

# Anticipatory lower limb muscle activity during a turning task

Lisa Ngan-Hing

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## Attestation of authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the qualification of any other degree or diploma of a university or other institution of higher learning, except where due acknowledgment is made in the acknowledgements.



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## Abstract

### **Objective:**

Two experiments were undertaken. The objective of Experiment One was to identify the lower limb muscles that were most frequently active during the early period of a step-turning task for further testing in Experiment Two. In Experiment Two participants undertook multiple trials of a step-turning task, 30 and 60° to the left and right of midline, at a self-selected pace in response to a visual cue. There were five objectives to Experiment Two. Firstly, to identify the predominant order in the onset of foot movement so that anticipatory muscle activity could be defined for this task. Secondly, to identify whether there is a consistent temporal order in movement onset between the head and the feet. Thirdly, to identify whether and how consistently anticipatory lower limb muscle activity is present bilaterally. Fourthly, to assess whether there is a consistent sequence in the onset of anticipatory muscle activity among muscles active in at least 80% of trials. The final objective was to identify whether there was a consistent temporal relationship in the onset of the anticipatory muscle activity present in at least 80% of trials, with the onset of head and foot movement.

### **Study Design:**

A repeated measures design was used.

### **Background:**

Anticipatory lower limb muscle activity in gait initiation and forward stepping studies has been reported to be consistently present, and associated with initial and important balance responses. Falls during turning are associated with a high incidence of hip

fractures in the elderly population. The presence of anticipatory lower limb muscle activity turning has not been previously reported.

**Participants:**

There were five participants in Experiment One, and ten in Experiment Two. All were between 18 and 40 years of age and did not have neurological or musculoskeletal disorders, or severe visual loss.

**Results:**

In Experiment One, four muscles were consistently active bilaterally, during the early period of step-turning and were: tibialis anterior, gastrocnemius, biceps femoris and gluteus medius. In Experiment Two the ipsilateral foot moved before the contralateral foot in 68% of trials towards the left, and 79% of trials towards the right. The onset of head movement consistently occurred before the onset of foot movement during turns towards both directions. The percentage of trials in which the four muscles were active in an anticipatory manner was low bilaterally, ranging from 12 to 38% of trials. Objectives that involved the further analysis of muscles active in at least 80% of trials were unable to be completed.

**Conclusions:**

During a step-turning task young healthy adults predominantly move their ipsilateral foot before their contralateral foot. The consistent onset of head movement prior to that of the feet, indirectly suggests that the visual system might influence the temporal onset of the feet. The low levels of anticipatory muscle activity during step-turning suggest that the lower limbs are not involved with the initial balance responses for this task thus making it inherently different to gait initiation and forward stepping.

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## Abbreviations

<b>COM</b>	Centre of Mass
<b>COP</b>	Centre of Pressure
<b>SEMG</b>	Surface Electromyography

## 1. INTRODUCTION

The ability to turn is an integral movement necessary for functional mobility and the completion of activities of daily living (Dite & Temple, 2002). However, in the elderly population falls which occur during turning are associated with a high incidence of hip fracture (Cumming & Klineberg, 1994), the reasons for which are unknown (Meinhart-Shibata, Kramer, Ashton-Miller, & Persad, 2005). There are multiple negative consequences to hip fractures including the loss of independent ambulation, the need for institutionalised care, morbidity (Norton, Butler, Robinson, Lee-Joe, & Campbell, 2000) and the economic burden associated with institutionalised care (Dite & Temple, 2002). Despite this, there little research on normal turning behaviour (Dite & Temple, 2002) and the biomechanics of turning (Meinhart-Shibata et al., 2005). The point of the turn at which the elderly fall has not yet been identified but investigating the anticipatory period prior to the initiation of the turn is valuable. This is because it can lead to insights concerning the prioritisation in the organisation of the task by the central system particularly within the context of motor programmes.

Motor programmes are one theory of how voluntary movement is organised (Schmidt & Lee, 1999; Shumway-Cook & Woollacott, 2001). A motor programme is believed to contain the pre-planned sequence of muscle activity prior to the initiation of the task (Keele, 1968), and includes both the muscle activity for the task as well as the postural muscle activity (Gelfand, Gurkinkel, Tsetlin, & Shik, 1971). Many gait initiation and forward stepping studies have used an anticipatory paradigm and have collected surface electromyography data (mainly in the lower limbs) with the aim of identifying the muscle activity (Assaiante, Woollacott, & Amblard, 2000; Crenna & Frigo, 1991; Elble, Moody, Leffler, & Sinha, 1994; Mann, Hagy, White, & Liddell, 1979; Mercer &



Sahrmann, 1999; Polcyn, Lipsitz, Kerrigan, & Collins, 1998). The methodological quality of those studies was poor overall with the general finding being that many muscles are active. The anticipatory lower limb muscle activity detected in those studies has been suggested to be responsible for generating a forwards fall at the ankle which initiates the movement (Cook & Cozzens, 1976; Crenna & Frigo, 1991; Herman, Cook, Cozzens, & Freedman, 1973), and to generate the medio-lateral anticipatory postural adjustment which assists with movement of the body's centre of mass onto the stance leg prior to stepping (Brunt et al., 1991; Lyon & Day, 1997). No reported study has investigated the presence and consistency of anticipatory lower limb muscle activity during step-turning, meaning that this and the initial balance responses are unknown. Few of the gait initiation and forward stepping studies have quantified how frequently muscles were active across repeated trials, and there has been little examination as to whether a consistent sequence of muscle onset exists among the most frequently active muscles. The muscles that are most frequently active are likely to have a key role for the task, and identification of their temporal relationship may have implications for falls rehabilitation.

There have only been two reported studies on the task of step-turning (Hollands, Ziavra, & Bronstein, 2004; Meinhart-Shibata et al., 2005). Step-turning is a task that has an obvious onset of movement (Stack, Jupp, & Ashburn, 2004) which simplifies the identification of anticipatory muscle activity. Meinhart-Shibata et al. (2005) reported that two different strategies in the onset of foot movement were used; an important finding that affects how anticipatory muscle activity should be defined for this task. Hollands and colleagues had used a multi-segmental body paradigm and reported that the onset of foot movement occurred after the onset of head movement, which

suggested that the visual system influenced the temporal movement onset of the feet. As the presence of anticipatory lower limb muscle activity has not been investigated during a step-turning task, its timing of onset in relation to that of the head is unknown. Establishing whether a consistent sequence in the onset exists between these events might indirectly indicate whether the visual system has a similar influence on the temporal onset of anticipatory muscle activity.

Given the limited amount of literature available on the task of turning (Dite & Temple, 2002; Meinhart-Shibata et al., 2005), and the high incidence of hip fractures from falls during turning in the elderly (Cumming & Klineberg, 1994), there is great need for additional research on turning. The use of an anticipatory and multi-segmental paradigm during the task of step-turning could provide insight into the central organisation of this task. This information would contribute to the small body of knowledge on the task of turning, as well as being of relevance to those in the area of falls rehabilitation.

## 1.1 Outline of the studies

Two experiments were undertaken involving the task of step-turning at a self-selected pace in response to a visual cue. The objective of Experiment One was to identify the lower limb muscles that were most consistently active during the early period of the task. There were five objectives in Experiment Two. The first objective was to identify which foot predominantly moved first because this would affect the definition of anticipatory muscle activity for this task. The second objective was to identify whether there was a consistent temporal relationship between the onset of head and foot movement. The third objective was to assess whether and how consistently the muscles identified in Experiment One activated in an anticipatory manner during repeated trials

of the step-turning task. The fourth objective was to identify whether there was a consistent sequence in the onset of muscles that were active in an anticipatory manner in at least 80% of trials. The fifth and final objective of Experiment Two was to examine whether there was a consistent sequence in the onset of the anticipatory muscle activity present in at least 80% of trials with the onset of head and foot movement.

## 1.2 Hypothesis

Because of the exploratory nature of both studies no directional hypotheses were adopted.

## 1.3 Delimitations

The following delimitations apply to both experiments.

1. Only young healthy adults who were aged between 18 and 40 years, who did not have severe visual loss, neurological or musculoskeletal conditions participated.
2. The data collected was limited to surface electromyography and motion analysis data.
3. Surface electromyography data was limited to muscles of the lower limb based on an initial selection of eight muscles, chosen from a literature review of studies on gait initiation and forward stepping.
4. The task under investigation was a step-turning task performed at a self-selected pace in response to a visual cue, 30 and 60° to the right and left from midline.

## 1.4 Operational Definitions

**Anticipatory muscle activity:** muscle activity that occurs prior to heel off or toe off in the first stepping leg during forwards stepping or gait initiation. In Experiment Two anticipatory muscle activity shall be defined as muscle activity that occurs prior to the onset of foot movement in the  $z$  direction of the predominantly first moving foot.

**Contralateral foot:** the foot which is furthest from the direction of turn during normal stance. Thus during turns to the right the contralateral foot is the left foot, and during turns towards the left it is the right foot.

**Contralateral strategy:** when the onset of movement of the contralateral foot precedes movement of the ipsilateral foot during step-turns.

**Early muscle activity:** muscle activity that occurs before the onset of toe off in the leg with surface electromyography electrodes during step-turns in Experiment One.

**Extent:** the size of angle of the step-turn measured in degrees.

**Forward stepping:** refers to the task where participants take a single step forwards.

**Gait initiation:** refers to the task where participants walk a short distance. The period analysed is the duration from quiet stance until the beginning of heel off or toe off in the first stepping leg.

**Ipsilateral foot:** the foot that is closest to the direction of the turn in normal stance. Thus during turns towards the right the ipsilateral foot is the right foot, and during turns to the left it is the left foot.

**Ipsilateral strategy:** when movement of the ipsilateral foot precedes the onset of movement of the contralateral foot during step-turns.

**Step-turn:** a turn undertaken in response to a visual cue from a position of quiet stance during which the entire body is re-aligned towards a set target.

**Steering:** turning to change the direction of walking without an interruption to the ongoing locomotion.

## 2 . REVIEW OF THE LITERATURE

### 2.1 Introduction

This chapter is divided into six main sections and begins with a description of the search strategies used to source the literature in this review. This is followed by a discussion of topics that are central to the experiments. Those key topics are: the theory of motor programmes, gait initiation, turning, and laboratory measurements. The key topics are followed by a review of studies on anticipatory muscle activity during gait initiation and forward stepping. This chapter concludes with a general summary.

### 2.2 Literature review search process.

Several searches were under taken to source articles on early muscle activity during turning and stepping. The most recent search was on February 6<sup>th</sup> 2006. Data bases that were searched were: Cinahl, Ebsco, Sport Discus, Amed, ProQuest Science and Springer journals. Articles with citations of key articles and authors were sourced using the Web of Science and Web of Knowledge data bases. Reference lists of key articles were hand searched. The key words and phrases used in the search were: turn, turning, step, stepping, gait, initiation, “gait initiation”, locomotion, “spin turn”, “step turn”, rotation, early, anticipation, anticipatory, preparatory, predictive, balance, posture, reactions, “balance reactions”, “postural reactions”, “anticipatory postural adjustment”, “anticipatory postural reactions”, “automatic postural responses”, muscle, muscles, muscle activity, “muscle responses”, synergy, “muscle synergy”, “postural set”, “postural synergy”, “whole body”, reaction, “reaction time”, strategy, strategies, electromyography, SEMG, EMG. These key words were used alone and in combination with one another.

Two separate searches of the previously listed data bases were undertaken to source articles relating to the surface electromyography methodology. The most recent search was on April 30<sup>th</sup> 2005. Key words and phrases used alone and in combination were: electromyogram, electromyography, EMG, SEMG, surface, muscle, muscles, muscle onset, anticipatory, “anticipatory postural”, “anticipatory postural adjustments”, balance, onset, timing, “onset determination”, processing, “processing tools”, computer, “computer algorithm”, analysis, placement, site, method, preparation, reliability, signal processing, “standard deviation”.

A search of the previously listed data bases was undertaken to source articles relating to the 3-Dimensional motion analysis methodology. The most recent search was on June 13<sup>th</sup> 2005. Key words and phrases used alone and in combination were: velocity, acceleration, onset, “motion analysis”, “3-D motion analysis”, three dimensional, kinematic, “kinematic data”, “lower limb”, legs, onset, “onset determination”, latency, initiation, movement, “movement onset”, gait, step and stepping. Information on the theory of motor programmes was obtained by searching the previously listed data bases and hand searching key articles. Articles citing work by key authors was sourced by using the Web of Science and Web of Knowledge data bases. The most recent search was July 26<sup>th</sup> 2005.

Seventeen studies were sourced on muscle activity during voluntary forwards stepping, gait initiation or step-turning. Studies were included if the primary aim was to investigate anticipatory lower limb muscle activity during any of the three tasks in trials with healthy young adults. The tasks of gait initiation and forwards stepping were included because of the paucity of studies on step-turning. Studies using perturbations and arm raising paradigms were excluded because these tasks are less similar to step-

turning compared with gait initiation and forwards stepping. It is generally accepted that anticipatory postural adjustments are task specific (Bent, Potvin, Brooke, & McIlroy, 2001; Diener, Horak, Stelmach, Guschlbauer, & Dichgans, 1991; McIlroy, Bent, Potvin, Brooke, & Maki, 1999; Nardone & Schieppati, 1988). Also, studies were excluded if their participants were solely older adults because it has been suggested that the pattern of early muscle activity changes with age (Henriksson & Hirschfeld, 2005; Mickelborough, van der Linden, Tallis, & Ennos, 2004; Polcyn et al., 1998).

In total, ten studies were included and seven studies were excluded. The reasons for exclusion were as follows: one study was excluded because the primary aim of the study was to compare different age groups resulting in a limited discussion of the young adults (Henriksson & Hirschfeld, 2005; 1997). Another study was excluded because it compared stroke participants to non-stroke participants and focussed the results and discussion on the stroke group (Kirker, Simpson, & Wing, 2000). Two studies were excluded because the main aim of the studies were to compare muscle activity across different tasks and few results were reported for gait initiation and stepping (Brunt, Liu, Trimble, Bauer, & Short, 1999; Sims & Brauer, 2000). The sole study on step-turning was excluded as the surface electromyography data was not collected during the anticipatory period but during the task (Hase & Stein, 1999). Work by Brunt et al. (1991) was excluded because the focus was on speed related changes. The study by Mickelborough et al. (2004) was excluded as its participants were limited to older adults. Work by Wang, Zatsiorsky and Latash (2005) was excluded because the analysis of the results focussed on the results for an upper limb task. The key aspects of the ten included studies are presented in Table 1 in alphabetical order. Only the results for the



young adults performing gait or forwards stepping tasks at a self-selected pace will be discussed in studies where different populations, tasks and task speed were studied.

**Table 1. Summary of studies**

<b>Author(s)</b>	<b>Year</b>	<b>Participant details</b>	<b>Muscles tested</b>	<b>Measure</b>	<b>Anticipatory movement event</b>	<b>Total number of trials per person</b>
Assainte et al.	2000	N= 8 7M 1F μ age N/A	GAST, TA, HS, QUAD, ABDO of swing leg. GM and TA of stance leg	SEMG	HO plus 300ms	10
Brenière et al.	1981	N= 7 M+ F N/A μ age N/A	SOL and TA bilaterally	SEMG	TO	40
Carlsöö	1966	N= 8 6M 2F μ age N/A	AH, SOL, TA, PL, BF, TFL, SACRO, RF, VL, and VM bilaterally	Fine wire EMG	Foot lift	N/A
Cook & Cozzens	1976	N= 10 6M 4F μ age= 36	TA, MED GAST, RF, HS, GM bilaterally	SEMG	TO	3-4
Crenna & Frigo	1990	N= 6 3M 3F μ age= 23	SOL bilaterally, TA, BF and VM unilaterally	SEMG	HO	30

Note: ABDO= abdominals, AH= abductor hallucis, BF= biceps femoris, GAST= gastrocnemius, GM= gluteus medius, HS= hamstrings, MED GAST= medial gastrocnemius, PL= peroneus longus, QUAD= quadriceps, VL= vastus lateralis, VM= vastus medialis, RF= rectus femoris, SACRO= sacrospinalis, SEMG= surface electromyography, SOL= soleus, TA= tibialis anterior, TFL= tensor fasciae latae. M= male, F=female, μ age= mean age in years, N/A= not available, HO= heel off, TO= toe off.

**Table 1. Summary of studies continued.**

<b>Author(s)</b>	<b>Year</b>	<b>Participant details</b>	<b>Muscles tested</b>	<b>Measure</b>	<b>Anticipatory movement event</b>	<b>Total number of trials per person</b>
Elble et al.	1994	N= 5 M+F N/A $\mu$ age 29	TA, MED GAST, RF, BF bilaterally	SEMG	TO	20
Herman et al.	1973	N= 12 M + F N/A $\mu$ age N/A	TA, MED GAST, SOL, RF, VM, MH, BF, GM, GMAX unilaterally	SEMG	TO	8
Mann et al.	1979	N= 10 5M 5F $\mu$ age N/A	ES, VM, RF, HS, GM, TA, PER, MED GAST bilaterally	SEMG	TO	2
Mercer & Sahrman	1999	N= 20 10M 10F $\mu$ age = 30	TA, GAST, SOL, HS, GM of stance leg. RF AND GM of swing leg.	SEMG	RF onset	20
Polcyn et al.	1998	N=20 10M 10F $\mu$ age = 25	TA, SOL, GAST bilaterally	SEMG	TO	10

Note: BF= biceps femoris, ES= erector spinae, GAST= gastrocnemius, GM= gluteus medius, GMAX= gluteus maximus, HS= hamstrings, MED GAST= medial gastrocnemius, MH= medial hamstrings, PER= peronei, VM= vastus medialis, RF= rectus femoris, SOL= soleus, TA= tibialis anterior, M= male, F=female,  $\mu$ = mean age in years, TO= toe off, HO= heel off, N/A= not available.

## 2.3 The theory of motor programmes

The theory of motor programmes is being presented because it is part of a theme within studies on anticipatory muscle activity during gait initiation and forward stepping. Motor programmes are one theory about how voluntary movement might be generated (Ghez & Krakauer, 2000) and there is ongoing debate as to the existence and content of motor programmes (Latash, 1993). Three lines of evidence support the existence of motor programmes: firstly tasks performed at high speeds are completed before peripheral feedback is possible; secondly reaction times increase with movement complexity suggesting that more time is needed to plan the task; and thirdly movements can still be completed despite deafferentation although performance is poorer (Schmidt & Lee, 1999).

Over time, concepts about motor programmes have evolved but the consistent feature has been that they are central plans about aspects of a movement that exist prior to the execution of the movement (Latash, 1993). The original definition of a motor programme by Keele (1968) which is still widely accepted (van Vliet, 1999), is that the motor programme contains a pre-planned sequence of muscle activation before the movement begins. Gelfand, Gurkinkel, Tsetlin, and Shik (1971) also suggested that the pre-planned sequence includes both postural muscle activity as well as muscle activity intended for the task. Additional instructions contained in a motor programme are thought to include the spatial features and angles through which joints will move, the movement forces and the responses to certain patterns of sensory information (Ghez & Krakauer, 2000). At present it is considered that generalised motor programmes exist for classes of actions rather than for individual actions. Generalised motor programmes

need additional parameters to define how it will be executed, and the output differs depending on those parameters (Schmidt & Lee, 1999).

Assuming that motor programmes specify the sequence of muscle activation in advance of a movement, researchers have attempted to identify those sequences in studies where repeated trials of voluntary forward stepping or gait initiation were performed under similar conditions (Assaiante et al., 2000; Brenière et al., 1981; Crenna & Frigo, 1991; Mercer & Sahrman, 1999). These anticipatory paradigms have been used to reduce the complexity of later movement related feedback. To identify a sequence of muscle activation the active muscles must firstly be identified, followed by the identification of the temporal order of onset among the muscles. Previous studies have shown that many lower limb muscles activate in an anticipatory manner during forwards stepping and gait initiation, but there is variability in how frequently they activate and their temporal order of onset with few explanations as to why (Assaiante et al., 2000; Mercer & Sahrman, 1999). This has contributed to the debate as to how strictly organised anticipatory muscle activity is (Hines & Mercer, 1997). Something that has been rarely attempted is the identification of the most consistently active muscles, and whether a consistent temporal order of onset exists among them. This would be useful information to those in the area of rehabilitation.

Errors can occur in motor programme execution and selection (Schmidt & Lee, 1999) which might contribute to some of the variability in how frequently muscles activate in an anticipatory manner and their temporal order of onset. Errors due to programme selection are rectified by selecting an alternative motor programme which is estimated to take 120ms to 200ms. Programme execution errors require a modification of the existing motor programme and this takes a shorter period between 30ms to 50ms. This

shorter modification time is possibly due to the use of central feedback loops that detect errors in the execution of a command rather than the action of the command. Currently it is not fully known how feedback is used to correct errors in a feedforward manner (Schmidt & Lee, 1999).

Another reason for some of the variability in how frequently muscles activate in an anticipatory manner and their temporal order of onset, might be due to subtle differences in the initial starting position of the movement, possibly due to changes in internal conditions such as fatigue. Differences in the starting position represent variability in human movement and result in changes to the control of movement largely because of altered environmental conditions. Variability in human movement is a natural consequence of the large number of degrees of freedom within a sensorimotor system that allow for human movement a concept originally identified by Nikolai Bernstein (Latash, 1993). There can be variability in both the control of a movement and the outcome of a movement when the same task is repeatedly performed under similar conditions, even if the same motor programme was used in each attempt at the task (Latash, 1993; Shumway-Cook & Woollacott, 2001). This situation illustrates the main limitation of the motor programme concept, which is that it does not clearly explain how the nervous system responds to changes in the environmental or musculoskeletal conditions (Shumway-Cook & Woollacott, 2001).

In the past, variability was perceived negatively by researchers (Newell & Corcos, 1993) but is currently perceived as a gateway to understanding the central organisation of movement (Latash, Danion, Scholz, & Schöner, 2004). Muscles which are consistently active in participants, across repeated trials of the same task must have a central role to the task because their activation is not variable. Identifying the most

consistently active muscles and their temporal order of onset would be important to those in the area of rehabilitation because these muscles would become the priority during the assessment and treatment process, for instance during the use of muscle facilitation techniques such as electrical stimulation. One method to determine the temporal order of muscle onset is to use the mean onset times for each muscle, however this method is not recommended because it does not necessarily represent the most common muscle recruitment sequence (Hines & Mercer, 1997). The alternative method used by Mercer and Sahrman (1999) is to rank the temporal order of muscle activation on a trial by trial basis, and then to calculate how frequently each different order of activation occurs across trials.

To summarise, motor programmes are thought to contain pre-planned representations of a movement including the sequence of muscle activity. Muscles that are consistently active during multiple attempts at the same task across participants are likely to have a vital role. Those muscles and whether a consistent temporal order of onset exists among them should be identified. Sequences should be identified using an analysis tool that ranks the order of events, rather than using the mean onset latencies. This information has important implications for rehabilitation. The major limitation with the theory of motor programmes, is that variability in the control and outcome of a movement during repeated attempts is poorly explained, and this contributes to the ongoing debate about how strictly controlled anticipatory muscle activity is.

## 2.4 Gait initiation

No published study has examined the existence of anticipatory muscle activity during turning tasks; therefore the majority of studies included in the literature review have

examined anticipatory muscle activity during gait initiation. This section is a review of important concepts relating to gait initiation. Gait initiation can be defined as the period between quiet stance and a state of steady gait. Gait initiation can be divided into phases and the end of the first phase has been commonly demarcated by either heel off (Brenière, Do, & Bouisset, 1987; Dietrich, Brenière, & Do, 1994) or toe off (Jian, Winter, Ishac, & Gilchrist, 1993) of the first stepping lower limb. Lower limb muscle activity detected by using surface electromyography which occurs before the onset of heel off and toe off has been labelled anticipatory (Crenna & Frigo, 1991), feedforward (Cowan, Hodges, & Bennell, 2001) or postural (Hines & Mercer, 1997; Mercer & Sahrman, 1999). The limitation with using heel off and toe off to denote the presence of anticipatory muscle activity is that the events are quite late and movement related activity may be detected meaning the activity is not strictly anticipatory. This limitation has rarely been acknowledged by researchers. For instance, if the onset of toe off is used to denote the presence of anticipatory muscle activity, muscle activity in the calf used to generate heel off will be detected.

The time taken for a muscle to activate in an anticipatory manner is influenced by prior knowledge about the type and amount of information about the task to be undertaken. This is because the information is used to organise parts of the motor programme (Anson, Hyland, Kötter, & Wickens, 2000; Brauer & Burns, 2002). Anticipatory postural adjustments are generated in a feed-forward manner based on predictions of an upcoming perturbation in response to a planned movement (Aruin, Ota, & Latash, 2001). In theory, feed-forward control uses sensory information such as vision to predict imminent perturbations based on experience and then to initiate proactive strategies. Sensory information and experience for prediction are regarded as essential for feed-

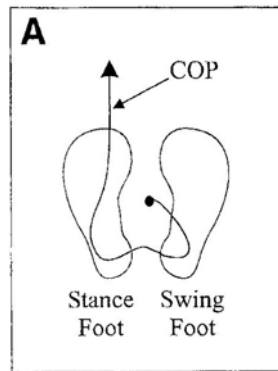


forward control to operate well (Ghez & Krakauer, 2000). The effects of the visual system on the temporal onset of anticipatory muscle activity have not been investigated in gait initiation studies. An indirect way to study the influence of the visual system is by examining the temporal relationship between the onset of anticipatory lower limb muscle activity and head movement. If the onset of anticipatory muscle activity occurs after the onset of head movement it is likely that visual information influences the temporal onset of the muscle activity. This is because it has been reported that eye movement precedes that of head movement (Hollands, Patla, & Vickers, 2002; Hollands et al., 2004).

It has been proposed that the anticipatory lower limb muscle activity during gait initiation and forwards stepping is involved with initiating a forwards fall at the ankles which allows the task to progress (Brenière et al., 1987; Cook & Cozzens, 1976; Crenna & Frigo, 1991; Herman et al., 1973), as well as generating propulsive forces during medio-lateral anticipatory postural adjustments (Brunt et al., 1991; Lyon & Day, 1997). However this assumption has not been further tested by examining the temporal order of onset among the medio-lateral anticipatory postural adjustment and anticipatory muscle activity. Presumably, muscles that initiate and control the medio-lateral postural adjustment would be active prior to the onset of centre of pressure (COP) changes above a threshold that distinguishes it from postural sway. The majority of studies on gait initiation have focussed on muscle control in the sagittal plane (Brenière et al., 1981; Cook & Cozzens, 1976; Crenna & Frigo, 1991; Herman et al., 1973; Polcyn et al., 1998), with few studies considering the muscles responsible for medio-lateral control in the frontal plane.

In a normal stance position the centre of mass (COM) is situated above and midway between the feet which act as the base of support. When a foot is lifted from the floor during forward stepping and gait initiation, stability is challenged by the reduced base of support. If the COM does not move towards the stance side before the foot lifts, the body becomes unstable because the COM will not be over the base of support and a fall may occur (Lyon & Day, 1997). The medio-lateral anticipatory postural adjustments are predictable preparatory balance responses during which there is an initial movement of the COP of the feet backwards and towards the stepping leg. This COP shift generates the initial momentum to move the COM towards the stance leg (Bent et al., 2001; McIlroy et al., 1999) and forwards (Dietrich et al., 1994) before the stepping leg lifts. The medio-lateral anticipatory postural adjustments occur at the foot-ground interface (Fiolkowski, Brunt, Bishop, & Woo, 2002) and are present during gait initiation and forward stepping (Brenière et al., 1987; Dietrich et al., 1994; McIlroy et al., 1999). Anticipatory postural adjustments are believed to be task specific (Bent et al., 2001; Diener et al., 1991; McIlroy et al., 1999; Nardone & Schieppati, 1988). Whether medio-lateral anticipatory postural adjustments occur during step-turning has not been reported to date.

Medio-lateral anticipatory postural adjustments are considered to be part of the motor programme for gait initiation (Brenière et al., 1987; Dietrich et al., 1994). They are considered to be present if there is an initial movement of the COP of the feet backwards and towards the stepping leg, by at least 4mm before the swinging leg steps (Bent et al., 2001; McIlroy et al., 1999). This is illustrated in Figure 1.



**Figure 1. Foot Centre of Pressure trajectory during gait initiation.**

Note: Adapted from Polcyn et al. (1998) page 1583. In this figure the initial trajectory of the COP backwards and towards the swinging foot is shown.

To summarise, it is presumed that anticipatory muscle activity during gait initiation is responsible for the initiation of a forwards fall at the ankles, as well as the control of the medio-lateral anticipatory postural adjustments. The medio-lateral anticipatory postural adjustments are predictable balance responses during which there is an initial shift of the COP backwards and towards the swinging leg. This shift assists with the movement of the COM towards the stance leg before the stepping foot lifts so that stability is maintained. To date no studies have reported whether anticipatory muscle activity exists during step-turning tasks. Should it exist, it is unknown whether it has a similar role to anticipatory muscle activity during gait initiation and forward stepping.

## 2.5 Turning

Turning is an important aspect of functional mobility that is necessary for the performance of activities in daily living (Dite & Temple, 2002). It has been reported that falls during turning whilst standing are eight times more likely to cause a hip fracture in older adults (Cumming & Klineberg, 1994), but the reasons for this are unknown (Meinhart-Shibata et al., 2005). There are multiple negative potential consequences to sustaining a hip fracture and these include: increased levels of

mortality, loss of functional independence and independent community ambulation, admission into long term nursing care (Norton et al., 2000) and the economic burden for this nursing care (Dite & Temple, 2002).

The work by Cumming and Klineberg (1994) did not identify at which point of the turn that balance was lost, but in general there is limited information on normal turning behaviour (Dite & Temple, 2002) and the biomechanics of turning (Meinhart-Shibata et al., 2005). For instance Thigpen, Light, Creel and Flynn (2000) found that healthy older adults who reported difficulty turning 180° during the Timed Up and Go test, turned significantly more slowly and took more steps compared to older adults who did not report difficulty turning. The reasons for this have not been identified (Meinhart-Shibata et al., 2005). The difficulties exhibited by the older adults whilst turning at a comfortable pace during the Timed Up and Go test (Hill, Denisenko, Miller, Clements, & Batchelor, 2005), suggest that future research on turning should include further testing of this task whilst it is performed at a self-selected pace.

Within the limited body of studies on turning, different contexts have been used. Turning has been investigated in the context of steering paradigms where participants are required to change direction whilst walking without an interruption to ongoing locomotion (Hase & Stein, 1999; Patla, Adkin, & Ballard, 1999; Xu, Carlton, & Rosengren, 2004). Identifying anticipatory muscle activity and postural adjustments during these paradigms is difficult because the turn is superimposed onto the task of locomotion, which adds complexity when identifying the onset of the turn. Hence the onset of the turn has been identified differently in existing steering studies. Additionally the anticipatory response may not be limited to just the step prior to the turn depending upon the timing of the cue (Patla et al., 1999).

Turning has been investigated in the context of ‘on the spot turns’ where a step-turn from a position of quiet stance is completed towards a specified point (Hollands et al., 2004; Meinhart-Shibata et al., 2005). Whilst these turns are considered to be less balance demanding compared to turns during steering (because the head stays over the base of support), the identification of the onset of the turn is less complicated (Stack et al., 2004). It is critical during research on anticipatory muscle activity that the onset of movement is accurately identified. Investigating the presence and consistency of anticipatory muscle activity during the step-turn may provide insight into the early balance responses and central organisation of the movement.

Earlier work which used a steering paradigm identified that co-ordinated relationships existed between the eyes and the head before turning to change direction. Saccadic eye movements were followed by head reorientation towards the new travel direction (Hollands et al., 2002). The influence of the visual system on the motor output of other body segments was investigated further in an important study by Hollands, Zivara and Bronstein (2004) during step-turning. In this study the temporal order of onset among multiple body segments (including the eyes, head, trunk and feet), were examined during a step-turning task at the fastest possible pace, involving five young healthy adults. Participants turned 10 times towards a light 45, 90 or 135° located to their left and right. The order of the light activation was randomised. The results indicated that a consistent temporal order of movement onset among the multiple body segments existed across all trials. Firstly, the eyes moved followed in order by the head, trunk and then the feet. Correlation analyses of the timing of movement onset between each body segment revealed significant correlations between the eyes and the head ( $r^2 = 0.74$ ), eyes and the trunk ( $r^2 = 0.59$ ) and the eyes and the feet ( $r^2 = 0.41$ ). The researchers concluded

that the temporal order of onset among the eyes, head and feet is co-ordinated and predictable. The onset of foot movement after the onset of eye movement suggests that the visual system has a strong influence on the timing of the foot movement. This valuable insight into the central organisation of the movement was possible because a multi-segmental body paradigm had been used.

The implications of this study by Hollands et al. (2004) for older adults who fall during turning might be that in the instances where vision has not grossly declined, there may be the prospect of assessing and retraining the temporal order of visual scanning strategies in relation to body movement. This might be particularly beneficial to the group of older adults who ‘mistrust’ their foot placement due to vague age related declines in proprioception, and whose visual strategies have adapted to gazing predominantly at their feet rather than where they are going.

There were limitations to the work by Hollands et al. (2004) firstly concerning the small number of motion analysis markers and their placement used to detect the multi-segmental movement. Only four markers were used, one on the top of the head, one on the seventh cervical vertebra and a marker on the big toe of each foot. Given that the onset of head and trunk movement was measured in the yaw plane, additional bilateral markers on the side of the face, head, acromion processes and anterior superior iliac spines may have enhanced the accuracy of the kinematic information. The second limitation to this study was that the temporal relationships were established based on the mean onset latencies for each event, rather than ranking the order of movement onset on a trial by trial basis. Hence it is possible that variations to the identified temporal sequence exist but they and their frequency of occurrence are unknown. Finally, although motion analysis markers had been placed on both feet, only the contralateral

foot marker was analysed and used to represent movement of both feet. Very recent work by Meinhart-Shibat et al. (2005) reported that young healthy participants generally stepped their ipsilateral foot first during a 180° step-turn from a quiet stance position. The implications of this are that future research should examine the order in the onset of foot movement to determine whether anticipatory muscle activity is present. This methodological complication had been avoided in most gait initiation and forward stepping studies by giving instructions on which leg to step (Assaiante et al., 2000; Elble et al., 1994; Mercer & Sahrman, 1999). The disadvantage with these instructions is that the preferred movement strategy cannot be identified and changes with age and pathology cannot be compared.

Meinhart-Shibata et al. (2005) compared the kinematics between a group of 10 young healthy adults (M age = 22 years), to a group of healthy older women (M age = 73 years) who did not have a history of falls. Participants completed a 180° turn on the spot, towards the left or right in response to a visual cue. Each participant completed a total of 48 trials. In addition to identifying the order of stepping between the feet, the turning rate was measured by the rotational velocity at the pelvis. The distance between the feet and the numbers of steps taken to turn were also examined. It was reported that in 76% of trials the young women stepped their ipsilateral leg first, whereas in 65% of trials the older women stepped their contralateral leg first. This occurred at similar frequencies towards both directions. The investigators considered that the strategy of stepping the contralateral leg first was a preparatory stepping strategy. The advantages of this strategy were that fewer degrees of hip external rotation were required during successive steps, and that there was a larger initial base of support.

The rate of turning was reported to be slower and more variable for the group of older women. Meinhart-Shibata et al. (2005) suggested that this slower turning velocity might make it easier to stop movement at the end of the task. Surprisingly, the distance between the feet and the number of steps taken were the same between the age groups. This might have been because the use of the preparatory foot strategy and slower turning velocities were adequate adaptive strategies for the maintenance of balance. Also, if participants had not been placed into an overhead harness (for safety), the kinematics may have been different as the harness may have increased the confidence levels of the older women. It is unknown whether the results of this study would extrapolate to smaller step-turns. Because the work by both Hollands et al. (2004) and Meinhart-Shibata et al. (2005) was delimited to kinematic data, the presence of anticipatory muscle activity and whether it is influenced by the visual system during step-turning is unknown.

To summarise, falls that occur during turning are more likely to cause hip fractures which have serious health consequences. Currently there is limited information on turning and more is needed on turns performed at a self-selected pace. No reported study has investigated whether anticipatory muscle activity is present during turning. Hence it is unknown whether its onset would be influenced by the visual system or whether there would be a consistent temporal relationship with the onset of head movement. Such information would provide insight into the central planning and balance strategies used during the early stages of a turn. In order to investigate anticipatory activity, the accurate identification of the onset of a turn is critical and this is simpler during step-turning tasks. There is the need to identify which foot moves first in order to define the presence of anticipatory muscle activity.



## 2.6 Laboratory measurements

The following is a review of the laboratory measurements that are used to identify the presence of anticipatory postural muscle activity.

### *2.6.1 Surface electromyography*

Three important topics on surface electromyography (SEMG) will now be discussed. They are: how to collect high quality SEMG signals, how to manage SEMG data and how to identify the onset of muscle activity.

#### *2.6.1.1 The quality of surface electromyography signals*

Surface electromyography detects the electrical activity in muscles and this is recorded as a SEMG signal (Cram, Kasman, & Holtz, 1998). A high quality SEMG signal has a high signal to noise ratio which makes the process of identifying the onset of muscle activity easier (Staude & Wolf, 1999). A high signal to noise ratio is achieved by reducing the levels of skin impedance and the sources of noise and movement artefacts (Cram et al., 1998; De Luca, 2002; Winter, 1990). Skin impedance can be reduced by using skin preparation techniques at the electrode sites including shaving, skin exfoliation and wiping with alcohol swabs. Sweating which increases the levels of skin impedance can be reduced by using electrodes with an electrolyte cushion (Cram et al., 1998; Winter, 1990). Skin impedance levels of less than  $10\text{k}\Omega$  are generally considered acceptable (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000).

There are many sources of noise; one source is ambient noise caused by electromagnetic devices which is absorbed by the SEMG leads. This absorption can be reduced by keeping the leads short and the participant as far as possible from the computer monitor

(Cram et al., 1998; Kamen & Caldwell, 1996). Absorption of ambient noise can also be reduced by using a SEMG system with common mode rejection and pre-amplifiers. The ground electrode in this system must have good skin contact, and be placed over a bony surface where there is no muscle activity (De Luca, 2002) such as the head of the fibula (Wang et al., 2005). Inherent noise from the power supply can be filtered out (De Luca, 2002; Winter, 1990). Movement artifacts are caused by swaying leads. Sway can be prevented by using short leads as well as taping them to the body and movement artifacts at frequencies between 10 to 20Hz can be filtered out (De Luca, 2002; Kamen & Caldwell, 1996; Winter, 1990).

It has been recommended that the levels of baseline muscle activity be reduced by encouraging participants to relax in between trials (Tomberg, Levarlet-Joye, & Desmedt, 1991), to reduce inaccuracies in identifying the onset of muscle activity (Hodges & Bui, 1996). Cross talk can be reduced by using small electrodes and decreasing the distance between paired electrodes to 1cm (Kamen & Caldwell, 1996). The presence of cross talk can be tested for by applying a resisted test to the targeted muscle (Winter, Fuglevand, & Archer, 1994).

The site of the SEMG electrode placement affects the quality of the SEMG signal. The electrode should not be placed on a motor end point because this is where the signal is unstable (De Luca, 2002; Kamen & Caldwell, 1996). Guidelines to the optimal sites for electrode placement have been developed by a collaboration of scientists referred to as SENIAM (Hermens et al., 2000). Electrodes should also be placed parallel to the muscle fibres to allow action potentials to be detected sequentially (De Luca, 2002; Kamen & Caldwell, 1996).

### *2.6.1.2 Management of the surface electromyography data*

The raw SEMG signal must be converted from an analogue signal to a digital signal so that a visual trace can be seen. If the sampling rate during this conversion is not high enough the SEMG signal will be distorted. Sampling at a frequency calculated by using the Nyquist Theorem will prevent signal distortion. The Nyquist Theorem requires the doubling of the highest frequency component of a SEMG signal (Hillstrom & Triolo, 1995). SEMG signals are rarely above 500Hz and a 1000Hz sampling rate has become the convention (Winter, 1990). The SEMG signal should then be full wave rectified, which is where all of the raw SEMG signal below zero is made positive (Cram et al., 1998; Kamen & Caldwell, 1996). Full wave rectification allows for the numerical quantification of the signal (Kamen & Caldwell, 1996; Winter, 1990).

Filtering the full wave rectified signal assists with the identification of muscle onset (Hodges & Bui, 1996). Filtering does cause the loss of fine details to a signal, hence it should be used judiciously (De Luca, 2002; Soderberg & Knutson, 2000). It has been recommended that SEMG signals up to 350Hz are retained as this will capture all but 5% of the signal information (Solomonow, 1997). In addition, De Luca (2002) has suggested that all signals between zero and 20Hz are filtered out because they are unstable.

### *2.6.1.3 Methods to identify the onset of muscle activity*

Two methods are commonly used to identify the onset of muscle activity from a SEMG trace: visual detection or computer programming techniques (Hodges & Bui, 1996; Soderberg & Knutson, 2000). The sole use of the visual detection method has been criticised as it has low intra and inter-rater reliability, and because the accuracy depends

upon the experience and skill of the examiner (DiFabio, 1987; Hodges & Bui, 1996). Computer programming techniques have perfect reliability (DiFabio, 1987) but the onset they identify may not always relate to a physiologically meaningful event (Stauden & Wolf, 1999). There are no standard computer parameters to determine the onset of SEMG activity, therefore testing of different parameters on the data to be analysed must be done. The use of the visual inspection method can help the investigator decide which computer parameters to use (Stauden & Wolf, 1999) by ensuring that the computer calculated onset of activity is appropriate and relates to a meaningful physiological event (DiFabio, 1987; Hodges & Bui, 1996).

It has been recommended that higher threshold levels are set for muscles that show high levels of background activity, in order to avoid generating Type I errors (Hodges & Bui, 1996; Stauden & Wolf, 1999). The threshold is regarded as the number of standard deviations above the baseline level of SEMG that must be surpassed to establish the onset of muscle activity. It is one parameter that must be set when using computer programming techniques to identify the onset of muscle activity. A higher threshold will cause the later identification of muscle onset (Hodges & Bui, 1996). It has also been recommended that the length of time that the muscle activity must exceed the threshold by is at least 25ms (Cowan et al., 2001; Sims & Brauer, 2000). In addition, the length of the SEMG trace should not be too long or else there is a higher risk that erratic bursts of background muscle activity will be identified as the onset of muscle activity (Hodges & Bui, 1996). The skilful use of these recommendations should enhance the accuracy of using computer programme techniques to identify the onset of muscle activity.

### *2.6.2 Motion analysis*

When investigating the presence of anticipatory muscle activity it is necessary to accurately identify the movement onset of the body segment that is of interest. Motion analysis systems are commonly used to record the 3-Dimensional movement during a task. This allows the identification of the onset of linear and angular kinematics of the body (Rowe, 1999). When the identification of movement onset is required for multiple body segments across many trials, a 3-Dimensional model of an individual can be built from the camera data to assist with this (Calvert & Bruderlin, 1995). The 3-Dimensional model makes it possible to use automated tracking systems that recognise and identify a set of markers on the body, and that reconstruct the 3-Dimensional movement. Some steps need to be undertaken to reduce the amount of error in the 3-Dimensional reconstruction process (Allard, Blanchi, & Aïssaoui, 1995). The cameras must be positioned in such a way that each marker is tracked throughout the movement, otherwise the use of the automated process may be jeopardised. The use of more cameras can help prevent this problem (Rowe, 1999). It is essential that the system is calibrated, and once this has occurred the position of the cameras must not alter during data collection (Ladin, 1995). Consideration must also be given to the number of markers used and their position on the body (Allard et al., 1995).

Markers should be placed on the participant to identify the different body segments of interest (Greaves, 1995). The location of the markers depends on the type of motion analysis system used and the segments of the body to be analysed (Rowe, 1999). As the system used in the current experiments is optoelectronic, retro-reflective markers will be discussed. The advantage of retro-reflective markers is that they are easy to attach to the body and are not limited by rotation. One disadvantage with retro-reflective markers is

that because of their brightness they can merge and appear as one marker if they are placed too close together. ‘Intelligent’ software is needed to distinguish between markers otherwise manual editing is required (Allard et al., 1995; Pedotti & Ferrigno, 1995). Each marker should be placed on a well defined body landmark that is easily identifiable across multiple images (Allard et al., 1995; Greaves, 1995). The marker should be a spherical shape which allows it to be seen from different directions (Pedotti & Ferrigno, 1995). The accuracy of the reconstruction process is enhanced by the use of an adequate number of tracking markers, which should be placed in such a way that they do not bias one position or plane of movement (Allard et al., 1995).

Both the visual inspection method and the automated programming methods can be used to determine the onset of movement for a body segment. Data from markers which indicates a change in the rate of movement such as acceleration data, can be analysed to determine the onset of movement (Aruin, 2003; Bouisset & Zattara, 1987; Zattara & Bouisset, 1986). Filtering the acceleration data assists with the identification of movement onset (Hollands et al., 2004). Because the automated system calculates the onset of movement based on the 3-Dimensional reconstruction, it is important that the above recommendations for the collection of motion analysis data are followed (Pedotti & Ferrigno, 1995).

In summary, high quality SEMG and motion analysis data should be collected, and appropriately analysed to assist with the accurate identification of the onset of anticipatory muscle activity.

## 2.7 Summary of the key topics

Falls that occur during turning are associated with a high incidence of hips fractures in older adults, but despite this there is limited information available on turning. In particular the presence and consistency of anticipatory lower limb muscle activity during step-turning has not been reported. Hence its temporal onset in relation to that of the head is unknown. Answers to these questions may provide insight into the central organisation and early balance responses during turning, which may have implications for those in the area of falls rehabilitation. As it has been reported that older adults have difficulty turning at a self-selected speed, future research on turning should include testing this speed.

Anticipatory muscle activity is believed to be a sequence of muscle activity that is part of the motor programme for a task but debate exists as to how strictly this activity is organised. Muscles which are consistently active across participants undertaking repeated trials of the same task must have a central role to the task and should be identified. The temporal order of onset among the most consistently active muscles and the head and the feet, should be identified by using a ranking system on a trial by trial basis, rather than using the mean onset time for each event.

The use of surface electromyography and motion analysis can assist with determining whether anticipatory muscle activity is present. The identification of the onset of body movement and muscle activity must be precise, because anticipatory muscle activity is that which occurs prior to the onset of a pre-defined movement event. The accuracy in identifying the onset of the muscle activity can be enhanced by collecting a high quality signal, filtering the signal and using the most appropriate parameters to identify the

onset. Accuracy in identifying the onset of body movement will depend on the calibration of the system, as well as the number and placement of the tracking markers and the cameras that are used.

In conclusion there is a great need for further research on the task of turning. Investigating the presence of anticipatory muscle activity during a step-turning task may provide insight into the early balance responses and central organisation of this task. This would contribute to the limited body of knowledge currently available on this task, and may have future implications for those in the area of falls rehabilitation.

## 2.8 Literature review of studies on anticipatory muscle activity during gait initiation and forward stepping

Research investigating anticipatory muscle activity during turning had not been previously reported; hence a review of the literature on anticipatory postural muscle activity during gait initiation and forward stepping was undertaken. These two tasks were the most similar to step-turning. The two aims of this literature review were: 1) to identify which muscles in the lower limbs are consistently active in an anticipatory manner; 2) to identify whether there is a consistent temporal order of onset among the most frequently active muscles that behave in an anticipatory manner. The information from this review would assist with the design of the current experiments, in particular by identifying the most appropriate muscles to collect SEMG data from.

The literature review is divided into three sections. The first section is a review of studies that had placed importance on interpreting the absence of muscle activity from a SEMG trace. These studies have been included in this review because they demonstrate the progress in research on this topic. The second section is a review of the studies that



have solely discussed the presence of muscle activation. The final section is a summary of the results for this review. Key features of the studies are summarised in Table 1 (see page 11).

### *2.8.1 Studies focussing on the absence of muscle activity*

The earliest study that examined anticipatory muscle activity during gait initiation was by Carlsöö (1966). Carlsöö had recorded ‘sudden’ changes in muscle activity before the stepping foot left the floor, and reported that many muscles were active in both the stance and stepping leg during this period. This was the sole study in the literature review where the fine wire method to collect electromyography had been used. Carlsöö (1966) had commented that some muscles had shown variability in activity across trials. However, the author had not identified how frequently each muscle activated across trials or assessed whether there was a consistent temporal order of onset among the muscles. Although many muscles were active prior to foot lift of the stepping leg, the author’s main summary was that walking was initiated by a loss of balance caused by a cessation in muscle activity particularly in soleus. The reasons for the emphasis on the cessation of muscle activity are unclear. Perhaps the author had been influenced by Sherrington’s work in the 1930s on active inhibition (Stuart, Pierce, Callister, Brichta, & McDonagh, 2001), or it may have been because few muscles that result in forces in an anterior direction had been active. Nonetheless this early work was important as it demonstrated the presence of anticipatory leg muscle activity, and influenced the direction of later research by Cook and Cozzens (1976); Crenna and Frigo (1991) and Polcyn et al. (1998). This later research would focus on the sequence of decreased calf muscle activity followed by tibialis anterior activity, rather than activity in biceps

femoris, peroneus longus and tensor fascia latae, which receive infrequent reference to in later literature.

The five remaining studies in this section of the literature review had all investigated whether the sequence of decreased calf muscle activity followed by tibialis anterior activity was present. Very similar methodologies were used across all five studies. In all of the studies the task of gait initiation was tested, and SEMG and force plate data had been collected. Participants were instructed as to which leg should step first and the cues to move were either visual or auditory. The total number of trials in the studies ranged from 30 to 280, but as few attempts had been made to analyse how frequently the sequence occurred, the number of trials became inconsequential. One difference between the studies was that dissimilar events were used to denote the presence of anticipatory muscle activity. Crenna and Frigo (1991) and Brenière et al. (1981) had used the event of heel off, whereas toe off was used in the other studies. As these events are rather late, some movement related muscle activity may have been detected.

Three of the studies concluded that gait was initiated by a forwards fall at the ankles caused by decreased gastrocnemius or soleus activity followed by a burst of tibialis anterior activity (Brenière et al., 1981; Cook & Cozzens, 1976; Herman et al., 1973). This conclusion is limited for many reasons, the main reason being that not one of the studies had identified how frequently this sequence occurred across repeated trials. Also, in two of the studies there was inadequate consideration of other lower limb muscles from which SEMG had been collected. For instance, Cook and Cozzens did not report the SEMG results for other muscles from which SEMG had been collected, and Herman and colleagues did not discuss the roles of other muscles that were active at the same time as tibialis anterior. The finding that on occasion gastrocnemius and soleus

were active at the same time as tibialis anterior was not discussed by Herman and colleagues. Given that this finding contradicted their key conclusion, it should have been given more attention.

There were limitations to the work by Brenière and colleagues, who had investigated the calf muscles and tibialis anterior (based on pilot work) to identify the earliest modification in the postural pattern. The authors had not described what the baseline postural pattern was, or how the SEMG data was analysed. Furthermore, in the main study, these authors had established that the sequence of calf inhibition, followed by tibialis anterior activation, existed by using the mean onset latencies of the events. The disadvantage of this data analysis method is that it may not represent the most common recruitment sequence (Hines & Mercer, 1997). Due to the selective or questionable analysis of the SEMG results in these studies, other unidentified muscles may be involved in gait initiation, and alternative sequences of anticipatory muscle activation may exist.

One plausible conclusion drawn by two of the studies was that later gastrocnemius activity might modulate the amount of forwards fall (Cook & Cozzens, 1976; Herman et al., 1973). However, the conclusions drawn by these studies should be viewed cautiously because of methodological limitations. Neither Cook and Cozzens nor Herman and colleagues described the methods used to identify the onset of muscle activity, and conclusions about decreased levels of SEMG were made without normalisation or quantification of the SEMG signals.

There was some improvement in the analysis of the data in two later studies by Crenna and Frigo (1991) and Polcyn et al. (1998). In these studies, how frequently the sequence

of soleus inhibition, followed by a burst of activity in tibialis anterior, occurred across trials was calculated. Crenna and Frigo found that the sequence occurred prior to heel off, bilaterally in 81% of a total of 80 trials, while Polcyn and colleagues found that the sequence occurred prior to toe off, bilaterally in 76% of 200 trials. Neither study had discussed why the sequence was absent in 20 to 32% of trials.

Crenna and Frigo concluded that the sequence was part of the motor programme for gait initiation because of the consistent temporal relationship between the two events, and because the sequence occurred regularly. However, Crenna and Frigo had referred to a definition of a motor programme which only included muscles that were active during a task, not muscles that were inactive. Yet, Crenna and Frigo had given emphasis to soleus inhibition, and the problem with this is that any muscle that shows little or no activity prior to heel off could then be considered part of the motor programme.

Another limitation of the two studies by Crenna and Frigo (1991) and Polcyn et al. (1998) concerns the criteria used to identify the presence of inhibition from a SEMG trace. Polcyn and colleagues did not present their criteria. Crenna and Frigo identified the presence of inhibition as the point where a drop in maximal activation occurred 50ms after the signal to move, and prior to heel off. This definition does not suggest inhibition but rather low level activity.

Nowadays, the idea in these five studies that muscle inhibition can be detected from SEMG data is questionable. Current knowledge suggests that multiple structures are potentially involved in the process of active muscle inhibition (Kandel, 2000), some of which cannot be monitored by SEMG. Furthermore the use of SEMG in recent times has been advocated as a tool to detect the presence of muscle activity rather than muscle

inhibition (Cram et al., 1998; De Luca, 2002; Kamen & Caldwell, 1996; Soderberg & Knutson, 2000). For this reason, the idea developed across the studies that gait is initiated by a forward fall at the ankles, due to a sequence of calf muscle inhibition followed by tibialis anterior activity based on SEMG findings alone, cannot be supported.

### *2.8.1.1 Summary of studies focussing on the absence of muscle activity*

Although the two key questions of this literature review were poorly answered by these studies, they do provide implications for future research. It is probable that tibialis anterior has a central role during gait initiation given that it consistently activates, and it is plausible that later gastrocnemius activity might modulate the level of the forwards fall. Hence, further investigation into these two muscles is warranted. Because these earlier studies had focussed on muscles at the ankle joint, the collection and analysis of SEMG from other lower limb muscles is necessary to examine whether they also behave in an anticipatory manner. It is necessary to calculate how frequently each muscle is active across trials to identify which muscles are central to the task. The use of mean latencies to identify whether a muscle sequence is present is not advised; instead a ranking system is preferable. Once a sequence has been identified, how frequently it occurs across trials should be evaluated. Consideration should be given to the proportion of trials in which the sequence is absent, and explanations for the variability should be provided. Most of these studies had used SEMG sampling frequencies that violated the Nyquist Theorem, which threatens the accuracy of the identified muscle onset times (Hillstrom & Triolo, 1995). Future research should include the use of appropriate sampling frequencies, and descriptions of the methods and criteria used to identify the onset of muscle activity.

### *2.8.2 Studies focussing on the presence of muscle activity*

In this section, the four studies had not examined whether muscle inhibition was present; instead they investigated which muscles were active. Three studies explored anticipatory muscle activity during gait initiation, whereas one study by Mercer and Sahrman (1999) examined the task of foot placement onto a step. Mercer and Sahrman were the only researchers in the literature review to use a choice reaction time paradigm. These authors felt that this might reduce the chances of the anticipatory response occurring before data collection began. In a choice reaction time paradigm the time it takes for a muscle to activate depends on the number of choices; generally the higher the number of choices, the longer the time until muscle activation (Ghez & Krakauer, 2000).

The speed at which the task was completed was not described in two studies (Assaiante et al., 2000; Mann et al., 1979). In the work by Mercer and Sahrman (1999) and Elble et al. (1994), participants were to complete the task at their fastest pace. The speed at which a task is completed is a consideration because it may be a parameter that influences the output of a generalised motor programme (Schmidt & Lee, 1999) and hence, which muscles activate. The events that denoted the presence of anticipatory muscle activity included heel off and toe off, the limitations of which have been previously discussed. Mercer and Sahrman used a different event which was the onset of rectus femoris, which was considered to be the focal muscle for their task. No study used a multi-segmental paradigm or assessed the order of muscle onset compared to the movement onset of other body segments. Key features to these studies are summarised in Table 1 (see 11).

Two studies by Elble et al. (1994) and Mann et al. (1979) had not assessed how frequently the muscles activated, or whether there was a consistent sequence in the order of muscle onset by using a ranking analysis. This limits how much can be inferred from the results. Elble and colleagues reported that gastrocnemius activity in the stepping leg occurred after tibialis anterior activity, and concluded that these SEMG events were stereotyped. This was premature, given that the sequence was detected by using mean onset latencies, and because their results represented only 7% of the data collected (16 trials out of 220). Mann and colleagues reported the presence of anticipatory activity bilaterally in rectus femoris, vastus medialis, hamstrings, the hip abductors and the peroneii prior to toe off. Neither of these studies addresses the key questions of this literature review.

The work by Mercer and Sahrman (1999) was included in this literature review because its aim was to assess whether an anticipatory postural synergy existed. Mercer and Sahrman defined a postural synergy as a sequence of anticipatory muscle activity that occurred prior to the onset of rectus femoris activation, in at least three out of the four trials analysed for each subject. The authors selected the four trials closest to the mean task speed for each individual, to enable the reduction in variability due to differences in the task speed. SEMG data was collected from muscles chosen on the basis of a literature search and unpublished pilot work. It was established in their pilot study that tibialis anterior activated bilaterally and simultaneously, and therefore in the main study, SEMG was collected from this muscle in the stance leg only.

Mercer and Sahrman (1999) found that the first muscle to activate was tibialis anterior in 93% of the total trials (447). The authors did not report how frequently the other tested muscles had activated. 60% of participants had a postural synergy but across the

group there was no predominant postural synergy. In the five most common synergies the key muscles that had been involved were gluteus medius, hamstrings and ‘gastrocnemius- soleus.’ Whether a consistent temporal order of onset existed among these key muscles had not been evaluated. The authors concluded that there was no fixed anticipatory postural synergy for foot placement onto a step; instead many solutions existed to achieve the task. Mercer and Sahrman also inferred that gluteus medius activity might be involved with the COP shift in a lateral direction.

The contribution of external parameters to the variability in the postural synergies had been small because similar laboratory conditions for data collection sessions, instructions practise trials and starting positions had been used, as well as the selection of trials closest to the mean task speed. Subtle changes in the starting position or postural alignment that were not detectable may have contributed slightly to some of the variability. Essentially this study suggests that there are high levels of variability in the temporal order of muscle activation for this task.

The frequent activation of tibialis anterior across trials and participants in the work by Mercer and Sahrman (1999) suggests it has a central role to the task. It has been proposed that the role of tibialis anterior during gait initiation is to cause the forwards fall at the ankle which assists with the initiation of gait (Brenière et al., 1981; Cook & Cozzens, 1976; Herman et al., 1973). One reason that Mercer and Sahrman had not found a consistent postural synergy might be that the role of other muscles is to modulate the effects of tibialis anterior activity. If this is the case, then it would not be possible for there to be a consistent reproducible relationship with tibialis anterior. Another reason that there had not been a predominant postural synergy might be



because the presence of the synergy had not been investigated among the muscles that were most frequently active.

To their credit Mercer and Sahrman (1999) were among the few authors to justify their selection of muscles, and to outline their procedure used to identify the onset of muscle activity. They were also the only authors to have clear inclusion and exclusion criteria for the participants. Limitations to this study were that the sampling frequency violated the Nyquist Theorem. Gastrocnemius and soleus were referred to by these authors as one muscle, but there are separate recommended SEMG sites for each muscle (Hermens et al., 1999). Because only the four trials closest to the mean task speed were included for analysis, the results of this study represent just 30% of the total trials undertaken. In summary, Mercer and Sahrman reported that tibialis anterior consistently activates first in 93% of 447 trials. Although there was no predominant anticipatory muscle synergy across the group of participants, 60% of individuals exhibited a preferred synergy of muscle activation.

The final study in this review was work by Assaiante et al. (2000). These authors reported that the first muscle to activate was tibialis anterior bilaterally, and this was followed by activation of gluteus medius in the stance leg. The authors had not described how frequently this sequence occurred across the 80 trials. Earlier work by Mercer and Sahrman (1999) had not found this sequence to be predominantly used in their group of participants. Assaiante and colleagues had analysed how frequently each muscle activated across trials but the results can only be estimated from the small bar graph. The percentage of trials in which each muscle activated in the stance leg was: gluteus medius 100% and tibialis anterior 85%. The results for the swing leg were: tibialis anterior 90 %, quadriceps 75%, gastrocnemius 75% and hamstrings 50%. The

period analysed was 700ms before heel off, to 300ms after heel off meaning that some gastrocnemius activity responsible for heel off was detected.

Although Assaiante et al. (2000) established that tibialis anterior was predominantly the first muscle to activate, its frequency of activation at 85 to 90% of trials was lower than that for gluteus medius which activated in 100% of trials. This had never been identified before. Assaiante and colleagues had not discussed why gluteus medius was more frequently active than tibialis anterior. This result was surprising given that previous researchers believed that tibialis anterior played a prominent role in gait initiation (Brenière et al., 1981; Cook & Cozzens, 1976; Herman et al., 1973; Polcyn et al., 1998).

Gluteus medius had received minimal attention in previous studies. Only two previous studies had collected SEMG data from gluteus medius (Mann et al., 1979; Mercer & Sahrman, 1999), and neither had calculated how frequently gluteus medius activated. In general, previous studies had focussed on ankle muscles that resulted in sagittal plane movement. Although Mercer and Sahrman (1999) had inferred that anticipatory gluteus medius activity was partially responsible for the lateral COP shift, the sequence of gluteus medius onset in relation to the onset of the medio-lateral anticipatory postural adjustment is unknown. Although gluteus medius was active in 100% of trials, it was not the muscle that activated first, suggesting that its temporal onset is more variable compared to tibialis anterior. The authors do not discuss their results in relation to motor control theories, but the consistent activity in gluteus medius and tibialis anterior suggests that they may have a central role in the gait initiation motor programme.

Limitations to the work by Assaiante et al. (2000) include the sampling frequency that violated the Nyquist Theorem, and the minimal details about the skin preparation

techniques and SEMG sites used. The speed at which the task was undertaken was not specified and the results could have been presented more clearly. No explanation was given on the selection of muscles tested, or why some were tested unilaterally and others bilaterally.

#### *2.8.2.1 Summary of studies focussing on the presence of muscle activity*

In this section of studies there had been some improvement in the analysis of the SEMG data. The most consistently active muscles across participants were tibialis anterior bilaterally and the stance leg gluteus medius. The consistent activation of these muscles suggests that they may have a central role as part of the motor programme for forwards stepping tasks. There is no agreement as to whether there is a consistent temporal order of onset among these key muscles, across participants. Few studies have examined this issue thoroughly. Whilst there may not be a predominant muscle sequence across a group of participants, individuals may exhibit a preferred muscle sequence. Additional muscles that warrant further investigation include gastrocnemius, hamstrings, quadriceps and the peroneii.

#### *2.8.3 Summary of the reviewed studies*

Few studies had addressed the key questions of this literature review which were firstly; to identify which muscles in the lower limbs are consistently active in an anticipatory manner during gait initiation and forward stepping. Secondly; to identify whether there is a consistent sequence in onset among the muscles that are most frequently active in an anticipatory manner. The quality of the studies in this area concerning the SEMG methodology and data analysis was generally low.

The answer to the first question was that tibialis anterior and gluteus medius were the most consistently active muscles, but this had only been quantified in two studies. The majority of studies had suggested that tibialis anterior had a central role during gait initiation, but had not tested how consistently it activated. It has been suggested that the anticipatory activity in tibialis anterior is responsible for initiating a forwards fall at the ankle. Gluteus medius had received little attention in most studies, and the finding by Assaiante et al. (2000) that it activated more frequently than tibialis anterior was a surprise. The proposed role for this muscle is an involvement with the lateral movement of the COP during the medio-lateral anticipatory postural adjustment. No clear answer was found for the second question of this literature review. The only study that had assessed whether a consistent order of onset existed among the most frequently active muscles was by Assaiante et al. (2000). These authors reported that tibialis anterior activated ahead of gluteus medius, but had not quantified how frequently this occurred.

It is acknowledged that differences exist between the tasks of gait initiation and step-turning. However, in order to decide which muscles to collect SEMG data from in the current studies, the body of research on the tasks of gait initiation and forward stepping was the most appropriate to refer to, compared to studies involving upper limb tasks or external perturbations. Therefore, the implications of this literature review for the current studies on step-turning are that SEMG should be collected from tibialis anterior, gluteus medius, hamstrings, gastrocnemius, quadriceps and peroneii bilaterally. In order to establish whether a consistent sequence of onset exists among the most frequently active muscles, the percentage of trials that each muscle is active must firstly be calculated. Then a system that ranks the order of muscle onset should be used to identify a sequence of activity. Should multiple sequences exist, then how frequently each

sequence occurs should be evaluated, and there should be discussion as to the reasons for the variability. It is essential that the recommendations for the collection of high quality SEMG, and suitable SEMG analysis methods are used to ensure that the identification of the onset of muscle activity is accurate.

## 2.9 Chapter summary

Topics that are central to the current experiments have been presented in this chapter and were: the theory of motor programmes, gait initiation, turning, laboratory measures and a review of the studies on anticipatory muscle activity during gait initiation and forward stepping. The following is a summary of those topics.

There is the need for further research on the task of turning because falls that occur during turning are associated with a high incidence of hip fractures in older adults. Currently there is a very limited body of research on this task. Investigating the anticipatory period may provide insight into the central organisation of the task because of the reduction in movement related feedback. One theory of movement is that of motor programmes which are believed to contain the sequence of muscle activity prior to the initiation of the movement. Muscles that are consistently active across participants and repeated trials are likely to have a central role to the task. These muscles and whether a consistent sequence in onset exists among them should be identified during a step-turning task. This information may have implications for falls rehabilitation. It is possible that if anticipatory lower limb muscle activity is present during step-turning, it may have similar roles in early balance that anticipatory activity during gait initiation is associated with.

The studies in the review on anticipatory muscle activity during gait initiation and forward stepping were generally poor in quality. The implications of that review are that the muscles from which SEMG should be collected during step-turning include: tibialis anterior, gluteus medius, hamstrings, gastrocnemius, quadriceps and the peronei bilaterally. In order to identify the onset of muscle activity accurately, recommendations on the collection and analysis of SEMG should be followed. Because there are two different foot strategies used during step-turning, this must be considered when denoting the presence of anticipatory muscle activity. Although toe off and heel off have commonly been used to define the onset of foot movement, these are late events and it may be more suitable to use an earlier event.

Another unanswered question is whether there is a consistent sequence in the onset of head movement and anticipatory muscle activity during step-turning. Establishing this could indirectly infer whether the visual system influences the temporal onset of the anticipatory muscle activity. This question could be answered by using a multi-segmental paradigm. However, there would need to be the accurate identification of the onset of body segment movement. This can be enhanced by following the recommendations for the reduction in 3-Dimensional construction error.

In conclusion there is the need for further research on step-turning at a self-selected pace. A great deal of information on the organisation of turning can be attained by investigating the task using an anticipatory and multi-segmental paradigm. In order for the findings to be robust, high quality SEMG and motion analysis data must be collected and the most appropriate techniques used to analyse the data.

### 3 . EXPERIMENT ONE

#### 3.1 Introduction

This chapter describes the methods and results for Experiment One and its implications for Experiment Two. The purpose of Experiment One was to determine how frequently lower limb muscles (out of a selection of eight), activated during a step-turning task at a self-selected pace. The most frequently active muscles would be tested further in Experiment Two. The period analysed for each trial included a maximum period of one second before the beginning of head movement until the beginning of toe off of the leg with the SEMG electrodes.

#### 3.2 Study design and participants

A repeated measures design was used. Ethical approval was granted by the Auckland University of Technology Ethics Committee (Appendix A) and all regulations set by that committee were fulfilled. A convenience sample was recruited by means of poster advertisement (Appendix B). Written explanations (Appendix C) were immediately forwarded to participants who contacted the investigator and were interested in taking part. Participants were encouraged to contact the investigator with any questions. Participants were included in the study if they had volunteered to participate, were between 18 and 40 years of age, had no neurological or musculoskeletal disorders, did not have severe visual loss and did not have a known allergy to taping materials.

A sample size calculation was undertaken assuming a statistical significance level of  $\alpha = 0.05$  and a power of 0.9. The calculation was based on published data from Hollands et al. (2004) on the latency of movement onset between the head and the foot segments. Using a paired t-test a sample size of seven achieved the level to detect a significant

difference in the latency of movement onset  $0.7s (\pm 0.5s)$ . There is no available research to base a sample size calculation on, to detect a significant difference in muscle activity onset during this task. A sample size of five was chosen for Experiment One because it was a pilot study.

### 3.3 Instrumentation

Surface electromyography and 3-Dimensional motion analysis data was collected simultaneously into one computerised data acquisition system (Qualisys Medical AB, Gothenburg, Sweden), and stored on hard drive for subsequent processing. A motion analysis system (Qualisys Medical AB, Gothenburg, Sweden) with nine cameras was used to record 3-Dimensional displacement data from reflection markers. The sampling rate was 240 Hz.

Surface electromyography was collected using an eight channel unit (AMT 8, Bortec Biomedical, Calgary, Canada) at a sampling rate of 1200 Hz. The specifications of the Bortec unit were: a bandpass frequency response of 10Hz to 1000Hz, input impedance of 10GOhm and a common mode rejection of 115dB at 60 Hz. The gain was set at 500 with variance of one. Bipolar SEMG signals between -10 volts to 10 volts were recorded. The SEMG electrodes contained two circular 1.5cm diameter recording areas spaced 1cm apart. The electrodes were bipolar, silver/silver chloride, self- adhesive and disposable (Norotrode 20™, Myotronics-Noromed, Inc, WA, USA). The ground electrode had a round 2cm diameter recording area and was silver/silver chloride, self adhesive, disposable with solid gel (Red Dot™, 3M Ontario, Canada).



### 3.4 Procedures

The following is a description of the procedures used in Experiment One.

#### *3.4.1 Motion analysis procedures*

Prior to each testing session the motion analysis system was calibrated. Participants wore a cap with its visor removed. Three reflective markers were placed on the head at the following locations: the forehead, middle of head (in a sagittal plane) and the occipital protuberance. Three markers were placed on the foot of the leg with the SEMG electrodes at the following locations: distal end of the first metatarsal, lateral malleolus and the heel. The markers were spherical in shape.

#### *3.4.2 Surface electromyography procedures*

SEMG was collected from the right leg of three participants and the left leg of two participants. All electrode sites were prepared by shaving and use of a skin exfoliate (Omni Prep® paste, D.O. Weaver & Co, CO, USA) followed by an alcohol wipe. Skin resistance levels of less than 10k $\Omega$  were accepted. Resisted tests of tibialis anterior and peroneus longus were performed to check for the presence of cross-talk. Electrode placements were modified if cross-talk was present. Active contractions of the eight muscles were completed so that the quality of the signal at baseline and during the early contraction period could be assessed. If the signal was poor, the sources for this were identified and resolved until the signal was of sufficient quality. Leads were taped to the participant's skin and clothing and participants stood about 2.5m from the computer system.

The reference electrode was placed on the head of the fibula. The SENIAM guidelines for electrode placement were followed (Hermens et al., 1999). SEMG was collected from eight muscles in one leg of each participant. The eight muscles were: tibialis anterior, peroneus longus, gluteus medius, adductor longus, the medial head of gastrocnemius, biceps femoris, vastus medialis and soleus. All muscles with the exception of adductor longus were included because they had been identified in the literature review as requiring further investigation. As there were muscles with antagonistic roles at the ankle and knee joints, adductor longus was included for testing because of its antagonistic role to gluteus medius at the hip joint.

### *3.4.3 Participant testing procedures*

At the beginning of the testing session, each participant received a verbal explanation of the participant information sheet (Appendix C), prior to signing the consent form (Appendix D). The testing procedures were based on the work of Hollands et al. (2004). All participants took part with their shoes off. The length of sessions varied between one and half hours to two hours. All testing occurred in the same laboratory. There was a five second sampling period for each trial, and a minimum baseline sampling period of one second. All trials were aligned to the beginning of the data collection.

Participants were asked to stand quietly and to fix their gaze at a centrally placed image of a star. Lights were positioned 60° to the left and right of the participant. Participants were instructed to place their feet in the same position relative to taped markings on the floor at the beginning of each trial. They were to place weight evenly on both legs and to wait for the verbal cue “Go”. After the cue, a random length of time of at least one second would pass and then one light would be switched on in a randomised order.

Participants were to turn and align their entire body to that light at a self-selected pace. Two test trials towards each direction were undertaken with each participant to familiarise them with the experimental protocol. All test trials were discarded. Participants completed a minimum of 10 trials towards each direction and a maximum of 20.

### 3.5 Data management

The following is a description of how the data was managed in preparation for analysis. Each file was cut to eliminate baseline data more than one second before the beginning of head movement. Muscle activity detected in that period would be related to postural activity rather than the task. Each file was cut at the point where toe off of the leg with the SEMG began. Cut files were then converted into TSV files using Qualisys software (Medical AB, Gothenburg, Sweden).

All of the raw SEMG data was processed off line using Lab View-6 software (National Instruments, Austin, USA). In order to assist with the identification of the muscle onset time, the data was full wave rectified and then filtered firstly, by using a 4th order Butterworth filter with a bandpass of 20 to 450Hz to eliminate unstable lower frequency signals and secondly, with a 4<sup>th</sup> order Butterworth bandstop filter between 49 and 51Hz to eliminate electrical noise.

### 3.6 Data analysis

#### *3.6.1 Motion analysis*

The onset of movement for the foot was determined by using the visual inspection method on the plotted velocity graphs for the forehead and the metatarsal markers.

### 3.6.2 *Surface electromyography*

The onset of the SEMG activity was determined using a computerised system (Lab View-6, National Instruments, Austin, USA). The parameters chosen for all muscles with the exception of soleus and peroneus longus were: a baseline sampling period of 50ms, a threshold of one standard deviation, and an onset window of 50ms. The sole parameter that was different for soleus and peroneus longus was a higher threshold of three standard deviations. This was chosen because these muscles exhibited higher levels of background activity. Each trial was visually checked to ensure that the onset related to a meaningful physiological event.

The threshold of one standard deviation has not been commonly used by previous researchers because of the risk in generating a Type I error. However, it was known that the most frequently active muscles identified in Experiment One would be retested in Experiment Two. A threshold of one standard deviation was considered to be the most suitable for the data after it was applied and visually examined. This can be seen in an example shown in Appendix E, where the identified onset of muscle activity using one, two and three standard deviations can be compared for tibialis anterior in one trial. A higher threshold caused a delay in the identification of the onset of muscle activity. How frequently each muscle activated, was calculated by dividing the number of trials in which the muscle was active by the total number of trials available for the muscle.

## 3.7 Results

The age of the five participants ranged from 22 to 35 years and the mean age was 28.8 years.

### *3.7.1 Total number of trials available*

Surface electromyography had been recorded from only one leg per participant. When participants undertook step-turning trials towards the leg with SEMG electrodes this leg was considered to be the stepping leg. When participants undertook trials step-turning away from the leg with the SEMG electrodes, it was considered to be the stance leg. The total number of trials available for each muscle towards both directions was calculated.

#### *3.7.1.1 Stance Leg*

The total number of trials for the stance leg was 69 and all trials could be analysed for six out of the eight muscles tested. Sixteen trials for gluteus medius were unusable from one participant so only 53 trials were available. Twelve trials for soleus were unusable from one participant so only 57 trials were available for this muscle. Trials were unusable due to high noise levels.

#### *3.7.1.2 Stepping Leg*

The total number of trials for the stepping leg was 64 and all trials could be analysed for six out of the eight muscles tested. Sixteen trials for gluteus medius were unusable for one participant so only 48 trials were available. Twelve trials concerning soleus were unusable for one participant so only 52 trials were available for this muscle. Trials were unusable due to high noise levels.

### *3.7.2 How frequently muscles activated*

How frequently muscles activated for each leg is shown in Table 2 as a percentage of available trials.

**Table 2. How frequently muscles activated across the trials**

Muscle	Stance Leg (%)	Swinging Leg (%)
Tibialis Anterior	100	100
Biceps Femoris	86	77
Gastrocnemius	84	65
Gluteus Medius	81	75
Peroneus Longus	45	45
Vastus Medialis	42	48
Soleus	46	28
Adductor Longus	38	48

### 3.8 Implications of Experiment One

The muscles that were most consistently active during the step-turning task were tibialis anterior, biceps femoris, the medial head of gastrocnemius and gluteus medius bilaterally. These muscles will be further tested in Experiment Two. It is acknowledged that not all of the muscle activity detected was anticipatory in nature because the period up to the beginning of toe off had been analysed. Gastrocnemius activity involved in generating heel off, and tibialis anterior activity responsible for ankle dorsiflexion, will have been detected. Therefore in Experiment Two an earlier movement event at the foot (the beginning of movement in the  $z$  direction), will be used to reduce this movement related activity. Peroneus longus, vastus medialis, soleus and adductor longus were active in less than 50% of the trials. This low frequency of activation suggests that their role for the task is less important. These muscles will not be tested further in

Experiment Two. Limitations of Experiment One were that motion analysis markers had been placed on just one foot. The onset of the light cue had not been recorded, and the number of trials performed by each participant was unequal. Therefore, in Experiment Two motion analysis data will be collected from both feet, the onset of the light cue recorded and the number of trials per participant will be equal.

## 4 . EXPERIMENT TWO: METHOD

### 4.1 Introduction

Participants in Experiment Two completed multiple trials of a step-turning task at a self-selected pace from a position of quiet stance. Participants turned towards the left and the right (direction) at 30 and 60° (extent) from midline. There were five objectives to Experiment Two. Firstly, to evaluate which foot predominantly moved first. Secondly, to identify whether there is a consistent temporal order in the onset of movement between the head and the feet. Thirdly, to identify whether and how consistently lower limb muscles activate in an anticipatory manner. Fourthly, to assess whether there is a consistent sequence in the onset of anticipatory muscle activity among muscles active in at least 80% of trials. The final objective was to identify whether there is a consistent temporal relationship in the onset of the anticipatory muscle activity present in at least 80% of trials, with the onset of head and foot movement. It was intended that each direction and extent would be individually analysed for all of the objectives.

### 4.2 Study Design and Participants

The study design, ethics approval, sample recruitment procedures and inclusion criteria were the same as those used in Experiment One (See Section 3.2, page 48). Based on the sample size calculation undertaken in Experiment One, 10 participants were used in Experiment Two.

### 4.3 Instrumentation

The instrumentation used for the collection of the surface electromyography and 3-Dimensional motion analysis data was the same as that used in Experiment One. In



Experiment Two, static and dynamic models of the participants were generated using visual 3-Dimensional software (Visual 3D™, Version 3.22.0, C-Motion Inc, Gaithersburg, USA) for data analysis purposes.

## 4.4 Procedures

### *4.4.1 Surface electromyography procedures and placement*

Surface electromyography was collected bilaterally from tibialis anterior, gluteus medius, biceps femoris and the medial head of gastrocnemius. The skin preparation procedures and placements were the same as those used in Experiment One (See Section 3.4.2, Page 50).

### *4.4.2 Motion analysis procedures*

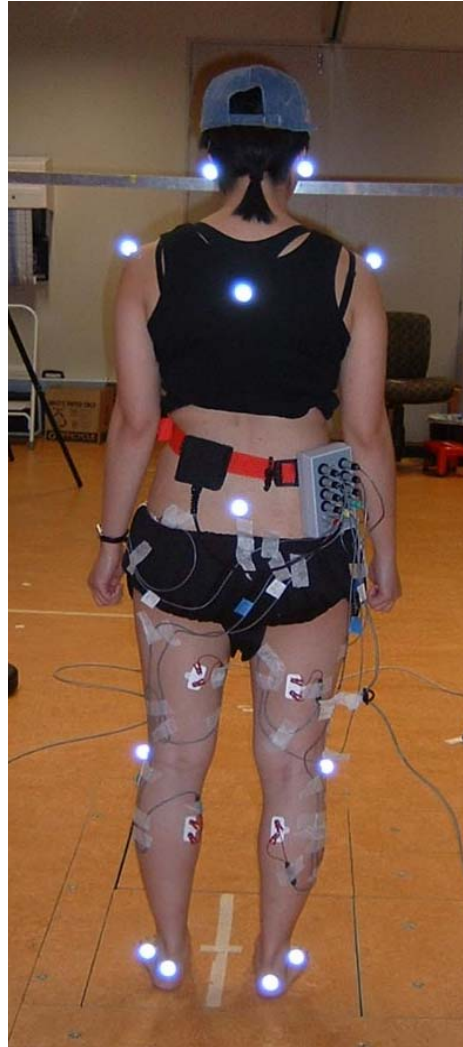
The motion analysis system was calibrated prior to each testing session. 25 calibration markers were used to generate a 3-Dimensional static model of the participant, to assist with identifying the movement onset of the head and the feet. All markers were reflective and spherical. Single markers were placed on the top of head, T6 and the PSIS. Markers were placed bilaterally at the temporomandibular joints, acromian processes, ASIS, thighs, medial and lateral epicondyles, shins, heels, medial and lateral malleoli and the medial aspect of the first metatarsal.

During the step-turning trials, the medial epicondyle and medial ankle markers were removed bilaterally so that 21 tracking markers remained. A moving model was created for each participant from the tracking markers. Both the static and moving models were generated using motion analysis software (Qualisys Medical AB, Gothenburg, Sweden),

and converted to C3D files. Figure 2 and Figure 3 show the anterior and posterior view of one participant with reflective markers and SEMG electrodes respectively.



**Figure 2. Anterior view of a participant with reflective markers and surface electromyography electrodes.**



**Figure 3. Posterior view of a participant with reflective markers and surface electromyography electrodes.**

#### *4.4.3 Participant testing procedures*

At the beginning of the testing session, each participant received a verbal explanation of the participant information sheet (Appendix C), prior to signing the consent form (Appendix D). A light array was positioned 1.5 metres in front of the participant with lights at 45 and 60° to their left and right, and one central light. The level of the lights was adjusted to eye level for each participant. In between trials there was a 20 second

break at the end of which the question “are you ready?” was asked by the investigator. Before replying “yes” participants would check that their foot position was consistent in relation to taped markings on the floor, put weight evenly on both legs, focus their gaze on the centre light and stand in a relaxed manner. A random amount of time after this response, one of the peripheral lights would be switched on. Participants would turn and align their entire body to that light at a self-selected pace. One test trial towards each light was undertaken to familiarise participants with the experimental protocol. These trials were discarded. Ten turns towards each peripheral light were completed in a randomised order, meaning that a total of 40 trials per participant were collected. The onset of the peripheral light was recorded by the data collection system. The light array as a participant would view it is shown in Figure 4.



**Figure 4. The light array**

## 4.5 Data Management

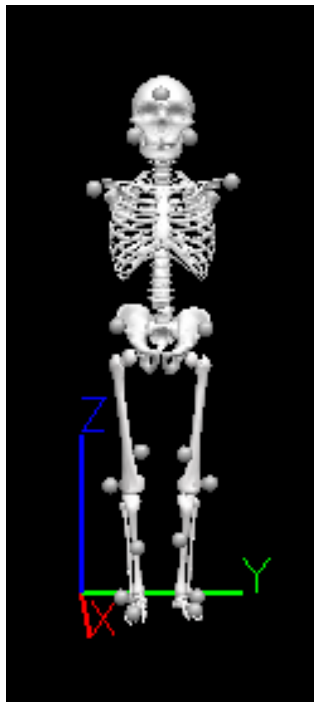
### *4.5.1 Surface electromyography data*

All of the raw SEMG data was processed using Lab View-6 (National Instruments, Austin, USA). The filtering parameters used were a 4th order Butterworth filter with a bandpass of 20 to 450Hz, and a 4<sup>th</sup> order Butterworth bandstop filter between 49 and 51Hz. All SEMG files were converted into C3D files and stored for subsequent processing.

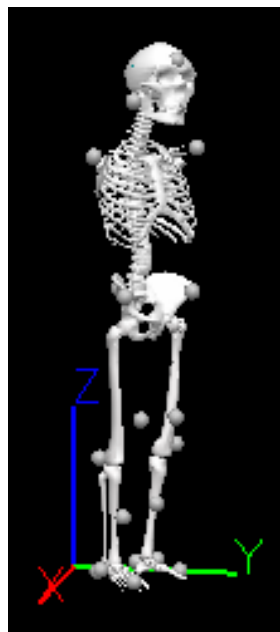
### *4.5.2 Motion analysis data*

Raw motion analysis files of participants standing statically were converted to C3D after all of their calibration markers had been identified using Qualisys software (Medical AB, Gothenburg, Sweden). A ‘Snapshot’ model of each participant turning was created by identifying all of their tracking markers in one trial. The ‘Snapshot’ model was applied to participants’ raw files using batch processing, an automated system that identifies the set of tracking markers across multiple trials and converts the files to C3D. The batch processing was successfully used for all trials.

Identification of the calibration and tracking markers was required to enable the use of automated software (Visual 3D™, Version 3.22.0, C-Motion Inc, Gaithersburg, USA) to identify the onset of head and foot movement. A 3-Dimensional biomechanical model was created from the C3D files of participants standing statically (Visual 3D™, Version 3.22.0, C-Motion Inc, Gaithersburg, USA), and applied to their step-turning files. An example of the applied 3-Dimensional model for the participant in Figure Two is shown in Figure 5 at the beginning of a turn. Figure 6 shows the participant at the end of a 60° turn to the left.



**Figure 5. 3-Dimensional model of a participant at the beginning of a turn.**



**Figure 6. 3-Dimensional model of a participant at the end of a turn 60° left.**

## 4.6 Data analysis

### *4.6.1 Surface electromyography*

The onset of the SEMG activity was identified using a computerised system (Lab View-6, National Instruments, Austin, USA). The parameters chosen for all muscles with the exception of gastrocnemius were: a baseline sampling period of 50ms, a threshold of two standard deviations, and an onset window of 50ms. The only different parameter used for gastrocnemius was a threshold of three standard deviations because it exhibited higher levels of background activity. Each trial was visually checked to ensure that the onset related to a meaningful physiological event. When more than one onset time was identified by the system, the first onset time after the light cue was chosen. How frequently each muscle was active prior to the onset of movement in the predominantly first moving foot (in the  $z$  direction) was calculated for each direction and extent.

### *4.6.2 Motion analysis*

Once the 3-Dimensional model was applied to the step-turning files, the velocity data for the head and the feet were low pass filtered at 6Hz. The onset of head movement was defined as the point where head velocity in the  $y$  direction exceeded 0.02m/s from baseline. The onset of movement for each foot was defined as the point where foot velocity in the  $z$  direction exceeded 0.01m/s from baseline. The onsets were obtained in an automated manner using Visual 3D™ software. All onsets were visually checked against plotted velocity graphs and by running each trial. Attention was given to ensure that the onset of head movement was identified at a time after the onset of the light cue.

## 4.7 Statistics

The Kendall coefficient of concordance ( $W$ ) non-parametric statistical test was used to determine sequences in the order of onset. Each tested event is given a mean ranking. For example, if three events were tested and a sequence in onset existed, then the events would each be ranked by numbers close to one, two and three. The event that is ranked closest to one would be the event that generally occurred first. If no sequence existed, then the ranking of the events would show no clear relation to one, two and three. The ranking is assigned a Kendalls ( $W$ ) value which is a number between zero and one (Siegel & Castellan, 1988). A Kendalls ( $W$ ) value closer to one indicates that there are high levels of agreement among the rankings, and that in most trials the order that has been identified will occur. If the Kendalls ( $W$ ) value is close to zero, this indicates there is low agreement among the rankings, and that in most trials alternative sequences to the one that has been identified will occur (Mc Call, 1996). The Kendalls ( $W$ ) value is assigned a P value to indicate the significance level of the level of agreement (Siegel & Castellan, 1988). Kendalls ( $W$ ) values less than 0.4 represent a low level of agreement. Values between 0.4 and 0.75 represent a fair to moderate level of agreement and values 0.75 and above represent a high level of agreement.

One limitation with the Kendall coefficient of concordance test with regards to the surface electromyography data is that trials in which a muscle has not activated cannot be included for analysis. Hence, only muscles that were active in an anticipatory manner in at least 80% of trials will be included in tests to identify a sequence in the order of onset. This will ensure that sufficiently large numbers of trials are tested. SPSS software was used to run the statistical tests (Version 11.5, SPSS Inc, Chicago, USA).



## 5 . EXPERIMENT TWO: RESULTS

### 5.1 Introduction

The results for the five objectives of Experiment Two are now presented. One hundred trials towards each direction (left and right) and extent (30 and 60°) were undertaken. There were 399 trials available for analysis. One trial was unusable because of poor quality SEMG (60° turn to the right). The age of the participants ranged from 20 to 32 years, and the mean age was 25 years.

### 5.2 The predominant order in the onset of foot movement

During turns towards the left, the right foot was considered to be the contralateral foot, and during turns towards the right the left foot was considered to be the contralateral foot. When the contralateral foot moved first this was called the contralateral strategy. When the ipsilateral foot moved first this was called the ipsilateral strategy (see Operational Definitions, Section 1.4, Page 5 ).

#### *5.2.1 The frequency of foot strategies used during turns towards the left*

How frequently the ipsilateral and contralateral strategies occurred during 200 turns towards the left for both extents are shown in Table 3 as a percentage of trials. The key result is that the ipsilateral strategy is predominantly used towards both extents.

**Table 3. The frequency of foot strategies used during turns towards the left**

Extent of left turn	Ipsilateral strategy (% of trials)	Contralateral strategy (% of trials)
30°	68	32
60°	69	31

### *5.2.2 The frequency of foot strategies used during turns towards the right*

How frequently the ipsilateral and contralateral strategies occurred during 199 turns towards the right for both extents are shown in Table 4 as a percentage of trials. The key result is that the ipsilateral strategy is predominantly used towards both extents.

**Table 4. The frequency of foot strategies used during turns towards the right.**

Extent of turn	Ipsilateral strategy (% of trials)	Contralateral strategy (% of trials)
30°	78	22
60°	81	31

### *5.2.3 Movement of the contralateral foot first*

An analysis was undertaken to examine how many participants moved their contralateral foot first, and how often they did this. 10 trials towards each direction and extent were analysed for each participant (apart from participant C who had only nine available trials for the turn 60° towards the right). It can be seen in Table 5 that nine participants moved their contralateral foot first at varying frequencies. Only one person (Participant I) never moved their contralateral foot first. Other notable results were that Participant C strongly favoured movement of their right foot first, whilst Participant F

favoured movement of their left foot first. This occurred for both participants during turns towards both directions and extents.

**Table 5. The number of trials that participants moved their contralateral foot first**

Participant	Turn to left		Turn to right	
	30°	60°	30°	60°
A	4	2	0	1
B	4	9	0	1
C	8	10	0	0
D	3	1	3	3
E	5	3	2	1
F	0	0	8	6
G	3	1	2	1
H	0	0	1	0
I	0	0	0	0
J	3	2	5	5

### 5.3 The sequence of movement onset between the head and the feet

The existence of a sequence of movement onset between the head and the feet was tested using trials in which the ipsilateral foot had moved first. The results are shown in Table 6. There is a clear mean rank order between the onset of head and foot movement. The onset of head movement precedes the onset of foot movement. In all instances the Kendalls ( $W$ ) value was 0.75 or higher indicating a high level of agreement, and that there would be little variation to this order of movement onset.

**Table 6. Sequence of movement onset between the head and the feet**

Direction and extent of turn	Number of trials	Mean rank order			Kendall ( <i>W</i> ) value	P value
		Head	Left foot	Right foot		
Left 30°	68	1.10	1.93	2.97	0.876	<0.001
Left 60°	69	1.04	1.97	2.99	0.943	<0.001
Right 30°	78	1.23	3.000	1.77	0.822	<0.001
Right 60°	80	1.29	2.96	1.75	0.750	<0.001

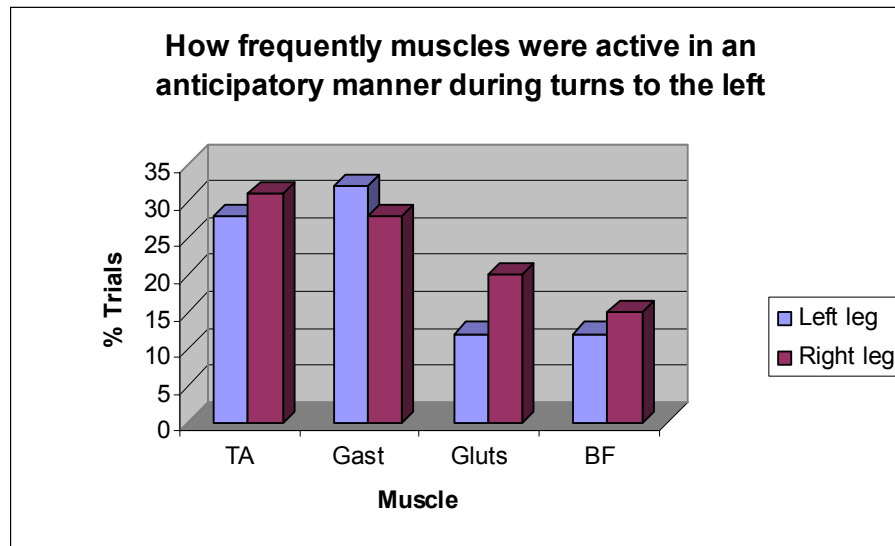
#### 5.4 How frequently muscles activated in an anticipatory manner

In Objective One it was established that the ipsilateral strategy was predominantly used during turns towards both directions and extents. The trials in which the ipsilateral strategy occurred were further analysed in this section. Anticipatory muscle activity was considered to be muscle activity that occurred prior to the onset of ipsilateral foot movement (see Operational Definitions, Section 1.4, page 5). How frequently each muscle was active in an anticipatory manner was calculated as a percentage of the ipsilateral trials towards each direction.

##### 5.4.1 *Anticipatory muscle activity during turns to the left*

The ipsilateral strategy occurred in 137 out of 200 trials towards the left. How frequently each muscle was active in an anticipatory manner is shown in Figure 7. Muscles activated in an anticipatory manner in only 12 to 32% of trials and this was

similar in both legs. Because the muscles were so infrequently active in an anticipatory manner, further analysis of each extent was not completed. Muscles at the ankle were slightly more active than the hamstrings and gluteus medius.

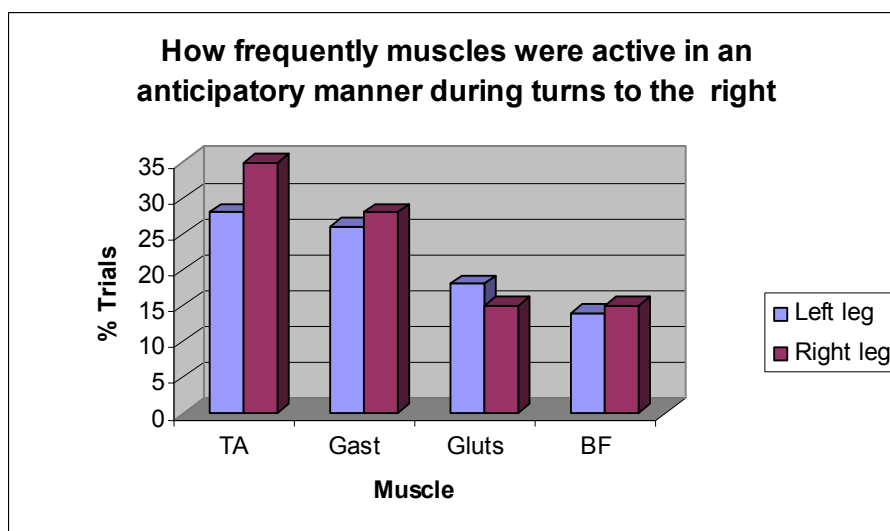


**Figure 7. How frequently muscles were active in an anticipatory manner during turns to the left**

Note: TA= tibialis anterior, Gast= gastrocnemius, Gluts= gluteus medius, BF= biceps femoris

#### *5.4.2 Anticipatory muscle activity during turns to the right*

The ipsilateral strategy was used in 158 out of 199 trials towards the right. How frequently each muscle was active in an anticipatory manner is shown in Figure 8. Muscles activated in an anticipatory manner in only 14 to 35% of trials and this was similar between both legs. Because the muscles were not frequently active in an anticipatory manner, further analysis of each extent was not completed. Muscles at the ankle were slightly more active than the hamstrings and gluteus medius.



**Figure 8. How frequently muscles were active in an anticipatory manner during turns to the right**

Note: TA= tibialis anterior, Gast= gastrocnemius, Gluts= gluteus medius, BF= biceps femoris

### 5.5 Sequences in anticipatory muscle activity

Because no muscle was active in an anticipatory manner in at least 80% of trials, two objectives could not be completed. The first was to identify whether a consistent sequence in onset, existed among muscles active in an anticipatory manner in at least 80% of trials. The second objective was to identify whether there was a sequence in onset among the head, feet and muscles active in an anticipatory manner in at least 80% of trials.

## 6 . DISCUSSION

### 6.1 Introduction

Before discussing the results in depth, it may be useful to re-visit the original key objectives of both current experiments. One objective of Experiment Two was to determine whether and how consistently anticipatory lower limb muscle activity was present during a step-turning task. As this had not been previously investigated, the most relevant lower limb muscles from which to collect SEMG from were unknown. Hence, the purpose of Experiment One was to identify the muscles that were most consistently active during the early period, up to the beginning of toe off in the leg with the electrodes. Although toe off had been a commonly used event to denote the presence of anticipatory muscle activity in gait initiation studies, it is a late movement event meaning that some of the muscle activity detected would not be anticipatory. For this reason in Experiment One, the muscle activity detected was considered to be early muscle activity, not anticipatory activity.

The first objective of Experiment Two was to identify the most predominantly used foot strategy towards each direction and extent of turn. Only those trials would be further analysed for the presence of anticipatory muscle activity. The criteria used to denote the presence of anticipatory muscle activity, was that the muscle activity had to precede the movement onset of the predominantly first moving foot in the  $z$  direction. In order to assess indirectly whether the visual system might influence the temporal onset of foot movement, the second objective of Experiment Two was to identify whether there was a consistent temporal order of onset between the head and the feet. The third objective of Experiment Two was to calculate how frequently the muscles were active in an

anticipatory manner. Two objectives concerning muscles that were active in at least 80% of trials could not be completed as no muscle activated that frequently in an anticipatory manner.

This chapter is divided into five sections. The first section discusses the motion analysis findings and the second section discusses the SEMG results. Limitations to the current experiments are discussed in the third section, followed by the fourth section on the clinical implications for physiotherapy. The final section is the recommendations for further research.

## 6.2 Motion analysis findings

### *6.2.1 The predominant order of foot movement*

In Experiment Two, irregardless of the direction and extent of the turn, movement of the ipsilateral foot (use of the ipsilateral strategy) occurred before movement of the contralateral foot in 68 to 79% of trials. These were very similar findings to earlier work by Meinhart-Shibata et al. (2005) with their group of young adults. The reasons why the ipsilateral strategy is predominantly used have not been investigated. One thought is that this strategy might allow the speed of the turn to advance more quickly, compared to use of the contralateral strategy. This idea is partially supported by Meinhart-Shibata and colleagues' findings that young adults who used the ipsilateral strategy, turned more quickly than older participants who generally used the contralateral strategy. However, it is likely there are other contributing reasons why the older adults turned more slowly. Another plausible advantage with the ipsilateral strategy is that it may reduce the number of steps required to complete the turn. Although Meinhart-Shibata and colleagues had not found a significant difference in the mean number of steps taken



between young and older participants, the number of steps taken during the use of each foot strategy had not been compared.

Meinhart-Shibata et al. (2005) had considered the use of the contralateral strategy by older adults in their study to be a preparatory strategy that might assist with balance by offering a larger initial base of support. No explanations were given as to why this strategy was used by young adults. In Experiment Two, although the use of the contralateral strategy was infrequent overall, the large majority of participants (nine out of ten) would intermittently use this strategy, and the reasons for this may not relate to balance. The variability in the foot strategy might simply be a consequence of the multiple degrees of freedom available in the body to produce movement. Only one person never varied their order of foot movement, a result that was an anomaly for the group.

Another reason that the contralateral strategy was used in Experiment Two was because two participants exhibited a foot preference, where one foot would generally move first towards both directions and all extents. Therefore, use of the contralateral strategy may not always be related to balance but due to normal movement traits and this is likely to occur in older adults. One tentative suggestion is that if older adults also intermittently alter their choice of foot strategy, their balance and co-ordination during the use of the least predominant strategy might be poorer and could contribute to falls. There might be some case for the assessment and rehabilitation of this task with older adults using both foot strategies, although an emphasis could still be given to the predominantly used strategy.

### 6.2.2 *The sequence of movement onset between the head and the feet*

The finding in Experiment Two that the onset of foot movement occurs after the onset of head movement, concurs with previous work by Hollands et al. (2004). Importantly, the order of movement onset had been identified in Experiment Two by using a ranking system via the Kendall Coefficient of Concordance ( $W$ ) test. The use of mean onset latencies as utilized by Hollands and colleagues, had been avoided because mean onset latencies do not always indicate the most frequent sequence of events (Hines & Mercer, 1997). This is the first study to identify sequences of movement onset by using a ranking system for this task. The step-turn task was performed at a self-selected pace in Experiment Two, and at a fast speed in the study by Hollands and colleagues. As the order of movement onset between the head and the feet appears to be consistent at both speeds of the task, this suggests that the sequence is an integral component to step-turning.

Hollands et al. (2004) and previous researchers (Hollands et al., 2002; Patla et al., 1999) had identified that eye movement generally preceded the onset of head movement. The likely reason that foot movement occurred after head movement, proposed by Hollands et al. (2004), was that visual information was used to influence the temporal onset of the foot movement. Although no data from the visual system was collected in Experiment Two to confirm the order of movement onset between the eyes and the head, it is likely that the sequence of movement found between the head and feet in Experiment Two is due to the reason proposed by Hollands and colleagues.

### 6.3 Surface electromyography findings

#### *6.3.1 How frequently muscles were active in an anticipatory manner*

The finding in Experiment Two that lower limb muscles activated in an anticipatory manner in just 12 to 38% of trials was unexpected. Anticipatory activity in the same muscles during previous research on gait initiation and forwards stepping, been reported to occur in 50 to 100% of trials (Assaiante et al., 2000; Mercer & Sahrman, 1999). There may be a number of reasons why anticipatory muscle activity occurred less frequently during step-turning, compared to gait initiation and forward stepping. One reason might be that the onset of foot movement in the  $z$  direction used to denote the presence of anticipatory muscle activity in Experiment Two, is a much earlier event than the onset of rectus femoris activity used by Mercer and Sahrman (1999) and the onset of heel off used by Assaiante et al. (2000). Later movement events are more likely to detect movement related activity. This is illustrated in the results for Experiment One, where higher levels of muscle activity are present because the later movement event of toe off had been used.

There is uncertainty as to whether anticipatory muscle activity was infrequent during step-turning because of differences in the speed of task performance. The step-turn in Experiment Two was completed at a self-selected pace, whereas the forward stepping task in the study by Mercer and Sahrman (1999) was performed at the participant's fastest possible pace. The faster movement pace might have caused a greater disequilibrium, resulting in a larger need for anticipatory muscle activity to provide the necessary stability. However, in the main gait initiation study by Assaiante et al. (2000), the speed of task completion was not specified. Because these investigators had also assessed infants, it is unlikely that the task was performed at the fastest possible speed.

Hence, the speed of task performance may not be the major reason that anticipatory muscle activity during step-turning occurred infrequently compared to gait initiation and forward stepping.

The less frequent occurrence of anticipatory muscle activity during step-turning compared to gait initiation and forward stepping, might be due to differences in stability demands as a consequence of kinematic differences between the tasks. Possibly, less balance is required during step-turning because the head stays over the base of support (Stack et al., 2004). One muscle reported to behave consistently in an anticipatory manner during gait initiation and forward stepping was tibialis anterior (Assaiante et al., 2000; Mercer & Sahrman, 1999). Tibialis anterior activity was believed to be centrally involved with moving the centre of mass in an anterior direction to generate the forwards fall required for these two tasks (Brenière et al., 1981; Crenna & Frigo, 1991; Herman et al., 1973). This forwards fall is probably unnecessary during step-turning and might explain why tibialis anterior was infrequently active in an anticipatory manner during step-turning. Furthermore, anticipatory muscle activity in gastrocnemius that was proposed to modulate the effects of tibialis anterior activity (Cook & Cozzens, 1976; Herman et al., 1973) would also be less likely to occur during step-turning.

Anticipatory muscle activity during gait initiation has been presumed to be involved with generating the medio-lateral anticipatory postural adjustment. During this adjustment there is a movement of the foot centre of pressure, to assist with the lateral shift of the centre of mass towards the stance leg, to enable balance to be maintained during stepping (Brenière et al., 1981; Brunt et al., 1991; Lyon & Day, 1997). It is unknown whether there is a similar foot centre of pressure shift during step-turning, but it is likely that the body's centre of mass moves towards the stance leg before stepping

occurs. Due to the infrequent activation of lower limb muscles in an anticipatory manner during step-turning, it is plausible that the manner in which the centre of mass moves laterally during step-turning might be inherently different to gait initiation and forward stepping. This idea is supported by the finding in Experiment Two that gluteus medius was not frequently active in an anticipatory manner. Gluteus medius is the lower limb muscle that has been associated with generating the lateral centre of pressure movement (Mercer & Sahrman, 1999).

If the lateral shift of the centre of mass is not generated by the lower limbs during step-turning then perhaps it is generated by the trunk. Work by Patla et al. (1999) using a steering paradigm supports this idea. Although there are differences in the inertial forces involved between the tasks of steering and step-turning, there may be some similarities in the strategy used to move the centre of mass laterally prior to stepping. In the work by Patla and colleagues, nine young adult participants were required to change their direction of walking 20, 40 or 60° to the right at the end of a nine metre walkway under two different conditions. In the first condition the cue to change direction was given at the beginning of the walkway. In the second condition the cue was given one stride before the turn needed to be completed. When the cue was given at the beginning of the walkway, participants would place their right foot closer to their left foot. During the stride prior to the turn, the order of movement onset was firstly head rotation to the right, a trunk roll to the left, trunk rotation to the right and right foot movement towards the right. When the cue was given one stride before the turn, there was a difference in the order of movement onset. Firstly there was a trunk roll to the left, followed by head and trunk rotation to the right, and then foot movement towards the right.

Patla et al. (1999) concluded that two possible strategies existed to control movement of the centre of mass towards the travel direction. The preferred strategy was an initial movement of the right foot closer to the left foot. The second strategy was an earlier trunk roll to the left during which the body acted as a double pendulum. The double pendulum was where the stepping foot moved in an opposite direction to the trunk, resulting in the movement of the centre of mass towards the direction of turn. Patla and colleagues referred to the trunk roll motion as part of the hip strategy identified by Horak and Nashner (1986). The hip strategy is where muscle activity at the trunk and thigh results in moments that are focussed at the hips to maintain balance. It may be that the effect of the trunk roll motion similarly results in increased moments at the hip joint during step-turning however, for clarity the trunk roll motion will be referred to as a trunk roll strategy and not as the hip strategy.

The conditions in Experiment Two were similar to the late cue condition in the study by Patla et al. (1999) because of the timing of the cue, and because the initial movement of the foot could not be used due to standardisation of the foot position. Therefore, it may be conceivable that the trunk roll movement in a direction opposite to the stepping leg has an important role in moving the centre of mass laterally towards the stance foot during step-turning. It is unlikely that trunk rotation alone moves the centre of mass laterally during step-turns. Trunk rotation occurs towards the direction of the turn regardless of the foot strategy used; however there are marked differences in the direction of the lateral weight shift depending on the foot strategy used.

A major limitation of the work by Patla et al. (1999) was that the sequence of movement events had been identified by using the mean onset latencies. The order of the movement events might have been different if a ranking system had been used. Another

limitation was that the movement of the centre of mass was based on the trajectories of only five markers. How accurately trunk movement was detected is questionable given that only three markers had been used, all of which were placed on the upper trunk. The accuracy may have been enhanced by using additional markers on the posterior and lower segments of the trunk. Finally, the criteria that had been used to determine the onset of the trunk roll were not clear.

Trunk roll has never been investigated in previous studies on step-turning. Further research is necessary to investigate the notion that a trunk roll strategy in a direction opposite to the stepping leg is important for movement of the centre of mass towards the stance leg during step-turning. Firstly, identification as to whether a trunk roll strategy consistently occurs during step-turns is required. As it is known from Experiment Two and work by Meinhart-Shibata and colleagues (2005), that different foot strategies are used during step-turning, the presence of the trunk roll during both foot strategies should be assessed. Secondly, force plate data should be collected from under each foot so that the spatial and temporal changes in distribution of the centre of mass during the trunk roll can be examined.

Meinhart-Shibata et al. (2005) raised the question as to why so many falls during turning cause hip fractures in older adults. One idea that had not been considered by the researchers is that the strategy used to move the centre of mass laterally during either the first or successive steps, might be ineffective or delayed and could contribute to falls. Meinhart-Shibata and colleagues had identified that older adults predominantly stepped their contralateral foot first. Due to the position of the lower limbs it may be difficult to shift weight onto the contralateral foot to allow a successive step. Both hips may be internally rotated (the ipsilateral hip being in relative internal rotation due to

pelvic rotation towards it). The slower rate of pelvic rotation characteristic in older women could result in the centre of mass being positioned for a longer period of time in a postero-lateral direction towards the ipsilateral hip, which may cause a tendency to fall in this direction. The combination of falling onto an internally rotated hip that is supporting a large amount of body weight may contribute to the increased incidence of a hip fracture. At this point, these are merely suppositions, but further research on the early manner in which the body's centre of mass movement moves towards the stance leg during step-turning is needed.

Finally, although anticipatory lower limb muscle activity during step-turning occurred infrequently, an explanation for its presence should be given. Gelfand et al. (1971) had proposed that anticipatory sequences of muscle activity included both the muscle activity relating to the task, as well as postural activity. Therefore, some of the muscle activity detected is postural activity. It is possible that in some instances the muscle activity is associated with lateral movement of the centre of mass, but this is not the preferred strategy to achieve this.

#### 6.4 Section summary: study findings

In summary, the key findings in Experiment Two were firstly that during a step-turning task, the predominant order in the onset of foot movement is ipsilateral foot movement followed by contralateral foot movement. However, the majority of participants would vary the order of foot movement in some of their trials. The second key finding was that the onset of foot movement consistently occurred after the onset of head movement. These findings concur with previous research. The third key finding was that anticipatory lower limb muscle activity occurred infrequently during step-turning. This



suggests that the lower limbs are not involved in the early balance responses for the lateral weight shift of the centre of mass during step-turning. As this has not been investigated in any published study to date, no comparison of the results is available.

## 6.5 Limitations of the current studies

Experiment One had been undertaken prior to the publication of the work by Meinhardt-Shibata et al. (2005) where different foot strategies were identified. In Experiment One, motion analysis data had only been collected from the foot of the leg with the surface electromyography electrodes. Early muscle activity had been identified by comparing the onset of muscle activity, with the onset of movement of this one foot. In some trials the opposite foot may have moved first, therefore some of the muscle activity that was identified was not strictly early. There may be some error in the levels of early muscle activity identified. However, the muscles that were identified as being the most consistently active muscles would not have altered, given that the error was systematic to all of the muscles. A second limitation to Experiment One was that the maximum number of muscles that could be tested was limited to eight, because of the equipment used. The decision was made based on the literature review to collect surface electromyography from only the lower limb muscles and to exclude the trunk. In retrospect, it seems that collection of surface electromyography from trunk muscles would have been valuable.

One limitation of Experiment Two was that the assessment of the trunk roll strategy had not been considered. There were also limitations with the Kendall Coefficient of Concordance ( $W$ ) statistical test to rank the order of muscle onset. Trials in which a muscle had not activated could not be included for analysis, causing a reduction in the

number of trials analysed. In both studies there was an attempt to standardise the foot position however, this does not assure that the distribution of the body's centre of mass will also be consistent. Therefore, in some trials there would have been slight differences in biomechanical demands and this may have influenced how frequently muscles behaved in an anticipatory manner.

## 6.6 Clinical Implications for physiotherapy

In Experiment Two the large majority of individuals exhibited variability in the order of foot movement. Therefore, it may be appropriate to assess and rehabilitate the performance of this task, using both foot strategies with older adults who report difficulty with step-turning, although emphasis can be placed on their predominant foot strategy. There are other special populations such as those with stroke, for whom this may also apply. The results of Experiment Two might be pertinent to future research on step-turning, and the development of alternative step-turning assessment tools.

Experiment Two concurred with previous work that the onset of foot movement occurred after the onset of head movement. The reason for this is possibly due to the use of visual information to plan the motor outflow of the lower limbs. Although data from the visual system during step-turning has not yet been reported, anecdotally in clinical practise there are older adults who habitually look down at their feet. There are many reasons why they do this, including a loss of confidence. In the instance that there is not severe somatosensory, proprioceptive or visual loss, there may be some benefit in training older adults to move their heads, and look towards the direction of their turn before they move their feet during falls rehabilitation. In the future, as research

progresses there may be formal development of segmental body co-ordination exercises among the eyes, head, trunk and feet.

## 6.7 Recommendations for future research

Recommendations for possible future research on the task of step-turning were made through out the discussion section. Those ideas and additional recommendations will now be summarised.

Further investigation into the strategies used by healthy young adults to move their centre of mass laterally prior to the first step is required. Whether a medio-lateral anticipatory postural adjustment occurs prior to step-turning should be investigated. Conjointly, the existence and effects of the trunk roll strategy on the lateral shift of the centre of mass would be very insightful. The collection of surface electromyography from trunk musculature would identify whether they are consistently active in an anticipatory manner. If so, this might support the idea that the trunk is involved in the initial balance responses for this task.

Similar research as recommended above for the young adults is required in special populations such as the elderly, and those with stroke or Parkinson's Disease. Given that movement of the contralateral foot first may be preferred by older adults, investigation into the biomechanical advantages and disadvantages of this strategy is essential; especially concerning the ease of lateral weight shift during the subsequent step. Stratification of participants based on visual, proprioceptive and range of movement loss may enhance the usefulness of the research. Further investigation into the levels of anticipatory muscle activity in both the trunk and the lower limbs, would identify which body segment is predominantly involved in lateral weight shift and early

balance strategies. Additionally, the collection of electro-oculography data during this task would identify the extent that the visual system influences the motor outflow of the lower limbs. Further research of this task when it is performed at faster speeds within both the young and elderly populations would be useful.

## 7 . CONCLUSION

Turning is an integral movement necessary for the completion of activities of daily living. However, it is a movement that is associated with a high incidence of hip fractures during falls in the elderly population. Despite this, little information exists on turning. The purpose of the current studies was to contribute to the body of knowledge on turning. Specifically, the presence and consistency of anticipatory lower limb muscle activity during step-turning was investigated, using a multi-segmental paradigm for insight into the prioritisation of the central system for the task.

The most frequently active lower limb muscles during the early period of step-turning were identified in Experiment One, and tested further in Experiment Two. The key finding in Experiment Two that the lower limb muscles activated infrequently in an anticipatory manner was unexpected. Previous research on gait initiation and forward stepping had reported the presence of consistent anticipatory lower limb muscle activity. That anticipatory activity, described in the above research was associated with the initiation of a forwards fall at the ankles, as well as the medio-lateral anticipatory postural adjustment.

The infrequent occurrence of anticipatory lower limb muscle activity during step-turning found in Experiment Two, suggests that this task may be inherently different to gait initiation and forwards stepping in two fundamental ways. Firstly, anticipatory muscle activity to generate a forwards fall is not necessary because the head stays over the feet and therefore within the base of support. Secondly, the strategy used to move the body's centre of mass towards the stance leg is not generated by anticipatory lower limb muscle activity, but by another part of the body, possibly the trunk. Further

research on step-turning is required to substantiate these speculations in both the young and older adult populations.

Another objective of Experiment Two had been to identify the predominantly used foot strategy. It was found that the ipsilateral strategy, where movement of the ipsilateral foot preceded movement of the contralateral foot, was predominantly used. Intermittently however, the strategy used would alter in the majority of participants. The reasons that have been proposed as to why young adults prefer to use the ipsilateral strategy include: the need for fewer steps to complete the turn, and that it might allow the turn to progress more quickly. Previous research reported that older adults prefer to use the contralateral strategy possibly because it provided a larger initial base of support, and required less hip external rotation for successive steps. These ideas need to be substantiated with research. Further investigation into the biomechanical and motor control advantages and disadvantages of both foot strategies is needed. Older adults are likely to have variability in their order of foot movement therefore, it may be appropriate to assess and rehabilitate the performance of step-turning using both foot strategies, although greater emphasis could be placed on their predominant strategy.

The final objective of Experiment Two had been to identify the temporal relationship in the onset of movement between the head and the feet. The results indicated that the onset of head movement preceded that of the feet, a finding consistent with previous research. It has been proposed that this sequence exists because visual information is used to influence the temporal movement onset of the feet. Currently in falls rehabilitation settings, there may be some clients for whom encouraging this sequence of movement would be beneficial however, further research is needed concerning the onset of eye movements during turning tasks in older adults.

In conclusion, the unexpected finding in Experiment Two that lower limb muscles were infrequently active in an anticipatory manner during step-turning has raised numerous further research questions. Still, Experiment Two has contributed to the body of knowledge on turning, and has offered some clinical implications for those in the area of falls rehabilitation. Additional research on this task is essential, given the serious issue that falls during turns are associated with the high incidence of hip fractures in the elderly population. (Winter et al., 1994)

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## 9 . APPENDICES

## Appendix A



# MEMORANDUM

## Academic Services

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To: Denise Taylor  
 From: **Madeline Banda**  
 Date: 29 April 2005  
 Subject: Ethics Application Number 05/64 **Anticipatory postural adjustments during turning tasks.**

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Dear Denise

Thank you for providing written evidence as requested. I am pleased to advise that it satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC) at their meeting on 11 April 2005. Your ethics application is now approved for a period of three years until 29 April 2008.

I advise that as part of the ethics approval process, you are required to submit to AUTEC the following:

- A brief annual progress report indicating compliance with the ethical approval given using form EA2 which is available online at [http://www.aut.ac.nz/research\\_showcase/pdf/appendix\\_g.doc](http://www.aut.ac.nz/research_showcase/pdf/appendix_g.doc), including a request for extension of the approval if the project will not be completed by the above expiry date;
- A brief report on the status of the project using form EA3 which is available online at [http://www.aut.ac.nz/research\\_showcase/pdf/appendix\\_h.doc](http://www.aut.ac.nz/research_showcase/pdf/appendix_h.doc). This report is to be submitted either when the approval expires on 29 April 2008 or on completion of the project, whichever comes sooner;
- You are reminded that, as applicant, you are responsible for ensuring that any research undertaken under this approval is carried out within the parameters approved for your application. Any change to the research outside the parameters of this approval must be submitted to AUTEC for approval before that change is implemented.

Please note that AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to make the arrangements necessary to obtain this.

To enable us to provide you with efficient service, we ask that you use the application number and study title in all written and verbal correspondence with us. Should you have any further enquiries regarding this matter, you are welcome to contact Charles Grinter, Ethics Coordinator, by email at [charles.grinter@aut.ac.nz](mailto:charles.grinter@aut.ac.nz) or by telephone on 917 9999 at extension 8860.

On behalf of the Committee and myself, I wish you success with your research and look forward to reading about it in your reports.

Yours sincerely

**Madeline Banda**  
**Executive Secretary**  
**Auckland University of Technology Ethics Committee**

Cc: Lisa Ngan-Hing [lisnga95@aut.ac.nz](mailto:lisnga95@aut.ac.nz)

From the desk of ...

Madeline Banda

Academic Services

Private Bag 92006, Auckland 1020  
 64 9 917 9999  
 New Zealand  
 ext 8044  
 E-mail: [madeline.banda@aut.ac.nz](mailto:madeline.banda@aut.ac.nz)  
 64 9 917 9812

Tel:

Fax:

## Appendix B



### **VOLUNTEERS NEEDED**

#### **The turn and step study.**

Volunteers are needed for a study examining balance during turning activities. This supervised study is being undertaken on the Akoranga campus of the AUT and is part of a student's Masters degree thesis.

The aim of the study is to investigate an important postural response. Little is currently known about which leg muscles are used and how quickly they contract when people turn. This information would be useful as many older adults fall during turning activities, sometimes resulting in injury and loss of confidence.

Participants will be asked for an hour and a half of their time to be assessed once in the laboratory. If you are between the ages of 18 and 40 years, do not have a known allergy to adhesive taping materials, a neurological or musculoskeletal condition, or severe visual loss then you may be suitable for this study.

If you are interested in volunteering with this study, or discussing this further please contact Lisa on the number below. Your help would be most appreciated.

Lisa Ngan-Hing Contact (09) 9179999 extension 7194 or 0211 75 0092  
Dr Denise Taylor Contact (09) 917 9999 extension 7080

## Appendix C



### Participant Information Sheet

**Date Information Sheet Produced:** 3/3/2005

**Project Title:** The turn and step pilot study.

**Researchers are:** Lisa Ngan-Hing and Dr Denise Taylor

**Address:** AUT, Private Bag 92006, Auckland

**Phone number:** 917 9999 ext 7080

#### Invitation

You are invited to take part in a research study that will explore an early part of your balance response as you turn and step. This supervised study is the work of a qualified physiotherapist as part of their Masters degree. You may be eligible for this study if you meet the entry criteria of: being between 18 and 40 years; you can stand and step around without a walking aid; you have no neurological or musculoskeletal disorders, or severe loss of vision and no known allergy to taping materials.

#### What is the purpose of the study?

The aim of the study is to examine an early part of a balance response called an anticipatory postural adjustment or APA. During a step forwards it is known that APAs happen quickly—usually before you can see or feel movement but not much is known about them when people turn and step. This study aims to find out which muscles of the leg produce APAs and how quickly they happen when a person turns and takes a step around at a comfortable pace.

#### How do I join the study?

If you wish to join the study please contact:

**Lisa Ngan-Hing (09) 917 9999 ext 7194 (Do leave a message with Jane Galle)**  
or 0211 75 0092

#### How are people chosen to be asked to be part of the study?

If you meet the entry criteria of: being between the ages of 18 and 40 years; you have no neurological or musculoskeletal disorders or severe loss of vision; no known allergy to taping materials and can spare an hour and a half of your time then we welcome your assistance.

#### What happens in the study?

When you ring, the researchers will discuss any of your concerns about participating, and answer any of your questions about the study. You will then be given about a week to consider if you would like to take part. If you decide to participate an appointment will be made for you to attend the research laboratory. When you arrive for your appointment, the details on this sheet will be discussed with you to check that you understand the details and are happy to participate. You will be asked to sign a consent form and will be given one copy to keep.

You will be asked to change into a pair of shorts so that small electrodes can be placed on different muscles on your legs. The electrodes detect muscle activity, are about four centimetres in size and have self adhesive pads. A little extra tape may be needed to assist with adhesion. It will be necessary to shave off hair where the electrodes will stick as this will help with adhesion, and will make removal of the electrodes more comfortable. The patch of skin where the electrode will stick will be cleaned to remove any skin oils or creams. There will be eight electrodes put on each leg including ones on the hip and thigh. So that your head movement



can be measured you will be asked to wear a hat with some markers on it. All the information from the electrodes and hat will be sent to a belt that you will wear around your waist and will be recorded by the computer.

You will then be asked to stand in a certain spot and underneath it will be a force plate that you will not notice. You will be asked to stand and face a central light. When you see another light turn on you will turn and step turn towards it at a comfortable pace. You will be asked to do this for up to sixty trials with rests as needed.

**What are the discomforts and risks?**

There might be a small chance that you are allergic to the adhesive pads on the electrodes or that you might receive a small cut whilst being shaved. If this occurs you will have access to the necessary health and counselling services at AUT.

**How will these discomforts and risks be alleviated?**

Low allergy taping products will be used to minimise any risk of allergy. You will be closely monitored during the trials to ensure that you are comfortable, and given opportunities to rest. You are also free to indicate when you need to rest or stop.

**What are the benefits?**

There are no direct benefits to you; however your participation would be most helpful in furthering knowledge in this area which eventually may help improve the rehabilitation of balance for older adults. You will have the experience of participating in a modern research laboratory.

**What compensation is available for injury or negligence?**

In the unlikely event of a physical injury as a result of your participation in this study, you will be covered by accident compensation legislation with its limitations. If you have any questions about ACC please feel free to ask Lisa for more information before you agree to take part in this study.

**How will my privacy be protected?**

Your confidentiality will be maintained in the following ways. No material which could personally identify you will be used in any reports on the study. Your identity will remain confidential to the researchers. Data collected in this study will be kept secure in a locked filing cabinet and office.

**What are the costs of participating in the project?**

There is no monetary cost to you. It will involve about one and a half hours of your time.

**Opportunity to consider invitation**

You will have a week to consider whether to take part after you phone the researcher.

**Opportunity to receive feedback on results of research**

If you wish, at the end of the study you will be sent a summary of the results of the study. It is usual for there to be a substantial delay between the time of your participation and the time of receiving these results. The results may be published in a journal and presented at a physiotherapy conference. The results may be used for publicity purposes.

**Participant Concerns**

You are welcome to discuss this information further with Lisa who will attempt to answer any questions you may have. If you have any queries or concerns about your rights as a participant in this study you may wish to contact Health Advocates Trust on 0800 555 055. Please feel free to contact Denise Taylor on 917999 ext 7080 if you have any other questions about this study.

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor.

Concerns regarding the conduct of the research should be notified to the Executive Secretary, AUTC, Madeline Banda, [madeline.banda@aut.ac.nz](mailto:madeline.banda@aut.ac.nz) , 917 9999 ext 8044.

**Researcher Contact Details:** Lisa Ngan-Hing. Masters Degree student. Phone (09) 9179999 ext 7194 or 0211 75 0092

**Project Supervisor Contact Details:** Dr Denise Taylor, Phone (09) 9179999 ext 7080

**Approved by the Auckland University of Technology Ethics Committee on 29.4.05, AUTC**  
**Reference number** 05/64



## Appendix D



### Consent to Participation in Research

Title of Project: The turn and step study

Project Supervisor: Dr Denise Taylor

Researcher: Lisa Ngan-Hing

- 
- I have read and understood the information provided about this research project (Information Sheet dated 3/3/2005).
  - I do not have a known allergy to adhesive taping materials, a history of neurological or musculoskeletal disorders or a severe visual deficit.
  - I meet the age criteria; 18-40 years.
  - I understand that taking part in this study is voluntary (my choice).
  - I have had an opportunity to ask questions and am satisfied with the answers that have been given.
  - I understand that I may withdraw at any time prior to and during the collection of data, without it disadvantaging me in any way.
  - If I withdraw, I understand that all relevant data will be destroyed.
  - I have read and understood the provision for ACC compensation in the 'Participant Information Sheet'.
  - I agree to take part in this research.
  - I wish to receive a summary the results of the research: tick one: Yes ☐ No ☐
  - I wish to receive the results : tick one :Yes ☐ No ☐

Participant signature: .....

Participant name: .....

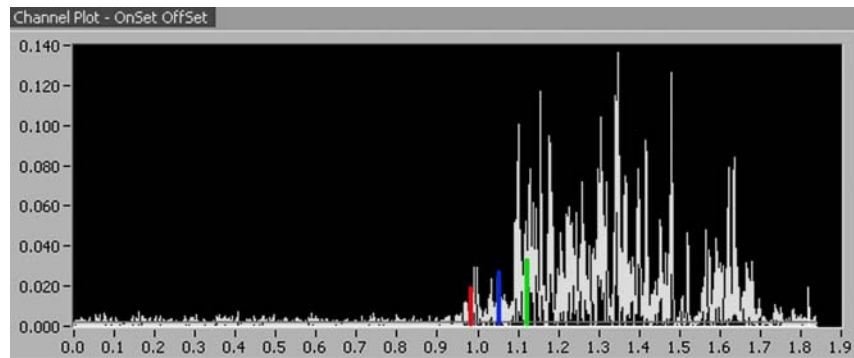
Participant Contact Details:

.....  
 .....  
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 .....

Date:

Approved by the Auckland University of Technology Ethics Committee on 29.4.05 Reference number 05/64. nb give a copy to participant to retain.

## Appendix E



### **Comparison of different thresholds to determine onset of muscle activity.**

Red line= 1SD, blue line= 2SD and green line= 3SD