do females and males display different kinematic movement patterns when performing a laboratory-constrained drop landing and can prior experience in a related activity (surfing) account for any differences in these kinematic variables?

Are the changes that occur in both performance outcome measures and movement coordination (kinematics and EMG) with practice on a novel whole-body task consistent between males and females? Furthermore do males and females derive the same improvements from a given volume of practice?

Can a recent advance in PCA, incorporating linear systems analysis to overcome limitations in qauntifying dynamic relations between signals, provide better insight into sex differences in movement and coordinative processes over the course of practice?

Significance

Few studies comparing male and female motor performance have included measures of coordination in a whole-body task. By including both males and females, any sex differences in coordination and the rate of learning can be established. If any sex differences were to be observed, this would have implications for the training and coaching of females in athletic, physical education and workplace settings. For example if females were to establish gains from practice at a slower rate than males, more time to practice and establish fundamental motor skills may be required.

The study of coordination and control in the human movement system is a fairly recent endeavour and includes multiple approaches that aim to uncover 'hidden' structure in skilled movement. Research that includes a longitudinal approach to quantifying changes with practice for whole-body tasks has been limited to date. Investigating the changes that occur with the development of skill can provide insight into the mechanisms underlying coordinated movement.

Scope

Chapter 1 presents a general introduction and review of sex differences in motor performance, learning and movement coordination. This includes a systematic exploration of landing and coverage of proposed biological and environmental explanations put forward to account for differences..

Chapter 2 presents a study that examined sagittal-plane kinematics in males and females performing a 60 cm drop-landing task. Groups representing three different degrees of experience in the sport of surfing (non surfers, recreational and competitive surfers) were included to explore the role that incidental experience in landing would have on performance.

Chapter 3 presents the common methodology for the second experiment that used a slalom ski simulator apparatus to investigate performance, whole body coordination and learning of a novel whole-body task.

Chapter 4 presents the first investigation from the slalom ski data; the initial performance and changes in performance and kinematics that occur with practice on the slalom-skiing simulator - in male and female participants. By controlling task requirements, prior experience (by using a novel task) and volume of practice, the sexes could be properly compared.

Chapter 5 presents a second literature review and background in the topic of whole body coordination, the techniques used to quantify this and the changes that occur with practice.

Chapter 6 presents a further analysis of the changes in coordination in males and females that occur with practice, incorporating a recently-developed advance in PCA method.

Chapter 7 provides a synthesis of the findings and future directions of research.

CHAPTER 1.

Introductory review

Sex differences in movement coordination and skill learning

The systemic search that was adapted within this section is published (almost in entirety) as a systematic review:

1.1.   General overview of the study of 'sex differences'

The exploration of differences between the sexes has captured the attention of researchers in the behavioural and biological sciences over the past 50 years. Research has encompassed areas such as anatomy and biochemistry [Aiello and Dean, 2002; McCarthy and Konkle, 2005], spatial perception [Halpern, 1996], emotional response [Hamann, 2005], attention [Bayliss et al., 2005], motivation and cognitive processing [Hamilton, 2008]. Despite persistent calls for careful consideration to be given to both the methodology of the research [Fairweather, 1976] and the often small differences and overlap in performance reported [Caplan et al., 1985], the idea that there are consistent and meaningful differences between males and females (in particular for cognition) still prevails in both the scientific community and popular culture at large [Eliot, 2011].

Continuing argument over whether differences actually exist has not restrained the number of competing theories about why differences either are or are not present. These are drawn loosely along the competing lines of biology or environment (or nature/nurture) [Eagly, 1995]. In explaining sex differences, researchers consider both the ultimate and proximate causes of difference [Becker et.al., 2008]. Ultimate causes explain traits in terms of the evolutionary forces acting upon the sexes (i.e. natural and sexual selection). Proximate causes include sex chromosomes/genetics and sex steroids/hormones (i.e. physiological factors) and phenotypic plasticity (i.e. environmental factors). Most research in the study of sex differences however has largely been descriptive; post hoc

explanations are then discussed where differences arise in a given domain. Perhaps due to the complexity of potential factors, what has resulted is a body of research where for every study confirming a sex difference; there appears another with evidence to the contrary [e.g. Bruton et al., 2013].

The common conclusion from these conflicting data is that there are many important mediating or confounding variables that interact and must be carefully considered when comparing the sexes on any task. These include but are not limited to prior training and/or strategy development, as well as contextual factors such as the instructions provided and other aspects the task set-up [Caplan et al., 1985]. Both environmental and biological adherents appear to agree with this assertion [Halpern, 1986].

1.2   Overview of sex differences in the sensory-motor domain

There has been less attention to the study of sex differences in the sensory-motor system where the relevant literature is fragmented across contexts as diverse as motor development, evolutionary psychology and sports medicine. Investigating sex differences can provide useful insight into the complex interplay between nature and nurture. Identification of the mechanisms that underlie such differences can help us understand not only differences between the sexes, but also between individuals of the same sex [Kimura, 2000].

1.2.1. Motor performance outcome versus movement production

Most of the literature on sex differences in sensory-motor performance has focused on the movement (or performance) outcome rather than the movement production (that would include measures of kinematics and coordination). For example, Thomas and French [1985] conducted an extensive review and meta-analysis of motor development that revealed males outperform females in agility, jumping, pursuit rotor tracking and throwing. However, Thomas and French [1985] could not address whether sex differences exist in movement production for these tasks, because the performance outcome is a product of the underlying movement process but does not provide any direct insight into that process. In most cases where sex differences in performance are reported, it is therefore uncertain

whether the males and females used a different movement pattern or technique that might explain the performance differences, or if movement was similar - with other factors influencing the outcome - as studies that include both of these are infrequent. The relationship between performance outcome and underlying movement pattern has important implications when discussing the basis of sex differences in the motor domain and this theme will be discussed over the coming sections.

1.2.2. Stereotypical movement patterns

First we need to consider if there is any evidence that suggests males and females do indeed differ the underlying movement pattern used in the process of performing motor tasks. Throwing is the task that has been most commonly used to study of sex differences in the context of motor skill. The sex difference in throwing *performance* is apparent from two years of age and appears to persist into maturity [Leme and Shambes, 1978]; males are both more accurate and can throw further distances that their female counterparts. Although objective measures of movement *production* are infrequent in the throwing literature, those that have at least included subjective measures of this, give rise to the concept of 'throwing like a girl' [Young, 1980; Fredrickson and Harrison, 2005]. This female throwing form is characterized by use of a forward-facing stance, with limited trunk rotation and range of motion through both back-swing and follow-through phases of the throw. Rather than engaging the entire body, movement is restricted to the shoulder and elbow joints and the sagittal plane of motion. Generally, even adult females tend to lag behind their male counterparts by multiple motor development stages when throwing patterns are compared using a standardised developmental scale [Roberton and Halverson, 1972; Leme and Shambes, 1978].

Research that objectively measures the movement production process (i.e. form and technique) most commonly has quantified movement in terms of kinematics, kinetics, muscle activation (electromyography), joint stiffness and inter joint coordination (reviewed in chapter 5). Few of the studies that employ these measures compare males and females; however sex-specific kinematic and coordination patterns have been shown in two studies of everyday tasks, namely, lifting [Lindbeck and Kjellberg, 2001] and forward reaching [Thomas et al., 1998]. Sex differences in movement production have recently received focused attention in the dynamic control tasks of side cutting and

landing within the athletic population [Malinzak et al., 2001; Padua et al., 2004; Noyes et al., 2005; Zazulak et al., 2007]. This research has arisen because of the disproportionately high incidence of non-contact anterior cruciate ligament (ACL) injuries in females [Agel et al., 2005]. Landing forms a critical element in a range of sports and presents a demanding challenge to the postural control system where large forces and postural disturbance must be negotiated [McNitt-Gray et al., 2001; Naylor and McBeath, 2008]. Differences in movement and posture during landing significantly affect the forces transmitted through the lower body, as well as overall success at the task [McNitt-Gray et al., 2001]. Given the extensive kinematic measures and large number of studies directly comparing males and females, this recent body of literature on landing therefore provides a unique opportunity to investigate sex-specific patterns of movement. This literature is comprehensively reviewed within this section of the thesis, but individual studies contend that females adopt sex specific patterns when performing landing tasks [e.g. Kernozek 2005]. Overall then, it can be seen that it is regularly assumed (despite few objective studies for tasks other than landing) that males and females adopt stereotypical movement patterns when performing a variety of tasks. The next question of interest – is why?

1.2.3. The loci of sex differences in motor performance and movement

As in the general study of sex differences, attempts to explain the presence of sex-specific patterns of movement and performance outcomes in females have drawn on multiple perspectives including biological and evolutionary [Watson and Kimura, 1989; Watson and Kimura, 1991], and social and environmental [Young, 1980; Fredrickson and Harrison, 2005; Williams 1996].

Biological factors

Most of the explanatory research has focused on throwing (due to the compelling differences in performance outcome) yet a comprehensive understanding of sex differences in this task has yet to be developed [Duffy et al., 2007]. Given its unique role in the history of humans, differences in throwing performance have been paid much attention among evolutionary psychologists who are concerned with ultimate causes of differences, which has resulted in hypotheses such as the hunter-gatherer explanation of the male throwing advantage [Kimura, 2000]. On another level, the common finding in

the motor development literature, of a divergence in motor performance between males and females at puberty, for other tasks including landing [Thomas and French, 1985; Yu et al., 2004; Quatman et al., 2006] suggests the possible involvement of sex hormones. This explanation entails a proximate, physiological basis for observed differences. There are some perspectives that maintain a fundamental difference in underlying neuromuscular motor control exists on the basis of genetics or hormones [Quatman et al., 2006; Field and Pellis 2008]. Even when the scope is limited to strictly biological factors such as these, it is obvious that the potential mechanisms underlying differences in the senosori-motor domain are complex. Differences at the level of the central nervous system have the potential to influence motor control characteristics through structural, perceptual and learning differences [Allen et al., 1991; Naylor and McBeath, 2008; Dorfberger et al., 2009].

When comparing the sexes on any given motor task, the most outward biological factors that would appear to influence performance are those relating to basic anthropometric or strength differences, since it is known that physiological differences manifest here [Aiello and Dean, 2002]. Differences would be expected then, especially for tasks where muscular power or body size is an important contributor to performance. This returns us to the important point from earlier, regarding the difference between performance outcome and movement production measures when comparing the sexes. Performance outcome measures such as speed, distance, and jump height are readily influenced by body morphology. Differences in performance outcome in many cases can be explained simply on the basis of the characteristics that differ on average, between males and females. Under these circumstances, the question to arise – is whether the difference in motor performance is truly indicative of males performing better? or simply a function of their anthropometric advantages? Caution is warranted when interpreting differences on these measures.

Biological factors and performance measurement – when is a sex difference a sex difference?
Comparing the sexes on motor tasks solely on the basis of performance outcome measures that emphasise maximal speed or strength is an unfair comparison. It is proposed here that we need to consider more broadly, whether males and females are equally successful in a task, despite apparent differences when these measures are employed. Part of the solution here is to also consider the

movement pattern however studies that include both are rare [Williams, 1996]. Anthropometric and strength factors can still influence movement production measures. Perhaps the question should be reframed to be regardless of any differences – are both the sexes performing optimally, given their individual set of constraints? The literature has begun moving away from focussing solely the isolated factor of sex to consider these factors [e.g. Beauleu, 2010; McLean, 2008]. To consider biological mechanisms or even to assert a sex difference in motor task performance in the first place, the question of whether both sexes might actually be performing equally successfully, given their constraints needs to be addressed. The idea that males and females tend to achieve similar ends by different means, but that this can be obscured when narrow measures of performance are used is not new [e.g McKarthy and Konkle, 2005], but bears particular relevance when investigating differences or the lack thereof in motor tasks.

Beyond biological factors

There is no question that males and females differ structurally on many counts, but in the context of motor skill, these may not be the most important determinants of performance. The viewpoint taken from hereon in is that despite the likely presence of biological differences across multiple levels of the system, the magnitude of any motor performance difference is determined by other factors. Returning to the differences found in everyday movement tasks, Thomas et al. [1998] found that familiar biological sex differences such as in anthropometry, flexibility or strength could not explain the distinctive movement patterns used by females in tasks that necessitate some bending of the trunk. Instead they suggested a potential role for environmental, constraints on stereotypical movement patterns. Likewise for landing tasks, only a weak association of strength, power and body or joint structure with sagittal plane movement patterns has been observed [Mizner et al., 2008; Shultz et al., 2009]. Differences in anthropometrics and strength therefore do not always result in divergent performances, suggesting other mediating factors are at play and these are introduced over the next few sections.

1.3. Minimal sex differences in movement exist in individuals with similar motor task experience - A systematic review of landing

1.3.1 Introduction

While a series of anatomical and strength differences in the hip and knee region [Quatman et al., 2011] appear to converge to produce a consistent sex difference specifically for knee abduction (height and weight matched individuals still differed) [Carson and Ford, 2011], it is not clear whether these factors exert such a strong influence on wider measures of the task of landing. As discussed earlier, sex-specific movement patterns may in general be expected on the basis of biological and other factors; we hypothesised that because the landing literature is based largely on athletes that compete in sports emphasising landing, sex differences in kinematics, muscle activation and joint stiffness will be diminished or absent. The important environmental factor that warrants consideration here is the role of specific practice or sports-related experience, because training has been demonstrated to modify neuromuscular control during landing [Masci et al., 2010]. Consequently, among athletic performers or indeed performers who are well practiced in any task, more homogeneous patterns of movement would be expected compared with non-trained individuals of either sex.

Detailed methodology and results for the systematic search are presented in appendix A.

1.3.2 Discussion of findings

This systematic review revealed findings from studies of landing and jumping tasks within an athletic or active adult population do not support the presence of sex-specific patterns of movement. This finding is consistent with our hypothesis that sex differences in movement patterns that might be expected on the basis of biological and environmental factors are likely to diminish or disappear in well-practiced female and male performers. Similarly, there was no convincing evidence for sex-specific patterns of muscle activation in the landing tasks. Lower values of leg stiffness, normalised to body mass, has been reported in females during landing but not hopping.

Kinematic and EMG studies of landing and jumping

The review provided little support for the presence of sex-specific patterns of movement in landing and jumping tasks in people drawn from an active population. Although 10 of the 15 kinematic studies reported significant sex differences in some kinematic variable(s), the aggregate findings for specific knee, ankle or hip joint angles showed sex differences only in a minority of studies. Furthermore, in some instances, the significant differences were in opposite directions in different studies. Where effect sizes and confidence intervals could be calculated, the support for sex differences appeared even weaker. In contrast, a recent review of knee abduction by Carson and Ford [2011] showed a greater knee valgus range of motion during landing in females compared with males and this appears to be the only kinematic variable for which a sex difference has been consistently supported. Since knee valgus loading is known to increase ACL loading [Markolf et al., 1995; Lloyd and Buchanan, 2001; Fukuda et al., 2003] and has been linked with injury during landing in adolescent females [Hewett et al., 2005], this finding has potentially important implications for ACL injury. Beyond this specific angle, however, the evidence for sex differences in landing kinematics is weak.

The review also found little support for the presence of sex-specific patterns of muscle activation. It has been reported routinely [Griffin et al., 2006; Shultz et al., 2009] that females use a 'quadriceps dominant' muscular activation profile during dynamic tasks such as the landing movements. While an earlier onset and greater activation of vastus lateralis and medialis in females were actually the most frequently reported differences in muscle activation noted in the review, five of nine studies failed to show any sex differences in knee extensor activity. Given the attention that has been given to the putative sex difference in quadriceps dominance as a risk factor for injury [Malinzak et al., 2001; Griffin et al., 2006], more convincing evidence in its support might have been expected to emerge from this review. A recent review of sex differences during cutting manoeuvres [Benjaminse et al., 2011] also failed to find quadriceps dominance in females. Aside from knee abduction [Carson and Ford, 2011], therefore, the findings from the kinematic and EMG studies reviewed are mutually

consistent in failing to support reliable sex differences in patterns of movement and muscle activity during landing and jumping tasks, within an active population.

Methodological quality assessment

The Quality Index [Downs and Black, 1998] was designed to assess a broad range of scientific literature but is applied mainly to randomized controlled trials. Of its original 27 questions, only nine were deemed relevant for assessing the non-interventional descriptive studies that constituted this review. While major flaws were not identified in any of the studies, closer inspection of the study methods revealed a need for more comprehensive outcome measures, particularly in the landing studies. Measures for the hip, knee and ankle joints at both initial ground contact and maximum joint excursion provide information on range of motion, but many studies provided only a subset of these measures (Table 1.2) such as maximum angles of excursion during landing [Fagenbaum and Darling, 2003; Russell et al., 2006; Earl et al., 2007; Kernozek et al., 2008; Herrington and Munro, 2010].

Some issues related to study methodology and sample size may provide an explanation for the inconsistencies in findings between the studies in the review. As already noted, there was considerable variation in task procedures between studies, yet even when grouping together comparable landing styles (for example unilateral stance), no clear pattern of sex difference was evident. For muscle activation, the inconsistent findings might be attributable to the variable nature of EMG measurement, where many data collection factors can influence the final result [Shultz and Perrin, 1999]. The sample size also may be a factor for many of the articles reviewed. Many biomechanical investigations use small sample sizes and may be underpowered statistically to find significant differences. However, some of the largest studies [Earl et al., 2007; Kernozek et al., 2008] failed to show any sex differences and reported mean values that were comparable to those in studies with smaller samples (Tables A.2 and A.3). Rather than an absence of significant differences due to low statistical power, therefore, these considerations suggest that no differences between males and females were actually present.

1.4　Practice and experience are key mediators of sex differences in motor performance and movement patterns

Given the review findings, it is proposed that the perspective on this topic needs to be expanded beyond the biological factors that are the traditional domain of research in movement science to include environmental factors that could influence motor performance via differences in motor experience and practice opportunities during childhood and adolescence. These factors are explored in further detail in this section.

1.4.1. Motor practice, experience and the development of skill

In the studies reviewed from the landing literature, both the female and male participants had gained substantial experience in landing movements through specific practice in their given sport and this was proposed to explain why no consistent differences were observed between them. Two of the kinematic studies in the review actually matched female and male subjects on the basis of competition level or prior training [Kernozek et al., 2005; Orishimo et al., 2009]. Kernozek et al. matched their cohort of female and male recreational athletes on the basis of years in the sport and frequency of practice, and showed no differences in landing mechanics (in the sagittal plane) between the sexes. Orishimo et al. [2009] studied professional dancers and reported similar landing mechanics in both sexes. They noted that dancers receive specific and long-term training in landing technique because it is an essential component of their art. The results of both studies therefore support the hypothesis that for landing, task experience plays an important role in shaping movement patterns, leading to a convergence in patterns in more skilled participants, regardless of sex. Lending further support to the importance of relevant prior motor experiences was the study of muscle activation by Medina et al. [2008]. No differences in activation of quadriceps and hamstrings were found between male and female athletes during landing, but a third group of female non-athletes did exhibit a different pattern of activation.

Until this point, the term motor task has been preferred to motor *skill* when comparing the sexes in the motor domain, despite the two terms being roughly equivalent. The latter has been avoided so far

because of certain connotations, namely its association with a certain level of proficiency in the task, with 'skill' often reserved for describing higher grades of performance. But when considering the role that factors such practice and experience play, it is necessary to now mention of the concept of skill. Defining skill has historically been a difficult endeavour, yet two characteristics of skills are widely agreed upon – they are learned, and goal directed [Adams, 1987]. A skill should be distinguished from a capacity, or ability, because a person may possess the capacity and ability to perform a given skill, but they cannot perform it until it is learned [Adams, 1987]. When we measure performance on a motor skill, with view to compare males and females, it should be realised then that we are measuring proficiency at that particular point in time, or in other words, the degree to which they have learned the skill. Repeated exposures or practice generally result in an improvement in performance as indexed by outcome and production measures [Adams, 1987]. It is illogical to compare the sexes on any motor task, without attempting to account for prior practice or engagement with the task.

Explicit, specific practice and training are expected improve task performance however other incidental or general motor experiences may also play a role [Orishimo et al., 2009]. 'Experiential factors' is the umbrella term commonly used to describe these elements that mediate the magnitude of any performance differences (experiential factors are considered a subset of environmental factors). Thus in the study of skilled dancers [Orishomo et al., 2009], it was the combined effects of specific training in landing and experience (over many years or practising dance) that were proposed to explain the absence of any differences in landing mechanics. Practice and even brief familiarisation [Stericker and LeVesconte, 1982] have been shown to ameliorate apparent differences between the sexes for both cognitive [Nazareth et al., 2013] and motor tasks [Golomer et al., 1997].

1.4.2 Accounting for experiential factors in the study of sex differences

Comparing the sexes on a novel motor skill may reduce specific practice effects and make the comparison more valid, yet wider experiential factors are less easy to control. Some studies focus specifically on relating activities practiced in childhood, including previous sports participation and toy preference to performance [e.g. Voyer, 2000]. In studying throwing, Williams [1996] employed a non-dominant limb paradigm to investigate the effects of practice. Males and females did not differ in

performance outcome when using the non-dominant limb, which was presumed to be equally un-practiced in both.

Participation or competition level when comparing specific tasks is also used to explore these factors; in a study of balance performance, Golomer et al. [1997] reported that differences related to sex were attenuated by physical training. Compared to their cohort of individuals trained in dance and aerobics, untrained individuals were the least skilled, irrespective of sex. A similar framework of grouping participants according to frequency and level of participation to explore the influence of experience on motor performance and movement pattern was used in the study reported in Chapter two. A less common manner for exploring the role that experience plays in determining to presence – or absence of sex differences is to employ longitudinal studies to directly measure the influence of practice on performance and movement. This topic is further expanded upon in the final section of this review, first a discussion of other environmental factors beyond practice and experience is provided.

1.5   Other environmental factors

1.5.1 Sociocultural factors

Despite recognition of their importance in the motor development literature, sociocultural factors have received little emphasis in studies of adults. In a philosophical account of female movement patterns, Young [1980] proposed that the tendency to "self-objectify" or view the body as an object, reflected cultural attitudes towards the body and resulted in timid, hesitant and incomplete movements, and also a tendency for motion to be concentrated in one body part - hence the concept of 'throwing like a girl' noted earlier [Young, 1980; Fredrickson and Harrison, 2005]. The tendency to self-objectify was manifested as a greater attentional focus on the appearance of the body from an external perspective than on the task being performed. Evidence for this proposal was provided later by Fredrickson and Harrison [2005] who demonstrated, in the action of throwing, that the degree to which a female views the self as an object impacts significantly on their motor performance. Even simple factors such as the difference in requirements for body comportment between wearing a skirt versus wearing pants throughout the childhood years may condition patterns of movement. Thus, for example, Thomas et

al. [1992] noted in their study of forward reaching that modesty concerns might have altered the degree of trunk inclination used by female subjects, depending on the type of garments worn during the experiment. Such differences in body comportment mean that the possibilities for action – affordances in Gibson's [1986] terms – of these modes of dress impose greater constraints on motor performance in females. Factors such as these may influence conditioned movement patterns, especially in young and novice athletes.

1.5.2 Stereotype threat and self-efficacy

Another element to the way social factors may impact movement pattern and the development of skill is evident in the concept of stereotype threat. This encompasses the idea that group stereotypes can influence individual performance in a negative way [Campbell and Collaer, 2009]. This has been extensively studied in the context of cognitive differences between females and males, such as spatial [Campbell and Collaer, 2009] and mathematical [Spencer et al., 1999] ability. Specifically, "stereotype threat is the sense of threat that can arise when one knows that he or she can possibly be judged or treated negatively on the basis of a negative stereotype about one's group" [Goff et al., 2008] (pg. 82). Womens' performance has been shown to be impaired compared to mens' where negative beliefs about ability are present. However these differences can be nullified by modifying these negative expectations [Seibt and Förster, 2004]. There is suggestion that sex stereotypes do exist in the context of motor skill, since to 'throw like a girl' is generally not a compliment to the motor prowess of females [Hively and El-Alayli, 2014]. This effect could operate in the context of movement skills in general.

1.5.3. Individual and personality factors

One of the mediators of stereotype threat is assumed to be confidence [Estes and Felker, 2012]. Believing that the group of which you are a part generally performs poorly causes a decrease in confidence and a cascade effect. Self-efficacy refers to a situation-specific area of confidence; it is the perception that one can perform a task successfully [Gentile et al., 2009]. Domain-specific measures of self-efficacy are consistently correlated with performance within that domain and this is considered

a reciprocal process whereby self-efficacy and performance affect each other in a positive manner [Gentile et al., 2009]. The influence of self-efficacy on motor skill performance and learning has been well documented and highlights the importance of considering psychological factors as potential mediators [Stevens et al., 2012]. Gentile and colleagues [2009] reported in a meta-analysis that athletic-related self-efficacy is greater in males than females. Differences in self-concept regarding the performance of select motor skills, were also shown by Smith and Clifton [1962]. Despite this study being loaded with capable females, they still rated their performance lower. Whether or not stereotype threat is involved, confidence in one's ability in a given skill will affect performance. This is yet another example of the multi-dimensional influences upon movement and motor performance. There has been very little research on these factors in the context of movement, although one exception is a study of car parking skill [Wolf et al., 2010]. This is a task that could be expected to have a negative stereotype towards female ability. Males were found to park with greater speed and accuracy than females in this real-world scenario. Both novice and experienced groups were included in this study and the findings highlighted the role of sociocultural factors because in the experienced groups, the results were not related to rotation skill (a key requirement for this task), but to self-assessment alone.

1.5.4 Environmental influences interact – practice, experience and resultant skill level are subject to social influences

As alluded to in the previous section, the level of skill attained via practice or relevant experience in motor tasks also appears to be subject to sociocultural influences. Young [1980] and Fredrickson and Harrison [2005] proposed that females exhibit specific movement patterns because of being less practised than males in using their bodies for motor tasks. If females accumulate less experience in motor tasks than males during childhood and adolescence [Dorfberger et al., 2009], then observed sex differences might be explained at least in part by differences in practice opportunities throughout early life. Society may intersect with practice and experience in motor tasks in general. Play, a key determinant in developing fundamental motor patterns, is an area in which sex-typed behaviour is encouraged by parents [Lytton and Romney, 1991]. Lehman and Witty [1930] investigated voluntary play preferences in boys and girls and reported that the activities boys were interested in contained a

greater motor or mechanical component. A more recent study of interest in sport spectatorship showed that males tend to be more interested than females in sport [Bahk, 2000]. Interest in an activity generally leads to further practice. Furthermore, we tend to be interested in what we are good at and so this may serve to further compound differential motor experience in males and females. In their conclusions, Lehman and Witty [1930] had the prescience to question whether any test of supposed 'motor ability' (performance) measures anything other than present attainment of the skill, rather than inherent motor capacity or ability (this is different to the concept of Fleishman's general motor abilities, here it was used more in the sense of *capability*). If the material used to test was equally familiar to females and males, then no differences between them would be expected.

1.6. The acquisition of skill from practice

After considering the role that prior engagement and the resultant level of skill attainment may play in shaping movement and performance for any given task, fundamental questions regarding the effects of practice arise: do males and females derive the same gains from a set volume of practice? Can males and females perform equally successfully given practice, regardless of their initial performance level? To answer these questions, it is necessary to investigate performance and the longitudinal development of motor skills over the course of learning a novel task. There are few relevant studies that have compared female and male performance within these parameters.

Non-human studies suggest that biological factors play a role in determining differences in motor learning [Jadavji and Metz, 1998]. The evidence for human motor learning is however scant; while sex differences are often addressed in a motor development context, motor learning research does not consider them [Wulf, 2013]. The only learning studies in humans have been limited to gesture production and the human praxis or imitation system – not on movement coordination during complex, whole body skills. Dorfberger et al. [2009] hypothesised a male performance advantage in a motor memory consolidation task involving learned finger sequences. Their data supported a male advantage - there were no differences between the sexes initially but the males gained more from practice. Cohen [2010] also investigated sex differences in the acquisition of complex movements of the hand. In contrast to Dorfberger et al. [2009] however, females exhibited an advantage in the

sequence learning, this was suggested as being related to an advantage in planning the movements, rather than execution. In a different vein, males and females were found to use different strategies in learning to overcome the conflict between vision and proprioception in a prism-adaptation task [Moreno-Briseño et al., 2010]. For these studies therefore, no clear pattern has been established. These tasks would draw more heavily on memory resources than more sports-related whole body tasks and the generalisability of these findings to the learning of whole body movements might therefore be questionable.

There appear to be no valid comparisons of females and males during the acquisition of skill for complex, whole body tasks. In the motor control and learning literature that is interested in the changes that occur with practice beyond performance outcomes, three distinct stages of acquisition are described – coordination, control and skill [Newell, 1985]. Coordination refers to the development of the relationships between the joints within the body that enable a movement solution to meet the task goal. Control refers to the process of refining the fit between the movement pattern and the task performance, to enable performance under different conditions. The final stage refers to the skilled optimisation of the movement pattern. A second introductory review (Chapter 5) provides further background to these concepts.

Chapters four and six address the issue of the changes that occur in movement patterns, that subserve improvements in motor skill performance, in both males and females. The inclusion of comprehensive measures including performance outcome and movement production, will enable us to investigate another question that few studies in motor learning and control have addressed, namely the relationship between performance outcome and movement production [Ko et al., 2013]. It could be the case that the same level of performance can be achieved by females and males given appropriate practice, but they differ in the movement patterns that they use to achieve this performance.

1.7   Summary and conclusions - A question of capacity

In considering evidence pertaining to either the presence or absence of sex differences in both motor performance and movement patterns when performing motor skills, an overwhelming number of

factors are involved. Most agree that there is a complex interaction between biological and environmental constraints [Halpern, 1986; Kimura, 2000] and numerous contextual factors related to the testing environment [Caplan et al., 1985] that determine performance.

We do not question the presence of biological differences between the sexes that may impinge on motor performance or movement in general. Rather we assert that these factors may not be the most important determinants of ultimate performance or success when it comes to motor tasks. The thesis therefore operates within the framework of an environmental explanation of sex differences; exploring the idea that the magnitude of any effect being complicit upon factors such as prior practice and experience. This is a necessary approach, given the crucial role that practice plays in the development of motor skill - by definition skill being that which must be learned.

We will compare the sexes on two tasks, namely drop landing and simulated slalom skiing. For the first skill, we attempt to control past relevant experience with landing, to investigate the role this may play in determining differences in landing kinematics. For the second, novel skill, male and female performance will be compared initially and tracked over the course of practice. This will also include measures of both performance outcome, and movement coordination, to explore the relation between these.

Ultimately, we are attempting to establish whether females and males possess a similar *capacity* for performing motor tasks in a skilled manner, that is, given a controlled volume of practice or prior task relevant experience, can they achieve similar performance levels?

CHAPTER 2.

Sex differences in landing are more apparent in recreational female surfers than in competitive surfers or non-surfers

2.1. Introduction

An extensive review and meta-analysis of motor development by [Thomas et al., 1998] has shown that males outperform females for various tasks including tracking, jumping and throwing. Attempts to explain these differences have invoked competing arguments, which generally differ in their emphasis of nature (biology) or nurture (environment) (as reviewed in Chapter one). Within a sporting context, historical differences in performance between males and females, particularly in Olympic sports and speed and endurance events, showed a marked narrowing from the 1950's until fairly recently [Dyer, 1986; Selier et al., 2007; Thibault et al., 2010]. It was suggested that this was at least in part a response to the adoption by females of practice and training regimes more similar to those of males and an increase in participation rates in female athletes [Wells, 1991]. This supports the idea that nurture plays an important role in determining the existence of any sex differences in performance and the degree to which they manifest. From a sport coaching and performance perspective, factors related to the environment are of interest as they are potentially modifiable via training.

Movement form or technique (as measured via kinematics) can provide useful information beyond that of the outcome of the performance alone because it can potentially be modified to improve performance [Devita and Skelly, 1992]. Recently, a large body of research has focused on whether differences in movement form exist between males and females for dynamic tasks such as jumping [e.g. Chappell et al., 2007], landing [e.g. Kernozek et al., 2008] and side cutting [e.g. Beaulieu et al., 2009]. This area of research has been motivated by the wide disparity in non-contact anterior cruciate ligament (ACL) injuries between males and females [Quatman et al., 2010]. However, despite the common assumption that females adopt different movement patterns [Lephart et al., 2002], in

particular landing and moving with greater knee extension and hip abduction, recent reviews have challenged this notion for both landing [Bruton et al., 2013] and cutting [Benjaminse et al., 2011]. While the inconsistency in findings is most likely due to a combination of factors [Bruton et al., 2013], we hypothesise that the amount of prior practice or experience, and by logical extension (given that practice is generally consistent with a higher level of skill), skill level will play an important role in determining landing movement patterns and may explain, at least in part, the contradictory results for females and males reported in the landing literature.

If females were to accumulate less experience or practice time for a motor task than their male counterparts, a 'sex difference' in movement and/or performance might eventuate for which the difference in practice and prior engagement would explain most of the variation. This was highlighted for the task of drop landing where, in a study that matched male and female participants on the basis of skill level (as indicated by competitive status) [Kernozek et al., 2005], no differences in movement form (lower limb kinematic/joint angles) were found. Perhaps more important was the findings of Orishimo et al. [2009], who investigated highly skilled dancers where both the males and females had practiced and been explicitly trained for many years in proper landing technique. No differences between groups were observed in landing technique. It is not known whether this finding is generalizable to groups who do not receive extensive explicit instruction in landing as part of their sport. The inclusion of a group of less highly skilled dancers in this study could have shed further light on the role of practice. Nevertheless, the evidence from these two studies supports the role of practice in shaping movement patterns of the lower limb.

In the present study we examined landing within a population who receive no explicit training in landing technique, namely, surfboard riders (surfers). Although not obvious to a non-surfer, landing is a critical component of skill in high-level surfing. In riding across the face of a wave, more skilled surfers not only move parallel to the beach, they also move up and down the face of the wave. A variety of manoeuvres can be executed upon reaching the top of the wave, most of which will result in the surfer returning to the pit or bottom of the wave where they must land centred over the board and absorb the momentum. Although the feet generally remain in contact with the board, this is still a

situation where ineffective landings result in higher forces being transmitted through the body [McNitt-Gray et al., 2001]. In surfing this may limit performance, as the ability of the surfer to successfully remain balanced (upright on the board) and transition smoothly from one manoeuvre to the next will be compromised if they do not land in a soft and controlled manner [Young, 1985]. The seamless transition or flow between manoeuvres is an important feature in the judging criteria for competitive surfing [ASP, 2014]. In contrast to the relation between landing and injury, the relation between landing pattern and sporting performance has not been discussed in the literature. Anecdotal coach reports, however, indicate that developing female surfers have difficulty with respect to performing effective landings and linking manoeuvres in a smooth manner.

This study was part of a wider project originally investigating neuromuscular characteristics of surfers and its aims were twofold: 1) investigate whether females and males display differences in movement pattern when performing a laboratory-constrained drop-landing task; and 2) explore whether prior practice and experience in the sport of surfing are related to kinematic variables in drop landing. Both recreational and competitive female and male surfers (representative of different amounts of experience with landing) were recruited and compared with non-surfing controls. It was expected that with more experience in surfing, the resulting greater exposure to landing would be reflected in the performance of this laboratory task. Specifically, we expected that greater experience with surfing would result in greater knee flexion at contact, and a greater overall range of motion in the joints of the lower limb (as these would represent a smooth and controlled landing), with no differences between experienced male and female surfers.

2.2. Methods

2.2.1. Participants

A convenience sample comprising 42 male (n = 21) and female (n = 21) participants was included in the present study. The cohort comprised six groups, each with seven participants, consisting of male and female competitive and recreational surfers, and non-surfing controls (Table 2.1). Recruitment of surfers, particularly competitive surfers, was difficult (due to the testing location and timing within

the competitive season) and the age range of the participants could not be controlled. The competitive surfers were somewhat younger than the recreational surfers and perhaps for this reason, there were no significant differences in the number of years of surfing participation between competitive and recreational surfers (females and males pooled). Competitive surfers, however, began surfing at a significantly younger age ($p < 0.05$) and surfed significantly more frequently than their recreational counterparts ($p < 0.01$). This coupled with the fact they had surfed a similar number of years despite the age difference, indicated it was valid to consider the competitive groups to have accumulated a greater amount of experience performing the movements associated with surfing. There were no significant differences for these experience related measures between female and male surfers (see Table 2.1).

Table 2.1. Participant characteristics.

Expertise	Sex	n	Age (years)	Height (cm)	Mass (kg)	Years surfing	Days/ week	Starting age (years)
Non-surfer	Male	7	34 ± 16	176 ± 5	78 ± 10	-	-	-
	Female	7	25 ± 6	165 ± 7	63 ± 6	-	-	-
Recreational	Male	7	31 ± 12	176 ± 5	73 ± 6	14 ± 14	2.9 ± 2.0	17 ± 9
	Female	7	33 ± 11	165 ± 4	65 ± 7	12 ± 14	2.9 ± 1.9	22 ± 10
Competitive	Male	7	21 ± 6	180 ± 6	74 ± 14	11 ± 2	5.5 ± 1.5	10 ± 5
	Female	7	27± 12	165 ± 9	59 ± 9	14 ± 9	4.7 ± 1.3	12 ± 5

Participants were recruited from the general surfing and university population by advertisements placed in surfing clubhouses and university common rooms. Competitive surfers were defined as those eligible for competition at the state level or above and involved in the sport for a minimum of four years. Recreational surfers had surfed at least one day per week for a minimum of two years and had not competed in (nor were eligible for) any competition above local club (board-riders) level. Non-surfers were included provided they had not attempted surfing on more than five occasions, were not involved in any other board sports (recreationally or competitively) nor were competitive in any

other sport. Participants were screened (via self report) for previous injuries and excluded if they had a history of serious hip, knee or ankle injury. All procedures were approved by the relevant institutional ethics committee and written informed consent was obtained from all participants prior to data collection.

2.2.2. Experimental procedures and data collection

Before commencing testing, the participants completed a short survey to describe their surfing history and current participation and competitive status. A 60 cm drop-landing task was used to assess movement pattern and neuromuscular control. Participants were instructed to step (not jump) off a purpose-built wooden platform (Figure 2.1) and land naturally, with both feet contacting the ground at the same time. They were asked to ensure that one foot landed on each of the adjacent force platforms. Each participant completed two familiarisation and five recorded trials, with no shoes.

Figure 2.1. Illustration of the drop-landing procedure.

A set of 24 retro-reflective markers (12 mm diameter) was used to define an eight-segment model of the trunk and lower limbs. The three-dimensional (3D) coordinates of these markers were captured at 100 Hz using 14 Eagle cameras and Cortex 1 software (Motion Analysis Corp, Santa Rosa CA, USA). Ground reaction forces were measured using two Kistler 9287B force platforms (Kistler Instruments, Winterthur, Switzerland; natural frequency: 500 Hz) embedded into the floor and sampled at 1000 Hz.

2.2.3. Data analysis

Marker trajectories were filtered at 6 Hz using a 4th-order, low-pass Butterworth filter and exported to KinTrak software for calculation of angular position data. Joint angles from the sagittal plane of motion for the leading hip, knee and ankle were computed. The leading leg was the one that first stepped off the platform. Participants were asked during the familiarisation trials to determine which leg felt most comfortable to step off with, and to perform each of the five measured trials beginning with this same leg. Angular position at the frame immediately prior to first foot contact with the force platform and the maximum angle reached during the downward phase of the landing were determined. The range of motion (RoM) was calculated as the angular displacement between these two time points. The peak vertical ground reaction force for the leading leg was captured from the force data and normalised to body weight (N). For both the joint angles and ground reaction forces, the mean for the five landing trials was calculated for each participant.

2.2.4. Statistical analysis

The participant mean for each of the dependent variables (joint angles of hip, knee and ankle at initial contact and maximum, and their RoM along with the VGRF) were analysed using a series of planned polynomial trend contrasts within a 2 x 3 factorial analysis of variance (ANOVA), with the independent factors of sex (female, male) and levels of surfing experience (non-surfer, recreational, competitive). Five planned orthogonal contrasts were carried out. 1) A test of the main effect of sex, to determine whether males or females had a different mean score for any particular variable. 2) A test for any linear trend against levels of surfing experience to determine whether values for any variables increased or decreased in a systematic linear fashion (irrespective of sex). 3) A test for any quadratic trend against levels of surfing experience to determine whether values varied in a convex or concave manner across levels of surfing experience (irrespective of sex). The final two contrasts provided a test for any differences between the sexes in terms of any 4) linear or 5) quadratic trend across levels of surfing experience. Levene's test of equality of variance was applied and for some variables where this statistic was significant, the adjusted F value calculated by the statistical software for non-equal

variances was used in determining the significance of the contrast. Where significant main effects were reported, effect sizes (Cohen's *d*) were calculated.

2.3. Results

The average joint angle data are presented in Table 2.2, with significant contrasts for the landing movement presented for each joint in the following sections.

Table 2.2. Mean joint angle data for the phases of landing.

		Males			**Females**		
		Non	Rec	Comp	Non	Rec	Comp
Initial contact	*Hip*	25.5 ± 13.7	28.3 ± 5.4	25.0 ± 7.9	22.5 ± 5.3	26.0 ± 8.9	21.0 ± 4.5
	Knee	-22.1 ± 8.6	-22.3 ± 3.5	-25.3 ± 3.4	-20.6 ± 8.1	-14.9 ± 4.3	-19.0 ± 5.6
	Ankle	-16.4 ± 6.6	-17.2 ± 3.5	-16.6 ± 7.1	-17.6 ± 5.9	-26.2 ± 2.1	-20.4 3.7
Maximum	*Hip*	79.8 ± 23.2	87.4 ± 16.0	85.7 ± 21.0	85.5 ± 16.8	87.7 ± 14.3	95.5 ± 27.3
	Knee	-89.8 ± 10.6	-93.3 ± 7.6	-77.2 ± 80	-97.3 ± 7.0	-83.4 ± 7.8	-105.8 ± 17.6
	Ankle	31.2 ± 5.4	33.8 ± 5.4	39.4 ± 5.9	32.9 ± 5.7	29.6 ± 6.7	39.9 ± 5.7
RoM	*Hip*	54.4 ± 9.8	59.2 ± 14.7	60.7 ± 15.8	63.0 ± 14.2	61.7 ± 11.9	74.5 ± 24.7
	Knee	67.7 ± 4.8	71.2 ± 5.1	81.1 ± 11.5	76.7 ± 7.0	68.6 ± 6.3	86.7 ± 19.3
	Ankle	47.6 ± 7.6	52.0 ± 6.9	55.9 ± 7.0	50.4 ± 11.0	55.8 ± 6.5	60.3 ± 6.0

2.3.1. Hip

None of the contrasts for the sagittal plane variables of the hip (initial contact, maximum and RoM) were significant ($F_{(1,36)} \leq 2.8$, $p \geq 0.09$).

2.3.2. Knee

Knee extension at initial contact displayed a significant main effect for sex (contrast 1; $F_{(1,36)} = 7.5$, $p < 0.01$). The females landed in a more extended position at the knee than the males (means: 18.2° vs 23.2° of flexion, respectively; ES = 0.84; Figure 2.2a). The range of knee flexion/extension displayed a significant linear (contrast 2; $F_{(1,36)} = 9.0$, $p < 0.01$) and quadratic (contrast 3; $F_{(1,36)} = 79.0$, $p < 0.05$) trend against surfing experience, with male and female competitive surfers showing the greatest range

of motion throughout the landing phase (Figure 2.2b). There were no significant differences for the maximum knee flexion angle ($F_{1,36} \leq 1.56$, $p \geq 0.22$).
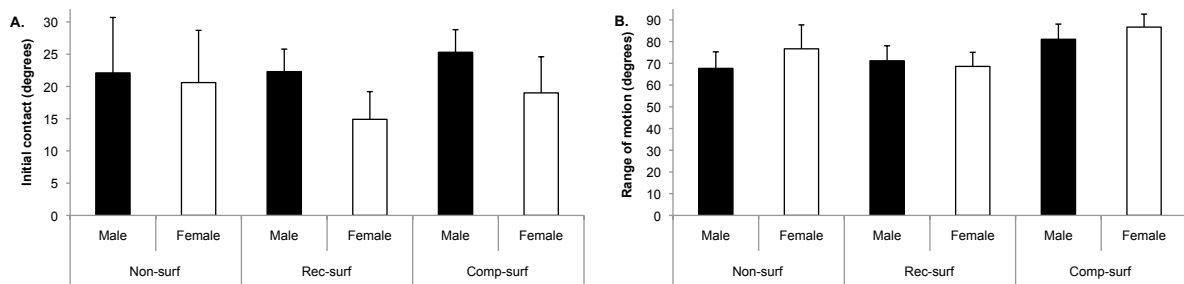
Figure 2.2. Group mean values for the significant contrasts observed at the knee joint. Initial contact angles are knee flexion; assigned positive for graphical purposes. and ankle; Non-surf: non-surfer, Rec-surf: recreational surfer, Comp surf: competitive surfer.

2.3.3. Ankle

Ankle plantar flexion at initial contact displayed a significant main effect for sex (contrast 1; $F_{(1,36)} = 8.5$, $p < 0.01$), with all of the female groups more plantarflexed than the male groups (means: 21.4° vs 16.7°, respectively; ES = 0.93; Figure 2.3b). This variable also displayed a significant quadratic trend against surfing experience; the recreational surfers showed the greatest plantar flexion (contrast 3; $F_{(1,36)} = 5.5$, $p < 0.05$) and the female recreational surfers in particular, using clearly more plantar flexion than all other groups. As with the knee, the range of ankle plantar/dorsiflexion showed a significant linear trend against surfing experience (contrast 2; $F_{(1,36)} =$, 0.05). The range of motion at the ankle was greatest in competitive surfers, followed by recreational and then non-surfers. The maximum ankle dorsiflexion angle also displayed a significant linear (contrast 2; $F_{(1,23)} = 12.2$, $p < 0.01$) as well as quadratic (contrast 3; $F_{(1,36)} = 4.7$, $p < 0.01$) trend against surfing experience (Figure 2.3c). Surfing experience resulted in a more dorsiflexed maximum angle than was the case for non-surfers. As with the difference for the initial contact ankle angle, however, when considering the linear trend, the female recreational surfers appeared to lie outside the expected pattern, in this case finishing the landing in the least dorsiflexed position of all groups (Figure 2.3a).
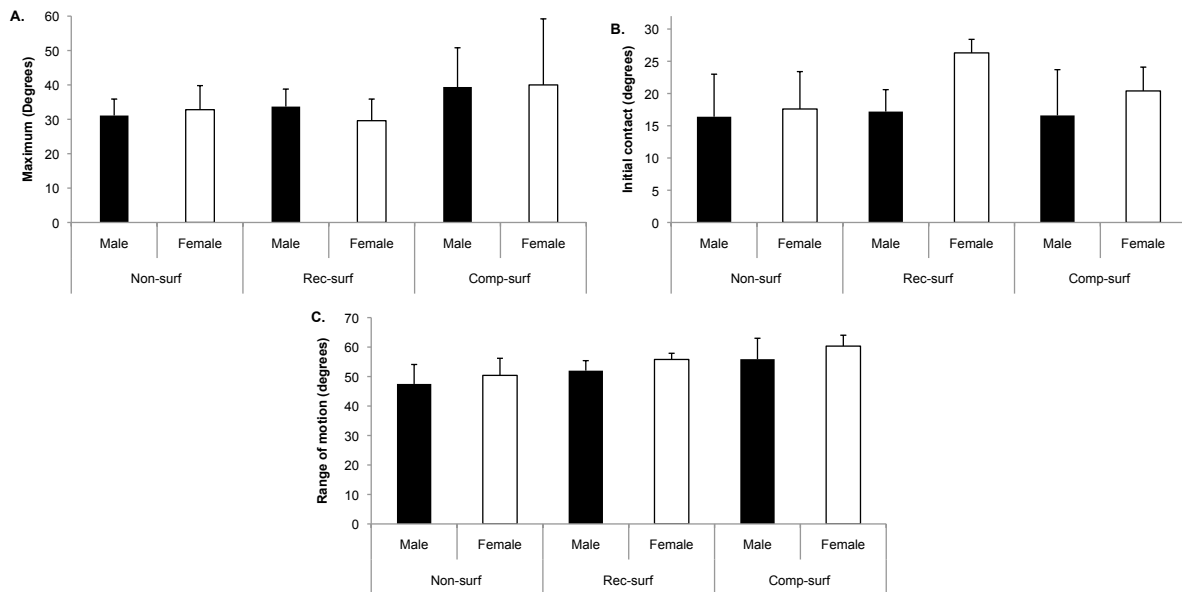
Figure 2.3. Group mean values for the significant contrasts observed at the ankle joint. Maximum angle is ankle dorsiflexion; initial contact angles is ankle plantarflexion; both are assigned as positive here for grahical purposes. Non-surf: non-surfer, Rec-surf: recreational surfer, Comp surf: competitive surfer.

2.3.4. Peak vertical ground reaction force

Vertical ground reaction force normalised to body mass displayed a significant quadratic trend against surfing experience ($F_{(1,36)} = 7.3$, $p < 0.01$). The pattern of results however was not the same in both groups. In the male surfers, there was a sharp increase in force from non-surfers to recreational surfers, while the competitive surfers showed the lowest force of all groups. In the female surfers, there was again an increase from non-surfers to recreational surfers, but here the competitive surfers showed a similar force to the recreational surfers. Hence, the competitive surfers did not conform to the same pattern in both groups (Figure 2.4).
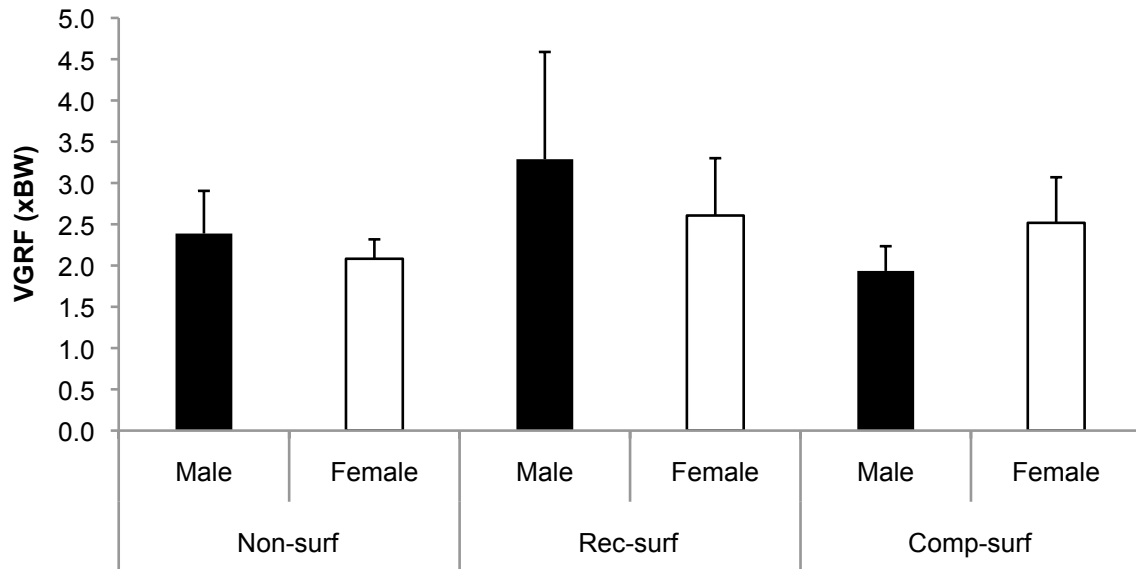
Figure 2.4. Group mean values for the peak vertical ground reaction force in the leading leg. Non-surf: non-surfer, Rec-surf: recreational surfer, Comp surf: competitive surfer.

2.4. Discussion

It was hypothesised that the amount of prior experience in surfing would be able to account for any differences in landing postures between males and females. The results however do not enable us to make a clear assertion either for or against this hypothesis for the population of surfers and non-surfing controls investigated. Overall there was a mix of significant trends across both sex and surfing experience.

With regard to sex differences, the two significant kinematic differences were apparent at the moment of initial contact. The females landed with more plantarflexed ankles and extended knees than males, in this phase of landing. This 'upright' posture immediately prior to ground contact in females has been reported intermittently in the literature [e.g. Lephart et al., 2002; Decker et al., 2003] and has been the subject of much interest in relation to its potential role in ACL injury [Griffin et al., 2006]. It was notably present here in particular for the recreational female surfers who showed the most ankle plantarflexion at ground contact (and also the least dorsiflexion at the end of landing). The finding of a sex difference here was contrary to our hypothesis, with the experienced female surfers still clearly different to the male groups for these knee and ankle measures at initial contact. However for the

ankle, this variable also showed a trend against experience; these two factors of sex and experience do therefore interact. In line with the majority of current literature [Bruton et al., 2013], sagittal plane hip motion showed no differences between males and females.

With regard to experience, both ankle and knee range of motion during landing increased with surfing experience and was greatest in the competitive level surfers, both female and male. The competitive surfers also showed the greatest ankle dorsiflexion at the end of landing. If we consider that the competitive surfers would in general be more skilled (they had practiced more frequently and from a younger age), this finding is in line with the well-established trend for increased amplitude of movement with increased skill in a motor task [Southard and Higgins, 1987; Vereijken et al., 1992].

Whereas the male groups showed clear incremental increases with surfing experience in the joint angle measures, this pattern was not so obvious for the female groups who displayed unexpected trends across experience for all except ankle range of motion (the non-surfers values fell between the recreational and competitive surfers). The female recreational surfers consistently deviated from the trend presenting as outliers that showed the smallest knee flexion and ankle dorsi flexion (i.e. greater plantarflexion) at contact, and the smallest knee range of motion and ankle dorsiflexion at the end of the landing. While somewhat unexpected here, these findings provide some evidence to support the anecdotal coach reports of recreational and young female surfers showing a tendency to adopt this upright pattern in the surf when landing from taking off and during manoeuvres on the wave. This pattern is a hindrance in terms of surfing performance and the results from this study may warrant further efforts to address these problems. Studies have shown that this so-called 'stiff' style of landing can be modified with specific practice [Myer et al., 2005] and may be related to fatigue [Edwards et al., 2010], decision-making [Edwards et al., 2010; Mache et al., 2013] and competition [Hughes et al., 2010].

The differences in landing kinematics beg the question – what is representative 'good' performance in the task of landing? The goal of landing is to re-establish balance within the base of support; successful landing therefore requires the absorption of force to brake the downward momentum of the

centre of mass and thus prevent the body from collapsing [McKinley and Pedotti, 1992]. The joint angle configuration (and muscular activity) at initial contact is representative of the strategy to absorb force, as activities to achieve this must begin prior to contact [McKinley and Pedotti, 1992]. Maximising the time over which the force is dissipated, will reduce peak landing force and is associated with 'soft' landings. Devita and Skelly [1992] define landing as 'stiff' or 'soft' based upon whether knee flexion reaches less than or greater than 90° in the downward phase. Both of these landing styles can enable successful landing, achieving the basic goal of remaining upright, however stiff landings have been associated with injury risk due to the increased force that must be absorbed. Generally then, a skilful landing could be considered to be one that minimises the peak vertical ground reaction force, to produce a smooth, controlled landing [Prapavessis and McNair, 1999]. Given that controlled, smooth landings are an important part of surfing performance the finding of a trend against surfing experience for knee flexion RoM suggested the surfers were better at landing, based on these criteria. Yet despite a significant quadratic trend against surfing experience, when it came to the peak VGRF, any clear effect of surfing experience was difficult to ascertain. While it might be expected that with greater surfing experience a lower normalised VGRF would present, this was the case in the male surfers, but not the females.

Previous studies have provided evidence that even when force is normalised to body weight, females exhibit greater peak forces than males [Salci et al., 2004], but this was not the case here. Furthermore the lack of a sex difference in ground reaction force also suggests that at least according to this performance criterion, both sexes landed with equal success, despite the different joint configurations at initial contact.

In exploring the link between these concepts of landing movement and performance, what was interesting was that despite the different knee and ankle postures adopted at initial contact by the recreational compared to their competitive female counterparts (Figures 2.3b and 3.4b), the reaction force at ground impact did not differ between these groups (Figure 2.4). It is possible that the link between posture and force is complicated and requires further kinetic analysis (i.e. inverse dynamics investigating joint torques and power). One of the most comprehensive landing studies to date

[Decker et al., 2003] also reported surprise at the lack of relation between initial contact posture and vertical ground reaction force. Male and female participants performed the landing with different contact postures, but there were no differences in VGRF This was one of the only studies to include kinetic data and indicated that the females preferred the 'extended' posture due to their selection of a muscular strategy that emphasised energy absorption at the ankle rather than the hip. Anatomical differences in pelvis shape and muscle architecture (size, fibre direction) were put forward as an explanation for why females might show greater preference for absorbing power at the ankle, as opposed to hip (in the males). Perhaps an alternate interpretation of the kinematic results here is to consider that the females adopted the extended posture on impact as a necessary means for attenuating the forces generated upon impact. Less knee flexion combined with greater ankle plantar flexion may allow more time to dissipate force, therefore explaining the lack of sex difference in peak VGRF.

As has been proposed in the motor control literature, there may exist a 'confluence of constraints' that act to shape movement patterns [Newell, 1986; Carson, 2004]. The complexity of control appears to be such that an individual focus may perhaps be more useful. Forcibly instructing participants to land with greater flexion may be a questionable practice. It is also possible that the surfers in our recreational and competitive groups were not equally representative of prior motor practice. There were no differences between the males and females within the competitive and recreational groups in terms of years of surfing and frequency of practice per week. However, it could be the case that the female surfers within each group had not had equal practice histories as the males in terms of conditions surfed and accumulated time on the waves (e.g. males may catch more waves per session and surf larger waves that are more demanding of landing skill). Specific practice conditions, beyond simply considering volume may hold the key to understanding differences; differential motor experiences therefore might still account for the patterns observed, but these factors were beyond the scope of this study.

What we have shown is that movement patterns during landing differed between groups on the basis of both sex and experience level, however it was not clear whether these patterns actually limited the ability to successfully perform the skill, as it is not simple to operationalise performance in this task.

Experience with the task was indirectly controlled for on the basis of competitive status yet despite this, differences in practice volume and engagement could still have been possible. The following chapters introduce a second investigation, where a novel skill was chosen and practice volume controlled for, to further explore these factors.

CHAPTER 3.

Common methodology for chapters 5 & 6

3.1. Participants

For the studies reported in chapters four and six, sixteen (8 male and 8 female) participants aged 21-59 years, with minimal to no prior skiing experience, volunteered. The males were significantly taller ($t = 3.1$, $p < 0.01$) and heavier ($t = 4.5$, $p < 0.01$) than the females but there was no significant difference in age between the groups ($t = 2.1$, $p = 0.06$) (Table 3.1). All participants were either mixed- (n =7) or right- (n =9) foot swing dominant according to the revised Waterloo footedness questionnaire [Elias et al., 1998]. The participants were recruited from a sample of convenience at The University of Sydney. This included staff and students from the Discipline of Exercise and Sport Science. The participants were from a relatively homogeneous sociocultural group, which would be expected to minimise the effects of otherwise uncontrolled sociocultural factors. They were given a detailed description of the procedures prior to data collection and underwent a basic screening for medical conditions, injuries or disabilities that would be perceived to effect performance on the task. No such conditions were reported and informed written consent was obtained for each participant.

Table 3.1. Participant characteristics.

	Age (yrs)	Mass (kg)	Height (cm)
M	33.4 ± *11.6*	76.9* ± *7.9*	177.8* ± 6.9
F	24.5 ± *4.0*	58.9 ± *8.1*	165.5 ± 9.2

* Denotes significant differences between male and female groups ($p < 0.05$).

3.2. General experimental set up

All data were collected in the Biomechanics laboratory at The University of Sydney using 14 infrared cameras (Eagle; Motion Analysis Corp., Santa Rosa, CA, USA) sampling at 100 Hz and using Cortex 1.0 software (Motion Analysis Corp., Santa Rosa, CA, USA) for calibration and capture, and a 64-

channel analogue to digital converter (NI PCI-6071E; National Instruments, Sydney, NSW, Australia). Cameras were spaced around the laboratory capture space to ensure all markers were in the field of view. The x, y and z-axes of the laboratory coordinate system (LCS) were defined as positive x in the direction the subjects were facing, positive y as a movement on the simulator platform to the right and positive z in the upward direction, with the origin indicated in the inset of Figure 3.1.
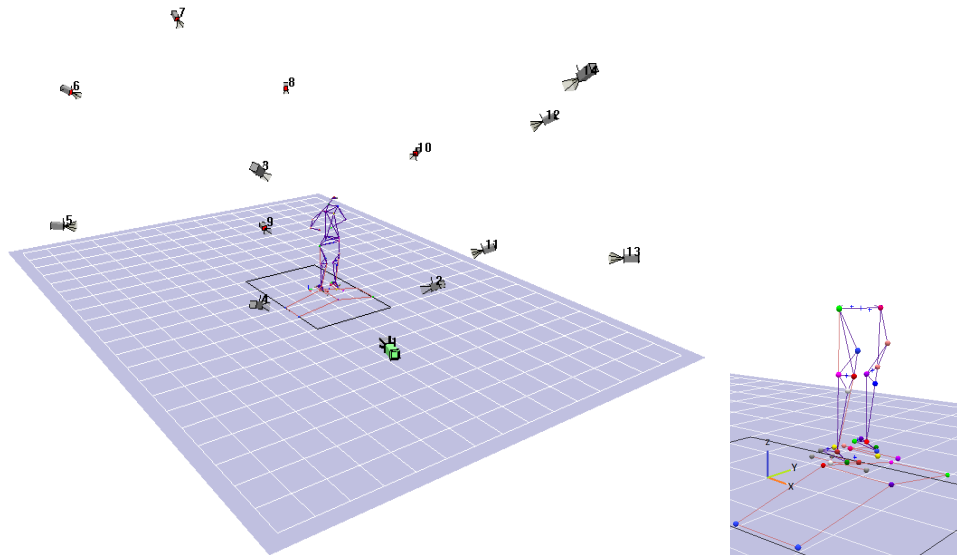
Figure 3.1. Camera positions in the laboratory with the participant on the skiing simulator. The inset shows the location of the origin of the LCS.

Participants attended five practice sessions, with data collected each day and all sessions completed within a three-week timeframe (the minimum time between sessions was one day, the maximum was seven). The time between sessions could not always be controlled due to demands on access to the biomechanics laboratory. EMG data were collected on days one and five only while kinematic data were collected for all five days. Participants wore black tights and singlets and performed all practice barefoot. A commercially available skiing simulator (PROSKI, Hocka Cesta, SH, Slovenia) served as the apparatus and consisted of a moving platform with two footplates, resisted by elastic bands, that rolls on wheels along two curved, parallel, convex metal rails. The platform rests in the middle of the arc and oscillates side to side in response to force applied by the user. The simulator had six elastic resistance bands and prescribed recommendations for the number of bands to be used according to six ranges of participant body mass (Table 3.2). The number of bands used in testing ranged from two to five.

Table 3.2. Manufacturer guidelines for the number of elastic resistance bands to be used based on the mass of the participant.

Mass Range (kg)	Number of bands
20-35	1
35-50	2
50-65	3
65-80	4
80-95	5
95-120	6

In order to capture the very first learning attempts, no familiarisation on the skiing simulator task was provided; participants were simply shown how to position themselves safely on the simulator's foot platforms whilst facing away from the safety handle bar. Participants were instructed to use the bar only if they felt a loss of balance that could result in a fall. In accordance with previous studies [Vereijken et al., 1992; Hong and Newell, 2006], when ready to begin, participants were instructed to hold their hands behind their backs and attempt to make the fastest, widest and smoothest movements possible. Twenty-five one-minute practice trials (with one-minute rest between) were performed each day for five days, completed within a maximum period of three weeks. Fifty-eight of the total 125 practice trials were recorded and of these, 25 clean trials (defined as no loss of balance or major stoppage) from across the five-practice sessions were analysed for each participant. Table 3.3 provides a breakdown of the 58 trials that were recorded (marked with 'x') and those planned to be included in the analysis (marked in red). More trials were recorded than the number to be analysed to ensure that enough trials free of falls, loss of balance or equipment mishaps (e.g. failed triggering of the EMG system, markers falling off the participant or equipment mid trial) were available for analysis. The number of such incidents was recorded. Although we planned to analyse the practice trial at the same point of practice across all participants, in some cases this was not possible, for example where the equipment or subject failed on the trial we wished to analyse. In these cases, the nearest available trial was used instead. The 25 trials analysed were therefore close to the same point in practice for all participants (i.e. within ± 5 trials).

Table 3.3. Trials recorded and planned for analysis.

Day	Trial number																								
1	1	2	3	4	5	6	7	8	9	10					15	16				20	21			24	25
2	26	27	28	29	30	31	32	33	34	35					40	41				45	46			49	50
3					55					60					65	66				70	71			74	75
4					80					85					90	91				95	96			99	100
5					105					110					115	116				120	121	122	123	124	125

Grey filled boxes indicate days when EMG was recorded. Trials that were recorded using motion analysis are numbered; trials planned for analysis are in red.

3.3. Experimental procedures

Before beginning the testing procedures on day one, the participants completed a series of pre-test questionnaires designed to ascertain their general physical and task-specific level of self-efficacy and degree of self-objectification. The questionnaires are shown in Appendix C and are described in the methods section of chapter 4. The revised 10-item Waterloo Footedness Questionnaire (WQF-R) validated by Elias et al., [1998] was administered to all participants (Appendix C). This questionnaire assessed foot preference for the manipulating and supporting foot in general day-to-day activities. Responses of i) left always, ii) left usually, iii) equal, iv) right usually, and v) right always were scored from −2 to 2, giving a range of scores from −20 for the most left-footed, to +20 for the most right-footed. Participants were then classified as left-, right- or mixed-footed according to the definitions in [Elias et al., 1998], whereby −7 to −20 was left-footed, −6 to 6 was mixed and 7 to 20 was right-footed.
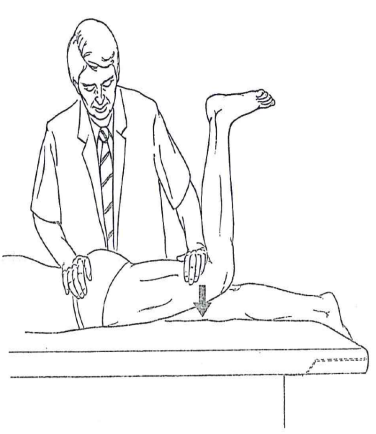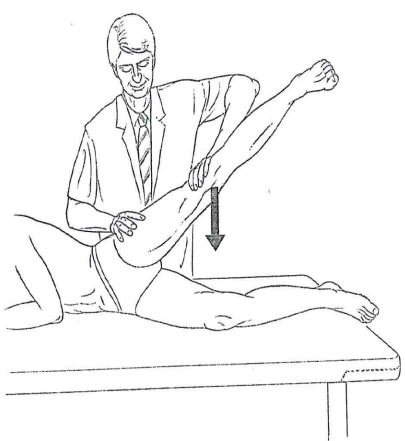
3.3.1. EMG preparation

Skin sites for surface electrode placement were prepared by abrasion using Nuprep abrasive gel (Weaver and Company, CO, USA) and alcohol swabs (Webcol, Covidien, MA, USA). Disposable Ag-Cl surface electrodes (Kendall Meditrace 100; Covidien, MA, USA) were placed bilaterally, with an inter-electrode distance of 2 cm over the following eight muscle sites: tibialis anterior, gastrocnemius (lateral head), vastus medialis, vastus lateralis, rectus femoris, biceps femoris, gluteus medius and gluteus maximus. Electrode placement followed the recommendations of [Basmajian and Blumenstein, 1980] for all muscles except rectus femoris, which was located according to SENIAM guidelines [Hermens et al., 2000]. The pre-gelled electrode centres were coated in a further layer of conductive electrode gel (Medtel Pty Ltd., Lane Cove, NSW, Australia) to ensure conductivity. All electrode sites were tested to ensure inter-electrode resistances of <15 kΩ and medical tape (Transpore, 3M Australia, Sydney, Australia) used to secure the electrodes. Where a site failed to meet this level, the electrodes were removed and replaced after further skin preparation.

On the first and last days of practice, electromyographic (EMG) signals were acquired using one of two 16-channel wireless systems - Telemyo 2400R for the first 11 participants (Noraxon, Scottsdale, AZ, USA) and Wave for the remaining five (Cometa, Cisliano, MIL, Italy). The Noraxon system consisted of leads attached to the electrodes on the skin, which connected to two transmitter boxes worn on belt straps across the waist. The boxes incorporated pre-amplifiers and the signals were transmitted wirelessly to the receiver box. The wave system was a fully wireless system, with small boxes attached via double-sided tape (1522 medical tape, 3M Australia, North Ryde, NSW, Australia) to the skin close to the electrode sites. These boxes both pre-amplified and transmitted the signals directly to a wireless receiver box. Signals were amplified (x 500), hardware filtered via an 8th-order Butterworth low pass filter with a cut-off of 500 Hz and a 1st order High pass filter with a 10 Hz cut-off. The sample rate was 1500 Hz throughout. The 16 analogue channels were synchronised with the data from the cameras.

After attachment of the electrodes and before any data were collected, the EMG signal from each muscle was inspected visually to ensure continuity. Participants then underwent a series of seven bilateral isometric muscle tests in an attempt to elicit the highest muscle activation during a maximum voluntary isometric contraction (MVIC) of 4-5 s duration. The efforts on each test were repeated three times, with a rest period of at least 60 s between each to prevent fatigue. The test postures utilised were expected to induce maximal activation in a specific muscle or muscle group (based on studies that have validated the tests before - see Table 3.4). However the maximum activation achieved in any muscle across all seven tests was used in the normalisation procedure detailed later. The procedures are displayed and described in detail in Table 3.4.

Table 3.4. Description of tests used to generate MVIC.

TEST	POSTURE & RESISTANCE	INSTRUCTION	NOTES
HIP EXTENSION	Lying in prone position on a plinth, with the side to be tested side flexed to 90° at the knee, resistance through the experimenters hand placed above the back of the knee.	"Lift your foot towards the ceiling"	
HIP ABDUCTION	Side lying with both legs straight, the leg is bought into 20° of abduction, resistance provided manually at the knee and ankle.	"Move your upper leg and foot towards the ceiling"	
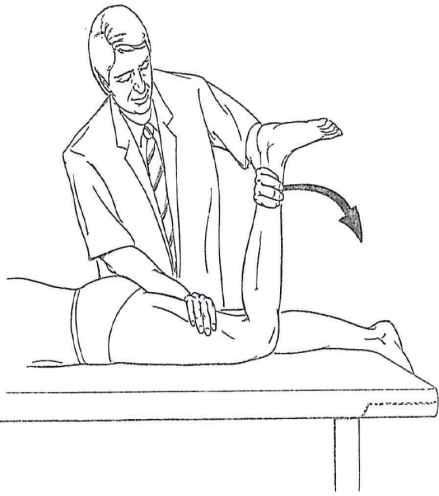
KNEE FLEXION			
	Prone lying on a plinth, with the leg to be tested flexed 45° at the knee and resistance provided manually to the ankle via a downward and inward force to target BF.	"Bend your knee so your heel moves towards your buttock"	*Seated hamstring curls have been described as ineffective in eliciting MVC, prone curls are prefereble [Rutherford et al., 2011].*

KNEE EXTENSION			
	Participants sat in a reclined chair, adjusted to ensure the hips were at 90° of flexion and the padded resistance bar sat just above the ankle. The knee was slightly flexed, one leg at a time.	"Extend your leg against the bar, whilst holding the chair for support"	*Seated testing with the hip fixed at 90° of flexion and the knee only slightly flexed has been the most common reported method to effectively elicit MVC from the quadriceps muscles [Maffiuletti and Lepers, 2003].*

ANKLE DORSIFLEXION AND INVERSION
(2 procedures employed)
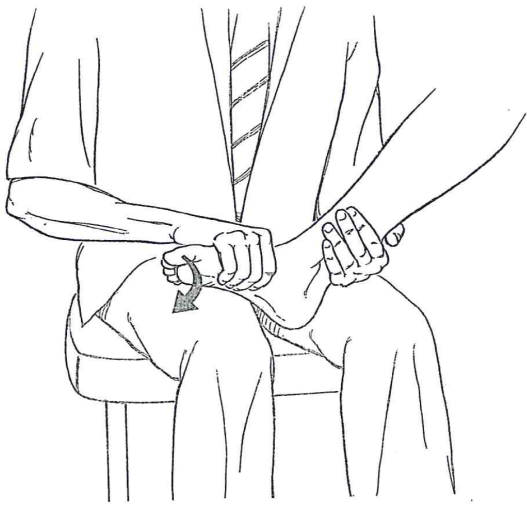
Participant seated on plinth, with knee extended and foot resting on tester, ankle plantar-flexed to 20.°. For the second method employed, participant seated with hip and knee at 90° and resistance provided by padded plate positioned across the foot.

"Bring your toes up towards your shin"

Studies detailing how this muscle should best be tested were not readily available. Hislop and Montgomery 1995] described a method for manual resistance. A master's thesis [Lenhardt, 2009] reported use of seated position with the hip and knee at 90° of flexion and a specially constructed device to resist the foot.

ANKLE PLANTARFLEXION

Seated calf raise, with fixed resistance provided across the base of the femur (above the knee) from a specially constructed piece of equipment.

"Push through the ball of your foot in an attempt to raise your knee"

This strong muscle is difficult to resist manually and without a standing squat machine available, we could not perform the most commonly used standing heel raise method [Hébert-Losier et al., 2011].

3.3.2. 3D motion analysis

Thirty-three markers were used to define a rigid 13 body-segment model. These consisted of 12 mm diameter Styrofoam balls covered with retro-reflective tape (8850 Silver self-adhesive tape; 3M Australia, Sydney NSW), glued to a flexible leather base and attached to the body using hypoallergenic double-sided tape (1522 Medical tape; 3M Australia, Sydney NSW). While the subject stood upright, markers were placed on bony landmarks on the head, upper trunk, shoulders, upper arms, elbows, inner wrists, lumbar spine, pelvis, thighs, knees, shanks, ankles and feet. Palpation was used to determine the appropriate locations. Markers were also placed on the skiing apparatus for calculation of performance variables. The locations of the markers are illustrated in Figure 3.2. Using the locations of some of the physical markers, a series of virtual marker points was defined according to external anatomical landmarks to provide the approximate location of joint centres within the body. These were required in order to calculate the joint coordinate system and the centre of mass locations of segments. Fifteen markers were also placed on the skiing simulator (on the fixed rails, moving platform and individual foot plates – see Figure 3.2) in order to characterise task performance.
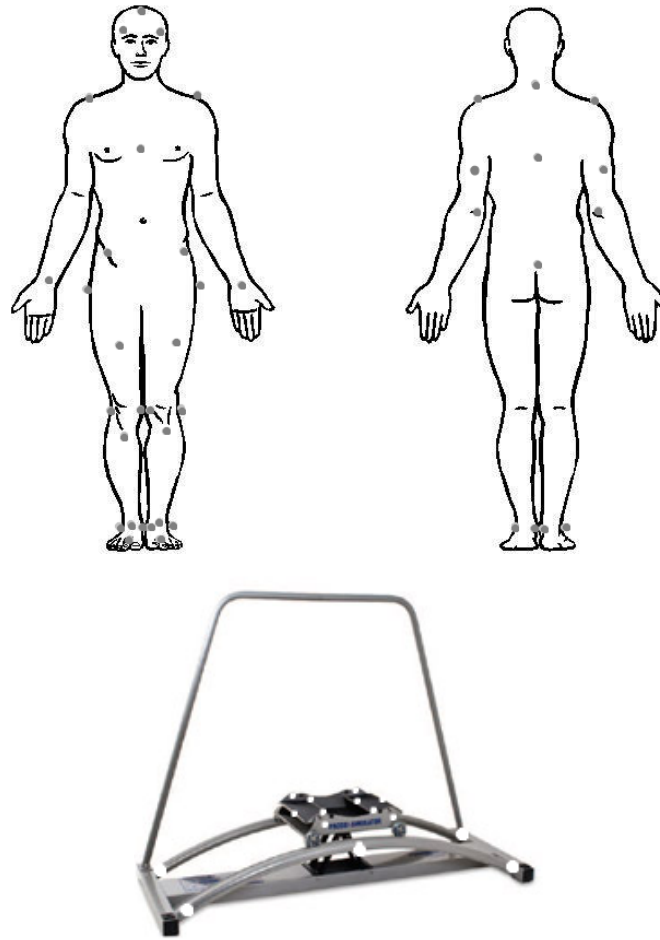
Figure 3.2. Marker placements used for the body (top) and the skiing-simulator (bottom).

Prior to data collection and practice trials on each day, the recording space was calibrated using a standard wand procedure and once the session began, participants were first asked to stand still on the simulator platform in a neutral anatomical position, arms to their sides and palms facing forwards. The platform naturally rests on the apex of the curve and as it is resisted, it is easy to remain still. This neutral trial data was used to define the biomechanical model, after which the software could identify and track the named markers in the practice trials.

3.4. Data processing

The x, y and z positional data of the markers were low-pass filtered (cut-off 2 Hz); this frequency was determined from spectral analysis of the marker positional data from a pilot subject performing the skiing manoeuvre. As movement on the platform was smooth (the movement involved no impacts that would result in high frequency oscillations), the low cut-off frequency was appropriate, with the

spectral analysis confirming no appreciable data loss. Coordinate data were transformed into angular rotations around each joint centre in the model described below and subsequently low-pass filtered (cut-off 5 Hz, standard with the software package) using Kin trak 7.1 software (The University of Calgary, AB, Canada). Body segments were defined using the markers to create three-point segments and the 3D angles between each pair of adjacent segments were calculated. Three non-collinear markers defined each body segment, with the exception of the forearm segment (no hand segment was defined) where only a proximal and distal marker were used (Table 3.5). As the participants were asked to hold their arms behind their back during the skiing task, the movement of the arms was expected to be minimal and of little importance to the overall movement. However, markers were still used on the arm and forearm to ensure that the whole body centre of mass could be calculated accurately. The segments were then combined to produce the joint angle data (Table 3.6).

The location of the whole body centre of mass was calculated via the same kinematic software. This calculation assumes that the body segments act as rigid bodies. The location of the individual segment centres of mass was defined by Dempster [1955] who developed the representation of this location as a proportion of the distance from the origin to the end-point of the segment. The average segment properties used as a standard reference for these proportions traditionally have been derived from cadaver studies e.g. [Dempster, 1955; Clauser et al., 1969]. To obtain values more relevant to our population however, we used the reference proportions that were derived from a study that used gamma ray scanning of both male and female subjects from a predominantly Caucasian, young and healthy population [Zatsiorsky et al., 1990]. The values from this study, as adjusted by De Leva [1996], were the preferred reference values for specifying the location of the segment centre of mass. However, because of the simplified two-segment trunk model and the location of the inner wrist to define the forearm, two values were sourced from Dempster [1955] to accommodate our definition. The segments, endpoints and proportions of segment length used are detailed in Table 3.7.

Table 3.5. Marker positions used to define the segments for 3D joint definitions.

Segment	Type	Marker location
Head	3-point	Forehead
		Left Tragus
		Right Tragus
Trunk/Thorax	3-point	C7
		Top of sternum
		T10
Upper arm	3-point	Top of acromion process
		Mid upper arm (on triceps muscle)
		Lateral epicondyle of humerus
Forearm	2-point	Lateral epicondyle of humerus
		Inner wrist
Pelvis	3-point	Left anterior superior iliac spine (ASIS)
		Right anterior superior iliac spine (ASIS)
		Sacrum (S1)
Thigh	3-point	Greater trochanter
		Mid-thigh
		Medial condyle of femur
Shank	3-point	Lateral condyle of femur
		Head of tibia
		Lower tibia
Foot	3-point	Medial malleolus
		Lateral malleolus
		Between head of 1st and 2nd metatarsal

Table 3.6. 3D joint angles calculated.

	Segments		
Angle	**Proximal**	**Distal**	**Angle names**
Neck	Head	Trunk	Cervical flexion/extension
			Cervical lateral flexion
			Cervical axial rotation
Shoulder	Trunk	Upper arm	Shoulder flexion/extension
			Shoulder abduction/adduction
			Shoulder internal/external rotation
Lumbar	Trunk	Pelvis	Lumbar flexion/extension
			Lumbar lateral flexion
			Lumbar axial rotation
Hip	Pelvis	Thigh	Hip flexion/extension
			Hip abduction/adduction
			Hip internal/external rotation
Knee	Thigh	Shank	Knee flexion/extension
			Knee abduction/adduction
			Knee internal/external rotation
Ankle	Shank	Foot	Ankle plantar/dorsi flexion
			Ankle pronation/supination
			Ankle eversion/inversion

Table 3.7. Details of the segments, end-points and relative segment lengths values used to define centres of mass location for calculation of the whole body centre of mass.

		CoM/segment length			
Segment	**Endpoints**	**Males**	**Females**	**Source**	**Modifications?**
Head	Left tragus to right tragus	0.50	0.50	*Zatsiorsky (1990)*	
Torso	C7 to mid ASIS point	0.63		*Zatsiorsky (1990),Dempster (1955)*	Yes. Thorax, abdomen and pelvis were either described as separate, or as one segment (trunk). Calculated as thorax plus abdomen minus pelvis.
Pelvis	Mid ASIS point to pelvis JC	0.35		*Zatsiorsky (1990),Dempster*	
Upper arm	Acromion process to lateral epicondyle of elbow	0.59	0.59	*Zatsiorsky (1990)*	Yes. Back to Zatsiorsky's original anatomical reference points.
Lower arm	Lateral epicondyle to inner wrist	0.68	0.68	*Dempster (1955)*	
Upper leg	Hip JC to knee JC	0.41	0.36	*Zatsiorsky (1990)*	
Lower leg	Knee JC to lateral malleolus	0.45	0.44	*Zatsiorsky (1990)*	
Foot	Lateral malleolus to between 1st and 2nd heads of metatarsals	0.50	0.50	*Zatsiorsky (1990)*	

CoM: centre of mass; JC joint centre

After the calculation and transformation of joint angles as described above, the 60 s joint angle time series were exported as text files. For 14 trials, the accompanying raw EMG time series were also exported. All subsequent computations were performed using Matlab (Version 7, The Mathworks Inc., Natick, MA, USA). Joint angles were low-pass filtered using an 8th-order zero-lag Butterworth filter with a cut-off frequency of 5 Hz. Raw EMG data were high-pass filtered at 10 Hz using a zero-lag 8th-order Butterworth filter, rectified and then low-pass filtered at 5 Hz to yield IEMG signals. All IEMG

signals were normalised to the maximum signals obtained across the MVIC tests, according to the following equation: (IEMG-baseline/MVIC – baseline * 100).

Individual skiing simulator cycles were identified from the position of the middle point of the foot platform (the virtual midpoint between the two footplates, see Figure 3.2) and time normalised to the full cycle using 101 points. One movement cycle corresponded to a movement from the centre to the left and return to centre (first 50% of cycle), then right and return to centre (second 50% of cycle). The IEMG signals, joint angles and all other calculated variables described in Chapter four (Table 4.1) were time-normalised relative to the platform movement cycle in the same manner. The beginning of each trial required the participant to start the platform moving from rest. This transient period may have been different for each person on each trial and this would affect the cycle-to-cycle average for the whole trial. Therefore, in line with previous studies [Vereijken et al., 1992 a & b], the first three cycles of each trial (except trial 1) were removed to eliminate the effect of the start-up. These were retained in the analysis for the first trial because they represented the participants' first encounter with the apparatus and it was expected that they might provide information about very early learning. All of the time series were visually inspected prior to any further calculation so as to ensure continuity for all variables.

CHAPTER 4.

Absence of sex differences in performance of a novel whole body movement task before and after an equal volume of practice

4.1. Introduction

Early research emphasised the role of practice in determining sex differences in motor performance. For example, Husband and Ludden [1931] reported that a male advantage for a pursuit rotor task was "obliterated with practice" (pg. 415). Indeed practice, and even brief familiarisation [Stericker and LeVesconte, 1982], have been shown to ameliorate apparent differences between the sexes for both cognitive [Nazareth et al., 2013] and motor tasks [Golomer et al., 1997]. Moreover, the role that interest and engagement play in determining motor performance was commented on by Lehman and Witty [1930]. Through a survey of voluntary play habits in boys and girls, they established that boys engaged in activities involving a motor or mechanical component at a greater frequency than the girls, suggesting that males had a greater interest or derived greater pleasure from such pursuits. They noted that greater participation in general by males also would result in disparate volumes of practice for many tasks. The measurement of performance on these tasks would then be "merely a statement of present attainment of the task" [Lehman and Witty, 1930] (pg. 245) rather than a reflection of sex differences in ability. Previously we highlighted the role of socio-cultural and environmental factors that may differentially influence the volume of practice and training in females and males and thereby shape motor performance [Bruton et al., 2013].

The most pertinent insights to have arisen from the research comparing male and female performance on a variety of tasks come from the factors that contribute to individual variations in performance irrespective of sex. Beyond prior engagement with relevant tasks, a related factor is perceived ability. Pre-existing beliefs about one's abilities on a task will affect performance, which may also be shaped by stereotyped ideas [Hively and El-Alayli, 2014]. In activities where a male advantage appears to be prevalent, such as path navigation and mathematics [Campbell and Collaer, 2009], the difference has

been shown to disappear through manipulation of such beliefs. For example, males and females performed equally on a visuo-spatial task when told that males and females perform equally on the task; this was not the case under normal conditions, where there was a male performance advantage [Campbell and Collaer, 2009]. This effect, where stereotypical beliefs impact task performance, is mediated largely through confidence [Estes and Felker, 2012]. The control or manipulation of confidence in performing a task was shown to account for differences in performance both within and between the sexes. When it comes to the physical and athletic domain, self-efficacy appears to be generally greater in males [Gentile et al., 2009] and this could affect both initial performance and learning of motor tasks [Smith and Clifton, 1962]. A perception of higher ability may also lead to greater engagement in practice with a task [Ryckman et al., 1982] and thus serve to extend differences.

When considering sex differences specifically within a motor system context, studies historically focused on simple, single- effector tasks that are easily measured in the laboratory [Wulf and Shea, 2002]. Males and females have been compared, mostly in terms of motor development, for tasks such as finger-tapping speed [Husband and Ludden, 1931], handwriting [Dorfberger et al., 2009] and fundamental motor skills [Fellowes, 2006]. With regard to the latter, common performance outcome measures include throwing distance and jumping height, for both of which there is a male advantage [Thomas and French, 1985] that might be attributable to anthropometric differences. Since anthropometric factors (e.g. strength, height, and weight) affect absolute performance outcomes for many tasks, it is prudent to also include measures of movement form or quality (kinematics) when comparing male and female performance. Determining the relation between movement pattern and performance outcome remains a challenge to motor learning research because investigations incorporating measures of both have been limited [Chen et al., 2005]. The present study set out to address this challenge by providing a comprehensive exploration of both performance and movement variables in the context of learning a new whole-body motor skill.

Recently, sex differences in movement form have been investigated within the context of ACL injury, where functional whole body movements such as landing and cutting have been considered. The evidence to emerge has been conflicting and when considered on the whole, appears weak for these

tasks (see [Beaulieu and McLean, 2012; Bruton et al., 2013] and Chapter one). For the task of landing where, owing to the sports injury emphasis, athletic populations have been the subjects in most research studies, we postulated that there would be inconclusive differences in movement form between males and females due to the mediating effect of sport-related practice [Bruton et al., 2013]. This view was supported by the negligible sex differences in kinematics observed in the two studies where past training experience was controlled [Kernozek et al., 2005; Orishimo et al., 2009]. Therefore, there is now reason to believe that there may be little difference between males and females in their ability to achieve similar levels of performance, except where tasks performance is measured solely on outcomes that allow anthropometric factors to dominate.

The purpose of the present study was to explore motor performance and learning of a novel whole-body task in male and female participants. The slalom skiing simulator was chosen because it provides a novel, whole-body task that can be learned in a relatively short time. The task has been well studied in investigations of motor learning [Wulf and Shea, 1998] and control [Vereijken et al., 1992; Almåsbakk et al., 2001; Hong and Newell, 2006a, b] over many years but to date, no studies have used the task to directly compare male and female learners. A notable feature of interest is that the side-to-side whole body movements on the simulator are predominantly in the frontal plane and this is the only plane where consistent sex differences have been shown in the landing and cutting movements studied in the context of ACL injury (see review by [Carson and Ford, 2011]). Moreover, none of the skiing simulator studies have included measures of muscle activation and so the changes in muscle activation with practice also warrant exploration.

In considering the proposal that females and males may differ little in their ability to achieve similar levels of motor performance with practice, the question whether the *rate* of learning of motor tasks differs between the sexes assumes considerable importance. This has gone largely unexamined thus far; one study of learning finger sequences provided evidence that males derive greater gains from practice than females [Dorfberger et al., 2009]. Alternatively, a 'female catch up effect' where females improve more from practice has been proposed [Thomas, Michael and Gallagher, 1994]. Hence, this question is the major focus of the current study. Learning a novel motor task in a laboratory

environment largely controls for the effects of prior experience of the task and for environmental factors that might affect females and males differentially under normal 'real-world' circumstances. Due to the novelty of the skiing simulator, there is little relevant prior experience (in participants with no prior skiing experience), so this task offers the opportunity to investigate performance increases for a controlled volume of practice. Factors of expectation and self-efficacy would still operate, however, and so these will be measured as part of the study. In their study of learning finger sequences, Dorfberger et al. [2009] highlighted the importance of not restricting the measurement of performance to a single time point. By measuring initial performance and also comparing the sexes after practice, they found no differences initially but the males gained more from practice. Hence, the trajectory of performance over practice time will be closely followed here. We hypothesised that since the skiing simulator task was novel and the volume of practice controlled, there would be minimal differences in performance outcomes between the sexes. It was also hypothesised that males and females would move in a similar way, indexed by kinematic and EMG data. While no sex differences are expected here, differences on an individual in rate of learning and practice gains on performance measures could be mediated by self-efficacy and this will also be explored.

4.2. Methods

The participants, apparatus and procedures were as described previously and only details relevant to the current chapter will be described here.

4.2.1. Outcome measures (see Table 4.1)

For each of the 25 recorded trials, the mean and standard deviation (SD) across all cycles within a trial were calculated for a series of dependent variables which characterised task performance. Where feasible, the half cycle values corresponding to movements to the left and right were calculated.

Platform performance variables: In order to provide information about the transient period of the initial start-up cycles (which were removed from the calculation of all other variables), the length of path (LoP) of the platform movement was measured over the first five seconds of each trial. This was calculated in degrees as the sum over the five seconds of the absolute difference between the values of

the platform angle at adjacent time points. The total number of instances of loss of balance (where the participant stopped moving during a trial in order to regain balance) and the number of falls (where the participant jumped or fell off the platform during a trial) were also recorded. In addition, the trial number was recorded on which each participant first achieved the maximum amplitude of platform excursion (by hitting the end of the range of the rails on the skiing simulator).

The angular amplitude (degrees) of the platform movement on the curved rails was calculated for each cycle from the coordinate data of the mid-platform marker. The maximum angular excursion in the left (positive) and right (negative) directions was derived from the centre of the arc made by the platform rails. The cycle duration (seconds) was the time it took for the platform to move from and return to the centre position on the rails after movements to both the left and right. The frequency of the platform movement was calculated in Hz as the inverse of the full (left and right) cycle duration. For the calculation of both the resonant frequency of the platform and the work done by the participant on the platform, the stiffness (Nm) of each of the elastic resistance bands was first measured using a hand-held force transducer (XTran Load Cell S1W; Applied Measurement, Bankstown, NSW, Australia). The forces (F) required to displace the platform along the curved rails over five specific distances (δ) from the centre position (20, 30, 40, 50 and 56 cm) were recorded first and then the stiffness (k) calculated as k = F/δ. Testing revealed that the stiffness was linear (r $\geq$ 0.99) across the five distances and close to equal (r $\geq$ 0.97) for the five bands that were used throughout data collection. From each participant's mass (m) and the number of bands used, the theoretical resonant frequency of platform motion was calculated according to the equation:

$$\text{Resonant frequency} = \frac{1}{2\pi} \frac{\sqrt{k}}{m}.$$

Because the male participants were on average heavier than the females, they required more bands on average than the females (see Table 4.3). More bands mean higher stiffness and higher force of resistance and assistance to the movement. This higher stiffness would allow quicker movements on the platform, leading to a shorter cycle duration. Hence, it would be expected that the theoretical resonant frequency would be higher in the males than the females, as was confirmed to be the case

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(one-sided $t_{14} = 1.99$, $p = 0.033$). Because the resonant frequency varies with $\sqrt{k/m}$, however, the higher stiffness was offset to a large extent by the higher mass in the males, so that the theoretical resonant frequency for both groups fell within a narrow range: mean = 0.625 Hz (range: 0.59-0.64) in the males and mean = 0.603 Hz (range: 0.55-0.63) in the females.

Using the stiffness equation above, the work per half cycle was calculated from the angular displacement of the platform and the force required to push the platform this distance. The maximum range of movement of the platform from the centre position to the end of the rails was 820 mm in either direction, which equated to an angular displacement of 18°.

CoM performance variables: Mean maximum angular displacement (degrees) of the each participant's CoM from the centre of the platform was calculated in the medio-lateral (y) and anterior-posterior (x) planes. The height of the centre of mass was calculated as the mean minimum position (cm) in the superior-inferior plane (z). For this to reflect the distance from the centre of mass to the platform (rather than to the floor), the distance between the platform and the floor at corresponding time points was subtracted from the minimum position. The minimum rather than the maximum distance between the CoM and the platform was used because previous research suggested that achieving a lower centre of gravity was a determining factor in skilled performance on the simulator [Vereijken et al., 1992]. Additionally, a normalised value of this variable was calculated by dividing it by the height of each participant's CoM when standing upright in the neutral anatomical position on the platform (i.e. the maximum distance between the platform and CoM, which varied according to each participant's height). For comparison with prior studies e.g. [Vereijken et al., 1992; Vereijken et al., 1997], the relative phase between the CoM movement and the platform movement in the frontal plane was calculated. This was the absolute difference between the phase of the platform minus the phase of the CoM, where:

$$\text{Phase of the platform} = \text{atan}\left(\frac{\omega\,Platform_y/\max(\omega\,Platform_y)}{\theta\,Platform_y/\max(\theta\,Platform_y)}\right)$$

$$\text{Phase of the CoM} = \text{atan}\left(\frac{\omega\,CoM_y/\max(\omega\,CoM_y)}{\theta\,CoM_y/\max(\theta\,CoM_y)}\right)$$

ω = angular velocity and θ = angular displacement.

Movement variables: The range of motion for each joint angle was calculated for each cycle and averaged across cycles. For the IEMG data, the average activation level across all cycles within each trial was calculated as a percentage of MVIC. Only the data for the first and last trials are displayed in the results for IEMG activation. The time normalised mean IEMG patterns for the first and last trials are depicted only where differences between males and females were evident on visual inspection of the 95% confidence intervals (where there was no overlap of the confidence intervals between the male and female traces).

Self-efficacy variables: Three questionnaires were employed to determine physical self-concept and self-efficacy (Appendix C). The first was a measure of trait self-objectification and involved ranking 10 physical attributes - five related to body image and five related to abilities - in terms of which had the greatest impact on physical self-concept and which had the least [Fredrickson and Harrison, 2005]. The scores for the sum of the image-related questions were subtracted from those for the ability-related questions to yield a total score ranging from -25 to 25, where a score of 25 reflected being most prone to considering one's body as an object. The second questionnaire was the physical self-efficacy scale (PSES) validated by [Ryckman et al., 1982] and involved 22 counterbalanced questions related to perceived physical ability and confidence in physical self-presentation. Each question was scored on a five-point Likert scale to yield a total self-efficacy score out of a maximum of 10. A third questionnaire, that incorporated both general and task-specific self-efficacy measures was developed by the authors, in accordance with the recommendations of Bandura [2006]. The first section included eight questions related to perceived self-efficacy in general ability to learn and perform non-specific motor skills and yielded a score out of a maximum of 80. The general motor skill self-efficacy task was designed to supplement the PSES, asking in general terms (i.e. not specifically related to this task) how confident the participants felt in learning physical tasks and how much value they placed on this ability. The second section related to task-specific self-efficacy on the skiing simulator where participants rated (out of 10) how well they felt they could meet the three requirements of the task instructions before the first practice trial. These requirements were the capability to 'balance on the

platform at rest', to 'set the platform moving and remain balanced', and to 'balance and move the platform quickly, fluently and consistently over one-minute'. The results are reported (out of 30) for the sum of all three components, as well as separately (out of 10) for the most difficult third component (speed and fluency).

4.2.2. Statistical analyses

Data for 25 trials over the five days of practice were analysed. The trials recorded on each practice day were shown in Table 2.3. Factorial analyses of variance (ANOVAs) were performed on the dependent variables. Three-factor ANOVAs with the independent factor of sex (male, female) and the repeated measures factors of side (left, right) and practice (25 trials) were carried out on the angular amplitude of the platform, cycle duration, work, maximum angular displacement of the CoM (frontal (y) and anterior-posterior (x) planes), height of CoM from platform and ranges of motion for each joint angle in all planes. The same analyses were used for the EMG activation levels but with only 14 practice trials because EMG was measured only on days one (9 trials) and five (5 trials). The remaining variables of LoP over the first five seconds and the relative phase between the CoM and the platform were analysed using two-factor ANOVAs with factors of sex (male, female) and practice (25 trials). One-way ANOVAs were used to compare males and females for the questionnaire measures. Tukey *post hoc* tests were used in all cases to determine the precise locus of any significant differences that occurred. Paired *t*-tests were used to compare the differences between the theoretical and measured resonant frequency of the platform oscillation on the first and last trials.

Table 4.1. Summary of outcome measures.

Outcome measures	Variables
Platform performance	Length of path travelled over first 5s (degrees)
	Number of instances of loss of balance over the practice period
	Number of falls over the practice period
	Number of trials required to reach maximum platform excursion
	Angular amplitude (degrees)
	Cycle duration (seconds)
	Oscillation frequency and resonant frequency (Hz)
	Work performed (Joules)
CoM performance	Maximum angular displacement in the medio-lateral plane (degrees)
	Maximum angular displacement in the anterior-posterior plane (degrees)
	Height – minimum position in the superior-inferior plane (cm)
	Height – normalised to height of CoM in standing (percentage)
	Relative phase between platform and CoM (degrees)
Movement	Joint ranges of motion (degrees)
	Average IEMG (percentage of MVIC)
	Mean pattern
Self-efficacy	Trait self-objectification score
	Physical self-efficacy
	General motor learning self-efficacy
	Perceived self-efficacy for speed and fluency on skiing simulator task
	Overall perceived self-efficacy for the skiing simulator task

4.3. Results

The results for task performance (platform and CoM), movement and muscle activity, and self-efficacy are presented in separate sections. Within each section, the results for practice are presented

first, followed by, the results for sex differences and finally the results for the left versus right side of the body. Where relevant, the changes between practice sessions, differences between the sexes and between the left and right sides are reported for each section.

4.3.1. Task performance

Male participants fell off the platform on significantly more occasions than the females (Table 4.2; $F_{(1,14)}$ = 4.93, $p < 0.05$). There were no significant differences between groups in the number of instances of loss of balance nor in the number of trials before the maximum amplitude of platform excursion was achieved ($F_{(1,14)} \leq 4.3$, $p \geq 0.056$).

Table 4.2. Basic platform performance measures (mean ± SD)**.**

Sex	Mean number of trials with falls	Mean number of trials with loss of balance	Mean number of trials before reaching maximum excursion
M	1.6* ± 1.4	4.8 ± 2.9	14.5 ± 5.6
F	0.4 ± 0.7	3.1 ± 1.4	41.0 ± 35.6

M: males, F: females. * Significant difference between M and F ($p < 0.05$).

Practice

All of the nine performance variables changed significantly with practice. For four of these variables (Figure 4.1), practice was the only significant effect ($F_{(24,336)} \geq 5.3$, $p \leq 0.05$), with no differences for sex ($F_{1,14} \leq 3.9$, $p \geq 0.06$) or side ($F_{(1,14)} \leq 0.4$, $p \geq 0.53$) for these four variables. The total path travelled (over the first 5s) increased significantly ($F_{(24,336)} = 44.7$, $p < 0.01$), with *post hoc* tests showing significant increases ($p < 0.05$) up until the 12th trial (trial 3, day 2) but none thereafter ($p \geq 0.056$). The relative phase between the platform and the CoM decreased significantly ($F_{(24,336)} = 12.0$, $p < 0.01$), approaching an in-phase relation with practice. *Post hoc* comparisons revealed that the phase angle had significantly decreased by the third trial ($p < 0.05$), with no further changes over the remaining trials ($p \geq 0.07$). Mean minimum height of the CoM from the platform decreased ($F_{(24,336)} = 20.3$, $p < 0.01$), with *post hoc* tests showing that significant changes occurred until the 16th trial (day 3) ($p < 0.05$), but not thereafter ($p \geq 0.4$). The height of the CoM normalised to the participant's height

also decreased with practice ($F_{(24,336)}$ = 5.3, $p < 0.01$). Mean maximum angular displacement of the CoM in the anterior-posterior plane increased in the positive direction ($F_{(24,336)}$ = 5.2, $p < 0.01$), indicating that the participants leaned further forward on the platform with practice. The cycle-to-cycle variability (SD) of these two CoM displacements did not change with practice ($F_{(24,336)} \leq 1.2$, $p \geq 0.26$).
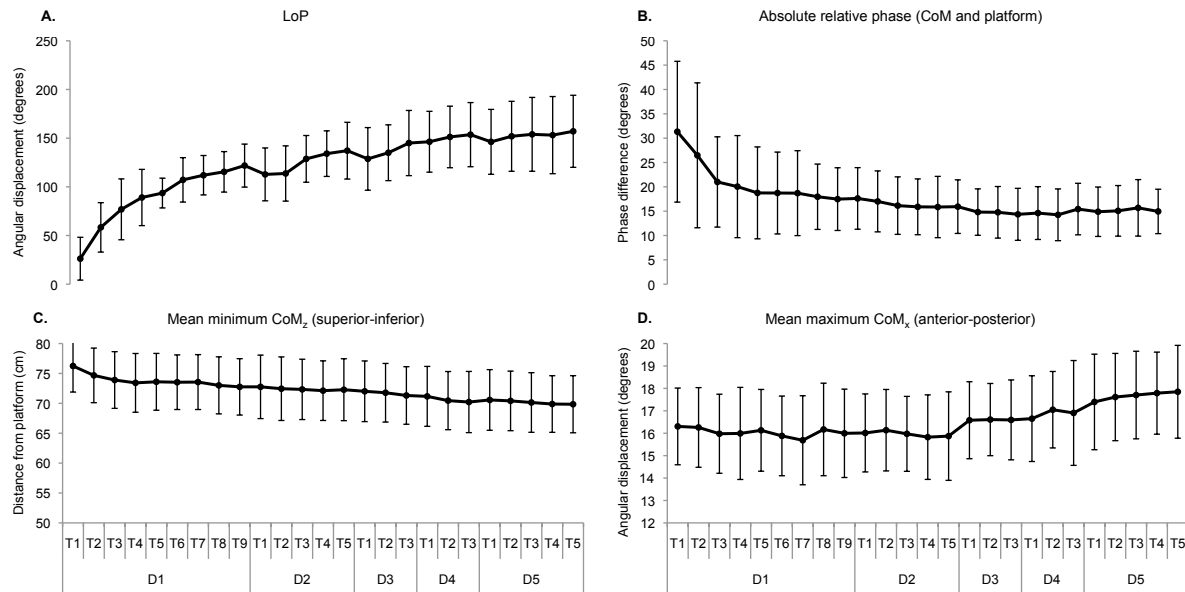
Figure 4.1. Performance variables (mean ± SD) for which significant differences occurred with practice only. The data are averaged over sex and side, for which there were no significant effects. a) Length of path over first 5 s. b) Relative phase between CoM and platform in the medio-lateral plane. c) Mean minimum height of the CoM from the platform. d) Mean maximum displacement of the CoM in the anterior-posterior plane. The x-axis labels are D: practice day, T: trial number on each day.

Sex

Three performance variables - cycle duration, platform frequency and work done on the platform - showed a significant difference between males and females (Figure 4.2) ($F_{(1,14)} \geq 6.7$, $p \leq 0.05$). None of the other six task performance variables showed sex differences ($F_{(1,14)} \leq 3.94$, $p \geq 0.06$).

The cycle duration was shorter in males ($F_{(1,14)}$ = 6.7, $p < 0.05$) and accordingly they moved the platform at a significantly higher frequency than females ($F_{(1,14)}$ = 8.5, $p < 0.05$) throughout practice. Platform frequency showed an increase with practice across both groups ($F_{(24,336)}$ = 2.3, $p < 0.01$). The theoretical resonant frequency of the platform was calculated for each participant and compared with

their observed frequency on the first and last trial of practice (Table 4.2). Of the 16 participants, 11 (5 male, 6 female) moved closer to the resonant frequency after practice, two (1 male, 1 female) showed no net change and three (2 male, 1 female) deviated away from the resonant frequency. The mean absolute difference between the theoretical and observed frequency reduced significantly ($F_{(1,14)} = 6.4$, $p < 0.05$) from the first to the last trial (0.09 ± 0.08 versus 0.04 ± 0.03). The change in this value was not significantly different between groups ($F_{(1,14)} = 0.6$, $p = 0.47$), indicating that both sexes moved toward their resonant frequency.
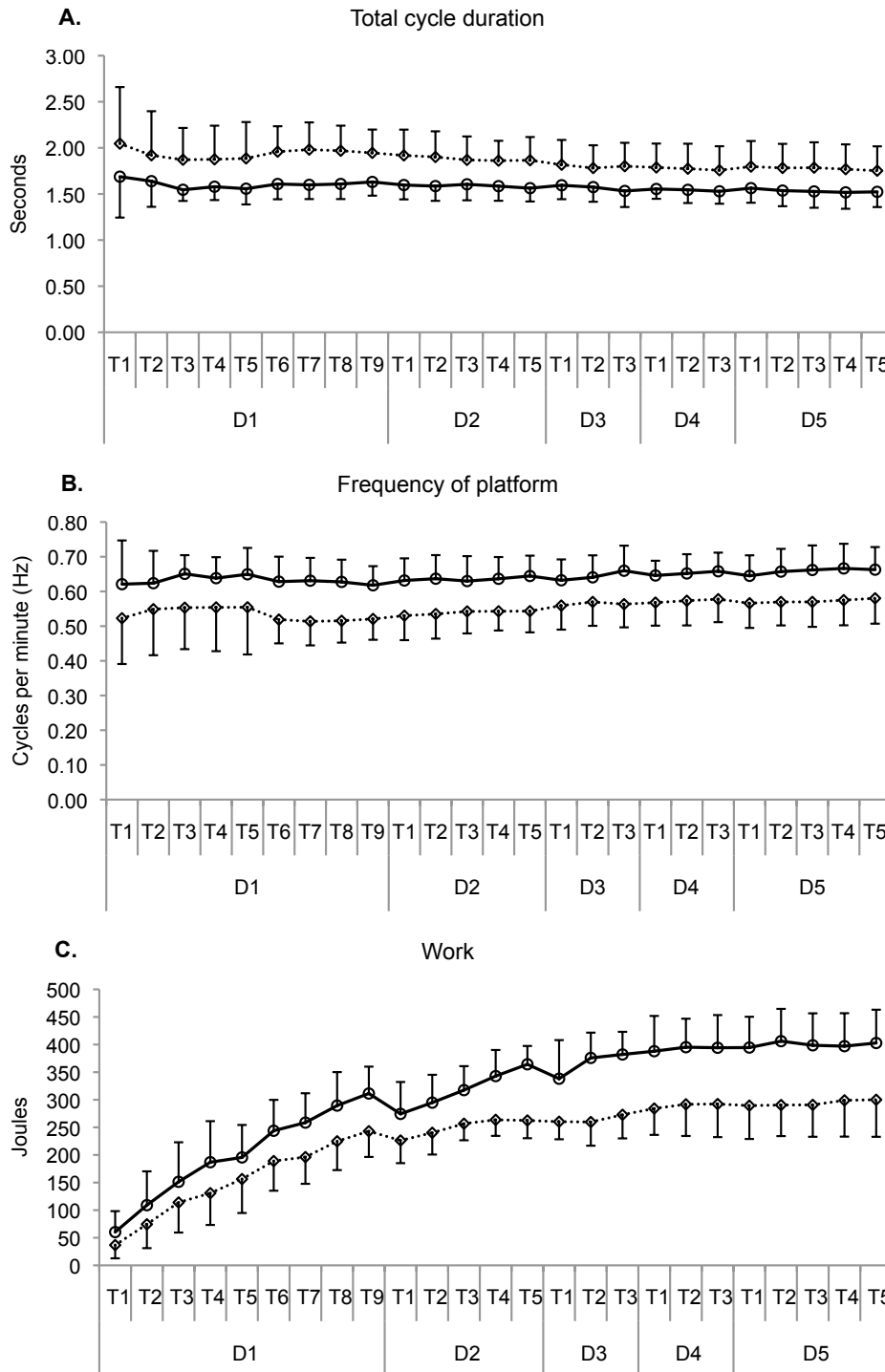
Figure 4.2. Performance variables (mean ± SD) that displayed significant differences between males and females. a) total duration of platform cycle. b) frequency of platform motion and c) work done on the platform. Dashed lines: females; solid lines: males. The x-axis labels are D: practice day, T: trial number on each day.

Table 4.3. Observed platform frequency and theoretical resonant frequency for each participant.

Sex	Mass (kg)*	Height (cm)	Number of bands	Trial 1 (first)	Theoretical frequency (Hz)	Trial 125 (final)
F	46	157	2	0.31	0.55	0.43
F	53	155	3	0.60	0.62	0.64
F	55	167	3	0.36	0.61	0.61
F	58	166	3	0.59	0.60	0.57
F	59	172	3	0.52	0.59	0.58
F	60	154	3	0.47	0.59	0.54
M	67	165	4	0.67	0.64	0.56
M	68	174	4	0.70	0.64	0.70
F	70	176	4	0.67	0.63	0.66
F	70	177	4	0.65	0.63	0.62
M	72	181	4	0.53	0.62	0.70
M	73	181	4	0.74	0.61	0.68
M	79	188	4	0.73	0.59	0.56
M	84	183	5	0.66	0.64	0.70
M	86	177	5	0.37	0.63	0.72
M	86	175	5	0.55	0.63	0.68

* The participants are ordered according to body mass.

The male participants performed significantly more work than the females ($F_{(1,14)}$ = 18.0, $p < 0.01$). The work done increased for longer in the males than the females ($F_{(24,336)}$ = 2.5, $p < 0.01$), *post hoc* tests showing an increase into the second day of practice (trial 12) in the males ($p < 0.05$), while the females did not show any increases after trial 7 on the first day ($p \geq 0.07$). The work per cycle was however more variable in the males than the females ($F_{(1,14)}$ = 15.44, $p < 0.05$). No significant differences between the sexes were observed for intra-trial variability of any other variable ($F_{(1,14)} \leq$ 3.9, $p \geq 0.06$).

The effect of practice on the height of the CoM (normalised to the participants' height) was different between males and females ($F_{(24,336)}$ = 1.8, p < 0.05), the post hoc tests showing that the males decreased its height on the first day until the 7th trial and not thereafter (p ≥ 0.21) while it did not decrease for the females (p ≥ 0.23 for all trials). No other task performance variables changed differently with practice between males and females ($F_{(1,14)}$ ≤ 0.51, p ≥ 0.93).

Side

There was a difference in performance between the left and right side of the body for four of nine variables, with the right side outperforming the left (Figure 4.3). Mean maximum angular displacement (medio-lateral) of the platform to the participants' right side was greater than to the left ($F_{(1,14)}$ = 500.1, p < 0.01). *Post hoc* tests of an interaction between side and practice ($F_{(24,336)}$ = 2.12, p < 0.01) confirmed that the displacement to the right was greater than to the left for each of the 25 trials of the five day practice period (p < 0.05). Performance on the left side reached a plateau (no further increase, p ≥ 0.11) two trials later (trial 18) than on the right (trial 16) (p ≥ 0.07). Movement to the right was also less variable than to the left ($F_{(1,14)}$ = 7.27, p < 0.05). The mean maximum angular displacement of the CoM from the platform in the medio-lateral plane (not shown) also was greater for movements to the right than the left ($F_{(1,14)}$ = 501.2, p < 0.01) and again movement to the right was less variable ($F_{(1,14)}$ = 7.33, p < 0.05).

The mean half cycle duration of the platform movements decreased with practice ($F_{(24,336)}$ = 3.0, p < 0.01), *post hoc* tests revealing that the decrease occurred until the 16th trial but not thereafter (p ≥ 0.23). Movements made to the left were of a greater duration than those to the right ($F_{(1,14)}$ = 54.1, p < 0.01). *Post hoc* tests of an interaction between side and practice ($F_{(24,336)}$ = 9.6, p < 0.01) confirmed that movements to the left were longer than to the right up to the 11th trial (p < 0.05) but not thereafter (p ≥ 0.23).

More work was performed when the platform was pushed to the participants' right than their left ($F_{(1,14)}$ = 280.38, p < 0.05). *Post hoc* comparisons showed that this was the case for all trials throughout the practice period (p < 0.01).
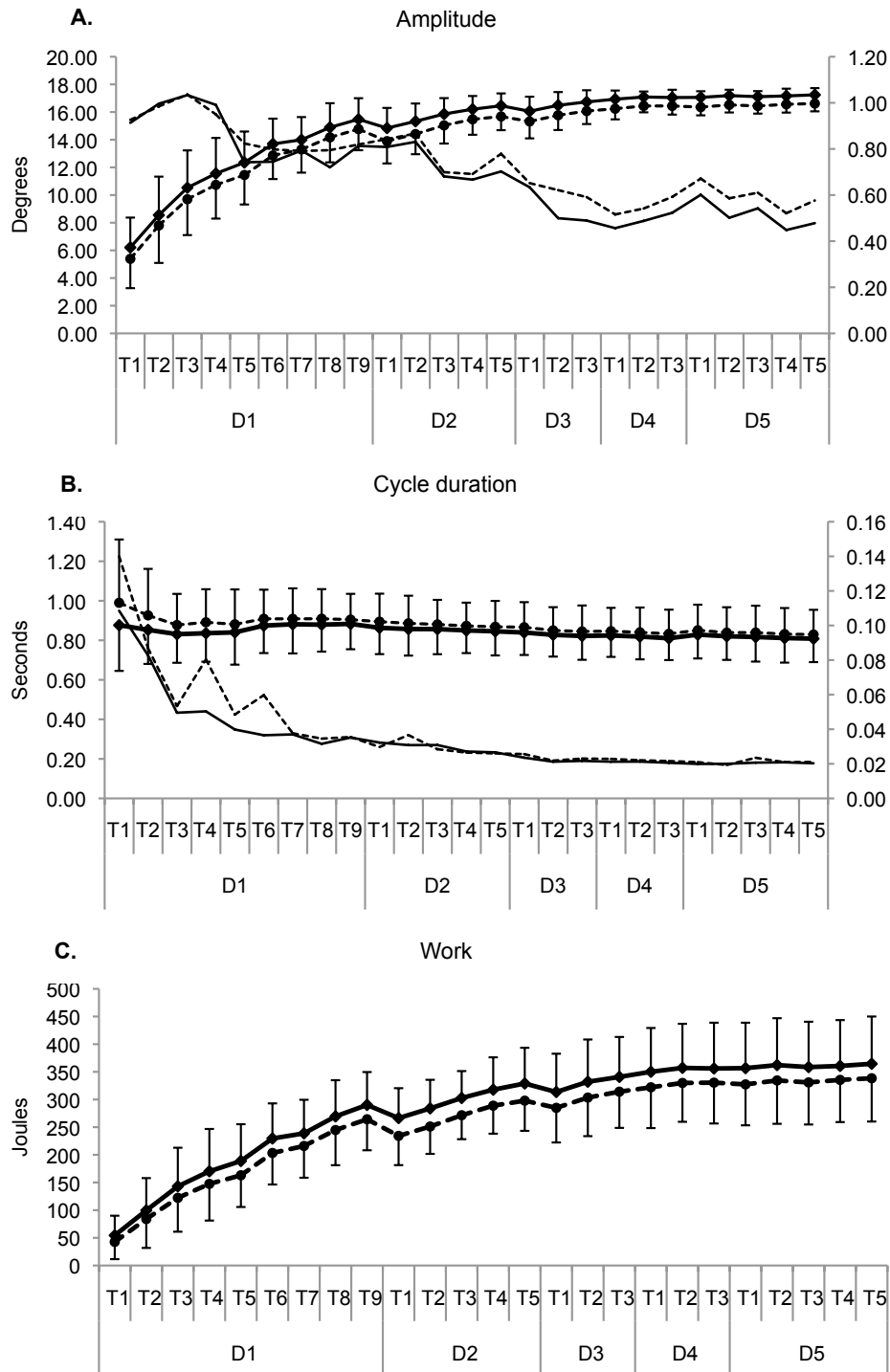
Figure 4.3. Performance variables (mean ± SD) that displayed significant differences for both practice and side. a) Mean maximum amplitude of angular excursion of platform motion. b) Half-cycle duration of platform motion. c) Work performed on the platform. Dashed (thick) lines represent movements to the participant's left; solid (thick) lines represent movements to the right. Also plotted in a) and b) are the cycle-to-cycle variability for which there were differences between left and right and an overall effect of practice (thin lines, dashed represent movement to the left, solid represents movement to right). The x-axis labels are D: practice day, T: trial number on each day.

4.3.2. Joint range of motion and muscle activity

Practice

The range of motion increased with practice at many joints throughout the body. In the sagittal plane, range of motion increased for the hip, knee and ankle ($F_{(24,336)} \geq 23.92$, $p < 0.05$). *Post hoc* tests revealed significant increases between each successive trial ($p < 0.05$), the increase plateauing after 10 trials for the hip ($p \geq 0.06$), seven for the knee ($p \geq 0.09$) and five for the ankle ($p \geq 0.07$). Frontal plane ranges of motion also increased for each of these joints ($F_{(24,336)} \geq 5.5$, $p < 0.05$). *Post hoc* tests revealed a significant increase with each successive trial for the hip and knee ($p < 0.05$) until no further increases occurred after trial 12 ($p \geq 0.09$) and five ($p \geq 0.32$), respectively. The ankle showed small increases in the frontal plane from the first trial until the increase became significant after 15 trials ($p < 0.05$). For the hip, there was also an increase in range of motion in the transverse plane ($F_{(24,336)} \geq 5.1$, $p < 0.01$), *post hoc* tests showing that the increase was significant after 15 trials ($p < 0.05$). Lumbar rotation increased in the sagittal and transverse planes ($F_{(24,336)} = 5.4$, $p < 0.01$), but there were no changes in the frontal plane (lateral flexion) ($F_{(24,336)} = 1.15$, $p = 0.28$). Cervical range of motion in the transverse plane (rotation) increased with practice ($F_{(24,336)} = 1.7$, $p < 0.05$), with no changes in the sagittal or frontal planes ($F_{(24,336)} \leq 1.4$, $p \geq 0.08$).

The mean activation level of all muscles except tibialis anterior ($F_{(13,169)} = 0.6$, $p = 0.8$) and gastrocnemius ($F_{(13,169)} = 1.2$, $p = 0.21$) increased significantly with practice ($F_{(13,169)} \geq 2.9$, $p < 0.01$). *Post hoc* tests showed that the differences from the first trial of day one were significant in most of the trials on day five. The results are summarised in Figure 4.4, which compares values for the first and last trials only.
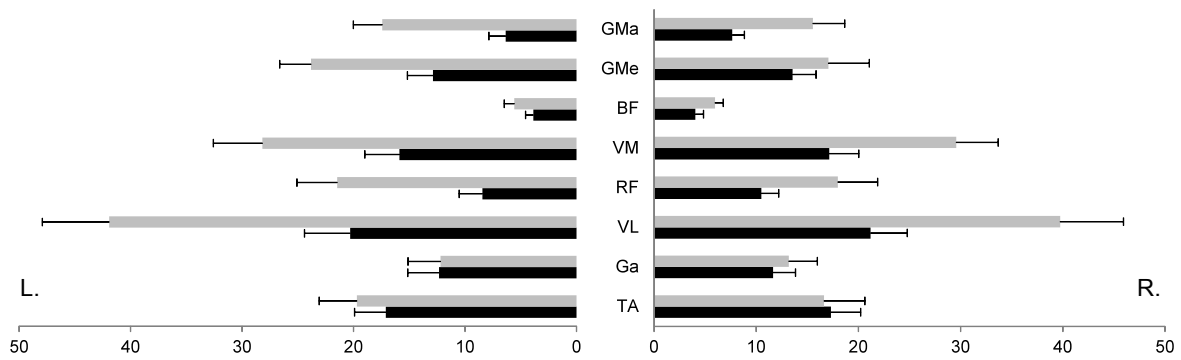
Figure 4.4. Mean EMG activation level (%MVIC) for first trial (black) and last trial (grey) for eight muscles bilaterally (left and right averaged). GMa: gluteus maximus, GMe: gluteus medius, BF: biceps femoris, VM: vastus medialis, RF: rectus femoris, VL: vastus lateralis, Ga: gastrocnemius, TA: tibialis anterior. Error bars are standard deviations. L: left side; R: right side.

Sex

There were significant differences between males and females for four joint ranges of motion in the lower limb (Figure 4.5). In the frontal plane, hip abduction/adduction range of motion increased with practice in both groups, but the mean increase was 20.1° more in the females than the males ($F_{(1,14)} = 25.7$, $p < 0.01$), who showed a more gradual increase with practice than the females ($F_{(24,336)} = 6.0$, $p < 0.05$). In the transverse plane (internal/external rotation), the females again showed a greater increase with practice than the males in hip, knee and ankle motion ($F_{(1,14)} \geq 5.6$, $p < 0.05$), resulting in 6.6-8.6° differences in range of motion by the end of practice. For hip internal/external rotation, the increase with practice was significant only for females ($F_{(24,336)} = 2.2$, $p < 0.01$), where *post hoc* tests showed a significant increase after 15 trials ($p < 0.05$), while there was no significant increase for males ($p \geq 0.052$).
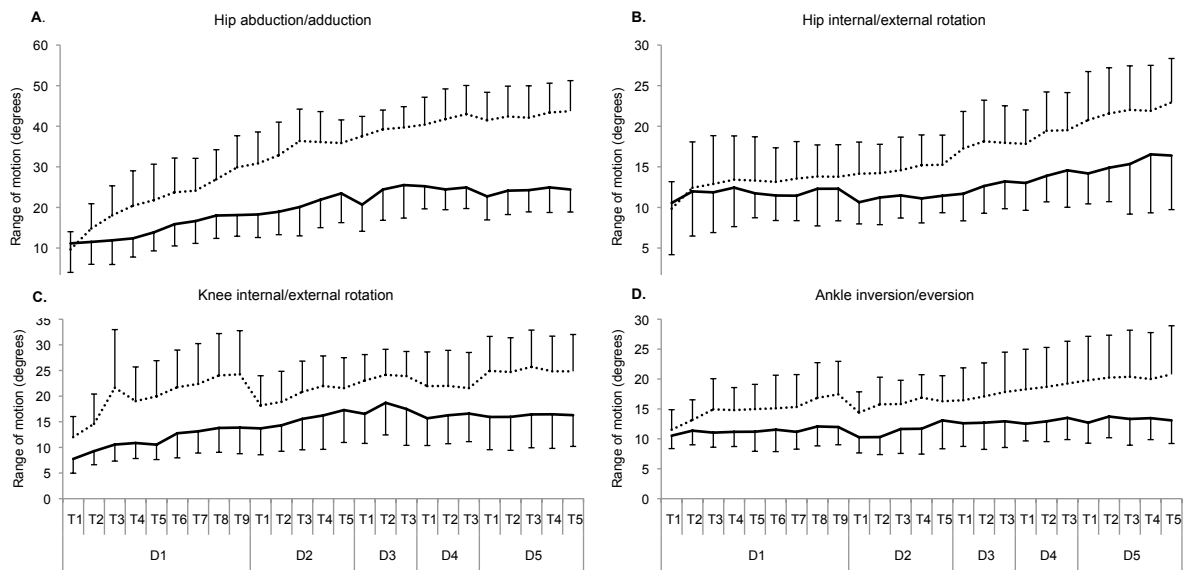
Figure 4.5. Range of motion (mean ± SD) for four joints that displayed a significant main effect difference between females (dotted lines) and males (solid lines). Data are averaged across left and right sides.

The male participants activated the gluteus medius more than the females ($F_{(1,14)} = 4.8$, $p < 0.05$). The change in activation across practice (Figure 4.6) was different in the two groups ($F_{(13,182)} = 2.6$, $p < 0.01$), the *post hoc* tests showing that the males increased activation from day one to day five ($p < 0.05$) while the activation level for the females did not change ($p \geq 0.99$).

The time-normalised joint angle and IEMG patterns for each platform cycle did not show any clear differences between males and females for most variables. The 95% confidence intervals were clearly separate between groups only for the joint motions of hip abduction and knee flexion (Figure 4.7). Females used a greater range of hip abduction than males (Figure 4.7A, B). The range of knee flexion was comparable between groups, but the males displayed more knee flexion throughout the entire cycle and reached a greater maximum knee flexion angle than females (Figure 4.7C, D)
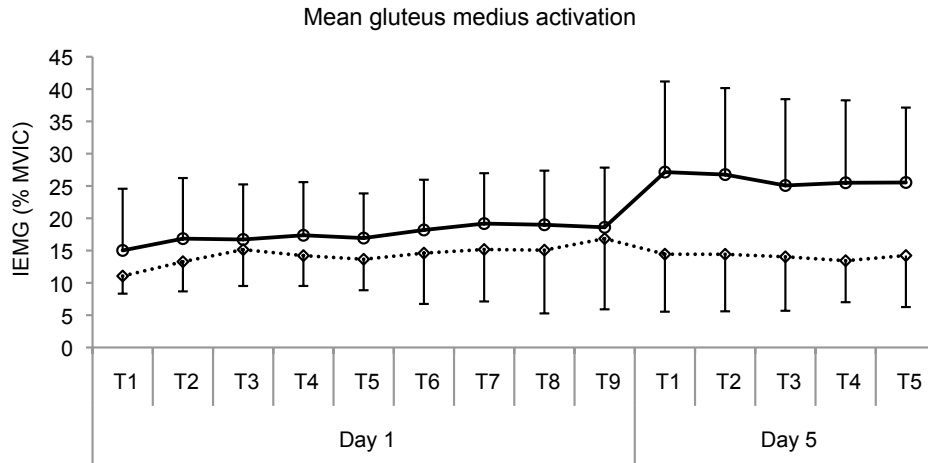
Figure 4.6. Gluteus medius activation (mean ± SD) across days of practice in male (solid line) and female (dotted line) participants. Data are averaged over the left and right sides.
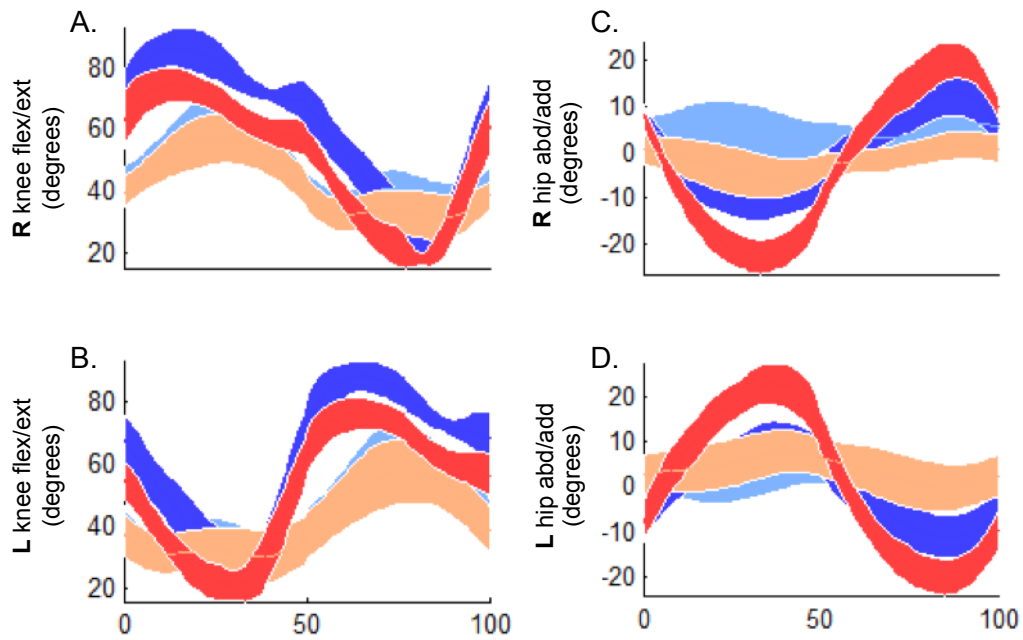
Figure 4.7. Differences between males (blue) and females (red) for mean time-normalised movement pattern before (lighter traces) and after practice (darker traces) for right and left hip abduction/adduction (A and B) and knee flexion extension (C and D). The first 50% of the cycle corresponds to platform movement from the centre position to the left (and return), while the second 50% corresponds to movement to the right (and return).

Side

There were no significant overall differences between the left and right sides for the lower limb joint ranges of motion nor for the level of muscle activation ($F_{(1,14)} \leq 2.4$, $p \geq 0.14$). For three muscles -

rectus femoris, gluteus medius and gluteus maximus - the extent of the increase with practice was greater on the left side ($F_{(13,182)} \geq 3.0$, $p < 0.01$).

4.3.3. Self-efficacy

The results for the questionnaires are presented in Table 4.4. The mean ratings were higher in males than females for all measures (with similar SDs) but the differences between groups were not significant for trait self-objectification (questionnaire one), total physical self-efficacy (questionnaire two) nor any measure of task-specific self-efficacy (questionnaire three) ($F_{(1,14)} \leq 3.2$, $p \geq 0.09$). Males did however exhibit significantly greater self-efficacy than females ($F_{(1,14)} = 4.92$, $p < 0.05$) for the general ability to learn and perform non-specific motor skills (questionnaire three).

Table 4.4. Self-efficacy scores (mean ± SD)

Group	Trait self-objectification	Physical self-efficacy	Motor self-efficacy	Speed and fluency	Ski-sim self-efficacy
M	-18.1 ±10.9	74.1 ± 7.7	57.6* ± 8.2	6.0 ± 2.8	22.1 ± 6.2
F	-11.5 ± 10.3	68.1 ± 11.3	49.8 ± 5.8	3.8 ± 2.1	16.9 ± 6.2

M: males, F: females. * Significant difference between M and F ($p < 0.05$).

4.3.4. Between-subject variability

Finally, although we have shown that there were minimal sex differences both for performance and learning of this skiing simulator task, it should be highlighted that there were very real differences in individual performance within both groups, especially on the initial trial. This between-subject performance variability decreased with practice in both groups, with all participants converging upon a similar level of performance despite the initial difference and any differences in self-efficacy. This general pattern is illustrated in Figure 4.8 for one of the key performance variables, angular displacement of the CoM in the medio-lateral plane. The initial and final performances of individual participants and the between-subject variability in the male and female groups show comparable patterns of convergence towards the same final values.
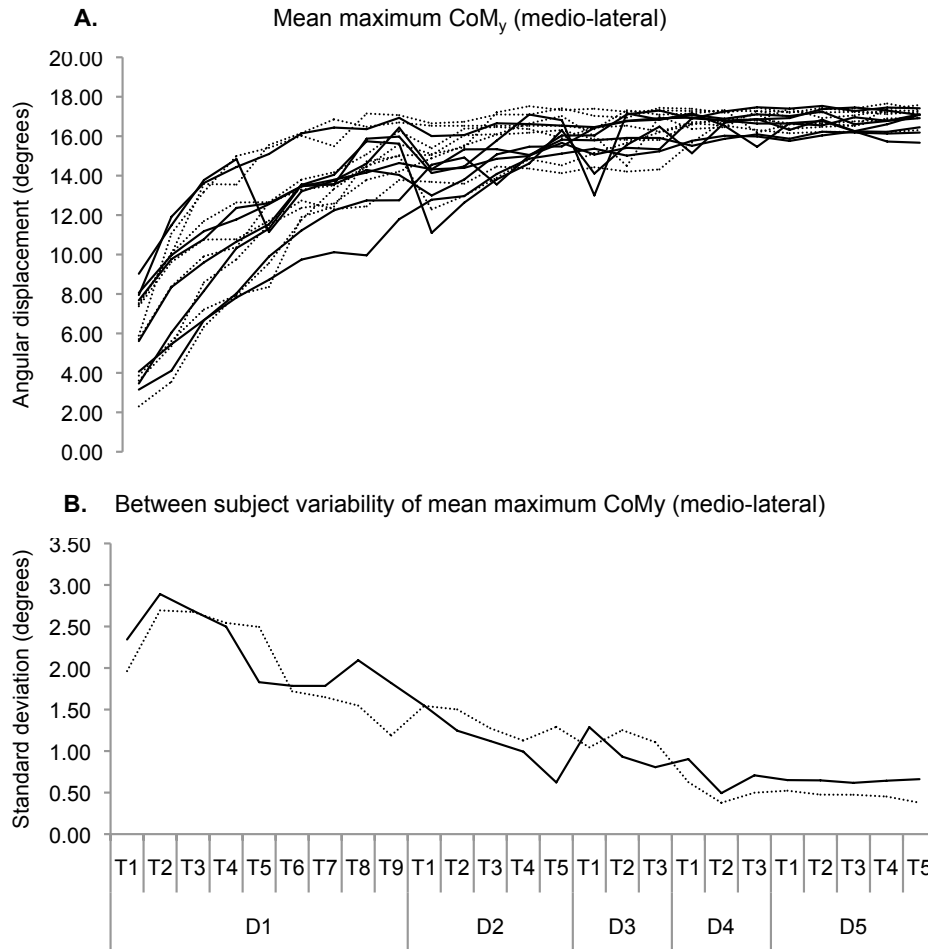
Figure 4.8. A) Individual progression with practice of all participants for angular displacement of the CoM in the medio-lateral plane. B) Between-subject variability for the male (dark line) and female (dashed line) groups for the same variable.

4.4. Discussion

The comprehensive performance, kinematic and muscle variables measured here showed that all participants, female and male, were successful in learning this novel whole-body motor task. They were instructed to make the fastest, widest and smoothest movements possible on the platform and the increases in platform frequency and amplitude, and decreases in cycle-to-cycle variability, demonstrated that they adhered to this instruction. The increase in range of motion at many joints and in the level of activation of nearly all muscles was consistent with their increased work on the platform. The change in the relative phase between the body CoM and the platform and the reduction in the height of the CoM is in line with changes with practice reported in previous studies of this task

[Vereijken 1992a]. The frequency of platform oscillation in nearly all participants at the end of practice was close to the optimal frequency for their mass.

The major finding from this study was that there were no differences between females and males in initial or final performance, or in rate of learning for a novel whole-body motor skill. An observed sex difference on a related pair of performance outcome measures can be accounted for on the basis of basic anthropometric differences interacting with the apparatus between the groups. Minor differences in the movement used to achieve the outcome were also largely explainable in the same way. We approach the findings by considering the interaction of individual and task constraints [Newell, 1986], which proves more fruitful here than generalisations on the basis of sex.

There was a male performance advantage for three closely-linked performance variables - cycle duration, platform frequency and work (Figure 4.3). Since the platform frequency is simply the inverse of the cycle duration, these measures reflect the aspect of same performance. Similarly, the work performed is closely related to this aspect of performance. Both of these variables showed higher values in the males. First, since work is the product of force and distance, the average force was higher in the males due the greater number of resistance bands assigned (on the basis of body mass). Second, because the males had a higher cycle frequency, they performed more cycles per minute and therefore they traversed a greater angular distance per minute. Hence, the product of these higher values accounts for their higher work. These three performance variables, therefore, simply reflect the higher theoretical platform resonant frequency in the males, which is largely attributable to their higher mass as it meant that more resistance bands were added to the system, which effects the performance potential on the system. Hence, this apparent performance advantage can be explained by the difference in average body mass between the groups, interacting with the task apparatus. Whereas one study using a similar skiing simulator recruited participants within a restricted weight range [Almåsbakk et al., 2001], others have not addressed the question presumably finding no differences in performance. The current study did not restrict the range in order to provide more representative groups, as unlike previous research, the aim was to compare males and females. The crucial finding here was that both male and female participants worked close to the optimal platform frequency for

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their mass and moved closer to that frequency with practice according to this task constraint (Table 4.4). Male and female performance and extent of learning therefore can be considered as being equivalent in this motor task, as despite the appearance of a difference, they were still performing to their theoretical optimal performance for this measure

Since there was little indication of differences between the sexes on any measure of performance outcome (other than that explained above), we set out to explore whether any differences in movement form or technique were apparent. Redundancy in the motor system dictates that there are many ways to achieve the same outcome [Bernstein, 1967]. However, there were few differences between males and females for the kinematic and EMG variables of joint range of motion and average muscle activation. Differences in the frontal plane for the hip and the transverse plane for the entire lower limb again appear to be a result of anthropometric factors bearing on the task. The main effects for sex in the frontal and transverse plane joint angle excursion can be attributed to the difference in average height between males and females. To achieve a similar amplitude of platform excursion, shorter participants have to make larger joint rotations about a central pivot. In the frontal plane, shorter participants require a larger range of hip abduction to achieve the same amplitude. The concomitant increased range of motion for the hip, knee and ankle joints in the transverse plane (Figures 4.5, 4.7A,B) can be related to the requirements of achieving greater hip abduction while remaining centred over the platform. So here we have a situation of what appear outwardly as differences, actually serving to make performance outcome (platform amplitude) more similar.

Gluteus medius was the only muscle to present any differences between males and females, with a lower level of activation in the females, especially on the final day of practice (Figure 4.6). This muscle acts as a prime hip abductor and since females used a greater range of hip abduction, it might have been expected they would activate it more, not less, than males. There was also an increase in activation with practice for males and not for females, even though females had a greater increase in range of hip abduction with practice. There are sex differences in the strength of gluteus medius, with females being weaker even when body weight differences are accounted for [Bohannon, 1997; Leetun et al., 2004]. Weakness logically might be thought to necessitate a higher activation of the muscle, but

strength and hip muscle activation have been shown to be only loosely correlated with movement kinematics [Shultz et al., 2009; Haines et al., 2011].

The situation here may bear some relation to the scenario in the landing literature, where the tendency to move into a greater valgus or adducted position of the hip for females is the only consistent difference that has been shown between the sexes [Carson and Ford, 2011]. While for landing this posture does not appear to represent ideal performance, potentially increasing injury risk, it may help explain the difference in muscle activation here. Landing in the adducted posture is sometimes associated with a lower activation of the gluteus medius [Hart et al., 2007], the increased range of adduction being attributed to the reduced activation of this hip abductor. It may be that to enable the greater abduction/adduction range in females dictated by the skiing simulator task, this muscle had to be activated to a lesser degree and momentum used instead to passively drive the movement. If this account is correct, it provides another example of how performance differences are better considered in terms of task constraints rather than sex.

Another difference between males and females that requires explanation was the difference in the pattern of knee flexion and extension, whereby the males showed greater maximum flexion than the females, but similar joint RoM (Figure 4.7C,D). This finding must be considered in the context of the height of the CoM from the platform, for which the absence of a sex difference (for both absolute and normalised height) is of significance in itself. Females generally have a lower standing centre of mass than males because, in addition to being shorter, there are sex differences in pelvis shape and size, and in weight distribution in the trunk [Aiello and Dean, 2002]. Hence, it would be expected that females would be significantly closer to the platform because of their lower height, but the results showed that the lowest absolute height of the centre of mass from the platform during performance was not different between groups. The greater maximum flexion at the knee in the taller males therefore can account for them achieving a CoM height similar to the females. What is unclear is why the females did not take advantage of their lower standing centre of mass to achieve an even lower CoM height, since this is a key variable in performance of this task [Vereijken et al., 1992a, b]; a lower CoM allowing for better performance. This importance was evident here in the CoM moving progressively

lower towards the platform with practice in both groups (Figure 4.1c). It could be that because the females achieved the maximum range of angular excursion of the platform, similar to the males, they did not need to reduce their CoM height any further. Alternatively, this finding may represent another instance of females not using adequate knee flexion for some tasks, as reported intermittently in the literature [Lephart et al., 2002; Decker et al., 2003] and similar to the finding in the drop landing study in chapter 2 where females landed with more extended knees at initial ground contact. Perhaps considered together, male and female participants used different strategies to achieve the same motor skill. Hip flexion/extension and CoM height were recently shown to be more important than frontal plane hip biomechanics in producing forceful sideways (frontal plane) movement [Shimokochi et al., 2013].

Unrelated to sex differences, a finding of interest was the presentation of performance asymmetries between movements made to the left and right of the simulator platform. In general the movements made with the right leg were of greater amplitude than those on the left, with higher frequency and more work performed (Figure 4.2). All participants were right-foot dominant, or mixed footed but biased towards the right. This result is therefore in agreement with established literature on lower limb dominance. In the lower limb the non-dominant leg is generally larger and better suited to a support role [Auerbach and Ruff, 2006], rather than the forceful swinging motion required of the dominant leg. As the lower limbs are used together in performing most activities, the non-dominant limb is often referred to as 'stance dominant' and the dominant limb as 'swing dominant' to reflect these properties [Grouios et al., 2009]. It therefore makes sense that the right-swing dominant subjects achieved higher platform performance on the right. Research into the upper limb suggests that each limb is specialised for different aspects of performance [Sainburg, 2002] and that the non-dominant limb joints exhibit greater proprioceptive sensitivity [Han et al., 2013]. It is unclear whether these differences that are evident in open chain arm movements also apply to the lower limb. Vereijken [1992a] did not measure performance to the left and right separately, but did however report leg asymmetries in performance. Joints of the right leg became uncoupled from each other, indicative of a greater exploratory role in the movement. However, this asymmetry only appeared with practice and hence was suggested as not

being related to dominance. Exploring limb dominance was not the aim of this study but it is interesting to note that despite the performance asymmetries, there were minimal other differences between the legs except for the increase with practice in average EMG levels being greater on the left for the three muscles that cross the hip (Figure 4.4). Perhaps this was an attempt to rectify the performance asymmetries but given this however, it is interesting to note that there was not a corresponding asymmetry in hip joint range of motion in the frontal plane.

The results from the questionnaires in this study revealed just one significant sex difference, the general physical self-efficacy for learning and performing non-specific motor skills was greater in males. While the male participants had a greater confidence in their ability to learn motor tasks, however, it did not appear to aid performance for this skiing simulator task as there was no correlation between self-efficacy and any of the performance measures. The number of falls over the 125 practice trials was also significantly different, with males falling more frequently. The number of falls from the platform could be conceived either as poor performance or an indicator of pushing one's physical limits. The reason for most falls appeared from observation to be participants trying to push the platform a greater distance before they had acquired adequate control of the balance and forcing requirements. That males fell a greater number of times appears to indicate that for this exploratory learning task, males were working harder to establish the boundaries of movement on the ski platform or "explore the biological workspace" in learning the skill [Newell, 1986]. Falls may also be associated with risk taking, which is reported to be greater in males [Byrnes et al., 1999]. Possible differences between the sexes in risk taking could lead to enhanced learning of more open motor skills. .

In summary, a comprehensive assessment of performance and kinematic variables has shown few differences between female and male participants. Those that were observed appear to be accounted for by anthropometric differences between females and males, specifically in body mass and height. These became relevant only due to the nature of the measurements and the apparatus upon which the skill was performed. However, the differences in performance for related performance outcome measures actually meant that the males and females were performing at their theoretical optimum. The

differences in hip range of motion also served to ensure the performance outcome of maximal platform amplitude was similar between males and females, despite their height difference. Given further consideration, these findings suggest that males and females were performing the task with similar success, within their individual constraints. Hence, we conclude that there are no explicit differences between males and females in the capacity to learn and perform a novel motor task over the same duration of practice.

Chapter 5

Part I

Historical and conceptual background to the study of coordination

5.1. A brief history

The human body is a highly complex system. When considering even the simple task of standing up from a chair, success relies on the orchestration of approximately 700 muscles crossing over 300 joints, each with movement in up to 3 planes of motion possible. When the number of neurones innervating each motor unit within each muscle is brought into this perspective, one realises that the task of coordinating such a large number of elements to produce purposeful movement is far from trivial. From the dictionary, to coordinate movement is to 'bring the (motor) elements into proper relation … so as to enable them to function effectively'. Over the last 50 years, research at the level of observable behaviour has been directed towards quantifying the spatial and temporal relationships that exist between both limb segments and muscles of the moving body. Understanding the interactions between such movement units provides insight into the underlying structure of control that allows the production of skilled movement.

By far the most influential figure in the study of coordinated motor behaviour has been the Russian physiologist Nikolai Bernstein (1896-1966). His observations provided the framework for the majority of study into the organisation and control of human movement. It is rare to encounter any behavioural research that does not refer to his ideas, in particular his elucidation of the 'problem' of motor control. Bernstein emphasised the importance of kinematic variables of movement and rejected the idea that control was a straightforward or direct link between the nervous system and the motor apparatus it controls [Bernstein, 1967]. In doing so, the problem became that of how the multitude of elements within the movement system are organised to produce coordinated movement. The large number of elements means that there exist multiple or redundant movement solutions for achieving the same movement task or outcome goal. The question then is how the system manages to arrive at a particular

solution, given the numerous options available. In many respects, this has become the defining question of the field [Newell and Vaillancourt, 2001].

In a landmark review, Turvey [1990] summarised the entire study of coordination into two rounds of theory and experiment, based on the insights of Bernstein, that attempt to understand the underlying organisation of the motor system that enables the 'problem' to be solved. In brief, the first round consisted of the initial efforts in the context of understanding how a large number of kinematic variables could be regulated and the second was conducted under the influence of dynamical systems theory. The manner in which the problem of complexity within the motor apparatus is overcome is a question of great contention, to the point that the field has been described as being in a paradigm crisis [Abernethy and Sparrow, 1992; Burgess-Limerick et al., 1994]. In simplest terms, two separate lines of inquiry differ in what they ascribe as the basis of the organisation; one a prescriptive internal controller within the central nervous system (CNS); the other a natural emergence from open interaction with the environment. It is fair to say that while debate may have tempered over the last 20 years, it appears to be a case of 'agreeing to disagree', rather than resolution of the crisis [Summers and Anson, 2009] Beyond this debate about the origin of organisation, others believe that the notion of complexity as a 'problem' should be rejected altogether, maintaining rather that having many ways to perform the same task is an advantage because it allows flexibility [Latash, 2012].

It was not within the aims of this thesis to enter the theoretical debate upon how and where this organisation may originate, but to provide a thorough description of coordination and control in males and females and their evolution with practice. Nevertheless an introduction to the different theoretical viewpoints and experimental approaches within the field is warranted. It has been said, in criticism of dynamical systems theory, "that as typically the case in science, one investigator's explanation is another investigator's description" [Walter, 1998] (pg. 330). This is an apt overview of the field of motor control. Proponents of dynamical systems consider the discovery and definition of physical laws of motion as the key to understanding coordination. However it was argued this view is akin to expecting that knowledge of planetary motion enough to reveal the mechanisms of gravity (which is not the case) [Walter 1998]. The first part of this review therefore details the historical background

and current state of play relating to the quantification of coordination and the solution to the 'problem' of controlling many motor elements.

One thing that is apparent is that although we may still be unsure of the details of how, the so-called problem of coordination by the CNS is seamlessly overcome many times a day in a healthy individual. Rather than investigating a problem therefore, the author feels it more appropriate to consider the task as investigating the *wonder* of motor control.

5.2. Redundant degrees of freedom… Problem?

The 'Bernstein problem' of adequately controlling many variables in a complex system is also formulated as the 'degrees of freedom' (DOF) problem. This generic term from the field of physics refers to the number of independent coordinates required to uniquely describe the configuration of elements within a system, without violating its geometry [Li, 2006]. As highlighted by [Newell and Vaillancourt, 2001; Newell et al., 2003] this loose definition that contains no mention of the specific variables of interest or the levels upon which they lie within the motor system, has caused confusion within the field. It appears that a degree of confusion still exists; the different meanings associated with 'degree of freedom' illustrate the above-mentioned split in the field and this point is elaborated further on. Bernstein did not clarify what specific degrees of freedom within the motor system he was referring to when describing his ideas on coordination but it is widely understood to be the kinematic joint space or the periphery [Newell and Vaillancourt, 2001]. Variables at this level of analysis have been labelled 'mechanical' degrees of freedom i.e. referring to the actual configurations of joint angles as they exist in space. Each joint angle within the system can rotate in up to three planes of motion; these permitted movements are the degrees of freedom. The sum across each of the joints in the body therefore constitutes the total degrees of freedom within this level of the movement system. To perform a movement task with a defined goal, a number of potential configurations or trajectories of the mechanical degrees of freedom exist that are capable of meeting the goal – there are more options than strictly required to achieve the task. This issue of redundant solutions is also evident at the neuromuscular level as the same outcome at a joint can be produced from different combinations of muscles or by using different timing and activation magnitudes with the same muscles. A key

observation of Bernstein from his now famous kinematic recordings of expert blacksmiths during the task of hitting a chisel (Figure 5.1), was that while the trajectory of the hammer remained invariant - hitting its target each time - the joint angle trajectories within the arm were different each strike. The degree of variation within the joints was therefore greater than that of the hammer. This suggested there was no single solution or stereotyped control involved in the production of the movement, instead each consecutive hit involved 'repetition without repetition'. These observations framed Bernstein's ideas on the construction of movement; specifically that it involves minimal interaction on the part of the controller. This example also highlighted the importance of variability in motor control and the difference between variability at the task or performance level versus that of the movement system.
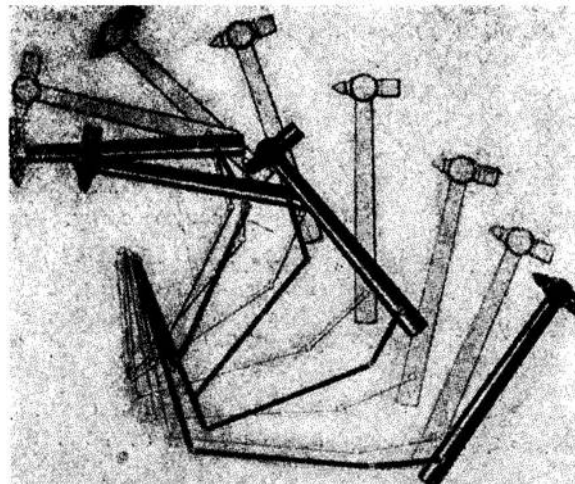
Figure 5.1. Original picture of the blacksmith's movements; the hammer hits the target each time despite different joint angle trajectories [Bernstein 1967].

5.3. Mastering redundancy by reducing the effective degrees of freedom

It was Bernstein's intuition that for the complex musculoskeletal system to become controllable - the movement problem to be solved - would necessitate a reduction in the number of elements individually controlled. In following the assumption from the previous paragraph that he was referring to kinematic variables, control would be made possible by minimising the number of individual joint rotations that required independent control or specification. An exploration of the mechanical or kinematic degrees of freedom at the periphery was an important pursuit within what Turvey [1990] described as the first round of theory and experiment and still forms an important component of study

in the field. It is feasible that the organisational principle of reducing the number of degrees of freedom that are under direct control may operate at multiple levels within the motor system; from kinematics through to the firing of motor neurones [Newell and Vaillancourt, 2001]. It has been hypothesized that together the different levels form a hierarchy of subsystems each operating at a low dimension and functioning together [Gelfand and Tsetlin, 1966]. Whatever the details may be, it is widely recognised that to deal with the overwhelming degrees of freedom (from the kinematic to neuronal level) to be coordinated, they are unlikely to be subject to individual control. It should be noted that while people may be able to restrict movement to a certain joint under some circumstances, this does not mean there is no concomitant control strategy being applied to a nearby joint, in order to achieve this. At most times – all of the degrees of freedom are being controlled – even if to produce the effect of no movement.

Reduction from a large number of elements in the joint parameter space, to a lower dimension in the control space was envisioned to occur via 'functional linkages' whereby the CNS unites elements into groups that can be controlled and directed by a single variable [Bernstein, 1967]. The problem then became one of defining how the many individual elements are constrained to act together within the motor system. By constraining elements together, defining their configuration becomes a simpler task as numerous outputs can be defined from a small number of inputs. The common cited example to illustrate this idea is the physical constraint of four independent wheels of a car that allows them to be controlled via the movement of one element only - the steering wheel. This elegant idea of simplification via constraint has become the cornerstone of a large part of motor control theory and experiment; and is encapsulated within terms such as synergy [Latash et al., 2007; Torres-Oviedo and Ting, 2010], coordinative structure [Tuller et al., 1982; Vereijken et al., 1997; Wang et al., 2013], mode [Balasubramaniam and Turvey, 2004] and module [Clark et al., 2010]. On face value and in some respects this idea provides a unifying concept within a fractured field, although there are models of control that do not draw upon the idea. Yet for the groups of researchers who do, the previous terms are not synonymous and have different connotations and meanings depending on the assumptions of

their research approach. Together with the 'degrees of freedom' they harness the notion of synergy and low dimensional control requires careful explanation and usage in order to avoid confusion.

5.4.   Original conceptions of synergy: coupling and correlation

Although the term synergy is synonymous with Bernstein, its earliest usage may be attributed to Charles Babinski (1857-1932) who detailed impaired coordination in patients with neuromuscular disorders and described 'cerebellar asynergies' as the basis of their problem [Clarac et al., 2009]. Babinski also described the presence of the specific postural adjustments or 'axial synergies' that result from the forward bending of the trunk [Alexandrov and Frolov, 2011]. Gelfand et al. [1971], in furthering the ideas of Bernstein's functional linkages, described the organisation of the kinematic joint angles into flexible, task-specific 'structural units'. The traditional notion of a synergy was therefore a task-specific and flexible arrangement of movement elements, essentially a term to convey the idea that relatively independent degrees of freedom were constrained to behave together as a single, functional unit to achieve a goal that would otherwise be unattainable. In an effort to provide distance from older connotations of the word synergy as a rigid stereotyped reflex, and minimise confusion with the unrelated description of 'synergist' muscles, the term 'coordinative structure' was introduced, and to begin with described a principle similar to that of synergy as outlined above (axial synergies or structural units) . The hallmark of a synergy in this sense is the coupling and sharing among elements within the system that result in correlated outputs, be it at the level of muscle activations, joints or effectors (limbs) [Turvey, 2007]. Early evidence from the kinematic level of analysis for the existence of synergistic control of body segments was provided from experiments on pistol shooting [Arutyunyan et al., 1968] and postural adjustments during breathing [Arutyunyan et al., 1969]. In expert pistol shooters, the movements at the wrist, elbow and shoulder interacted with each other such that movement at one joint that would normally be expected to shift the trajectory of the pistol endpoint was compensated for by movement at another joint, resulting in better stability of the pistol and therefore more successful performance. This compensatory control, where variability in one joint trajectory is 'automatically' compensated for by an adjustment in another, suggests that the joints

are being controlled as a single unit rather than individually and that the movements are not independent of one another.

Investigating the correlation between patterns of movement outputs from various levels of the motor system can therefore provide insight into the underlying structure of coordination. There is evidence from a range of tasks that peripheral movement outputs at various levels of analysis are highly correlated. The evidence for this will be presented later. For now it can be noted that according to many researchers, a high correlation among elements reflects a reduction in the dimensionality of control - there are fewer variables in space to be independently controlled because the close relationship means that changes in one parameter are translated to all others. Therefore the degrees of freedom problem is simplified because despite the numerous outputs present, they are controlled in a lower dimensional space. This does not solve the mystery of coordination entirely however, because investigating the co-variation among elements in a system, while providing a useful indication of structure, does not provide any direct insight into how the correlated patterns of output are formed.

5.5. Low dimensional control space: a simple concept yielded a multiplicity of approaches

5.5.1. Diverging developments in the study of synergistic control

Latash et al. [2007] asserted that the measurement of correlated patterns within peripheral performance variables is addressing a 'pseudo-Bernstein' problem because it cannot directly address the language of control within the CNS. Indeed, most recent research into motor coordination reflects a change in emphasis from exploring correlated outputs at the periphery to attempts at explaining *how* these patterns form. The result has been the development of various frameworks for determining which low-dimensional component is actually 'controlled' and how. This constitutes the split nature of the field whereby groups of researchers pursue disparate paths in detailing how the degrees of freedom come into relation and what a synergy represents. Nevertheless, uncovering the underlying pattern from movement outputs that compose coordinated behaviour (addressing the so-called 'pseudo problem') is still an important area of research because a comprehensive account of the relationships

that exist between variables can provide the foundation for addressing deeper questions of control. Chapter 6 compares two methods from the literature that have been used in quantifying these relationships. The following sections summarise the different approaches and conceptions of synergy that have been derived from this inward-bound quest toward understanding motor control and provide evidence for the existence of low-dimensional control.

5.5.2. The Uncontrolled manifold (UcM)

Latash et al. [2007] contended that most research has focused only on the sharing aspect among elements within a synergy, rather than other factors such as stability and flexibility of the output. They extended their definition of synergy from the simple grouping of elements to incorporate a requirement that the elements be involved in error compensation. The focus was on flexible control of execution variables to regulate task-relevant variability [Tresch and Jarc, 2009]. This definition of synergy was inspired by the 'principle of least interaction' proposed by Gelfand [1971] that posited a hierarchical network with afferent and efferent signals in the CNS organised to reduce central processing demand. By having the elements within a synergy adjust their contributions to minimise error in the final output, less action is required by the controller. Building upon this definition, [Schoner, 1995; Scholz and Schoner, 1999] developed a computational method to assess this notion of synergy within the uncontrolled manifold (UcM) hypothesis.

While the uncontrolled manifold has been referred to as synonymous with the term synergy [Turvey, 2007], it should be recognised that in some respects it stands in direct contrast to the traditional ideas of a synergy acting to reduce degrees of freedom [Tresch and Jarc, 2009]. The approach is based on the concept that the end effector of a movement system is the only controlled variable. The method requires the movement task (output) analysed to have a spatially defined goal state, which limits its application [Huys et al., 2004]. When attempting to stabilise the output of the end effector, the controller organises elements into a subspace (the UcM) that corresponds to a desired performance value. Within the space, the elements are not individually controlled and are free to vary within the bounds of the performance parameter. By minimising the parameter controlled to consider only the output (the task requirement), the issue of controlling many degrees of freedom is resolved [Latash et

al., 2007]. However this approach does not operate under the traditional view of multiple degrees of freedom being a 'problem', in other words that the controller attempts to choose specific solutions or reduce its available options. Rather the CNS is seen to 'allow' multiple movement options within an acceptable range of end effector output. Synergies according to this definition do not eliminate redundant degrees of freedom in the Bernsteinean sense, rather the 'abundant' [Gelfand and Latash, 1998] degrees of freedom are used to minimise error. The variable nature of movement and multiple degrees of freedom therefore are not viewed as a problem but as inherent to the control strategy.

The UcM method has been used to quantify movement patterns and synergistic relationships between variables in a range of tasks including finger coordination [Park et al., 2010], sit to stand [Reisman et al., 2002], bimanual pointing [Verrel et al., 2012], circle drawing [Tseng and Scholz, 2005] and shooting [Scholz et al., 2000]. The method invokes structures that are outwardly similar to synergies when applied at the level of muscle activations, known as m-modes [Krishnamoorthy et al., 2003]. These are groups of muscles that are correlated and therefore controlled together. These then act as the elemental variables in the subspace, groupings necessitated by the realisation that muscles are not controlled individually and therefore cannot make up the elemental variables in the UcM [Latash and Krishnamoorthy, 2005]. According to Latash's definition of the term, these modes do not qualify as synergies, but rather groups of muscles that can be manipulated into 'task-specific subspaces' (synergies according to latash). They do however meet the original definition of synergy described earlier, in that they are groups of correlated variables that can be controlled together. .

The UcM method has mostly been applied to tasks involving postural perturbation [e.g. Krishnamoorthy et al., 2003; Krishnamoorthy et al., 2004; Asaka et al., 2008]. M-modes, corresponding to groups of muscles that scale in parallel according to task requirements, are generally found to consist of groups of dorsal or ventral muscles that are recruited depending on the direction of the postural perturbation [Krishnamoorthy et al., 2003]. The key idea here is that control via these modes is at a lower dimension of control than individual muscle activations. Practice at a load-release task performed while standing on a narrow support provided evidence that these modes may change in composition (the muscles involved) and in the combination of these modes into synergies (from co-

contraction to reciprocal activation) [Asaka et al., 2008] with practice at a task. These research findings further emphasise the flexible nature of synergies, whereby changes occur with practice and experience. In addition to m-modes at the level of muscles, 'force modes' have been studied at the level of kinetics via research into coordination and force sharing, in particular between the fingers [Danion et al., 2003]. Studying finger coordination is further complicated however by the possible interaction between both neural and peripheral constraints that enslave the fingers to produce force together and may change with the task [Kim et al., 2008]. The examples in this section provide further evidence of structured low-dimensional control outputs at multiple levels of the movement system.

5.5.3. Neurophysiological and neuromechanical approaches

Some neurophysiological research has embraced the traditional idea of a synergy as a grouping, especially in terms of muscles, where interest lies in determining why particular patterns of muscle activations are chosen by nervous system [Ting and McKay, 2007]. Similar notions of low-dimensional control have existed in the field over many years, as applied to reflexes [Sherrington, 1910], central pattern generators [Grillner and Wallen, 1985] and spinal force fields [Giszter et al., 1993]. A reduction in the dimension of control at the biomechanical level is proposed to reflect a similar reduction at the level of neural circuitry [Ting et al., 2012]. From the definition of D'Avella et al. [2003], synergies are coherent activations in space or time of a group of muscles. Conceptualised as building blocks for movement, they represent the minimal number of base elements that are able to generate all movements within a behavioural repertoire [D'Avella et al., 2003]. Research by D'Avella and colleagues [2003] has provided supporting evidence using electrically-invoked leg movements in spinalised frogs. Combinations of three time-varying muscle synergies were extracted from the simultaneous recording of the output from many muscles. These synergies were able to account for the full range of the natural defensive kicks of the frog, proposed by their modelling to occur via independent scaling in amplitude and shifting in time of the three synergies. Human locomotion has also been the subject of intensive research in this vein. Muscle activation patterns are believed to represent the drive of central pattern generators in the spinal cord [Ivanenko et al., 2006]. It was shown that EMG output from 32 muscles during treadmill walking could be reduced to patterns of

temporal activation of just five independent components [Ivanenko et al., 2004]. There is therefore ample evidence from this field to support the idea of low-dimensional, modular control, especially at the neuromuscular level.

A slightly different interpretation, yet still dependent upon spinal circuitry for the implementation of control, is that a synergy is controlled by a single neural command signal and reflects a translation between neural commands and control at the level of the task [Ting, 2007; Ting et al., 2012]. In some respects this is similar to the concept of reduced dimension via task-level control of the UcM approach. Rather than maintaining an end-effector within an acceptable limit of performance variability however, the centre of mass (CoM) has been emphasised as the low-dimensional, task-level variable that is controlled by the CNS [Ting and McKay, 2007]. Responses to postural perturbation have also been a key area of inquiry for research in this vein, as maintaining the CoM within the body's base of support is in effect the task goal for this movement [Ting and McKay, 2007]. A small number of synergies or patterns of activation among muscles have been shown to give rise to a continuum of postural responses in control models in both the cat [Ting and Macpherson, 2005] and humans [Torres-Oviedo and Ting, 2007]. Indeed, research into postural responses has always expressed the general notion of synergy as linkage, especially since the discovery of the specific hip-, knee- and ankle-mediated responses underlying balance strategies that were proposed to reflect postural synergies [Horak and Nashner, 1986].

The common ground for most neurophysiological investigations of low-dimensional control is the assumption that patterns of correlated output at the periphery reflect the underlying neural architecture in particular spinal interneuronal circuits [Ting et al., 2012]. This assumption has recently been criticised from within the field, where it has been suggested that the correlations reflect task-level and mechanical constraints rather than neural control strategies [Kutch and Valero-Cuevas, 2012]. This criticism of speculation about the specific physical foundation of muscle synergies based on correlated outputs of muscle activity is perhaps warranted and brings us to an important distinction that can highlight a difference between the approaches summarised in this section. This is the idea of hard-wired versus soft–wired linkages as the manifestation of synergy. As described by Neilson [2010],

these concepts do not have to be mutually exclusive; both hard-wired and soft wired, task-specific synergies may be present within different levels of the motor system and be orchestrated by different mechanisms. One way to reconcile the various conceptions of synergy therefore, especially between the neuromechanical and dynamic systems theory approach that is reviewed next, is to consider that they are not attempting to explain the same phenomena. Confusion may arise when identical methods are used in exploring different phenomena, as discussed in Part II of this Chapter.

For the sake of balance, it should be realised that are other views within the neurophysiological and computational motor control theoretical landscape that do no invoke the idea of modular, or synergistic control. For example instead of invoking synergies, optimal feedback control theory proponents [e.g. Todorov and Jordan, 2002] attempt to solve the problem of redundancy by adding the constraint that the movement solution must optimise a cost function [Diedrichson, 2010]. Synergies or correlations are considered to be the by-products of he control scheme, rather than a control principle in themselves. Alternate models such as 'good enough' control [Loeb 2012], state that redundancy is an inbuilt function of the control system, where having multiple solutions allows for an acceptable movement solution to be quickly found. Insetad of reducing the dimensionality of control signals, to assist in the computation of a theoretical optimum, they propose the nervous system takes advantage of the high dimensional signals, to quickly find a solution to meet a given task goal [Loeb, 2012].

5.5.4. Ecological psychology and dynamic systems theory

The proposition that synergies or correlated outputs reflect task and not neural constraints poses a concern for researchers attempting to define specific neural structures but not for those operating from the dynamic systems perspective. The search for low-dimensional control structures in movement was redefined within the dynamic systems framework, a joint endeavour between physical biology and ecological psychology. This involved a marked shift in perspective on the nature of constraint, constituting what Turvey defined as the second round of theorising on the Bernstein problem [Turvey, 1990]. Coordinated movement was considered an emergent result of the dynamic interaction between task, environmental and organismic constraints [Newell, 1986], and control was the prerogative of none of these constraints. The search here was not geared towards defining specific kinematic or

neural 'controlled' variables but rather identifying the underlying abstract, global parameters (laws) that express the relation between these variables for any given task. Invariance in any kinematic variable was interpreted as an emergent property of the interaction among elements in the system and not a reflection of an a priori rule, command or prescription from the CNS [McDonald et al., 1989]. This is in direct contrast to the neuromechanical and physiological views detailed in the previous section that rely on the existence of 'inverse models' [Wolpert and Kawato, 1998] as the manner in which muscle activations are computed within the CNS from kinematic variables (see Figure 1.2).
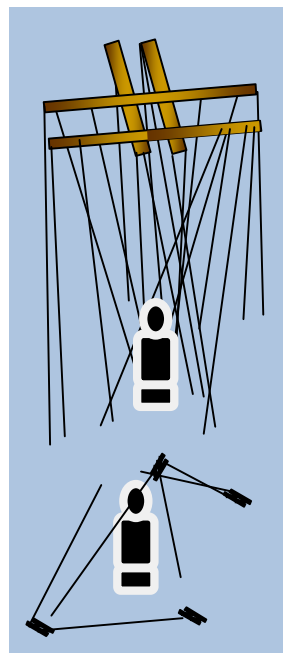
Figure 5.2. Pictorial representation of the difference between dynamic systems and centrally-controlled theories of movement organisation. In the top half, each segment is controlled prescriptively via a central agent (the hand in this example), whereas in the bottom half, the segments self-organise via relationships between one another.

The dynamic systems approach employs mathematical tools adapted from non-linear systems analysis, including that of synergetics [Haken, 1977; Haken et al., 1985] and other natural physical approaches [Kugler and Turvey, 1987], with the aim of providing formal definitions (equations) of the physical laws that organise and constrain coordinated behaviour [Turvey, 2007]. The movement apparatus is modelled as a non-linear dynamic system that evolves over time. Dimensionality decreases over time as the system settles into stable ordered patterns among the kinematic variables [Mitra et al., 1998]. Biological coordination under this view therefore shares similar properties with other systems in

nature (for example weather formations such as clouds and storms) that self-organise into regular patterns or structures. These patterns form without the input of any external controller; instead transactions with the wider environment are the basis of the 'self' organisation. The self-organisation of variables within such biological systems is possible as these systems are thermodynamically open to the environment. A key feature of an open system is the existence of non-equilibrium phase transitions - sudden changes in the macroscopic organisation induced by gradual changes in environmental conditions (e.g. temperature gradients in cloud formation). Movement tasks exhibiting an abrupt change in their coordinative relationships, such as gait transitions from walking to running [Haken, 1977], have therefore been of particular interest to researchers in this field and some have extended these concepts beyond switches in real time movement coordination to include theories on motor development and learning [Newell et al., 2001; Newell et al., 2003].

As stated earlier, the aims of the dynamicists revolve around uncovering abstract equations of motion that specify the time evolution of coordination or specifically, the relation between variables. The low-dimensional control space according to this view is defined by a specific equation of constraint. Defining the equation is dependent upon the determination of a variable that is composed in some way from the original variables but that changes over a longer timeframe [Mitra et al., 1998]. This low-dimensional 'essential' [Kugler et al., 1980] or 'collective' [Newell, 1986] variable (formally known as an order parameter) reflects the qualitative aspects of the pattern by summarising the relations between its parts. The coordination pattern is therefore characterised by the nature and value of this variable [Kugler et al., 1980]. The hallmark of dynamic approaches is the circular causality that results where the pattern is expressed by a collective variable that enslaves or orders the subsystems that in turn act on and generate the collective variable [Mitra et al., 1998]. The variables at the micro (variable) level 'govern and are governed by' the macro (pattern) level organisation. Studying non-equilibrium phase transitions in coordination can enable the determination of essential variables. Stemming from the non-linearity, certain configurations naturally exhibit greater stability; these correspond to 'preferred' modes of coordination. A loss of stability is both the cause and symptom of

a transition from one mode to another. The states of stable equilibrium that present after a transient in the variable space are known as attractors.

In summary, therefore, the predominant method for studying the reduction in the degrees of freedom from the dynamical approach is via formal modelling of the topological landscape of potential (attractor) states. This analysis requires the invariant attractor states to be characterised by one or more essential variables (formally referred to as order parameters). To discover the underlying structure (dimension) of the coordination then involves modelling the potential function of the movement that expresses all possible configurations of the degrees of freedom within the system under specific constraint conditions, and discovering the stable solutions for such equations.

The shift from measuring kinematic variables to identifying order parameters that define the relationships between these variables began with Haken modelling the bimanual "finger wiggling" (abduction/adduction) experiments of Kelso to yield the Haken-Kelso-Bunz (HKB) model that describes bimanual coordination [Haken et al., 1985]. For this task, the order parameter that summarises the coordination is the relative phase between two limb segments. Changes in this value are a result of increasing the control parameter - movement frequency in this case. Two preferred modes of coordination - or attractor spaces - exist naturally for bimanual tasks at a low movement frequency: in-phase (0°) and anti-phase (180°). Increasing the movement frequency results in destabilisation of the anti-phase pattern. Due to the requirement for temporal evolution, rhythmic movements such as finger wiggling have been the preferred phenomena for analysis via the dynamic systems approach. Proponents maintain that the best model for promoting a detailed understanding of synergy is the frequency locking of limbs and limb segments [Turvey, 2007]. A synergy from this perspective is analogous to the equation of constraint that specifies the time evolution of the coordination. Experimental research incorporating dynamical methods redefined the term 'coordinative structure' from the simple idea of groupings among local-level variables to that of a coherent, macroscopic spatio-temporal pattern that is generated under non-equilibrium constraints in an open system [Kugler et al., 1980].

5.6. Changes in coordination over the course of practice – freezing and freeing

The previous paragraphs summarised a variety of theoretical and experimental avenues that have developed to explore the basis of coordinated motor behaviour. Commonly accepted was the notion that degrees of freedom are constrained together and operate as groups; these 'synergies' compress the many possible dimensions of the movement system into a smaller control space that can be defined by only a few dimensions [Turvey, 2007]. It was seen that controversy lies in the nature of the linkages (constraints); opposing theories of how the movement elements become assembled into these structures were briefly outlined. Taking a step back from theory now, an obvious method for investigating the basis and development of coordination is through observation of changes in the organisation of the system that occur with practice.

Surprisingly few investigations have compared coordination in the early and late stages of motor skill [Newell and Vaillancourt, 2001]. The description of coordination early in practice has been almost exclusively the domain of ecological approaches. Studies that do exist at least in the spirit of this approach have incorporated whole body movements involving multiple degrees of freedom in rich perceptual environments [Shaw and Alley, 1985]. Again we return to the formative ideas of Bernstein, whose intuitive anecdotes of how the degrees of freedom problem is solved also included a three-stage model of learning that described the conversion to a controllable system [Bernstein, 1967]. In the early stages of practice, the learner was said to simplify the control process by eliminating redundant degrees of freedom via "tetanic elimination" (pg. 108), resulting in rigid, limited movement of the segments. Further practice would result in the release of this temporary restriction as the elements became gradually incorporated and organised into a coordinated movement structure (synergy). The third stage involved optimisation, whereby the learner is "able to utilise entirely the reactive phenomena that arise" (pg. 109). By exploiting the passive forces, energy expenditure can be reduced. The solution to the movement problem for a given task therefore changes over time with practice. These ideas were expressed as the freezing (in the early stages of practice) and freeing (in the second stage of practice) of the degrees of freedom by Turvey et al. [1982]. It should be noted that freezing or

eliminating degrees of freedom from the system to be controlled is an alternative strategy for overcoming redundancy to that of linking elements together in a functional manner to *effectively* reduce their number. Bernstein's observations framed early research investigating the development of coordinative structures with practice. This work aimed to measure the freezing and subsequent freeing of degrees of freedom at the level of mechanical/kinematic degrees of freedom - joint angles - over the very early stages of practice.

Early experiments therefore measured changes in joint angle excursions and the cross correlations between joints, in particular of the same limb. Inter-joint coordination patterns in these studies were quantified using simple cross-correlation coefficients calculated from comparison between two joint movement time-series within the limb such as shoulder and elbow flexion-extension. The type of relationship - either in-phase (+) or anti-phase (-) - was indicated by the sign of the coefficient and the degree of coupling by the absolute value of the coefficient, with 1 indicating a strong coupling effect between joint motions and 0 indicating independence of the joint motions. A high degree of correlation among elements was taken as an indication that they were behaving as a fixed unit and that the number of independent joint motions involved was reduced. Applying these methods and assumptions, Newell and co-workers [Newell & Van Emmerik 1989, McDonald et al. 1989] provided early evidence in support of the idea that degrees of freedom are 'freed' with practice. In a study of handwriting that compared the dominant and non-dominant arms [Newell and Van Emmerik, 1989], significantly higher correlations were observed in the non-dominant (unpractised) left arm of the right-handed participants, compared with their dominant. This suggested that over the course of practicing handwriting over many years with the dominant hand, there was an increase in the degrees of freedom. However, 10,000 practice trials were deemed insufficient to show a decrease in the correlations within the non-dominant arm. This research therefore showed only indirect evidence for the freeing. Similar findings were reported comparing the limbs on a dart-throwing task [McDonald et al., 1989], with the non-dominant arm exhibiting higher overall cross correlations and additionally for this task, a practice effect presenting as a decrease in correlations in the dominant arm was noted. Observations to this

same effect were also reported in a comparison of intra-limb coordination in beginner and expert players performing a volleyball serve [Temprado et al., 1997].

In addition to the use of cross correlation to explore early notions of freezing and freeing of variables within the joint space, the range of motion of a joint was also used to index its increased involvement with practice. The early study of pistol shooters [Arutyunyan et al., 1968] provided evidence for an increase with practice in the motion of more distal joints to complement the motion of the shoulder. In similar vein, an increase in motion of the distal arm segments was shown with practice of a racquetball shot [Southard and Higgins, 1987].

5.7. The slalom-skiing simulator task in the study of changes in coordination changes with practice

The studies cited in the previous paragraph all attempted to provide experimental evidence for the ideas relating to freezing and freeing of degrees of freedom in the peripheral, kinematic joint space during the earliest stage of learning. It was expected that this could be achieved by analysing simple relationships between pairs of joints and also the joint ranges of motion. Perhaps the most seminal work in this direction was that of Vereijken et al. [1992a], for the task of learning a slalom-skiing movement. The authors studied what they described as two processes within Bernstein's notion of early practice: 1) that individual degrees of freedom would initially be frozen or eliminated and therefore present with little amplitude of movement and 2) that strong linkages between the individual degrees of freedom would initially be present and decrease with practice. In an attempt to show the first process in action, they measured ranges of motion (RoM) of individual joints and expected that variability about the mean would increase with practice. To address the second process, they measured the correlation coefficients between joint pairs and expected that the correlation would decrease with practice. After only two trials of practice, the joint amplitudes in the lower limb increased and no further changes were observed thereafter. The couplings between joints were moderate to high to begin with and showed an overall decrease for the dominant limb only. These observations were interpreted as evidence of an increase in both the number of degrees of freedom controlled and an increase in the independence of the motions of these degrees of freedom - collectively interpreted as

'freeing' of the degrees of freedom with practice. Before beginning a critique of the above conclusions, and introducing subsequent skiing-simulator studies that attempted to move beyond the foundational 1992a paper, a general introduction to the slalom-skiing task is provided.

5.7.1. The slalom-skiing simulator

This task occupies an important space within the motor control and learning literature. Beginning first with Den Brinker [1982], it has been returned to many times because it offers a novel, whole-body task that can be learned within a relatively short timeframe. This makes it a practical candidate for investigations into skill acquisition and coordination changes with practice. The task involves side-to-side movements performed whist balanced upon a platform that moves along two metal rails. Elastic bands resist the platform and the subject must learn to produce the correct timing of force application to keep the platform moving in a cyclical manner. The task has been utilised extensively by Wulf and colleagues to investigate principles of motor learning, including focus of attention [Wulf et al., 1998], feedback and instructions [Wulf et al., 1998] and use of physical guidance [Wulf and Shea, 1998]. The rhythmic, oscillatory movements of the platform have also been embraced by dynamic modelling approaches, with a series of papers concerned with modelling the non-linear stiffness and damping functions that are exploited within the platform system to produce the movement [Delignières et al., 1999; Nourrit et al., 2003; Teulier et al., 2006]. One of these studies [Nouritt et al., 2003] had participants practise for 14 weeks and revealed subtle changes at the platform level well beyond the point where coordination changes in the body had ended.

Another branch of research incorporating the skiing simulator task investigated changes at the global energetic level and measured oxygen consumption and changes in economy of movement with practice [Almåsbakk et al., 2001]. Economy of energy expenditure is considered an important aspect of optimal performance. Although there was an increase with practice in the amount of work performed on the platform, participants used less energy for the same work after practice. Such an increase in energy efficiency is considered one of the main outcomes of coordinated body movement and there is evidence to suggest that energetic cost may represent the optimisation criterion driving the discovery and stabilisation of new coordination modes [Sparrow et al., 2007].

The skiing-simulator task therefore has a track record of producing interesting findings in this field. Of studies that have used this task to characterise coordination of movement, all have employed analysis of results at an individual level in the small samples studies, which range from three [Teulier et al., 2006] to five [Vereijken et al., 1992; Hong and Newell, 2006a,b] participants, and changes with practice have not been pooled across participants. Furthermore, no previous skiing- simulator research has compared male and female performance, although it has been suggested that the timeframe of release or change in the organisation of degrees of freedom might differ between individuals [Hong and Newell, 2006a]. The literature reviewed in Part I provided evidence that such individual differences may manifest as differences in movement skill between males and females for any given task. Evidence will also be presented that the only clearly-established kinematic differences between males and females reside in movements in the frontal plane during landing tasks and so movement in this plane on the simulator will be of particular interest. Extensive practice and a comprehensive set of measurements of both performance and coordination will be employed in the current study to explore whether sex differences exist both in performance and the development of coordination. The inclusion of local energetic measures (EMG) will complement the previous studies and provide new information on coordination (at the level of muscular degrees of freedom) for this task.

5.7.2. Progression of ideas beyond the original concept of freezing and freeing

Returning to skiing-simulator studies that focused specifically on coordination, Vereijken et al. [1992a] indicated that a limitation of their study was its focus on holonomic constraints and proposed that non-holonomic abstract laws of motion should instead be the focus of study. Holonomic constraints are constraints on mechanical or physical coordinates; non-holonomic constraints are constraints on velocities and therefore have a time varying aspect. In the spirit of dynamical systems theory, therefore, a follow up study [Vereijken et al., 1992b] aimed to characterise the task-performer relationship and incorporated mathematical modelling of the relation between the platform and performer in order to distil the order parameter (the low-dimensional task variable) that characterises this relation. Taking a lead from other dynamical modelling efforts [e.g. Haken et al., 1985], the relative phase between the motions of the performer (operationalised as the location of the CoM) and

the platform was suggested to be the order parameter because the coupling between these variables stabilised with practice. A third study [Vereijken et al., 1997], again using the same dataset, employed an informal pendulum modelling approach to relate changes in this order parameter to motion of the whole body. The movements of the body were investigated via the height and motion of the CoM (rather than individual joint relations). Changes in body configuration reflecting three distinct stages of learning were described by modelling the body-platform system as different types of pendula (simple, compound and buckling). An important finding in the context of the present work was that participants required an increasingly flexed body position to achieve the best performance on the task. Maintaining an upright body beyond the early stages of learning would therefore limit a performer's ability to progress on this task. This provided another motivation for using this task to investigate potential differences between male and female performers, because it has been suggested that females use more upright postures; The study reported in chapter two addressed this issue by measuring the prevalence of extended knee postures in a cross-sectional study of high- and low-skilled surfers performing a landing task.

The most recent skiing-simulator research from Hong and Newell [2006a, b] reflects an even more marked departure from the kinematic level of analysis towards a dynamic systems approach. One study [2006b] investigated both 'global' (CoM-platform relationships) and 'local' (inter-limb relationships) levels. According to the theory of non-linear self-regulating systems, the local variables 'govern and are governed by' the global variables. The link between these levels was proposed to be the platform oscillation cycle frequency. A spectral analysis revealed that the sagittal-plane motion of the CoM became entrained with practice to a similar modal frequency as the frontal-plane movements and these were related to the platform movements. The proportion of peak power to total power increased for these variables but not at the same stage of practice, indicating different timeframes for the stabilisation. For the local inter-limb variables that included the relationship between the knees, performers used both in phase and anti-phase knee motions to achieve the same global movement pattern and the degree of coupling between the knees increased with practice. The main findings of the paper were that while learned changes occurred in local-limb motions, there was no change in the

phase relation between performer CoM and the platform in the frontal plane. This phase relation (order parameter) was therefore unrelated to or had no direct correspondence with the organisation of the limb segments in this case.

The aim of all skiing-simulator studies subsequent to the original study of Vereijken et al. [1992a] was to remedy a perceived limitation in the conception of Bernstein's freezing and freeing of *mechanical* degrees of freedom. Part of the problem was his idea regarding the *direction of the change* with practice, in particular when it comes to the 'freeing' of degrees of freedom. Vereijken et al. [1992a] interpreted Bernstein's idea as proposing an increase in the number of mechanical degrees of freedom within the system and that this could be indexed by changes in joint range of motion. However, this approach ran counter to the expectation in dynamic systems theory of a decrease in degrees of freedom with practice so as to yield a low-dimensional system. Subsequently, the universality of an increase in the number of mechanical degrees of freedom as a learning mechanism was questioned [Newell et al., 2003] and it was argued instead that the number might increase or decrease depending on the task. To finally overcome the conflict about whether the degrees of freedom should decrease or increase with practice, Newell and colleagues called for a clear distinction between mechanical (kinematic) degrees of freedom at the behavioural level and the degrees of freedom required to model the underlying attractor dynamics [Newell and Vaillancourt, 2001]. The subsequent skiing-simulator research therefore culminated in a distinction being made between mechanical degrees of freedom and the dimension of the system, along with the pursuit of a dynamic approach in understanding coordination.

It is contended here that the distinction between mechanical (kinematic) degrees of freedom and the degrees of freedom required to model the attractor dynamics, as in [Newell and Vaillancourt, 2001], does not provide the clarity intended. This is especially the case where the definition of mechanical degrees of freedom implies a consideration of only the joint ranges of motion. Instead, the interpretation of freezing and freeing should be questioned further. The evidence suggests that the idea that joint degrees of freedom are 'frozen' or entirely eliminated from control is misguided [Koshland et al., 1991; Latash et al., 1999]. An increase in range of movement at a joint does not therefore reflect

an increase in the number of degrees of freedom in the system because the mechanical/kinematic degrees of freedom of the system are always present, even if minimally involved, and must be subject to a control strategy - such a co-contraction - even to achieve a state of minimal (range of) motion. All of the degrees of freedom are being controlled, at all times., even when no motion is occurring at the joints. The original Vereijken et al. [1992a] paper described two processes occurring with practice that together equated to 'freeing' - an increase in the number of 'mechanical' degrees of freedom (RoM) and a decrease in the coupling between them (cross-correlations). This scenario however is contradictory to the well-established idea that practice is associated with the development of coordinative structures or synergies, because the hallmark of such structures is an increase in joint coupling and as a direct consequence, a decrease in the degrees of freedom controlled. Moreover, examining cross correlations cannot differentiate between temporary restrictions early in practice on range of motion at selected joints and the later integration of these joints - freed of restriction - into a flexible 'synergy', because the correlation coefficient is independent of the amplitude of the signals. There does indeed appear to be a problem with the terminology of Bernstein, but the redefinition adopted by some dynamic systems theorists does not provide clarity. This debate is expanded upon in Part II.

Part II.

Tools for studying degrees of freedom and dimensionality –

Principal component analysis (PCA)

5.8. Introduction: PCA in the study human motor behaviour

The first part of this chapter reviewed the seminal skiing-simulator research into coordinative structures including the progression of ideas in the study of coordination from a kinematic to a dynamic level of analysis. The concept developed was that the analysis of the behaviour of the degrees of freedom can provide valuable insight into the relationships governing them. A common tool used for these purposes is principal component analysis (PCA). This multivariate statistical technique has been adopted within the movement sciences for its ability to reduce the dimensionality of large data sets. It has become a key tool in the study of dimensionality in the motor system - all of the different approaches introduced in Part I have applied PCA to sets of kinematic, kinetic and EMG signals in order to reduce dimension and reveal the underlying coordination patterns. The most recent skiing-simulator research also included PCA and this forms the foundation and point of comparison for the study in chapter five of this thesis.

The main purpose of PCA is to summarise the most important information within a dataset, achieved by representing the variation of a limited number of components that explain the maximal amount of variance [Wang et al., 2013]. The original set of signals is converted via an orthogonal transformation into a set of uncorrelated 'principal components' (PCs). The components that account for only a small degree of variance in the original pattern can be discarded and a reduction in the dimensionality of the data set can thereby be achieved. Although there have been concerns for discarding the variance, in terms of the reproducibility of the original data once this has occurred (DeRugy et al. 2013), this is appears more a problem when considering EMG signals. There is evidence to suggest that discarding the variance does not affect the ability to produce reconstructions that achieve a good fit with the prior

movement traces [e.g. Wang et al., 2013; Maurer O'Connor and Bottum], when kinematic signals are in question.

PCA is one of numerous matrix factorisation techniques that may be used for the decomposition of complex datasets into a smaller number of components. Factor analysis, independent components analysis and non-negative matrix factorisation techniques have all been applied to movement, however PCA has been the most common [Wang et al., 2013]. Nonnegative matrix factorisation has been applied increasingly to EMG data (add ref). All techniques are similar in that they model observed data as a linear combination of a small number of factors. Despite different assumptions, similar results in terms of data reduction have been achieved using all of these methods [Tresch et al., 2006].

PCA has been used within the movement sciences for three related purposes: a) *Determine redundancies in datasets*, including kinetic, kinematic and EMG variables; the PCs can distil the most relevant features to provide insight into the possible control mechanisms underlying the movement, such as in locomotion [Wootten et al., 1990; Mah et al., 1994]. b) *Identify patterns in dataset*s through analysing the relative contribution of the original variables to the composition of the PCs; tasks that have been investigated include but have not been limited to: reaching [D'Avella et al., 2006], catching [Bockemühl et al., 2010] trunk bending [Alexandrov et al., 1998], swinging [Post et al., 2003] and juggling [Post et al., 2000]. c) *Discriminate between patterns* of coordination in different populations performing the same activity; for example between patients with knee osteoarthritis and lower back pain versus controls in walking [Deluzio and Astephen, 2007] and lifting [Wrigley et al., 2006], between different variations of the balance response to perturbations [Ko et al., 2013], between speed and shoe conditions in running [Maurer et al., 2012], between loaded and unloaded walking [Lee et al., 2009] and between variation in lower limb coordination when performing sideways cutting movements [O'Connor and Bottum, 2009].

5.9. PCA, dimension and degrees of freedom

As described at the conclusion to Part I, there has been a differentiation between the mechanical and the dynamical degrees of freedom by certain researchers. Dimension was defined specifically as capturing the number of *active or dynamical* degrees of freedom required to model the attractor dynamics. The number of PCs identified by PCA was offered under a dynamic systems approach as representing the number of equations of constraint (i.e. dynamical degrees of freedom), or order parameters, required to model the behaviour [e.g. Hong and Newell, 2006a]. Hong and Newell [2006a] questioned whether Bernstein was referring to the collective spatial and temporal organisation of the movement or to the motions of individual joint angles at the behavioural level. They contended that it was the latter and that focus should move towards the former. Li [2006] proposed that the term 'functional' degrees of freedom (fDOF) was preferable to 'dynamical' or 'active' degrees of freedom when distinguishing between these alternate levels of description. The (mechanical) degrees of freedom are the original variables in the joint space and the functional degrees of freedom reflect the minimum number of those variables that are *independent* and can account for the behaviour of the original degrees of freedom. The functional degrees of freedom therefore relate to the control space, which is generally considered to be of lower dimension than the space of the data (by all of the approaches in part I, not just dynamical systems). Li [2006] described deterministic and statistical methods used to determine the number of fDOF. The deterministic method defines the number of remaining DOF that can vary independently after the imposition of a specific constraint. In this case, the equation of constraint that acts upon the system is known *a priori*. Where the equations of constraint remain unknown for a particular movement - which is almost always the case - statistical methods including PCA can define the number of components that are required to adequately represent the entire set of kinematic degrees of freedom. In this way, the number of fDOF can be *estimated* without defining the exact relationships or constraint equations acting upon the system.

In a foundational investigation, Haken [1996] recognised that estimating the number of functional degrees of freedom relates to the estimation of the potential number of equations of constraint and therefore is only an initial step *before* beginning a dynamic systems analysis. After completing a PCA,

he attempted to model his experimental data using an equation with one order parameter [Haken, 1996]. Although he suggested that the close fit between the model and the data provided "a good indication that the movement could be described by one *or more* order parameters" (pg. 188), he explicitly stated that the number of PCs may or may not relate to the number of constraint equations. PCA simply provides a manner to expose the 'hidden' dimension underlying a complex set of variables and therefore provides an estimation of the number of variables that exist in the control space. It provides a more powerful analysis tool in the study of coordination than simple cross correlations between joint pairs, because the correlations between each variable and all others are formalised.

The assertion of a clear differentiation between dynamical and mechanical degrees of freedom within any system begs the question of the relationship between these two levels. The distinction between them can give the false impression that they refer to entirely separate variables, when in reality, they describe the same variables (e.g. time series motions), but from alternate levels of analysis. Recently, the terms functional and dynamic degrees of freedom are have been used interchangeably which may begin to alleviate the perception [e.g. Ko et al., 2013]. That the principal components (or fDOFs) are clearly related to the original mechanical degrees of freedom is evidenced by the ability to reconstruct the original data from the PCs. This occurs via the linear summation from projected eigenvectors, and for both EMG and kinematic signals in walking, can achieve a good fit between the original and reconstructed data [Wootten et al., 1990; Daffertshofer et al., 2004]. The loading structure or weighting coefficients provide further information on the link between the PCs and the original variables (or between the two levels of description – the joint space and the control space). These coefficients are the correlations between original variables and each PC. Indeed the functional interpretation of such coefficients has been the guiding purpose of most studies incorporating PCA, under advice originating from Kachigan, [1991]. In a study of postural coordination modes from a dynamical perspective, Ko et al. [2013] stated that analysing these coefficients allowed the formalisation of the nature of the movement pattern produced by the functional degrees of freedom (PCs). Describing the loadings of the original variables onto each PC provides information on the

qualitative organisation of the original variables into synergies. Through identification of significantly weighted variables and modes of coordination, insight into the nature of synergies that constitute the control space can be obtained. These procedures, however, are not confined to dynamic systems theory but have been used in all applications of PCA.

It may be noted that the differences between investigators in the concept of what a principal component actually represents can be seen to parallel the differences between investigators highlighted in Part I in the concept of what a synergy represents. The principal components yielded from movement-related variables represent a formal manner to reduce the dimensionality of the dataset and thus explore the hidden structure that constitutes the level at which control of the movement variables may occur. This structure is a reflection of the underlying synergies that allow for effective control. Depending on the theoretical orientation of the investigator, the synergies may in turn be related to either the number of second-order differential equations of constraint or to the nature of the control signal originating in the CNS.

5.10. PCA and changes in coordination with practice

As detailed in the introduction to Part II, PCA is a useful technique for reducing the dimensionality of complex datasets and has proven successful in doing so for numerous motor tasks. Only five studies, however, have adopted the technique to explore changes in correlation and coupling in multiple motor outputs as they change with practice. All five studies have been conducted under the umbrella of dynamic systems theory.

5.10.1. Haken 1996 – Pedalo

Haken [1996] was the first to apply PCA to characterise changes in coordination with practice for a whole body task. The oft-quoted finding was that the number of PCs required to account for the majority of overall variance in the movement pattern decreased to a single component after practice. However certain limitations in this study need consideration. The task employed was learning to move forward on the 'Pedalo', an 8-wheeled device with two footplates linked by a rigid bar, with propulsion achieved by moving the legs up and down (figure 5.3).
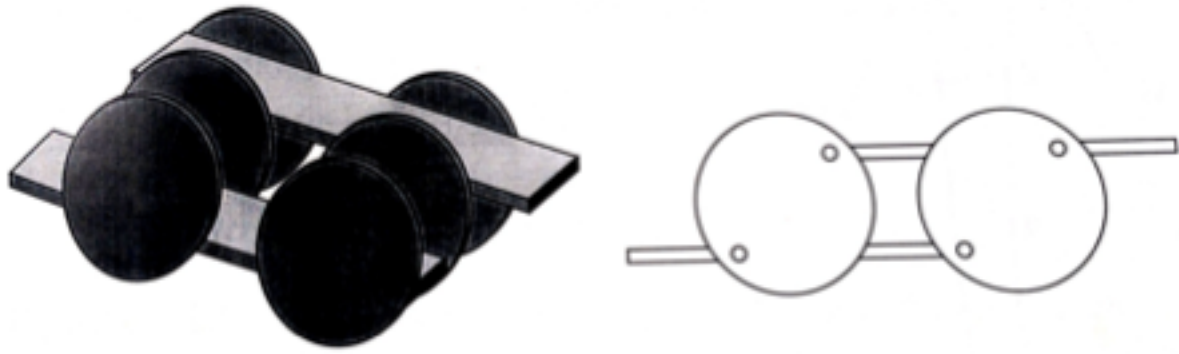
Figure 5.3. Schematic diagram of the Pedalo device. Reproduced from Haken [1996].

Two-dimensional (2D) joint angles of each segment (shanks, thighs, trunk, head, forearms, and arms) relative to the horizontal or vertical calculated from light-emitting diode positioned over the joints yielded 22 individual time series being subjected to analysis. Data from both early and late stages of practice for only one participant (Haken) were included in the analysis. No details on the extent of practice were provided. The eigenvalues derived from the analysis were presented graphically (Figure 5.4) and each movement cycle was analysed separately. The value of the first eigenvalue increased with practice (indicating that the more variance was accounted for by the first PC), rendering the second and third eigenvalues as "small or even negligible" (pg. 179), but no numerical data were reported. This result was suggested as confirming that the coordination mode of the movement after practice could be described by only one dimension.
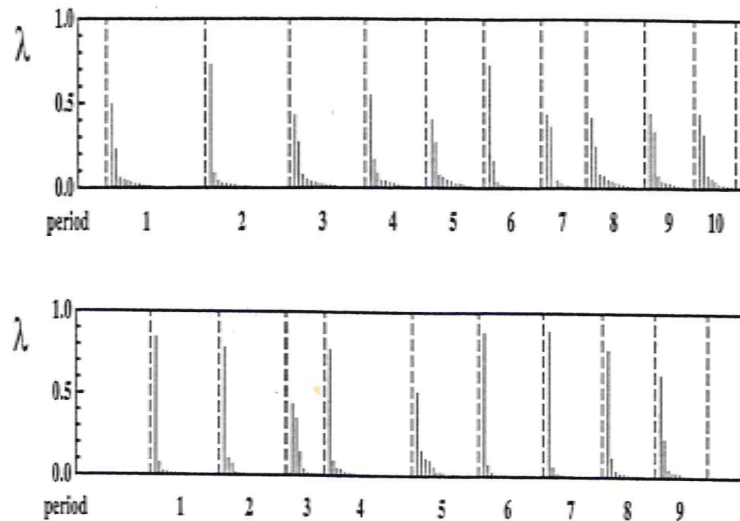
Figure 5.4. These graphs are adapted from Haken [1996], showing the results of PCA conducted on each of 10 movement cycles before practice (top trace) and after practice (bottom trace). The values on the x-axis are the cycle numbers (the broken vertical lines separate the cycles) and the values on the y-axis are the amount of variance accounted for by each eigenvalue, with the value of the first component seen to be generally higher after practice.

5.10.2. Ko et al. 2003 - Balance task

Ko and colleagues [2003] offered a 2D analysis of six participants learning a dynamic balance task on a moving platform. Participants completed 40 trials over two days and the first and last five trials of each day were analysed. This study included a diverse range of variables, both in the mechanical and dynamical space, in an attempt to provide experimental evidence for all three stages of Bernstein's proposed learning progression. The task required a decrease in range of motion about the joints in order to successfully negotiate the perturbations. This decrease in joint RoM required with practice was offered as evidence contrary to Bernstein's observations of initially freezing out and then freeing degrees of freedom, and in support of task-specific changes in coordination. For the PCA, the x and y components of motion for six body segments were included. Two PCs were sufficient to account for 96% of the variance of movement patterns before practice and 98% of the variance after practice. The lack of significant change with practice may reflect the fact that this was a relatively simple balance task that may not have been sufficiently taxing to demonstrate learning of a new coordination mode.

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5.10.3. Chen et al. 2005 - Return to Pedalo

Chen et al. [2005] revisited the Pedalo task to provide a more complete account of the movement, employing 3D motion analysis. Four participants practised the task, performing 50 trials each day over a seven-day period. The main emphasis of this study was on developing a dynamical account of the convergence of degrees of freedom on to a steady state with practice. In addition to the non-linear modelling of performance curves, they included PCA of 3D displacements of 13 body segments and two reference points on the Pedalo, yielding a 45-dimensional dataset. The individual participants in this study did show a general trend of a decrease in the number of significant PCs after practice, but in contrast to Haken's analysis where one component could account for most of the variance of movement patterns, three to six components were still required to account for the most of the variance of the data after practice. The discrepancy in findings between the studies is likely to be attributable to the higher dimension of the dataset here (45 vs. 22 time series) and the fact that the measurements were in 3D instead of 2D.

5.10.4. Hong and Newell 2006 – Slalom-skiing simulator

Movements on the slalom ski simulator were examined in two studies in this thesis and therefore the Hong and Newell [2006a] study is highly relevant to examine here. There were five male participants who practised over five days and 18 variables (3D translations of segment centres of mass) were included in the PCA. Unlike the two Pedalo studies, the number of PCs required to account for 90% of the total variance was never less than three for all participants and did not decrease with practice. This was offered as counter evidence to the decrease in dimension with practice that had been reported. However the overall amount of variance accounted for by each PC did increase with practice. The contribution of the first PC increased to about 60% of variance accounted for, with a concomitant decrease for the third PC. Moreover, after practice, a more consistent structure than before practice became evident in the weighting of variables onto each component. The number of PCs did not decrease but this still suggests a decrease in overall dimension for this task.

5.10.5. Hodges et al. 2005 – Open chain soccer chip kick

Hodges et al. [2005] investigated changes in limb range of motion and spatio-temporal coordination across joints in the non-dominant lower limb in one subject practising a soccer chip kick over 9 days (425 trials). 3D time series motions of the hip, knee and ankle (9 signals) were subjected to PCA. Three PCs accounted for 84% of the variance on day one and 87% on day 5 and the contributions of each component did not change significantly with practice. The authors here expected an *increase* in the number of PCs with extended practice, representing an increase in the independence of joint control, and so the result was contrary to their expectation.

5.10.6 Summary findings of investigations into practice using PCA

Three of these five studies, therefore, found some evidence for a decrease in dimensionality with practice (indexed by either a decrease in the number of PCs or a significant increase in the percentage variance accounted for by the first PC), while no clear change in dimensionality was found by Ko et al. [2003] and Hodges et al. [2005]. The findings of this research regarding the number of degrees of freedom, therefore, could not be interpreted to support a 'release' of degrees of freedom with practice at least not within the functional control space.

5.10.7. PCA in cross sectional investigations of skill

A complementary method for investigating changes with practice is to employ PCA in an attempt to differentiate the patterns of motor output between high-skilled and low-skilled performers. One study in this vein reported greater coupling of finger flexion angles during a grip task in pianists compared to non-pianists [Fernandes and Leite De Barros, 2012], a finding consistent with lower dimension in the trained subjects, however the results of the PCA were not reported in full. Maurer et al. [2012] reported not on the number of PCs or the variance they account for, but rather were concerned with differences between groups in the variables that weight most heavily on the first PC. Finally, a study of cello-bowing in expert and novice participants [Verrel et al., 2013] revealed larger loading of the distal joint angle variables (finger, wrist and elbow) onto the first PC in experts, with beginners'

motion dominated by the shoulder. The finding that the amplitude of wrist movement also was greater in the experts was interpreted as evidence for a proximal to distal 'freeing' of the degrees of freedom.

5.11. Limitations of previous research using PCA to investigate changes with practice

PCA relies on the application of rules, criteria and conventions for its interpretation and these can limit comparison between studies. Rules have been debated for estimating the number of significant PCs or for the cut-off limit of what represents a significant PC in terms of variance accounted for [Jackson, 1993]. Components whose eigenvalues are >1 are generally considered functionally significant [Merkle et al., 1998]. However, a common practice has been to report the number of components required to account for 90% of the variance. This is an arbitrary cut-off for which no strict rules apply.

Studies also vary greatly in the size and nature of their datasets. For example, in the studies cited above the datasets ranged from nine [Hodges et al., 2005] to 45 [Chen et al., 2005] time series signals and included variables from both 2D and 3D kinematic measurements. Many kinematic investigations using PCA have employed joint or segment translations as opposed to joint rotations, yet Ko et al. [2013] maintained that joint rotations derived from the interaction between segments were more appropriate in PCA than joint displacements that were driven primarily by the mechanics of their platform. The nature of the variables will determine the information that is coded within the dataset.

None of the PCA research that has included changes with practice has included EMG measures, even though changes in EMG pattern, activation and timing can reveal important aspects of coordination. The change in EMG with practice has been explored outside the scope of PCA and although PCA has been extensively applied to EMG datasets, none have analysed changes with practice for these variables. Bringing the two together to Explore both the neuromuscular and joint level and documenting changes on a day-to-day basis may therefore provide further insight into the changes in coordination with practice. Whether the findings of prior skiing simulator research can be generalised is also questionable because all of this research has included analyses of individual participants only.

It has been suggested that the changes documented by PCA show differential individual trends [Hong and Newell, 2006a]. However traditional PCA has proven successful in differentiating movement pattern between groups of male and female participants for gait [Maurer et al., 2012] and side cutting motions [O'Connor and Bottum, 2009. Hence, comparison of a male and female cohort may enable the investigation of whether sex differences in coordination are apparent in the results from PCA. We hypothesised that with practice, any differences would disappear.

5.12. Limitations of traditional PCA when applied to dynamic movement data

Returning to the results from the slalom skiing study by Hong and Newell [2006], the PCA did not suggest a reduction in the number of components required to account for the pattern after practice (despite the increase in the variance accounted for by the first). The authors suggested this ran counter to previous findings from PCA and proposed that this was due to task constraints and the use of higher dimensional (3D) analysis (i.e. more degrees of freedom to begin with) than earlier studies. The study reported in chapter five sought to readdress this question by employing a recent development that enhances the power of PCA when applied to signals that are related dynamically [Wang et al., 2013]. A detailed presentation of this technique and the results that justify its use is available [Wang et al., 2013] and only a condensed outline is provided here. The method was developed to overcome a specific limitation in the ability of Pearson's product-moment correlation coefficients (PCC) to adequately quantify the relation between signals when differences in phase relation and/or amplitude ratio between signals are present. In the case of phase differences between two signals, in particular where the phase relation is other than in phase (0°) or out of phase (180°), PCC may be inadequate in identifying the relation. Figure 5.5 demonstrates this limitation, illustrating how the correlation can become artificially low depending on the phase relation between otherwise highly similar waveforms.
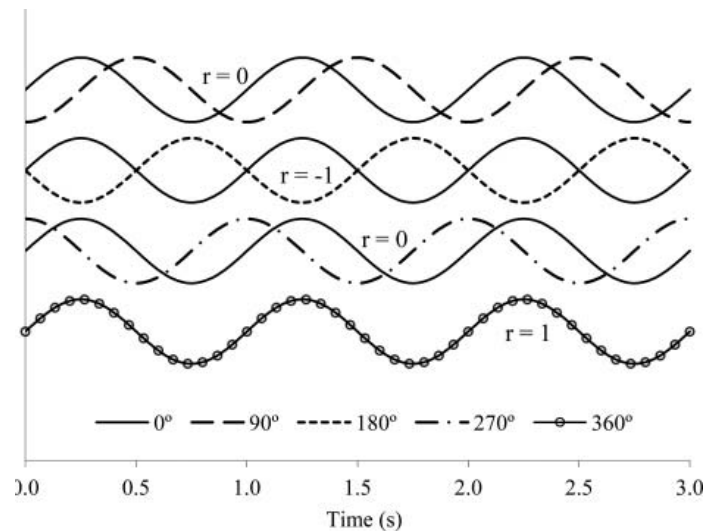
Figure 5.5. The effect of a phase shift on the correlation coefficient. The four solid lines show three cycles of the same 1 Hz sine wave. The four broken lines show the same sine wave lagged by 90°, 180°, 270°, or 360°. At 360° lag, a full cycle, the broken line exactly overlaps the solid line (0° lag). The *r* value on each pair of waveforms shows the correlation of each lagged waveform with the 0° lag waveform, demonstrating how the correlation switches between 0 and ±1 with each 90° increment of lag between the signals. Reproduced from Wang et al. [2013]

Furthermore, the limitation highlighted is not confined to phase shifts, but applies more generally when a dynamic relation exists between signals. Dynamic in this sense refers to the property whereby linearly related waveforms can appear dissimilar in pattern. Examples of dynamic relations cited include the input-output relation of a low-pass filter, where the output is a smoothed version of the input. When a filter of this nature is applied in real-time, a phase lag will also result. Evidence was presented that dynamic relations between various elements within the motor system are a common occurrence. In the presence of such relations, PCC can fail to detect similarity in the waveforms and therefore give the impression that they are independent when they are not. The results from Wang et al. [2013] indicated that unless analytical procedures are applied that can identify such dynamic relations, the number of degrees of freedom underlying the coordination was likely to be overestimated when using traditional PCA.

Wang et al. [2013] demonstrated how linear systems analysis based on cross-correlational and spectrographic techniques [Bendat and Piersol, 1971; Neilson, 1972; Ada et al., 1993] could

overcome these limitations in the application of PCA by taking into account the phase differences and frequency-dependent variations in amplitude ratios between signals. Instead of a single cross correlation value, multiple correlations can be computed for a pair of signals, by lagging the second signal one sample at a time and calculating the cross-correlation at each time point. This is known as the cross correlation function. In a linear systems analysis, the cross correlation and autocorrelation (signal correlated with itself over time multiple time lags) functions of input and output signals (e.g. joint angles) are converted into the frequency domain via the Fourier transformation. This yields the frequency spectrum of the signals and the cross power spectrum between the two. Information on the multiple correlations is converted to a form that may be utilised by providing measures of gain, phase and coherence-square versus frequency. When the frequency spectra are computed, the output spectrum is separated into two components: the coherent portion that is linearly related to the input and the remnant (noise) that is not accounted for. The linear relation between the signals is described as a transfer function comprising the gain and phase. The total output is the sum of the coherent and remnant portions (Figure 5.6).
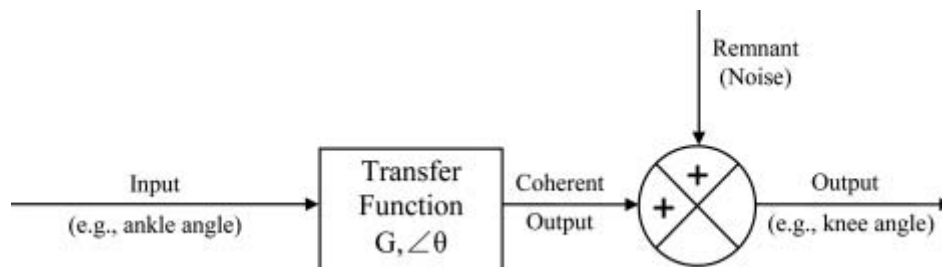
Figure 5.6. Schematic diagram of linear systems analysis of angle signals. G = gain; θ = phase angle. Reproduced from Wang et al. [2013].

The main features yielded from a linear systems analysis then are the coherence square, gain and phase frequency response functions. These give information about the ratio of coherent to total output, the amplitude ratio of output-input and the relative phase of output-input at each frequency, respectively. To produce a single measure of the relation between the signals at all frequencies (required for the matrix in PCA), a further step is required. For this, the overall coherence (OC) was calculated [Lay et al., 2002; Oytam et al., 2005] to provide a measure of the ratio of the variance

across all frequencies of the coherent output and the total output (see Figure 5.6). The OC is analogous to the coefficient of determination (Pearson's R^2) and allows the PCA to be computed.

When applied to three kinematic joint angle signals from walking data in six (three male, three female) participants, the use of the coherence matrix resulted in an improved performance of PCA to detect pattern and reduce the dimensionality of the data set [Wang et al. Unpublished data.]. The first PC alone accounted for 98% of the variance of the three signals, while in comparison the traditional PCA based on PCC required all three PCs to account for this variance. Another notable result was the weightings of the original variables onto the PCs. All of the joint angles were significantly loaded onto the first PC derived from the OC matrix and so the functional interpretation of the loading structure, normally required to establish the nature of the modes of control represented by the PCs, was not required. The behaviour of all joint angles could effectively be established from a single PC (dimension). The results showed that the dimensionality of the coordination was overestimated using conventional PCA, whereas a more parsimonious structure was identified with overall coherence.

This new PCA technique is employed in the study reported in chapter five to quantify coordination on the skiing simulator task and establish whether a further reduction in dimensionality can be achieved than observed in previous research. By quantifying coordination over different stages of skill, the sensitivity of this technique in quantifying changes in dimension with practice could be tested. Logically, it could also provide a sensitive measure to investigate differences in the coordination and control of whole body coordination between male and female participants.

CHAPTER 6.

Changes in coordinative structure with practice – PCA

6.1. Introduction

To control the human body and enable the performance of even the simplest motor task requires the orchestration of numerous elements across multiple levels of the system. Furthermore, there exist multiple options with which to complete any given task. Such complexity renders it unlikely that the elements are controlled at an individual level. The idea that human movement is therefore simplified, or made possible, via the organisation of elements into a smaller set of modules that consist of functionally linked elements has existed for many years cf. [Gelfand et al., 1971]. Bernstein [1967] was the first to articulate coordinated movement as the 'mastery of redundant degrees of freedom', a concept that has inspired experimental investigations that attempt to reveal how the organisation (mastery) is achieved. Exploring the changes that occur with practice of a motor skill can provide insight into the development of control mechanisms. It is generally accepted that movement is organised into a low-dimensional control space that is developed with practice e.g. [Mitra et al., 1998]. The decrease in the number of independent elements in the motor system that are directly controlled occurs via the incorporation of variables into a control structure that is characterised by coupling and correlation between elements. This should not be confused with the notions of 'freezing and freeing' [Tuller et al., 1982], that imply an increase in the number and involvement of individual elements in the system over the course of practice.

Quantifying the coordination between elements within the motor system has proven a difficult proposition, one that still consumes and divides the efforts of many researchers. In general it requires methods that can reveal the underlying pattern of organisation reflected in the relations between any given set of elements that comprise the movement. Principal component analysis (PCA) has proven a useful technique in decomposing complex sets of movement data to achieve these aims and has been described in detail elsewhere [Daffertshofer et al., 2004]. EMG, kinematic and kinetic variables have

been successfully reduced into smaller groupings that can account for a large degree of the variance in the original movement variables for a variety of tasks, including gait [Ivanenko et al., 2004], grasping and digit coordination [Latash et al., 2002], and response to postural perturbation [Latash and Krishnamoorthy, 2005]. The simplified set of independent, 'principal components' (PCs) derived from such analyses represent the underlying control structure of the movement. PCA provides a non-biased statistical tool to quantify correlation and coupling between a set of variables. By measuring the correlations between all variables in a data set, as opposed to early investigations that measured correlations only between individual pairs of joints, a more comprehensive insight into whole-body coordination is possible [Li, 2006].

A limited number of studies have used PCA to explore changes in the human motor system as they occur longitudinally throughout practice and to date, none of these have included EMG signals in the analysis. The first documented study [Haken, 1996] used a cyclic 'Pedalo' locomotion task and the results are often cited as evidence of a decrease to a one-dimensional space with practice. However, the analysis in this study was only of one participant and was performed on individual cycles of movement. Furthermore, no detail of the practice volume was provided. Subsequent studies have replicated the decrease in dimension with practice (indexed by the number and value of PCs) for this task [Chen et al., 2005] and for a balance task [Ko et al., 2003], but the decrease was not to the extent that one PC could account for the majority of variance. Moreover, the most recent study in this vein did not show the general trend towards a decrease in the dimension of the system with practice [Hong and Newell, 2006a]. It was suggested this was due both to the constraints of the slalom skiing simulator task used and to the large number of variables entered into PCA.

Two of the studies cited above [Haken, 1996 and Chen, 2005] employed 2D kinematic analyses while Hong and Newell [2006a] employed 3D analysis. The different nature of the variables may be a limiting factor in the comparisons between studies using PCA. Beyond these methodological differences, however, concerns have been raised over the suitability of PCA to investigate movement data [Wang et al., 2013]. Specifically, standard PCA methods utilise Pearson's product moment correlation coefficients (PCC) to quantify the strength of the relations between variables, but the PCC

may be unable to detect valid couplings in some instances. When signals are related in a dynamic linear way, such that differences in phase relation and or amplitude ratio are present, an alternate analysis is required to best quantify the relation [Wang et al., 2013]. Otherwise, variables that are linearly related will appear independent when that is not in fact the case and this would lead to an overestimation of the number of components from PCA. By incorporating a linear systems analysis [Bendat and Piersol, 1971; Ada et al., 1993] to investigate correlation in the frequency (rather than temporal) domain, and incorporating a measure of overall coherence [Lay et al., 2002; Oytam et al., 2005], it was shown that dynamic linear relations could be accounted for and the performance of PCA in detecting dimensionality improved [Wang et al., 2013]. It is possible, therefore, that the recent skiing simulator study [Hong and Newell, 2006a] was unable to detect changes in dimension with practice due to the presence of dynamic relations in the data.

We set out to investigate whether a decrease in dimensionality of the motor system with practice on the slalom skiing simulator task could be detected using the alternate method for PCA described by Wang et al. [2013] and whether the change was consistent for both male and female participants. Both kinematic and EMG signals were collected from male and female participants. It was hypothesised that when comparing results from the two methods, PCA based on an overall coherence (COH) matrix would reveal a lower dimensional space than that based on the standard PCC matrix due to its ability to account for linear dynamic relations in the data. Although there were some differences in movement pattern described in chapter 4, we expected to find no differences between males and females.

6.2. Methods

Data collected from the previous study of sex differences in performance of the slalom skiing simulator task (described in chapters 3 and 4) were analysed here. The participants, apparatus and procedures were as described previously and only details relevant to the current investigation will be described here.

6.2.1. Data processing

PCA was performed on two sets of movement variables: 30 joint angles and 16 IEMG signals. All 25 practice trials collected over five days for each participant were subjected to the analysis for joint angles (Table 3.3) along with the corresponding 14 trials where IEMG data were collected. For each of the datasets (joint and IEMG), the first step in conducting the PCA was the computation of the matrix that allows for comparison of all signals with each other and forms the basis of further exploration of the relations between pairs of variables. Two different matrices were computed and therefore two separate and methodologically distinct PCAs performed. The PCC matrix was derived here to provide a point of comparison with the results yielded from the alternate method recently described by [Wang et al., 2013], which employed a COH matrix to quantify correlation in the frequency domain. The time series for the computation of the matrices in each case were the full 60 s trials but, in line with previous studies [Vereijken et al., 1992], with the first three cycles removed to eliminate the effect of the start-up transient. Customised Matlab software was used to perform the dynamic linear systems analysis [Bendat and Piersol, 1971; Ada et al., 1993] and compute the COH values. A condensed outline was provided in Part II, section 5.12 and a detailed presentation of this technique can be found in Wang et al. [2013].

The eigenvectors and eigenvalues were derived separately from the PCC and COH matrices and provide the basis of the results. The series of eigenvalues resulting from a PCA each represent the contribution of each factor to the total variance of the original dataset and are ordered in decreasing size of this contribution. We investigated any changes resulting from practice in the percentage of overall variance in the dataset that was accounted for by the first/largest component. The common convention of the number of PCs required to account for 90% of the total variance was also employed. Furthermore, an investigation of the weightings of the original variables onto the first three PCs was presented graphically to gain further insight into the coordinative structure of the movement.

The main outcome variable from each of the principal component analyses was the proportion of variance accounted for by the first PC. Analyses of variance (ANOVAs) were performed on this dependent variable for both the joint angle and IEMG data. Two-factor ANOVAs with the independent factor of sex (male and female) and the repeated measures factor of practice (25 practice trials for joint angles, 14 for IEMG) were carried out. Although the first PC was the main variable of interest, two-factor ANOVAs with the factor of method (COH and PCC) and the repeated measures factor of PC (from 1-10 PCs) were also carried out.Tukey *post hoc* tests were used in all cases to determine between which time points any differences occurred. Paired *t*-tests were used to compare the number of PCs required to account for 90% of the variance for the first and last practice trial.

6.3. Results

The initial analyses were carried out with a factor of sex. The results indicated that there were no significant differences between male and female performances for any of the outcome variables (joint angle or IEMG), either for results based on the COH ($F_{(24,336)} \leq 2.82$, $p \geq 0.1$) or the PCC ($F_{(24,336)} \leq 3.6$, $p \geq 0.08$). Accordingly, the data presented are the mean for all 16 participants.

6.3.1. Variance accounted for by the first PC for successive practice trials – joint angles

The percentage of overall variance in the dataset that was accounted for by the first PC is shown as a function of practice in Figure 6.1. For the results based on the COH matrix of the joint angle signals, there was a significant increase with practice ($F_{(24,336)} = 8.2$, $p < 0.01$). *Post hoc* Tukey tests revealed that it took eight practice trials for the gradual increase to become significant ($p < 0.05$). The variance accounted for in practice trials one and two was significantly less than in trials 10-25 inclusive. There were no significant differences between trials after day one ($p \geq 0.74$). The percentage accounted for on the first trial was 72% and plateaued at close to 80% over the final trial.

In contrast with the results for PCA based on COH, the variance accounted for by the first PC using the PCC matrix was considerably lower. The percentage accounted for on the first trial was 38% and was 42% on the final trial. A significant effect of practice was observed ($F_{(24,336)} = 2.2$, $p < 0.01$)

although *post hoc* tests revealed that this was not a consistent increase over practice as with the COH. Trial one accounted for less variance than trials 6-12 ($p < 0.05$), but was not significantly different to any of the later practice trials ($p \geq 0.08$). The variance accounted for by the first PC using this method therefore showed no consistent increase with practice and was about half that accounted for by the first PC based on the COH matrix.
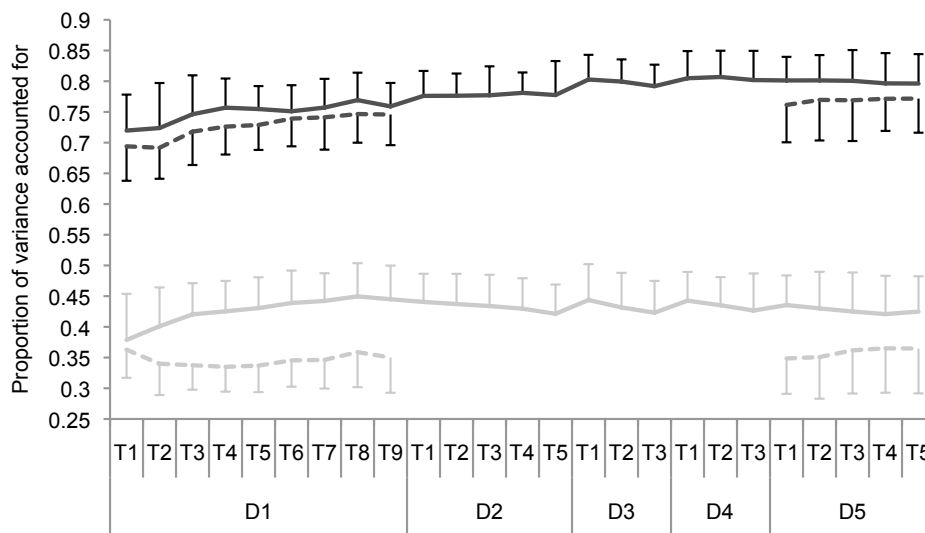
Figure 6.1. Proportion of variance accounted for by the first PC (mean ± SD) across the 16 participants for joint angles (solid line) and IEMG (dashed). Upper trace (black): results from PCA based on COH matrix; lower trace (grey): results from PCA based on PCC matrix.

6.3.2. Variance accounted for on the first and last trials of practice – joint angles

The eigenvalues for by the first 10 PCs computed from both the COH and PCC matrices for the first and final practice trial appear in Figure 6.2. Before practice, fewer PCs were required to account for 90% of the total variance when using COH compared to PCC (5.5 vs. 8.3). The effect of practice on this number was significant only for the results of COH, which decreased to 3.8 ($t = 3.7$, $p < 0.01$). The number of independent components required to account for the movement therefore decreased with practice. There was a large difference in the percentage of variance accounted for by subsequent PCs when comparing the two methods ($F_{(1,9)} = 233.4$, $p < 0.01$), with far less of the variance accounted for by the PCA based on the PCC compared with the COH.
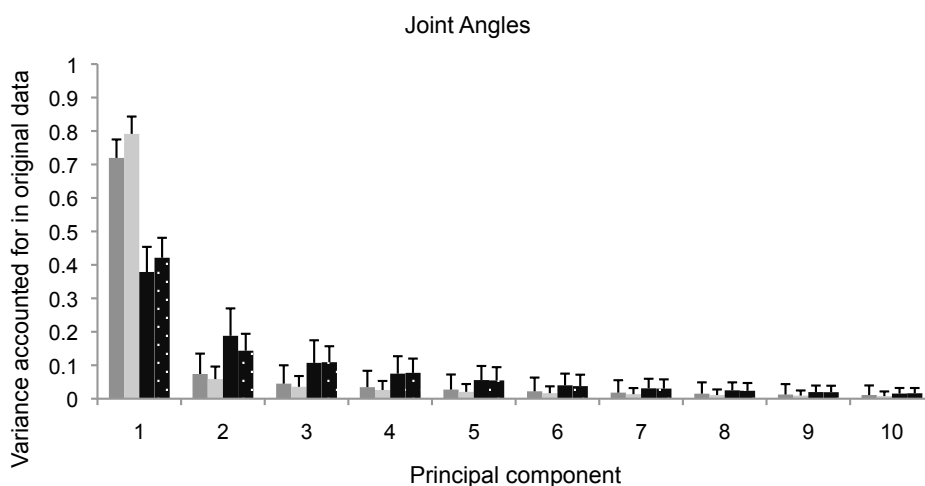
Figure 6.2. Variance accounted for (mean ± SD) across the 16 participants by successive PCs before and after practice using PCA based on COH and PCC. COH trial 1: dark grey; COH trial 125: light grey; PCC trial 1: black; PCC trial 125: stippled black.

6.3.3. Variance accounted for by the first PC for successive practice trials - IEMG

The results of the PCA conducted on the IEMG signals were similar to those for the analysis of joint angles. The percentage variance accounted for by the first PC derived from PCA based on the COH increased significantly with practice ($F_{(13,156)}$ = 15.07, $p < 0.05$). In contrast, there was no significant change with practice for components yielded by the PCA based on the PCC ($F_{(13,156)}$ = 1.2, $p = 0.2$). The variance accounted for by the first PC for IEMG was slightly less than for the joint angles and approached a peak of 77%. *Post hoc* tests revealed that the increase from the first trial was significant after the 6th trial ($p < 0.05$), with trials one and two accounting for significantly less variance than trials 6-14 inclusive. There were no differences between any of the trials after trial eight ($p \geq 0.4$). The variance accounted for by the first PC was greater for the analysis using the COH matrix compared to the PCC matrix, which again was about half of that accounted for by the PC based on the COH.

6.3.4. Variance accounted for on first and last trials of practice - IEMG

The eigenvalues for by the first 10 components for the IEMG signals from 16 muscles on the first and last practice trials are shown in Figure 6.3. The number of PCs required to account for 90% of the variance in the data decreased significantly with practice for the PCA based on COH, from 6.5 to 5.1(t =11.5, $p < 0.1$). A marked difference in the variance accounted for by subsequent components between

the COH and PCC was again obvious ($F_{(1,9)} = 49.6$, $p < 0.01$), with those for the PCC of a greater value.
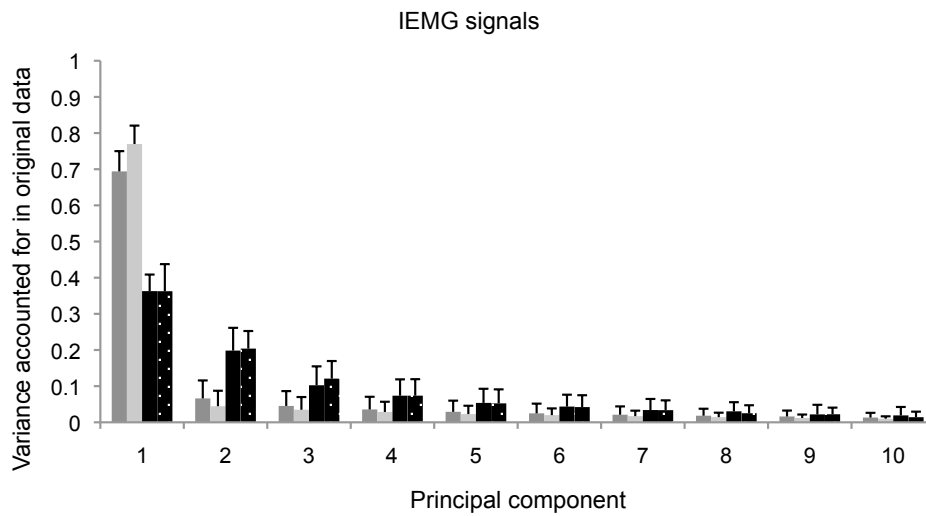
Figure 6.3. Variance accounted for (mean ± SD) across the 16 participants by successive PCs before and after practice using PCA based on COH and PCC. COH trial 1: dark grey; COH trial 125: light grey; PCC trial 1: black; PCC trial 125: stippled black.

6.3.5. Component loadings

The correlations between each joint angle and the first three PCs derived from each PCA are presented for the last practice trial in Figure 6.4. According to the criterion that a correlation > 0.25 between a raw variable and a PC is significant for a dataset this size [Kachigan, 1991], all of the raw variables loaded significantly onto the first PC for the analysis based on COH. The six shoulder angles, lumbar flexion/extension and cervical flexion/extension loaded the least strongly onto the first PC and loaded most strongly onto the second PC and to a lesser extent, onto the third PC. Nevertheless, the loadings of these shoulder, lumbar and cervical variables onto the second and third PCs were clearly less strong than their loadings onto the first PC.

When compared to the COH analysis, the PCC analysis showed fewer variables loading significantly onto the first PC and the strength of the correlations was clearly lower. The six shoulder muscles and lumbar and cervical flexion/extension had the weakest loadings onto the first PC and, unlike the PCA based on COH, had stronger loadings onto the second PC and third PCs than the first.
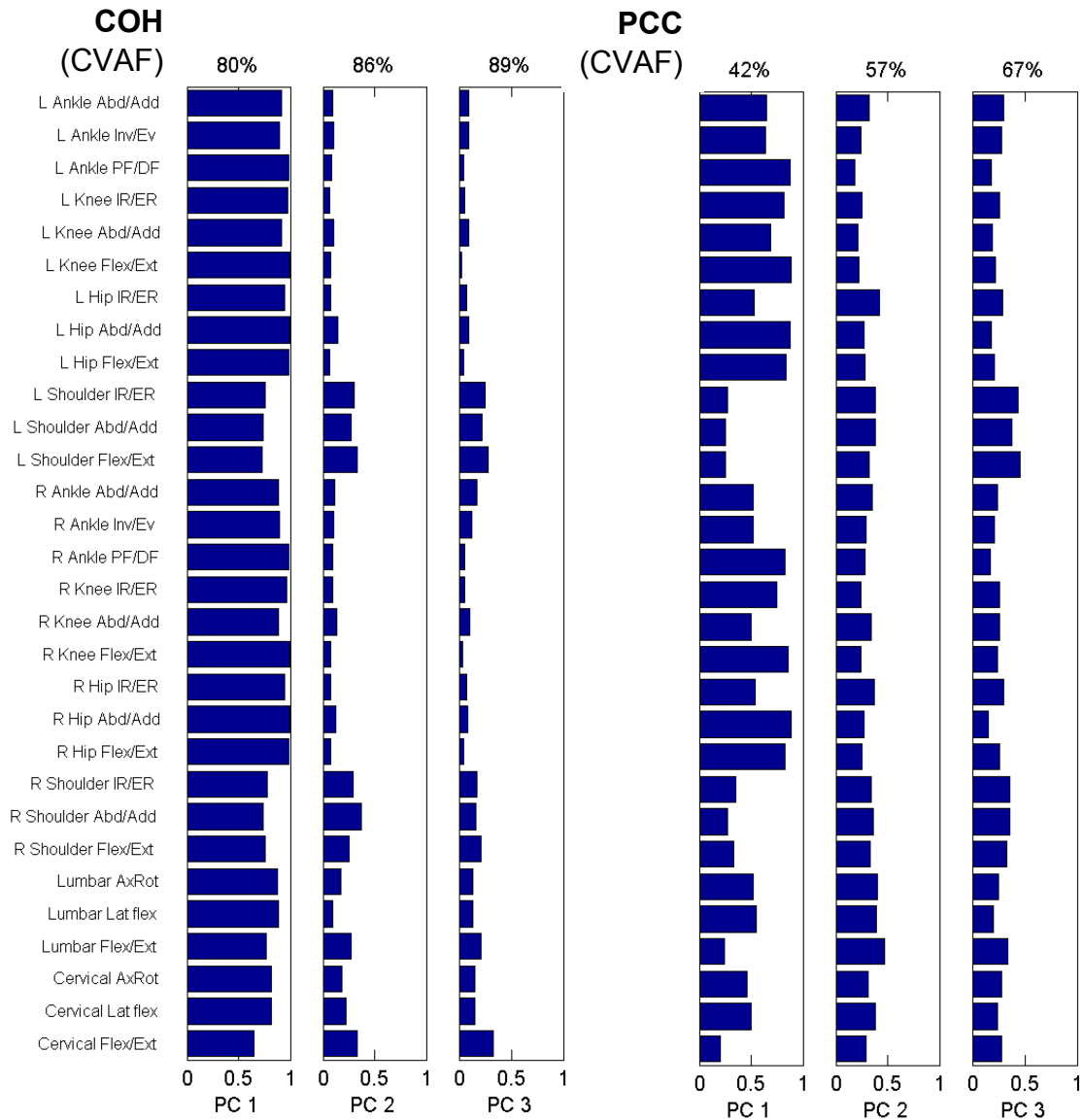
Figure 6.4. Mean post-practice weightings of individual joint angles onto the first three PCs derived from PCA using COH (left) and PCC (right). The cumulative variance accounted for (CVAF) by the three PCs is presented at the top of the figure.

A similar pattern of findings was repeated for the analysis of the IEMG signals (Figure 6.5). All of the muscles loaded strongly onto the first PC when the COH matrix was used, but there were no clear loadings of any muscle onto the second and third PCs. When the PCC matrix was used, no discernible structure to the grouping of muscles was apparent. None except the right and left tibialis anterior loaded more strongly onto the second or third PCs than the first.
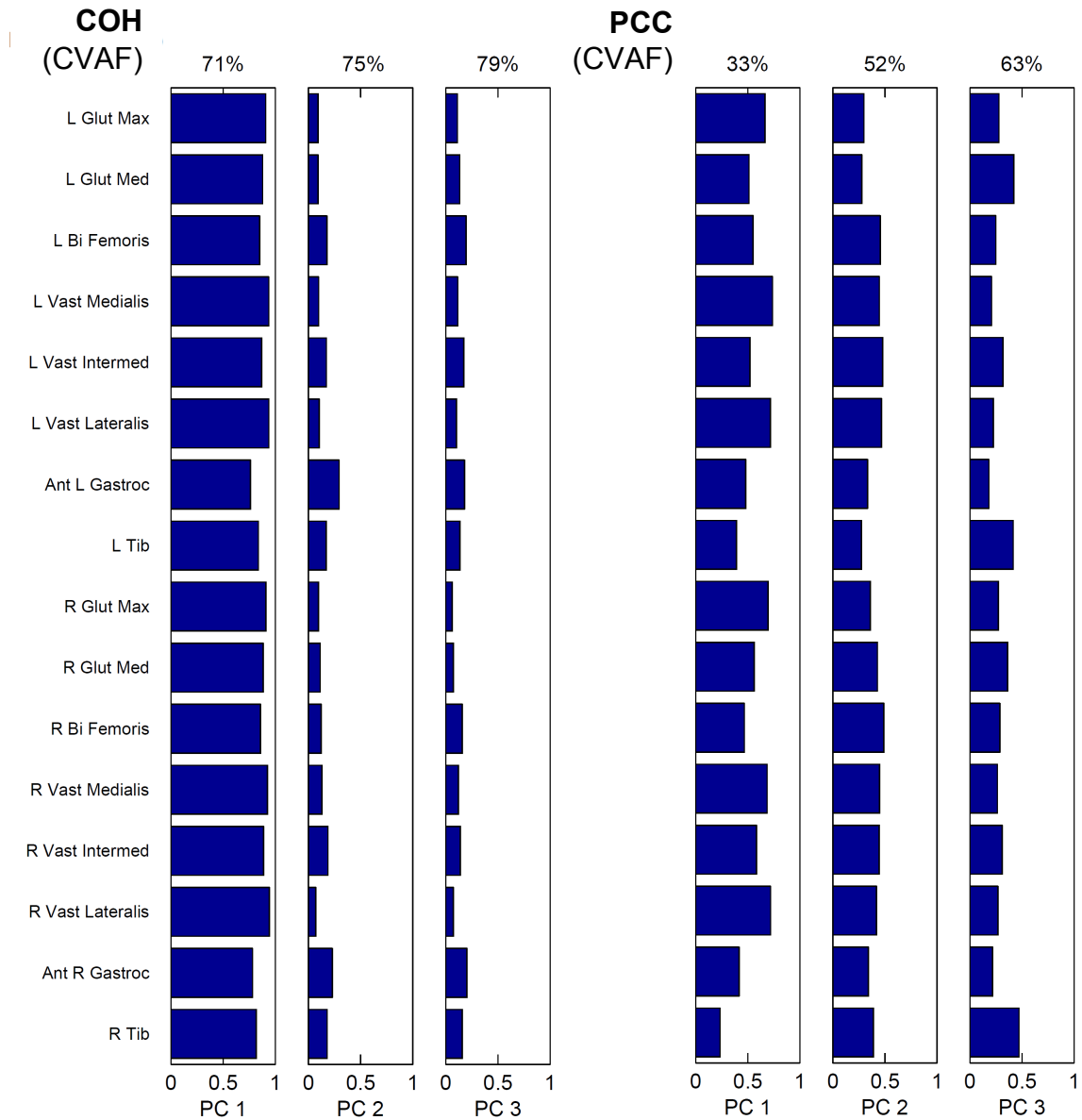
Figure 6.5. Mean post-practice weightings of individual IEMG signals onto the first three PCs derived from PCA analysis using COH (left) and PCC (right).The cumulative variance accounted for (CVAF) by the three PCs is presented at the top of the figure.

6.4. Discussion

The present study has revealed that the complex pattern of whole body movement on the skiing simulation task can be captured by a small number of independent PCs and that this low dimensionality decreases with practice. This finding was only the case when the PCA was performed using an overall coherence matrix in accordance with the method of [Wang et al., 2013]. The standard PCA method that employs a matrix of Pearson correlation coefficients to quantify correlation required

far more PCs to account for the variance of the dataset and did not detect any meaningful changes in dimensionality over the course of practice for either the kinematic or IEMG datasets. When the COH matrix was employed, the first PC accounted for a clearly greater amount of variance and all the raw variables loaded most strongly onto the first PC in both datasets. This method was therefore better able to detect the underlying structure of the coordination and the changes in dimension that occurred with practice.

In contrast to earlier research from the same slalom skiing movement [Hong and Newell, 2006a], the number of PCs required to account for 90% of the variance in the kinematic patterns decreased significantly with practice in the current study. It has been customary in interpreting PCA results to use this criterion of the number of components required to account for 90% of the variance as an arbitrary cut-off [Jackson, 1993]. However, this criterion does not work well here. A single component explained close to 80% of the variance in both datasets, while the second component for both the kinematic and IEMG data accounted for only a small percentage of the variance after practice, 6.0% and 4.5% respectively. The importance of this second PC is questionable since variances of less than 5% are generally considered not to be functionally significant or are associated with noise. Therefore, when using a PCA method that accounts for linear dynamic relations in the data, only one or at most two components were identified and higher PCs did not contribute to the structure of the coordination (Figures 6.2, 6.3). The 20% of unexplained variance therefore must be attributed to variability or 'noise' in the coordination and/or to measurement noise in the angle time series.

Ample research has supported the idea that for a range of motor tasks both IEMG and kinematic signals show a high degree of coupling that allows them to be decomposed into a fewer number of independent components that account for a majority of the variance in the original data set. The variance accounted for by the first PC derived from PCA gives a strong indication of the overall dimensionality of the signals arising from the motor system. Using data pooled across participants, a clear increase in variance accounted by the first component was shown in both kinematic and IEMG datasets. Considered individually, the direction of change was consistent for all participants. The

coupling between joint movements and muscle firing patterns within the system therefore increased with practice and may reflect the evolution of control towards a lower dimensional control space. The study by Hong and Newell [2006a] of this same task also showed an average increase in the variance accounted for by the first PC of ~4%. The key difference however was in the amount of variance accounted for by this component, the first PC in the current study accounting for 80% of total variance of the kinematic dataset compared to the 45-50% in the Hong and Newell study. The increase in coupling as a function of practice reflects improved coordination. It has been shown that an increase in movement speed can contribute to the increase in coupling [Ko et al., 2013] and an increase in speed was observed here, as documented in chapter 4.

Further evidence supporting the finding of low dimensional control for this task can be found in the structure of the loadings of individual variables onto each PC. The significant weightings of raw variables are traditionally used to gain further insight into the construction of movement. This relies on there being meaningful groupings of the raw variables that load onto individual PCs. Each PC is then considered to reflect an independent control mode [Hong and Newell, 2006; Ko et al., 2013] or program [Ivanenko et al., 2006] and the significant PCs together comprise the control space that underlies the organisation of the whole movement. Previously [Hong and Newell, 2006a] described the emergence of three major components after practice comprising groupings of raw variables that reflected distinct elements of performance on the task. The first related to force production in the medio-lateral plane, the second related to superior-inferior motion and the third related to balance. The groupings of raw variables for each component were largely in accordance with a distinct plane of motion. The results from the PCA based on the PCC matrix in the current study, however, did not suggest such a structure, even after practice (Figures 6.4, 6.5). This could reflect differences in the results of PCA when using joint angular rotations here versus segment CoM translations in the Hong and Newell study. However, although they did not present data for the joint rotation signals, these authors reported that they found no difference in results between PCA based on joint rotations and joint translations. Joint angular rotations nevertheless have been suggested to provide more relevant information than segment translations for evaluation of coordination [Ko et al., 2013].

When considering the results from the PCA based on the COH matrix in the present study, the need for interpretation of weightings, to a large degree, did not arise. All variables in both the kinematic and muscle datasets loaded most strongly (>0.70 for all except cervical flexion/extension) onto the first PC. This contrasts with most previous research utilising PCA. That the higher components accounted for so little variance and did not have any strong loadings of the raw variables is contrary to the assertion that a single coordination mode cannot account for the behaviour of limb variables on this task [Hong and Newell, 2006a]. Furthermore, the shoulder movement variables clearly stood out as the most strongly loaded variables onto the minor second and third PCs, suggesting that these variables were the most independent from all other variables. Arm motion was not an important element of this task as participants were instructed to hold their arms behind their backs. As a result, the movements were of small amplitude and variable nature, mostly representing an artefact of the trunk and torso movements. It was also possible that these movements varied according to the adoption of individual postures by participants. If these largely irrelevant signals were removed from the analysis, the dimensionality would likely be further decreased.

When considering the results of the present study in the wider context of research that has investigated changes in coordination as they occur with practice, complications arise related to terminology, levels of analysis, and description and interpretation. Traditionally, theoretical and empirical studies in this vein are based on the original ideas of Bernstein [1967]. In particular for learning, his description of a three-stage progression in the acquisition of skilled movement has been foundational. Subsequently, this was simplified as the 'freezing and freeing' approach to overcoming the many degrees of freedom in the motor system encountered in early learning [Tuller et al., 1982]. This language implies an initial freezing followed by an increase (freeing) in the number of degrees of freedom with practice. Numerous empirical studies attempted to quantify this proposed increase e.g. [McDonald et al., 1989; Vereijken et al., 1992a; Temprado et al., 1997]. Overall however, this research has been hindered by the lack of an operational definition of 'freezing and freeing' and hence different measures have been employed in an attempt quantify these changes, including joint amplitudes, pairwise cross-correlations between joints and more recently, PCA [Verrel et al., 2013].

An increase in amplitude of movement and a decrease in cross-correlations were posited as evidence for 'freeing' of degrees of freedom [Vereijken et al., 1992a]. The implicit theoretical expectation here is that motion becomes more differentiated with skill, interpreted as an increase in the independence of elements within the system as skill develops. An example of such a hypothesis was evident in a case study of learning a chip-kick, where the expectation was an increase in joint amplitude, a decrease in cross-correlation and an increase in dimensionality as indexed by PCs [Hodges et al., 2005].

The hypothesis that the degrees of freedom will increase with practice, however, is contradictory to the general assumption that mastery of coordination is achieved by decreasing the number of independent elements within the system. To overcome this apparent conflict, some investigators e.g. [Verrel et al., 2013] have championed the need to consider a 'coordinated freeing' whereby any apparent increased involvement or differentiation of degrees of freedom is made possible by an underlying coordination structure. Others have criticised the simplicity of Bernstein's account of changes regarding both number and nature of degrees of freedom. Newell and Vaillancourt [2001] suggested a series of theoretical postulates that expanded upon Bernstein, emphasising the distinction between degrees of freedom and dimension. Specifically degrees of freedom were assigned to the mechanical level, and indexed principally by changes in individual joint amplitudes, while dimension was described as "the number of dynamical degrees of freedom that are required to model the attractor dynamics of the movement system" (pg. 697). In addition they proposed that the direction of change (increase or decrease) in both degrees of freedom and dimension was dependent on the task. Distinguishing in this way between the number of elements in the system (mechanical degrees of freedom) and the number of those that are *independent* (dimensions), implying that these refer to entirely separate entities, does not however achieve the clarity required. The term degrees of freedom cannot be limited in definition to joint angles, since it may equally be applied to neurons, motor units, muscles, body segments, joint angles or forces. Li [2006] proposed a distinction between degrees of freedom (DOF) and *functional* DOF (fDOF), whereby the fDOF indicate the 'collective variables' that capture the organisation of the system according to the dynamical systems approach to

coordination. Based on this distinction, by using the raw DOF as the input, PCA affords a means for quantifying the number of such fDOF and hence identifying the dimensionality of the system. This cannot be achieved by investigating joint amplitudes.

Against this muddled theoretical background, the findings of the present study can provide clarity about the relation between degrees of freedom and joint amplitudes in motor learning. The crucial element here was the identification of dynamic linear relations between movements and muscles (as indexed by the COH matrix) in the PCA [Wang et al., 2013]. By incorporating such mathematical relations, the PCA revealed that the whole-body movements on the slalom skiing simulator were inherently low-dimensional in nature. The most important and perhaps surprising finding was the large amount of variance accounted for by the first PC even on the very first trial (Figures 6.1, 6.2, 6.3). This indicates that there was a very high degree of coupling between joint angles and muscles from the first moment the participants attempted the task (at least after the first three cycles, which were eliminated to remove any onset transient movements). Large increases in amplitude of body movements (Figure 4.4) took place over the course of practice. This 'freeing' of movement, however, was independent of the degrees of freedom of the movement. The change in degrees of freedom in fact was quite modest (Figure 6.1, 6.2, 6.3). One might have expected the movements in the first trials to be poorly coupled, so that a number of significant independent components would be identified. However, one might have a similar expectation of human foetal movements, yet high-resolution ultrasound recordings of movements in utero show that even our very earliest movements appear to be 'coordinated' [Prechtl, 1997]. From the beginning, foetal movements are patterned into recognisable forms. They are variable in speed, force and temporal sequence but there is no stage of amorphic and random movements [Prechtl, 1997]. If random movements were subjected to PCA, one would expect a high number of independent components to be identified. The conclusion arising from the application of principal component analysis based on dynamic linear relations between movements and muscles, therefore, is that human movements in general are highly coupled and low-dimensional, even when unskilled at a new motor task.

CHAPTER 7.

Summary of conclusions

This thesis has provided a thorough account of the development of skill and whole body coordination in females and males. Sex differences in motor performance appear, to a large degree, to be a result of differences in accumulated experience.

In Chapter two, movement patterns during landing differed between groups on the basis of both sex and experience level; however it was not clear whether these patterns actually limited the ability to successfully perform the skill. The sex differences appeared only at the time before initial contact and may represent different strategies used to perform the task with the same degree of success. Experience with the task was indirectly controlled for on the basis of competitive status yet despite this, differences in practice volume and engagement could still have been possible.

Chapter four introduced a second investigation, where a novel skill was chosen and practice volume controlled for, to further explores these factors. For the whole-body ski task that comprised the studies in Chapters four and six, no differences were observed in the rate of learning or the degree of coordination. A comprehensive assessment of performance and kinematic variables showed few differences between female and male participants. Those that were observed appear to be accounted for by anthropometric differences between females and males, specifically in body mass, as this became relevant due to the nature of the specific performance measure and the apparatus upon which the skill was performed. However, the differences in performance for related performance outcome measures actually meant that the males and females were performing at their theoretical optimum. Given further consideration, these findings suggested that males and females were performing the task with similar success, within their individual constraints. Hence, we conclude that there are no explicit differences between males and females in the capacity to learn and perform a novel motor task over the same duration of practice.

Overall were important findings given that some suggestions are prevalent in society of a stereotypical female motion pattern. Given the right practice conditions, there is no reason to expect that females should be destined always to 'throw like a girl'. The exploration of individual and sociocultural measures indicated that males and females were differentiated for most measures but few significant differences were found, perhaps due to the small numbers of participants. Importantly, these did not hinder performance on the task. Further study of these factors may be warranted, especially in groups more predisposed to confidence issues such as young developing athletes.

Employing a recently developed advancement in the application of principal component analysis to movement data, whole body coordination in female and male participants was quantified with sufficient sensitivity to detect changes that occurred with practice on this task. There were no differences between males and females when performing and learning the ski task, when coordination was indexed via these methods. This provided further support to the idea that differences between the sexes have a minimal impact on motor performance, given equal experience with a task.

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APPENDIX A.

Systematic search: Sex differences in the kinematics and

neuromuscular control of landing

The purpose of this review was to evaluate systematically the evidence for sex differences in movement pattern and muscle activation during landing tasks and in the related neuromuscular property of leg stiffness. This will provide a step towards a more complete understanding of movement control in females and males. Although the studies reviewed were stimulated by a higher incidence of injuries in females, our purpose here was not to inquire into mechanisms of injury per se.

Methods

A systematic review was conducted by two authors (MRB and NOD) and included all studies that directly compared females and males using kinematic and neuromuscular (electromyography, dynamic stiffness) measures during drop landing, jumping and/or hopping tasks. No restrictions were applied to the jumping protocol used, both uni and bi-lateral landing being included.

Search strategy

Studies were included that met the following criteria: human subjects, English language, healthy recreational participants or competitive athletes, comparing male and female subjects of at least 16 years of age. Studies were excluded if they were review articles e.g. [Benjaminse et al., 2011; Carson and Ford, 2011] or conference papers, included landing but did not present kinematic or electromyographic (EMG) data in numerical form e.g., did not present data for both males and females [Pappas et al., 2007; Ambegoankar et al., 2011] or investigated subjects who had knee or hip pathology. An electronic database search was performed by one reviewer (MRB) on 10/3/2012. Relevant studies were identified through CINAHL (1981 to present), MEDLINE (1950 to present), PsychINFO (1806 to present), Scopus (1960 to present), SPORTDiscus (all years) and Web of Science (all years).

A general search stream included terms related to sex and gender, kinematics and lower limb joints, and neuromuscular topics: Sex, Gender, Female*, Male*, Knee, Hip, Ankle, Kinematic*, Knee flexion angle, Neuromuscular, Biomechanic*. In order to yield more specific results, this was combined with a 'leg movement task, EMG and leg stiffness' stream which included the following terms: Landing, Drop-landing, Drop-jump, Forward jump, Landing mechanics, Landing strateg*, Leg stiffness, Spring-mass or mass-spring, Hopping, Electromyograph*, EMG, Muscle activation. Two authors (MRB and NOD) applied the inclusion/exclusion criteria by reading the titles and abstracts.

Study selection/quality assessment

A methodological quality assessment consisting of an adapted version of the Quality Index developed by Downs and Black [1998] was applied by two authors (MRB and NOD). The modified questions deemed relevant for this review are presented in Appendix B.

Data extraction

Kinematic, EMG and leg stiffness outcomes were extracted from each relevant study. The mean scores for female and male groups were recorded, as well as whether sex differences met statistical significance. Kinematic data were grouped according to joint movement (hip, knee, ankle) and where possible, task protocol. Since the kinematic studies used varying biomechanical conventions to define each joint angle, the angles reported were converted into measures that could be compared across studies. A positive value was assigned to hip flexion, adduction and internal rotation, knee flexion, and ankle plantarflexion, and a negative value to rotations in the opposite direction. Knee abduction (valgus) was not included in the review because an extensive review of sex differences in this joint movement was reported recently [Carson and Ford, 2011]. EMG data were grouped according to muscle recorded.

Pooling of extracted data via a meta-analysis was deemed infeasible for any of the components that form this review (kinematic, EMG or leg stiffness) because of the diversity between studies in terms of participants (sport played, level of participation and training history) and methodology (biomechanical definitions, EMG normalization procedures and task procedures including type of

landing, height of landing and outcome measures). Instead, in accordance with a review by Carson and Ford [2011], the effect size (Cohen *d*) and 95% confidence intervals for the non-centrality parameter were estimated for each study that presented mean and standard deviation data (no study reported standard error). Significant sex differences from multiple studies were reported only for knee flexion/extension and ankle dorsi/plantarflexion, and so effect sizes were calculated for those movements only. No consistent significant differences were reported for any hip angles, nor for any EMG or neuromuscular variables and hence, no effect sizes were calculated for these variables. Since not all studies provided sufficient information to calculate effect size, the results for each kinematic measure are presented firstly in terms of the number of studies out of the total that reported a significant effect, and secondly in terms of effect size for the studies for which this could be calculated.

Results

The search results are presented in three sections; kinematics, EMG activation and stiffness.

Literature search

The search stream yielded 6316 articles, reduced to 4255 after removal of duplicates (Figure A.1). Six additional articles identified from bibliographical references were included. Following review of titles and abstracts, a total of 56 articles were considered for further review; 26 met the complete inclusion/exclusion criteria and were included in the review. Studies excluded either were not relevant or did not provide requisite data. Among those excluded were studies which presented data for female athletes only or did not directly compare males and females e.g. [Pappas et al., 2007; Ambegoankar et al., 2011], had participants under the age of 16 [Yu et al., 2004; Barber-Westin et al., 2006] or did not present relevant data in numerical form [Noyes et al., 2005; Nagano et al., 2007; Shultz et al., 2010]. Also excluded were studies which investigated only frontal plane kinematics, as these have been reviewed recently by Carson and Ford [2011].
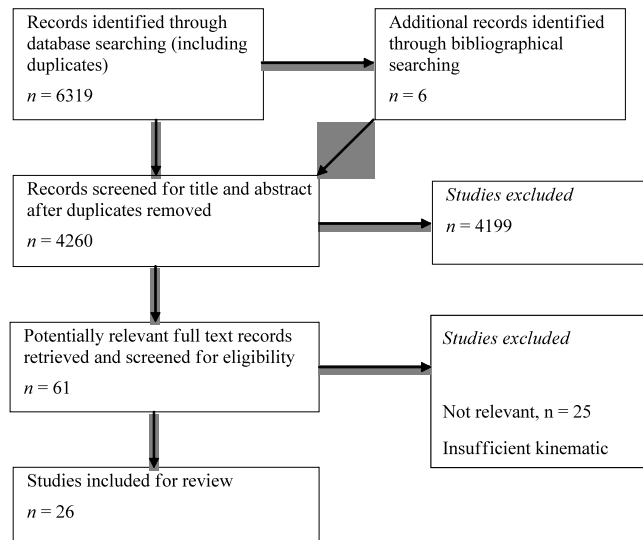
Figure A.1. Systematic search results flowchart.

Methodological quality assessment

Results for the quality assessment are presented in Table A.1. All studies scored highly (≥ 7/9) for the adapted Quality Index and no serious deficiencies in any area were identified.

Table A.1. Study characteristics and methodological quality assessment (MQA) scores.

Study	Year	N male	N female	Population	MQA Total
Kinematics					
Brown et al.	2009	13	13	Not reported	**8**
Chappell et al ^	2007	17	19	Recreational athletes	**9**
Decker et al.	2003	12	9	Recreational volleyball and basketball players	**9**
Earl et al	2007	18	19	Recreationally active	**9**
Fagenbaum & Darling ^	2003	6	8	Collegiate basketball players	**7**
Hughes et al	2010	6	6	Collegiate volleyball players	**8**
*Hughes and Watkins**	2008	5	5	Collegiate volleyball players	**8**
Huston & Wojtys	2001	8	8	Recreational and competitive team sport athletes	**9**
Jacobs et al.	2007	15	15	Recreational athletes	**8**

Kernozek et al.	2005	15	15	Recreational athletes	**9**
Kernozek et al.	2007	16	14	Recreational athletes	**9**
Lephart et al.	2002	15	15	Collegiate basketball, volleyball and soccer	**9**
Orishimo et al.	2009	12	21	Professional dancers	**9**
Salci et al.	2004	8	8	Collegiate volleyball players (1st division)	**8**
Schmitz et al.	2007	14	14	Recreationally active	**9**

Electromyography

Carcia and Martin	2007	10	10	Recreationally active	**9**
Cowling and Steele	2001	7	11	Recreationally active	**9**
Ebben et al.	2010	12	12	Collegiate athletes	**9**
Hart et al.	2007	8	8	Collegiate soccer players (1st division)	**8**
Medina et al.	2008	19	38	Collegiate basketball players	**7**
Shultz et al.	2009	39	39	Recreationally active	**8**
Urabe et al.	2005	7	8	Collegiate basketball players	**8**
Zazulak et al.	2005	9		Collegiate soccer players and track athletes (1st division)	**9**

Stiffness

Demirbuken et al.	2009	11	11	Not reported	**9**
Padua et al.	2005	15	15	Recreational basketball, volleyball and soccer players	**9**
Granata et al.	2002	11	10	Recreationally active	**8**

Lower body kinematics during landing and jumping tasks

Of the 26 articles in the review, 15 [Huston et al., 2001; Lephart et al., 2002; Decker et al., 2003; Fagenbaum and Darling, 2003; Salci et al., 2004; Kernozek et al., 2005; Russell et al., 2006; Chappell et al., 2007; Earl et al., 2007; Hughes et al., 2007; Jacobs et al., 2007; Schmitz et al., 2007; Hughes

and Watkins, 2008; Kernozek et al., 2008; Brown et al., 2009; Orishimo et al., 2009; Herrington and Munro, 2010; Hughes et al., 2010] included kinematic measures during landing and jumping (Table A.2). Three-dimensional (3-D) motion analysis was most frequently employed. Six distinct jumping and landing techniques were identified, unilateral drop landings being the most common. Further methodological variation arose from the number of trials, planes of motion and joint angles measured, and jump heights - which ranged from 20 cm [Lephart et al., 2002] to 60 cm [Decker et al., 2003] (Table A.2). The outcome measures for each protocol were not comparable in many studies, making it difficult to synthesize their results. Initial ground contact was the most frequent time at which measurements of joint angle were made. The position at landing is considered a feed forward or preparatory movement strategy [Thompson and McKinley, 1995] and the range of motion is related to both the initial contact posture and the level of muscle activation used to control the downward momentum [McNitt-Gray et al., 2001]. Hence, three of the most common outcome measures were selected to characterize kinematics during the landing manoeuvre: the joint angle at initial ground contact (IC), the maximum joint angle in the downward phase after landing (max) and the range of motion (RoM) between these two time points.

Females were reported to have significantly less knee flexion at initial ground contact in 5/11 studies (Table A.2), but only 1/8 studies for which effect sizes and confidence intervals could be calculated supported this difference (Figure A.2 a). Of the 3 studies for which an effect size could not be calculated, 2 reported significantly less and 1 reported significantly more knee flexion in females. Maximum knee flexion (8/9 studies) was not significantly different between the sexes (Table A.2). Females showed significantly greater RoM at the knee in 3/6 studies but this difference was supported by effect size and confidence intervals in only 2/5 studies (Figure A.2 b).

Females were reported to have significantly greater ankle plantar flexion at contact in 2/5 studies (Table A.2), but this difference was supported by effect size and confidence intervals in only 1 of these studies (Figure A.2 c). Maximum ankle dorsiflexion was significantly different between the sexes in only 1/5 studies (Table A.2). Females showed significantly greater ankle plantar/dorsiflexion

RoM in 3/4 studies (Table A.2) but this difference was supported by effect size and confidence intervals in only 2 of these studies (Figure A.2 d).

No reliable differences between the sexes were demonstrated in any hip kinematic variable, being reported in only 3/11 studies. Significantly greater hip flexion at initial ground contact in females was found in 1/7 studies, maximum hip flexion was less in females in 1/6 studies, and hip flexion RoM was not different in 5/5 studies (Table A.2). Significantly greater hip internal rotation at contact was reported in 1/2 studies. Greater hip internal rotation RoM was found in 1/1 study. No other significant differences in hip kinematics were reported.
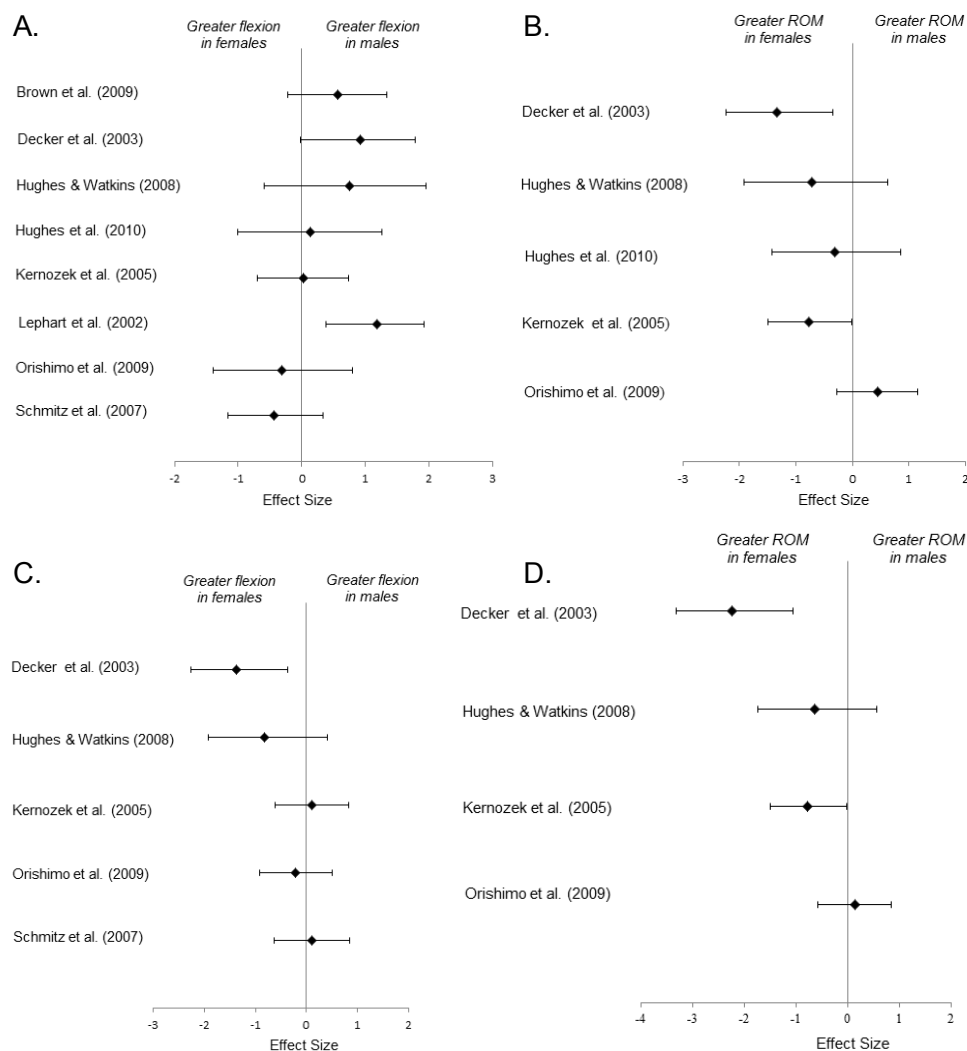
Figure A.2. Effect sizes where significant differences were reported for kinematics. A) Knee flexion angle at initial ground contact; B) Knee flexion RoM; C) Ankle plantarflexion angle at initial ground contact; D) Ankle plantar/dorsiflexion RoM

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Table A.2. Knee, ankle and hip kinematics for jumping and landing tasks.

Joint movement + author	Task		Initial Contact		Maximum		Range of motion	
			Mean ± SD (male)	Mean ± SD (female)	Mean ± SD (male)	Mean ± SD (female)	Mean ± SD (male)	Mean ± SD (female)
Knee Flexion								
Brown et al. (2009)	Unilateral drop-landing - max vertical jump		21.8 ± 12.8	16.1 ± 6.2				
Fagenbaum & Darling (2003)	Unilateral drop-landing	25.5 cm	#	# *				
Jacobs et al (2007)	Unilateral forward jump-landing				42.1 ± 8.79	39.51 ± 8.9		
Kernozek et al. (2008)	Unilateral drop landing	50 cm			67.2 ± 11.9	64.2 ± 10.8		
Lephart et al. (2002)	Unilateral drop-landing	20 cm	31.0 ± 9.9	17.4 ± 13.0*				
Orishimo et al (2009)	Unilateral drop-landing	30 cm	1 ± 7	3.5 ± 4.4	59.2 ± 12.5	58.7 ± 5.5	58.2 ± 8.7	55.1 ± 5.6
Schmitz et al (2007)	Unilateral drop-landing	30 cm	38.9 ± 7.1	42.5 ± 9.4				
Chappell et al. (2007)	Bilateral forward-jump		24.0	17.0*				
Decker et al. (2003)	Bilateral drop-landing	60 cm	30.0 ± 7.7	22.8 ± 8.0*			63.4 ± 9.3	75.8 ± 9.1*
Earl et al. (2007)	Bilateral drop-jump	30 cm			96.3 ± 14.1	94.4 ± 11.7		
Hughes et al (2010)	Bilateral drop landing - max vertical jump		20.3 ± 4.7	19.5 ± 6.9	67.2 ± 12.9	78.0 ± 8.1 *	46.9 ± 14.9	50.6 ± 7.4 *
Hughes & Watkins (2008)	Bilateral drop landing - max vertical jump		19.6 ± 6.4	14.8 ± 6.3*	62.6 ± 12.1	67.9 ± 12.5	43.0 ± 14.0	53.1 ± 13.8*
Huston and Wojtys (2001)	Bilateral drop-landing	20 cm	8.0	5.4	89.0	86.0	58.0	54.0
		40 cm	10	5.4*	95	93	68	66
		60 cm	16	7*	105	103	75	77
Kernozek et al. (2005)	Bilateral hanging drop-landing	60 cm	14.9 ± 4.4	14.8 ± 5.5	88.9 ± 11.4	78.3 ± 13.4	64.1 ± 14.9	74.3 ± 11.2

Study	Task	Height						
Salci et al. (2004)	Bilateral drop-landing	40 cm			72.7 ± 14.3	63.8 ± 7.1		
		60 cm			84.9 ± 3.2	75.7 ± 8.1		
Ankle plantar/dorsiflexion (+/-)								
Kernozek et al. (2008)	Unilateral drop landing	50 cm			-24.3 ± 8.0	-23.6 ± 4.7		
Orishimo et al (2009)	Unilateral drop-landing	30cm	33.2 ± 5	34.2 ± 4.4	-18.5 ± 4	-17 ± 4.2	52.2 ± 5.8	51.5 ± 4.8
Schmitz et al. (2007)	Unilateral drop-landing	30 cm	65.7 ±6.3	65.0 ± 5.6				
Decker et al. (2003)	Bilateral drop-landing	60 cm	11.3 ± 5.1	21.3 ± 9.6*			41.6 ± 6.9	58.0 ± 7.9*
Hughes & Watkins (2008)	Bilateral drop landing - max vertical jump		17.1 ± 10.3	25.1 ± 9.3*	-31.4 ± 6.5	-31.5 ± 5.9	48.5 ± 12.8	56. 5± 11.1*
Kernozek et al. (2005)	Bilateral hanging drop-landing	60 cm	22.3 ± 5.8	21.7 ± 5.8	-23.7 ± 7.6	-32.7 ± 5.8*	47.2 ± 10.3	54.3 ± 7.8*
Salci et al. (2004)	Bilateral drop-landing	40 cm			-29.1 ± 9.2	-30.2 ± 7.4		
		60 cm			-30.1 ± 9.7	-30.5 ± 6.7		
Hip Flexion								
Brown et al. (2009)	Unilateral drop-landing - max vertical jump		22.2 ± 7.2	30.4 ± 6.6*				
Jacobs et al (2007)	Unilateral forward jump-landing				26.1 ± 9.5	23.5 ± 8.7		
Kernozek et al. (2008)	Unilateral drop landing	50 cm			26.7 ± 14.4	40.7 ± 9.6		
Lephart et al. (2002)	Unilateral drop-landing	20 cm					6.7 ± 9.9	7.1 ± 5.6
Orishimo et al (2009)	Unilateral drop-landing	30 cm	-2.6 ± 10.7	5.9 ± 8.5	20.0 ± 16.6	28.7 ± 10.2	23.2 ± 6.7	23.3 ± 9.0
Schmitz et al (2007)	Unilateral drop-landing	30 cm	16.7 ± 7.6	21.6 ±6.3				
Chappell et al. (2007)	Bilateral forward-jump landing		48.0	46.0				
Decker et al. (2003)	Bilateral drop-landing	60 cm	30.8 ± 7.8	24.0 ± 10.6			50.4 ± 13.0	57.9 ± 13.8
Hughes & Watkins (2008)	Bilateral drop landing - max vertical jump		13.9 ± 5.8	13.7 ± 5.9	29.2 ± 7.9	39.1 ± 11.9	15.3 ± 9.3	25.3 ± 11.8

Study	Landing	Height	Initial contact M	Initial contact F	Maximum M	Maximum F	Range M	Range F
Kernozek et al. (2005)	Bilateral hanging drop-landing	60 cm	19.3 ± 7.4	18.8 ± 7.4			30.8 ± 17.2	38.9 ± 15.2
Salci et al. (2004)	Bilateral drop-landing	40 cm			67.3 ± 17.0	52.8 ± 9.8*		
		60 cm			74.2 ± 14.4	68.9 ± 13.2		

Hip internal/external rotation (+/-)

Study	Landing	Height	Initial contact M	Initial contact F	Maximum M	Maximum F	Range M	Range F
Brown et al. (2009)	Unilateral drop-landing - max vertical jump		4.4 ± 5.9	7.8 ± 7.9*				
Lephart et al. (2002)	Unilateral drop-landing	20 cm					3.1 ± 2.2	7.5 ± 3.7*
Chappell et al. (2007)	Bilateral forward-jump landing		-12.0	4.0				
Earl et al. (2007)	Bilateral drop-jump	30 cm			5.2 ± 5.0	1.6 ± 5.1		

Initial contact: joint angle at the moment of first ground contact, **Maximum:** maximum angle reached during the downward phase of the landing manoeuvre, **Range of movement:** the range of joint movement between initial contact and maximum angle.

* Denotes significant difference between male and female values, $p < 0.05$.
# Denotes females significantly greater than males, but mean values not reported.

EMG activity during landing and jumping

In 10 of the articles retrieved [Cowling and Steele, 2001; Fagenbaum and Darling, 2003; Urabe et al., 2005; Zazulak et al., 2005; Carcia and Martin, 2007; Chappell et al., 2007; Hart et al., 2007; Medina et al., 2008; Shultz et al., 2009; Ebben et al., 2010], EMG activity was reported for various muscles during landing and jumping (Table A.3). Vastus lateralis (7 studies) and biceps femoris (8 studies) were most commonly measured. A variety of approaches was used to measure muscle activation, with 3 studies reporting time to activation relative to initial ground contact while 8 studies reported peak and/or mean activation within specific pre- and/or post-contact time intervals. The EMG data were presented either as normalized to maximum voluntary isometric contraction or as a root-mean-square value. The range of landing protocols utilized was similar to the kinematic studies.

No reliable differences in muscle activation between the sexes were demonstrated across the 10 studies retrieved (Table A.3). No sex differences in activation of rectus femoris were observed (0/4 studies). Greater mean or peak activation of vastus lateralis or medialis in the female population was reported in 3/8 studies, while 2/8 studies showed these muscles to be recruited significantly earlier in females. However, 4/8 studies did not show any sex differences for these muscles. Only 2/8 studies of hamstring muscle activation reported any significant sex differences, with females displaying greater activation of biceps femoris in one study and delayed recruitment of semimembranosus in another. No sex differences in activation of gastrocnemius were observed in two studies that measured this muscle. Gluteal muscle activation was measured in 3 landing studies. Lower mean gluteus medius activation in females was reported in 1/3 studies and lower mean and peak gluteus maximus activation was reported in 1/1 study.

Table A.3. Hip, thigh and shank muscle activation during jumping and landing tasks.

Muscle + Author	Task	Measurement	Time of measurement	Mean ± SD (male)	Mean ± SD (female)
Rectus Femoris					
Cowling & Steele (2001)	Unilateral forward-jump	Time to activation (ms)	Activation time relative to contact	65 ± 30	95 ± 41
Medina et al. (2008)	Unilateral drop-landing 32 cm	Time to activation (ms)	Activation time relative to ground contact	-588.5 ± 77.3	-619.8 ± 79.3
Zazulak et al. (2005)	Unilateral drop-landing 30.5 cm	Peak %MVC Mean %MVC	250 ms post-ground contact	45.1 ± 25.0 25.8 ± 14.9	66.2 ± 31.9 39.6 ± 19.6
Ebben et al. (2010)	Bilateral drop-jump maximal vertical jump	Time to activation Peak %MVC	Pre-ground contact	69.4 ± 35.2 26.1 ± 21.9	57.7 ± 8.1 19.7 ± 10.6
Vastus Medialis					
Cowling & Steele (2001)	Unilateral forward-jump	Time to activation (ms)	Activation time relative to contact	121 ± 29	124 ± 49
Medina et al. (2008)	Unilateral drop-landing 32cm	Time to activation (ms)	Activation time relative to contact	-200	-408.1 ± 51.1
Urabe et al. (2005)	Unilateral drop landing maximal vertical jump	Mean %MVC	Between 15-55° knee flexion	140 ± 51	216 ± 54*
Ebben et al. (2010)	Bilateral drop-jump maximal vertical jump	Time to activation Peak %MVC	Pre-ground contact	64.1 ± 12.2 40.1 ± 36.4	52.3 ± 9.8* 38.0 ± 30.1
Vastus Lateralis					
Cowling & Steele (2001)	Unilateral forward-jump	Time to activation (ms)	Activation time relative to contact	93 ± 29	120 ± 46
Fagenbaum & Darling (2003)	Unilateral drop-jump 25.4 cm	Peak %MVC	Pre- and post-ground contact	#	# * (> in females)
Hart et al. (2007)	Unilateral forward-jump 60 cm	Mean RMS	200ms post ground contact	16.9 ± 21.3	14.5 ± 7.5

Urabe et al. (2005)	Unilateral drop landing maximal vertical jump	Mean %MVC	Between 15-55° knee flexion	158 ± 67	229 ± 108
Chappel et al. (2007)	Bilateral forward-jump	Mean %MVC	Pre-, flight and post-ground contact	#	#
Ebben et al. (2010)	Bilateral drop-jump maximal vertical jump	Time to activation Peak %MVC	Pre-ground contact	62.1 ± 16.3 30.5 ± 13.2	46.9 ± 10.1* 24.95 ± 16.4
Shultz et al. (2009)	Bilateral drop-jump 45 cm	Mean %MVC	Pre- and post-ground contact	# #	# *(27%>) # *(13%>)
Biceps Femoris					
Cowling & Steele (2001)	Unilateral forward-jump	Time to activation (ms)	Activation time relative to contact	115 ± 65	173 ± 54
Fagenbaum & Darling (2003)	Unilateral drop-jump 25.4 cm	Time to activation Peak %MVC	Pre- and post-ground contact	#	#
Hart et al. (2007)	Unilateral forward-jump 60 cm	Mean RMS	200 ms post-ground contact	5.9 ± 4.4	8.2 ± 6.0
Medina et al. (2008)	Unilateral drop-landing 32 cm	Time to activation (ms)	Activation time relative to contact	#	#
Urabe et al. (2005)	Unilateral drop landing maximal vertical jump	Mean %MVC	Between 15-55° knee flexion	50 ± 7	45 ± 12
Chappel et al. (2007)	Bilateral forward-jump	Mean %MVC	Flight and landing	#	#
Ebben et al. (2010)	Bilateral drop-jump maximal vertical jump	Time to activation Peak %MVC	Pre-ground contact	80.0 ± 23.9 26.2 ± 21.4	81.5 ± 19.0 16.7 ± 13.1
Shultz et al. (2009)	Bilateral drop-jump 45 cm	Mean %MVC	Pre- and post-ground contact	#	# * (29%>) # * (54%>)
Semi-membranosus					
Cowling & Steele (2001)	Unilateral forward-jump	Time to activation relative to contact	Activation time relative to ground contact	113 ± 46	173 ± 54*
Medina et al. (2008)	Unilateral drop-landing 32 cm	Time to activation (ms)	Activation time relative to ground contact	#	#

Study	Task	Measure	Timing	Male	Female
Urabe et al.(2005)	Unilateral drop landing maximal vertical jump	Mean %MVC	Between 15-55° knee flexion	43 ± 24	42 ± 12
Ebben et al. (2010)	Bilateral drop-jump maximal vertical jump	Time to activation Peak %MVC	Pre-ground contact	103.6 ± 96.2 39.5 ± 45.9	80.7 ± 22.2 36.3 ± 47.3

Gastrocnemius

Study	Task	Measure	Timing	Male	Female
Cowling & Steele (2001)	Unilateral forward-jump	Time to activation relative to contact	Activation time relative to ground contact	141 ± 111	140 ± 84
Hart et al. (2007)	Unilateral forward-jump 60 cm	Mean RMS	200 ms post-ground contact	2.8 ± 4.2	2.3 ± 2.3

Gluteus Medius

Study	Task	Measure	Timing	Male	Female
Hart et al. (2007)	Unilateral forward-jump 60 cm	Mean RMS	200 ms post-ground contact	7.2 ± 3.2	2.6 ± 0.9*
Zazulak et al. (2005)	Unilateral drop-landing 30.5 cm	Peak %MVC Mean %MVC	250 ms post-ground contact	79.3 ± 30.4 43.2 ± 13.7	69.2 ± 28.2 39.9 ± 18.5
Carcia & Martin (2007)	Bilateral drop-landing 30 cm	Peak %MVC Mean %MVC	Pre-ground contact	36.1 ± 16.7 18.1 ±6.2	65.8 ± 66.0 29.1 ± 27.7

Gluteus Maximus

Study	Task	Measure	Timing	Male	Female
Zazulak et al. (2005)	Unilateral drop-landing 30.5 cm	Peak %MVC Mean %MVC	250 ms post-ground contact	98.0 ± 33.4 53.9 ± 18.0	69.5 ± 30.2* 37.5 ± 15.6*

%MVC: percentage of maximal volitional contraction; **RMS:** root mean squared.

* Denotes significant difference between male and female values, $p < 0.05$.

# Denotes variable was reported but without numerical data.

Leg stiffness in hopping and landing tasks

Four articles included a measure of whole leg vertical stiffness. Three of these investigated two-legged hopping at preferred frequency [Granata et al., 2002; Padua et al., 2005; Demirbuken et al., 2009] and one a landing task [Hughes and Watkins, 2008]. All studies reported absolute leg stiffness to be significantly lower in females. Two studies also reported stiffness normalized to body mass. Females displayed significantly less relative leg stiffness in the single study of the landing task but this difference was not evident in the bilateral hopping task.

APPENDIX B.

Methodological Assessment tool

Assessment of methodological quality - modified Downs and Black questionnaire

Question 1 – Is the hypothesis/aim/objective of the study clearly described? (*Question 1)*

Question 2 – Are the main outcomes to be measured clearly described in the introduction or methods? (*Question 2)*

Question 3 – Are the characteristics of the subjects included in the study clearly described? *(Question 3)*

Question 4^ – Are the task procedures clearly described? *(Question 4)*

Question 5 – Are the main findings of the study clearly described? *(Question 6)*

Question 6 – Were the subjects asked to participate in the study representative of the entire population from which they were recruited? *(Question 11)*

Question 7 – Were the statistical tests used to assess the main outcomes appropriate? *(Question 18)*

Question 8 – Were the main outcome measures used accurate (valid and reliable)? *(Question 20)*

Question 9 – Did the study have significant power to detect a clinically important effect where the probability value for a difference being due to chance is less than 5%? *(Question 27)*

A score of 1 was allocated for each question where the answer was "yes". Questions adapted from Downs and Black (1998). The original question number from Downs and Black is shown in parentheses.

^ *The wording of question 4 of the Downs and Black questionnaire was modified to conform to the non-interventional studies in this review.*

APPENDIX C.

Questionnaires

Basic participant screening

THE UNIVERSITY OF **SYDNEY**

PARTICIPANT PRE TEST QUESTIONAIRE

Name: …………………………………………………..

Date of Birth: …………………………………….

Age………

Skiing History:

Do you have any ski experience at all? If yes please indicate how many times or years you have been skiing………

Have you ever participated at a competitive level……………………………………………………………………

Injury/Illness status:

Do you have any current injuries? Or have you had recent surgery? If yes, please provide details.

……
……

Have you had any major hip, knee or ankle injuries in the past?

……
……

Are you aware of any other reasons why you shouldn't participate in the lower leg exercise learning protocol outlined in this study?

……
……

Other Sports and Training History:

Are you involved in any sports, either competitively or recreational (please list)

……
……

Do you exercise regularly? If so, how many times on average per week would you be active?

……

What sort of training and/or exercise do you regularly complete?

……
……

Skill acquisition in males and females
 [Version 1 May 2012]

Trait self-objectification

Acquisition of skill in males and females using a slalom ski simulator

THE UNIVERSITY OF
SYDNEY

QUESTIONNAIRE 1

INSTRUCTIONS

We are interested in how people think about their bodies. The questions below identify 10 different attributes. We would like you to rank these body attributes from that which has the greatest impact on your physical self-concept, to that which has the least.

Note: It does not matter how you would describe yourself in terms of each attribute. For example you may not consider yourself to physically fit, however physical fitness may still have a large impact on your self-concept.

Your answers will remain confidential, we ask you to be as honest as you possibly can be. There are no "right" or "wrong" answers.

WHEN CONSIDERING YOUR PHYSICAL SELF CONCEPT, HOW IMPORTANT TO YOU ARE EACH OF THE FOLLOWING . . .

a) Physical Coordination?   f) Physical Attractiveness/image?
b) Health?   g) Energy level (e.g. stamina)?
c) Weight?   h) Firm and Sculpted Muscles?
d) Strength?   i) Physical fitness level?
e) Sex Appeal?   j) Measurements (e.g. chest, waist, hips)?

RANK OF ATTRIBUTE

Please read over all the attributes. Then, record your rank by writing the letter of the attribute next to its importance.

MOST IMPORTANT ....

SECOND MOST IMPORTANT ....

THIRD MOST IMPORTANT ....

FOURTH MOST IMPORTANT ....

FIFTH MOST IMPORTANT ....

SIXTH MOST IMPORTANT ....

SEVENTH MOST IMPORTANT ....

EIGTH MOST IMPORTANT ....

NINTH MOST IMPORTANT ....

LEAST IMPORTANT ....

Skill acquisition in males and females
 [Version 1 May 2012]

Physical self-efficacy

Acquisition of skill in males and females using a slalom ski simulator

THE UNIVERSITY OF SYDNEY

QUESTIONNAIRE 2

Please read the following statements and indicate by checking a box, how strongly you either agree or do not agree with them at this point in time.

Your answers will remain confidential, we ask you to be as honest as you possibly can be. There are no "right" or "wrong" answers.

1) I have excellent reflexes

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

2) I am not graceful and agile

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

3) I am rarely embarrassed by my voice

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

4) My Physique is rather strong

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

5) Sometimes, I don't hold up well under stress

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

6) I Can't run fast

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

7) I have physical deficiencies that sometimes bother me

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

8) I don't feel in control when I take tests involving physical dexterity

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

9) I am never intimidated by the thought of a sexual encounter

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

10) People think negative things about me because of my posture

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

Skill acquisition in males and females
 [Version 1 May 2012]

11) I am not hesitant about disagreeing with people bigger than me

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

12) I have poor muscle tone

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

13) I take little pride in my ability in sports

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

14) Athletic people usually do not receive more attention than me

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

15) I am sometimes envious of those better looking than myself

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

16) Sometimes my laugh embarrasses me

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

17) I am not concerned with the impression my physique makes on others

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

18) Sometimes I feel uncomfortable shaking hands because my hands are clammy

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

19) My speed has helped me out of some tight spots

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

20) I find that I am not accident prone

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

21) I have a strong grip

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

22) Because of my agility, I have been able to do things which many others could not do

Strongly agree ○   Agree ○   Neutral ○   Disagree ○   Strongly Disagree ○

PSES scale by Richard M Ryckman and colleagues. First developed, 1982.

Skill acquisition in males and females
[Version 1 May 2012]

Skiing-simulator task and general motor learning self-efficacy

Acquisition of skill in males and females using a slalom ski simulator

QUESTIONNAIRE 3

Part 1

As a participant in this study, you will be instructed to make side to side movements while standing on a slalom ski simulator.

Using the scale from 1 to 10 that is described below, please rate how certain you are *at this moment in time,* that you can achieve each of the following things –

1	2	3	4	5	6	7	8	9	10
Cannot				**Moderately**					**Highly certain**
Do at all				**Can do**					**Can do**

1. Balance on the platform with your hands behind your back ……
2. Make back and forth movements fluidly and keep a rhythm for 1 minute ……
3. Make the widest possible arc on the apparatus and maintain a constant, fast speed ……

Part 2

Refer to the second scale below to answer part 2. Generally speaking, how strongly do you identify with each of the following statements –

1	2	3	4	5	6	7	8	9	10
Strongly				**Neither agree**					**Strongly**
Disagree				**Or disagree**					**Agree**

1. I am quick to learn or "pick up" new skills or motor tasks ……
2. I generally see myself as uncoordinated when it comes to movement ……
3. I could become competent at any skill I put my mind to ……
4. I could throw an object to hit a target (30cm wide) 5m away ……
5. If someone throws an object such as a ball towards me, I will instinctively move to avoid it, rather than attempt to catch it ……
6. In my lifetime, I have found myself attracted towards learning or trying new motor skills or sports ……
7. I would be put off by having someone watching me attempt a new skill ……
8. I place a high value on being able to move well ……

Skill acquisition in males and females
[Version 1 May 2012]

Waterloo footedness assessment tool

Acquisition of skill in males and females using a slalom ski simulator

THE UNIVERSITY OF SYDNEY

WATERLOO FOOTEDNESS QUESTIONNAIRE

Name:……………………..

Instructions: Answer each of the following questions as best you can. If you *always* use one foot to perform the described activity, circle **Ra** or **La** (for right always or left always). If you *usually* use one foot, circle **Ru** or **Lu**, as appropriate. If you use *both* feet, *equally often*, circle **Eq**.

Please do not simple circle one answer for all questions, but imagine yourself performing each activity in turn and then mark the appropriate answer. If necessary, stop and pantomime the activity

1.	Which foot would you use to kick a stationary ball at a target?	La	Lu	Eq	Ru	Ra
2.	If you had to stand on one foot, which would it be?	La	Lu	Eq	Ru	Ra
3.	Which foot would you use to smooth sand at the beach?	La	Lu	Eq	Ru	Ra
4.	If you had to step up onto a chair, which foot would you place on the chair first?	La	Lu	Eq	Ru	Ra
5.	Which foot would you use to step on a fast moving bug?	La	Lu	Eq	Ru	Ra
6.	If you were to balance on one foot on a railway track, which would you use?	La	Lu	Eq	Ru	Ra
7.	If you wanted to pick up a marble with your toes, which foot would you use	La	Lu	Eq	Ru	Ra
8.	If you had to hop on one foot, which would you use?	La	Lu	Eq	Ru	Ra
9.	Which foot would you use to help push a shovel into the ground?	La	Lu	Eq	Ru	Ra
10.	During relaxed standing, people initially put most of their weight onto one foot, leaving the other leg slightly bent. Which foot do you put most of your weight on first?	La	Lu	Eq	Ru	Ra
11.	Is there any reason (i.e. injury) why you have changed your foot preference for any of the above?	**YES**	**NO**			
12.	Have you ever been given special training or encouragement to use a particular foot for certain activities?	**YES**	**NO**			
13.	if you have answered **YES** for either Q11 or Q12, please explain:					
14.	If you were to stand on a skateboard or surfboard and roll forwards, which leg would you feel most comfortable with as your front leg?	L	R			

APPENDIX D.

Ethics Documentation

Participant consent form

THE UNIVERSITY OF SYDNEY

Discipline of Exercise and Sport Science
Faculty of Health Sciences

ABN 15 211 513 464

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PARTICIPANT CONSENT FORM

I, ...[PRINT NAME], give consent to my participation in the research project

TITLE: POSTURAL AWARENESS AND CONTROL IN MALE AND FEMALE SURFERS

In giving my consent I acknowledge that:

1.   The procedures required for the project and the time involved (including any inconvenience, risk, discomfort or side effect, and of their implications) have been explained to me, and any questions I have about the project have been answered to my satisfaction.

2.   I have read the Participant Information Statement and have been given the opportunity to discuss the information and my involvement in the project with the researcher/s.

3.   I understand that I can withdraw from the study at any time, without affecting my relationship with the researcher(s) or the University of Sydney, now or in the future.

4.   I understand that my involvement is strictly confidential and no information about me will be used in any way that reveals my identity.

5.   I understand that being in this study is completely voluntary – I am not under any obligation to consent.

6.   I consent to: –
i)   Audio-taping   YES ☐   NO ☐
ii)   Video-taping   YES ☐   NO ☐
iii)   Receiving Feedback   YES ☐   NO ☐

If you answered YES to the "Receiving Feedback Question (iii)", please provide your details i.e. mailing address, email address.

Feedback Option

Address: _____

_____

Email: _____

Participant information statement

THE UNIVERSITY OF
SYDNEY

ABN 15 211 513 464

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Skill acquisition in males and females

PARTICIPANT INFORMATION STATEMENT

You are invited to take part in a research study into the acquisition of skill in males and females. The object is to investigate the evolution of skilled movement (coordination) when learning a novel skill. The changes resulting from practice will be compared between males and females. The study is being conducted by Michaela Bruton (PhD candidate) and will form the basis for the degree of Doctor of Philosophy at The University of Sydney under the supervision of A/Prof Nicholas O'Dwyer and Dr Mark Halaki.

If you agree to participate in this study, you will be asked to complete a series of practice sessions where you learn and refine a new skill. The task to be performed will utilise a mechanical ski simulator, used in conjunction with the 3D motion analysis lab. You will need to attend the Cumberland Campus, Faculty of Health Sciences (Lidcombe) for 5 practice sessions. Sessions one and five will take approximately 3-4 hrs each, the other three sessions will take approximately 1 hour each. The sessions will be scheduled over a 2-3 week period and at times most convenient to you.

The testing will require you be fitted with 40 reflective markers (attached with double-sided tape) to capture your body movements and self-adhesive surface electrodes to record muscle activation signals. You are advised to wear tight fitting clothing (gym clothes/ bike shorts including sports bra for females is best) so that there is minimal interference with the markers and electrodes. The 40 reflective markers will be attached to the upper and lower body. Thirty-three self-adhesive electrodes will be attached to your skin over muscles of the lower limb and include the calf, quadriceps, hamstrings and gluteals (8 muscles x 2 legs x 2 electrodes per muscle plus one ground electrode). In order to prepare the skin for collection of muscle signals, it is necessary for the area to be shaved, abraded and swabbed with alcohol; this may result in mild skin irritation. Muscle activation data will only be collected on days 1 and 5, however the joint markers will be attached for all 5 days of testing.

All aspects of the study, including results, will be strictly confidential and only the investigators named above will have access to information on participants. A report of the study may be submitted for publication, but individual participants will not be identifiable in such a report.

While we intend that this research study furthers knowledge in the area of skill acquisition and coordination it may not be of direct benefit to you.

Participation in this study is entirely voluntary: you are not obliged to participate and - if you do participate - you can withdraw at any time. Whatever your decision, it will not affect your relationship with the university or staff.

When you have read this information, Michaela will discuss it with you further and answer any questions you may have. If you would like to know more at any stage, please feel free to contact Michaela Bruton (0423174220), michaela.bruton@sydney.edu.au OR A/Prof Nicholas O'Dwyer (93519886).

> **Any person with concerns or complaints about the conduct of a research study can contact The Manager, Human Ethics Administration, University of Sydney on +61 2 8627 8176 (Telephone); +61 2 8627 8177 (Facsimile) or ro.humanethics@sydney.edu.au (Email).**
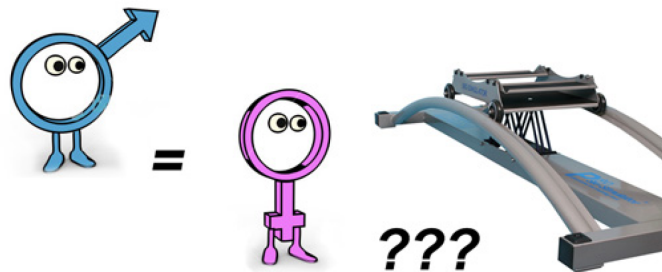
This information sheet is for you to keep.

Volunteer flyer

 THE UNIVERSITY OF SYDNEY

Discipline of Exercise and Sport Science

Skill acquisition in males and females

Volunteers Required

ANY PERSON AGED 18-45 WITH NO OR MINIMAL SKI EXPERIENCE, WHO IS INTERESTED IN LEARNING AND PRACTISING A FUN NEW SKILL…

We are investigating whole body coordination during the learning of a new skill. This will involve *exercise on a ski simulator* and we are interested in any differences between males and females. The project requires you to attend 5 practice sessions within a 3-week period. Sessions 1 & 5 take 3-4 hours each, sessions 2-4 take 1 hour each (including set-up). We will be collecting body movements throughout the practice and muscle activation data in sessions 1 & 5.
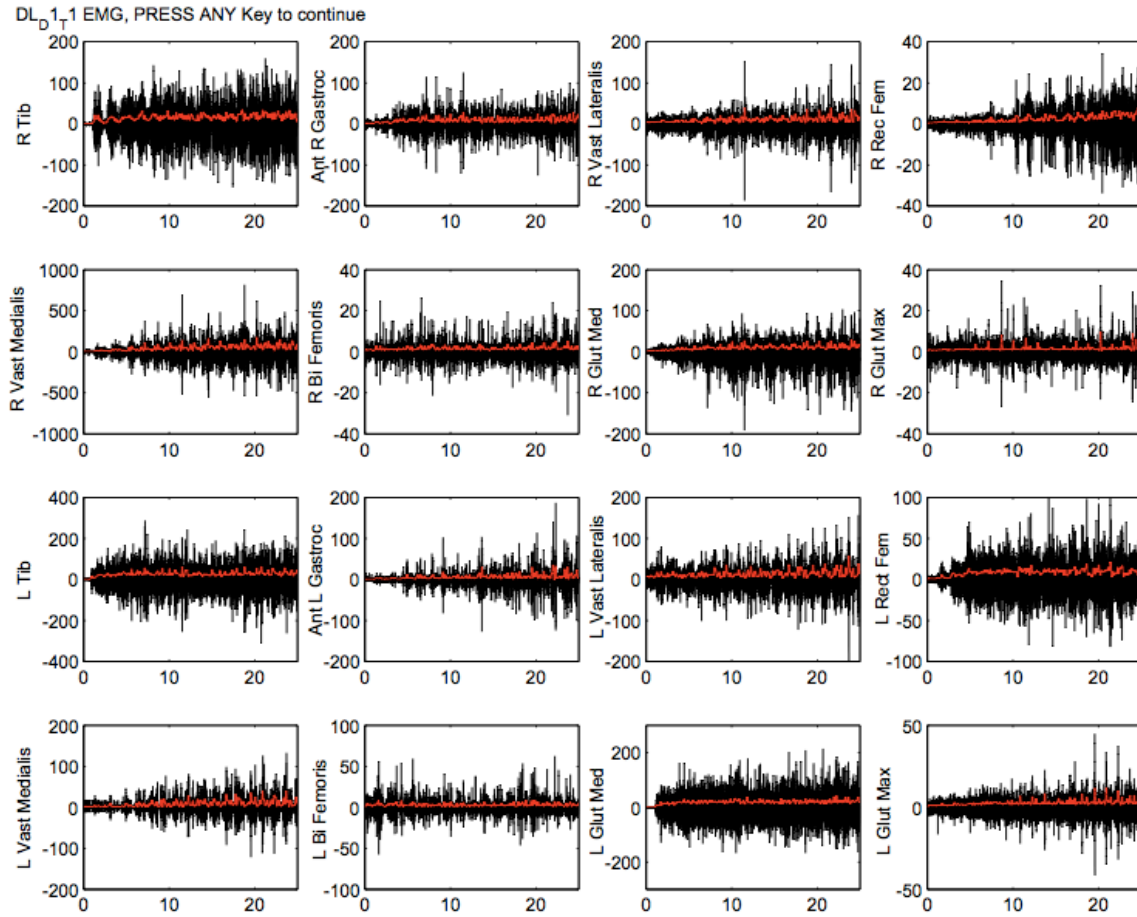
ersion 3 [25-06-2012]

Skill acquisition in males and females
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APPENDIX E.

Sample raw IEMG data

25s from trial 1.

25s from same participant, trial 125.