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By

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ABSTRACT

Slips are considered one of the most common causes of major accidental injuries. The objective of this thesis is two-fold. The first objective is to determine the role of the subtalar joint during a slipping perturbation. The second is to determine if certain footwear characteristics, that may restrict the normal function of the subtalar joint (i.e., insole stiffness and heel counter stiffness), will change the response to unexpected heel contact slipping perturbations.

Forty-two participants (30 females, 12 males) were recruited from a university aged population (21.19 years ± 2.7 years). Trials were performed over a 10 m walkway with rectangular sheets of sandpaper placed at each foot contact. Ten participants performed walking trials barefoot while the other 32 participants were randomly assigned to one of four footwear conditions (n=8) (condition 1: flexible insole, soft heel counter; condition 2: flexible insole, stiff heel counter; condition 3: rigid insole, soft heel counter; condition 4: rigid insole, stiff heel counter). Electromyography (EMG) signals were collected from eight lower limb muscles (tibialis anterior, peroneus longus, medial gastrocnemius, rectus femoris and medial hamstring). Kinematic data was collected using a 20 marker set-up. Marker triads were placed on the tibia, calcaneous and mid-foot to determine subtalar joint motion. Kinetic data was collected using forces plates embedded in the walkway. Unexpected slips were presented after a predetermined number of normal walking trials. Wax paper adhered to the underside of a sandpaper sheet was exchanged on the second force plate to cause an unexpected heel contact slip perturbation.

Overall, 20 participants experienced a slip. Within the barefoot condition, 80% of the participants experienced an unexpected slip perturbation. The prevalence of slips was not as great within all of the footwear conditions (25% - 50%). During slip trials the average onset of eversion occurred slightly later than in normal walking trials, but was not statistically significant.

The tibialis anterior elicited a burst of activity during the middle phase of stance that is typically not seen during normal walking. The average onset of tibialis anterior activity was earlier with the similar durations and relatively higher magnitudes than normal walking. During slip trials, the peroneus longus did not have significantly different onsets or durations and the magnitudes were slightly higher compared to normal walking trials. During slip trials, the medial gastrocnemius onset was not found to be significantly different when compared to normal walking trails, but the magnitudes were significantly lower.

A higher rate of vertical loading was the only significant finding that would have indicated an increased risk of slipping within the barefoot condition; while lower stance durations, gait velocities, heel velocities, and smaller shank and foot-floor angles indicated an increased risk of slipping within the shod conditions. These finding would suggest that individuals who were in the shod conditions would have been at a higher risk of slipping than the barefoot condition, which should have resulted in higher incidences and severities; when in fact, the severity and incidences of slips was much lower. Therefore, the footwear, along with decreasing loading rate, must offer a level of stability to the foot and ankle during heel contact that controls foot motion. In particular, decreasing the rate of pronation or eversion at the time the slip was detected, which would likely decrease the severity of the slip; evident due to diminished recovery times.The peroneus longus does contribute to controlling subtalar motion alongside the tibialis anterior and finally, footwear characteristics that restrict normal subtalar joint motion seen in barefoot individuals will help decrease the risk of slipping and decrease the severity, improving chances for recovery.

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GLOSSARY OF TERMS

Abduction (AB): Movement of a segment of limb towards the midline of the body (Hamill and Knutzen, 1995).

Adduction (AD): Movement of a segment of limb away from the midline of the body (Hamill and Knutzen, 1995).

Ankle Joint Complex (AJC): A term referring to the ankle/talocrural joint comprised of an articulation between the tibia and fibula (tibiofibular joint), and the tibia and the talus (tibiotalar joint/subtalar joint). Primary function is shock absorption (Hamill and Knutzen, 1995).

Antero-posterior (AP): Refers to movement along the y-axis in the transverse plane; anterior representing towards the front of the body, posterior towards the back of the body (Hamill and Knutzen, 1995).

Available Coefficient of Friction (ACOF): The amount of friction a given surface will provide. $\mu available = (F_{mediolateral}^2 + F_{anteroposterior}^2)^{1/2}/F_{vertical}$ (Siegmund et al., 2006).

Anterior Superior Iliac Spine (ASIS): A landmark of the pelvis located on the most anterior, superior aspect of the iliac crest, "hip bone" (Moore and Dalley, 2006).

Base of Support (BOS): The amount of surface in contact with the environment that provides stability to an individual. During locomotion it is defined as the area under the feet bordered by the anterior, posterior, medial and lateral aspects of the foot/feet in contact (Perry et al., 2001).

Biceps Femoris (BF): A muscle which is proximally attached to the lateral ischial tuberosity and distally attaches to the posterior lateral condyle of the tibia and the head of the fibula. The biceps femoris is primarily responsible for extension at the hip and flexion and lateral rotation at the knee (Hamill and Knutzen, 1995; Hall, 2003).

Body Weight (BW): Refers to an individual's mass (kg) being acted on by gravity (m/s^2) expressed in Newtons (N) (Hall, 2003).

Bureau of Labour Statistics (BLS): A unit of the United States Department of labour that collects and processes statistical data on the labour force (www.bls.gov).

Center of Mass (COM): Refers to the balancing point of the body where an individual's mass is evenly distributed, sum of the torques is equal to zero (Hamill and Knutzen, 1995).

Center of Pressure (COP): Represents a single point of application where all of the ground reaction forces are being applied back onto the foot. Pressure is equal and opposite to the force being applied to the ground and is measured by a force plate. COP is calculated using horizontal and vertical forces divided by their moments (Perry et al., 2007).

Coefficient of Friction (COF): A ratio of shear to normal forces ($F_{anteroposterior}/F_{vertical}$) defining the friction properties of the foot-floor interface (Marigold and Patla, 2002).

Dorsiflexion (DF): An anatomical term defining flexion at the ankle where by the relative angle between the foot and leg decreases (Hamill and Knutzen, 1995).

Electromyography (EMG): Measures the amount of electrical activity within the muscle to define the amount of muscle activation, timing and magnitudes. (Hamill and Knutzen, 1995).

Eversion (EV): An anatomical term defining movement of the foot occurring at the intertarsal and metatarsal articulations. The lateral aspect of the foot lifts and the sole of the foot faces away from the midline of the body. The sole of the foot is rotated outward (Hamill and Knutzen, 1995; Hall, 2003).

Foot Flat Response (FF): A term used to describe the trailing limb response during an unexpected slip perturbation. Characterized by the placement of the entire sole of the shoe slightly behind the leading foot (Moyer et al., 2009)

Gluteus Maximus (GMAX): A muscle which is proximally attached at the posterior illium, iliac crest, sacrum, and coccyx and distally attaches to the gluteal tuberosity of the femur and iliotibial band. The gluteus maximus is primarily responsible for external and lateral rotation of the thigh (Hamill and Knutzen, 1995; Hall, 2003).

Ground Reaction Force (GRF): Reactive forces provided by the ground that are equal in magnitude and opposite in direction to forces applied to the ground by an individual (Newtons III law). Measured using a force plate in the antero-posterior, medio-lateral and vertical components and reported in Newtons (N) (Hall, 2003).

Heel Contact (HC): The stage of gait when the lead limbs heel contacts the ground; signified when vertical ground reaction forces exceed a threshold of 12 Newtons (N).

Inversion (IV): An anatomical term defining movement of the foot occurring at the intertarsal and metatarsal articulations. The medial aspect of the foot lifts and the sole of the foot faces towards the midline of the body. The sole of the foot is rotated inward (Hamill and Knutzen, 1995; Hall, 2003).

Kinematics: The description of a body's motion without referring to the forces that caused the motion (i.e., displacement, velocity and acceleration) (Hamill and Knutzen, 1995).

Kinetics: The description of a body's motion with respect to the forces that caused the motion (i.e., gravity, ground reaction forces etc.) (Hamill and Knutzen, 1995).

Medial Gastrocnemius (MG): A muscle which is proximally attached at the posterior medial and lateral femoral condyles and distally attaches to the tuberosity of the calcaneous through the Achilles tendon. The medial gastrocnemius is primarily responsible for flexion at the knee and is a major plantar flexor at the ankle (Hamill and Knutzen, 1995; Hall, 2003).

Mid-Flight Response (MID): A term used to describe the trailing limb response during an unexpected slip perturbation. Characterized by the forefoot contacting the ground more rapidly and posteriorly that the FF response (Moyer et al., 2009)

Minimum Response (MIN): A term used to describe the trailing limb response during an unexpected slip perturbation. Occurred with less severe slips where the trailing limbs trajectory was similar to that of normal gait (Moyer et al., 2009)

Newton (N): A unit of force derived for Newton's second law Force (N) = Mass (Kg) · Acceleration (m/s^2) (Hamill and Knutzen, 1995).

Normal Force (NF): Synonymise with vertical ground reaction force. Is a measure of the vertical component of the ground reaction force measured in Newtons (N).

Normal Walking Trials: Represents dry trials were the participant is novel to the slip perturbation (see also pre-slip).

Peroneus Longus (PL): A muscle which is proximally attached to the head and upper two-thirds of the lateral fibula and distally attaches to the lateral surface of the first cuniform and first metatarsal. The peroneus longus is primarily responsible for plantar flexion and is a major everter of the ankle (Hamill and Knutzen, 1995; Hall, 2003).

Plantarflexion (PF): An anatomical term defining flexion at the ankle where by the relative angle between the foot and leg increases (Hamill and Knutzen, 1995).

Pre-slip (PreS): Represents dry trials were the participant is novel to the slip perturbation.

Post-slip (PS): Represents dry trials after the participant has experienced a slip perturbation.

Rectus Femoris (RF): A muscle which is proximally attached to the anterior inferior iliac spine (ASIS) and distally attaches to the patella via the patellar tendon. The rectus femoris is primarily responsible for flexion at the hip and extension at the knee (Hamill and Knutzen, 1995; Hall, 2003).

Required Coefficient of Friction (RCOF): Threshold of the shoe-floor interface to minimize the risk of a slip (Redfern et al., 2001).

Slip Trials (S): Represents the trials were the slip mat was introduced to cause a perturbation.

Soleus (SOL): A muscle which is proximally attached to the posterior proximal fibula and proximal two-thirds of the posterior tibia and distally attaches to the tuberosity of the calcaneous through the Achilles tendon. The soleous is primarily responsible for plantar flexion at the ankle (Hamill and Knutzen, 1995; Hall, 2003).

Standard Deviation (STDev): Refers to the average of the deviation of scores about the mean; calculated by taking the square root of the variance (Howell, 2004).

Tibialis Anterior (TA): A muscle which is proximally attached to the upper two-thirds of the lateral tibia and distally attaches to the medial surface of the first cuneiform and first metatarsal. The tibialis anterior is primarily responsible for dorsiflexion and inversion at the ankle (Hamill and Knutzen, 1995; Hall, 2003).

Toe Down Response (TD): A term used to describe the trailing limb response during an unexpected slip perturbation. Iinvolves just the tip of the forefoot contacting the ground more anteriorly that the MID response (Moyer et al., 2009)

Toe-off (TO): The stage of gait where the toe of the trail limb lifts of the ground; signified when vertical ground reaction forces drop below a threshold of 12 Newtons (N).

Utilized Coefficient of Friction: synonymous with available coefficient of friction.
$\mu = (F_{mediolateral}^2 + F_{anteroposterior}^2)^{1/2-} / F_{vertical}$ (Heiden et al., 2006).

Vastus Lateralis (VAS): A muscle which is proximally attached to the greater trochanter and lateral linea aspera and distally attaches to the patella via the patellar tendon. The vastus lateralis is primarily responsible for extension at the knee (Hamill and Knutzen, 1995; Hall, 2003).

Workplace Safety and Insurance Board (WSIB): Works to provide and promote workplace health and safety information, training and compensation (www.wsib.on.ca).

Chapter 1: Introduction/Literature Review

1.1 Overview

Falls are considered one of leading causes of unintentional work-related injuries requiring medical treatment (Cham and Redfern, 2001, Redfern et al., 2001). In 2008, falls accounted for 20.1% (15,706) of all injuries reported to the Workplace Safety Insurance Board (WSIB). Of these, 72 % were same-level falls. Slips have been identified as the most common cause of a same level fall reported in the workplace (WSIB, 2010).

A slip has been defined as, "the loss of a stable interaction between the foot or footwear and the ground surface" (Hamill and Knutzen, 1995). This is most commonly caused by improper footwear characteristics (i.e., tread, midsole, heel height, etc.), flooring type (concrete, tile, ice etc.) and/or due to contaminants from spills (i.e., oil, water, food, etc.). Slips have been identified as one of the most common causes of unintentional work-related injuries (Cham and Redfern, 2001) and it is therefore important to investigate. Further, the incidence of slips and falls has not significantly decreased over the past decade (WSIB, 2010). This may be attributed to the truly unexpected nature of slips.

Previous research has examined the biomechanics of a slip perturbation in great detail. Cham and Redfern, (2001) have reported that a slip occurs due to a reduction in available friction resulting in a decrease in the production of shear and normal ground reaction forces; lower coefficient of friction. They found that there was greater heel displacement and velocities shortly after heel contact compared to normal walking trials. A parallel study identified that successful active balance recovery attempts will occur between 25-45% of stance or else a fall is imminent. During this recovery attempt, there appeared to be a passive ankle moment coupled with an increase knee flexion and hip extension moment. This response works to stabilize the ankle joint and recover normal ankle joint trajectories, bringing the base of support (BOS) back under the centre of mass (COM) (Redfern et al., 2001). Previous research has indentified many crucial aspects of what a natural response to a slip perturbation is, but has not been able to identify strategies to successfully decrease the risk of unexpected slips and falls. Furthermore, when looking at responses to heel contact slipping perturbations studies have simplified the measurement of the movement within the ankle complex to two dimensions about the ankle axis; reporting that the ankle plantarflexes in response to an anterior translation in the sagittal plane (Cham and Redfern, 2001; Hughes et al., 1995).

The foot and ankle are the first link to our environment during normal locomotion. It is here that a slip will first be detected by our somatosensory/kinesthetic systems (i.e., cutaneous receptors, golgi tendon organs, muscle spindles and joint receptors) due to changes in pressure under the foot and/or joint trajectories at the ankle. As we age, deficits in cutaneous sensation under the foot (Zehr and Stein, 1999; Perry, Santos and Patla, 2001; Perry, 2006), reaction time (McIlroy and Maki, 1996; Thelen et al., 1997; Maki, Edmondstone and McIlroy, 2000; Tseng, Stanhope and Morton, 2009) and muscle force production in the lower limbs (Thelen et al., 1996; Barry, Rick and Garson, 2005, Rose and Gamble, 2006) may make these individuals at a higher risk of experiencing a hazardous slip. Therefore, investigation of normal subtalar joint motion during a slip recovery for young individuals free of neurological or biomechanical deficits will give insight into its function. If in fact the subtalar joint motion is found to be associated with ability to recover from a slip then we can explore further the implications of methods of subtalar modulation (i.e., footwear or orthotics) in an attempt to improve the chances for recovery and minimize risk of falls due to same-level unexpected slips.

The following sections within this chapter will provide a more in depth analysis of the current literature as it pertains to slips and falls in the workplace (1.2), the environmental interaction of the shoe/foot-floor interface (1.3), an outline of the biomechanics of normal gait (1.4) in comparison to the biomechanics of a slip (1.5), an introduction to the subtalar joint function (1.6) and an outline of the interaction of different footwear characteristics on balance control (1.7). The final sections will present the rational for this research (1.8) and the research objectives, questions and hypotheses (1.9).

1.2 Slips and Falls in the Workplace

Falls that occur in the workplace are considered one of the leading causes of unintentional work-related injuries requiring medical treatment (Lehane and Stubbs, 2001; Cham and Redfern, 2001) and are a major issue in many developed countries (Holbein-Jenny et al., 2007). A fall may be defined as an unintentional change of position to a lower level due to the inability to recover ones balance; the centre of mass (COM) travels too far outside of the base of support (BOS) causing an unstable system (Hamill and Knutzen, 1995; You at al. 2001). The number of same-level falls reported have risen from 65% to 72% of all fall incidences that result in an injury within the past decade (WSIB, 2010) (Figure 1.1a). The USA Bureau of Labour Statistics (BLS) reported that falls accounted for 16.8% of all non-fatal injuries resulting in lost workdays and attributed to 12% of job-related deaths in 1998 (Cham and Redfern, 2001). For 2000, the Workplace Safety Insurance Board (WSIB) reported 20 fatalities as a result of falls in the workplace (WSIB, 2010). Based on the subtotal of fall incidences it may appear that these statistics have been declining, but in actual fact, the overall incidence of injuries reported to the WSIB have declined and the incidence of same-level falls have slightly increased (Figure 1.1b). Therefore, there is still a serious concern as falls due to slips and trips still accounted for 13% of all non-fatal work-related injuries involving lost time reported by the BLS for 2006 (Verma et al., 2008). Falls in any workplace pose a serious health risk that needs to be addressed.

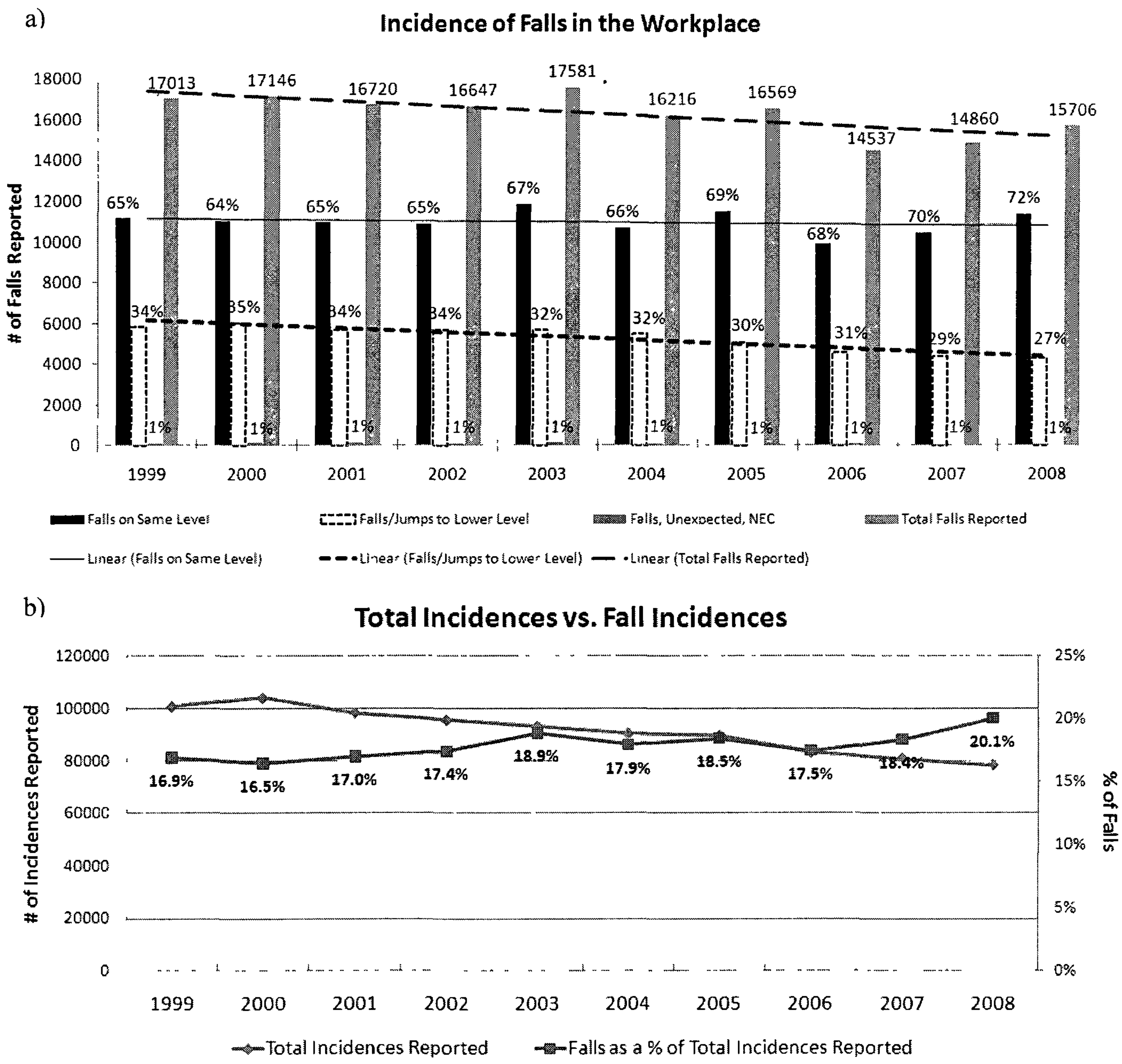


Figure 1.1: **a) Incidence of injury due to falls on same-level, jumps to lower level and other. b) Trend of total number of incidences reported compared to the % of fall incidences (WSIB, 2010).**

The single most common cause of a same-level fall is a slip (approximately 64% of all cases) (Cham and Redfern, 2001). Slips are commonly defined as "the loss of a stable interaction between the foot or footwear and the ground surface," usually attributed to footwear characteristics (i.e., tread material, tread hardness, tread design, etc.), flooring type (i.e., concrete, tile, ice, etc.) or contaminates from spills (i.e., oil, water, food, etc.) (Hamill and Knutzen, 1995). Slips are considered one of the most common causes of major accidental injuries; accounting for 43% of same level-fall fatalities in the workplace from 1992-1998 (Cham and Redfern, 2001). It is estimated that 3.6 million working days are lost each year due to slips and trips (Lehane and Stubbs, 2001); that consists of more than a quarter of workers who sustained same-level fall-related injuries missing 30 days or more (Cham and Redfern, 2001; WSIB, 2010). It is apparent that same-level falls are causing serious injuries, leading to missed days, costing upwards of $4.4 billion dollars a year in direct and indirect expenses (Lehane and Stubbs, 2001; Maynard, 2002). Non-spinal fractures have been one of the most common injuries reported. Same-level falls attribute to 80% of work-related fractures of the hip, wrist and ankle in women alone (Verma et al., 2008; You at al., 2001). Slips are a major hazard in any workplace as they cause severe injuries resulting in lost time and billions of dollars in claims.

The WSIB states that, "far too many workplace injuries are caused by slips, trips or falls and all of them are preventable" (WSIB, 2010). If this is the case, then why are slips and falls still one of the most common workplace safety issues costing billions? It may be that the mechanisms of slips and falls may not be clearly understood yet. Age may also be playing an important role in this issue that has not been extensively examined. It is essential to examine the previous literature to gain a better understanding of these complex issues and determine where more research is necessary. By better understanding the mechanisms of slips and falls, severe injuries and fatalities could be avoided, especially in the workplace.

1.3 Environmental Interaction: The Footwear and Floor Interface

It has been estimated that 51% (32% males, 19% females) of same-level falls in the workplace were initiated by slips that occurred due to floor contaminates (Beschorner et al., 2007). Contaminants, mainly liquid in nature, have a major effect on the footwear-floor interface increasing the potential for slips and falls. It is this environmental interaction of the footwear-floor interface that has been the focus of most of the primary research in this area. Previous literature has identified many environmental factors that will influence the potential of a slip: the type of floor, contamination and the interaction between the footwear and the floor, called the coefficient of friction (COF) (Li and Chen, 2004).

The COF is simply the ratio of shear ground reaction force, measured in the antero-posterior direction, to force normal to the interface or vertical ground reaction force. It is used to describe the relationship between the footwear and contact surface (Beschorner et al., 2007). A slip has the potential to occur when the difference between the available coefficient of friction (ACOF) and the peak required coefficient of friction (RCOF) is less than zero (ACOF-RCOF= $COF_{diff} < 0$) (Li and Chen, 2004; Hanson, Redfern and Mazumdar, 1999). The COF between footwear and a contact surface is usually measured using a sophisticated device called a 'slipmeter'. These devices work by applying a normal force (NF) at a certain angle and speed with the entire shoe outer sole in contact with the surface to determine the opposing shear force. A floor contaminate will decrease the COF by minimizing the amount of shear force that can be produced or available friction to oppose the forward translation of the heel upon contact during gait. As weight transfer begins to that foot, the NF increases, further reducing the COF. A slip is most likely to occur when NF are between 35-90% of body weight on the lead foot (Beschorner et al., 2007). The COF is a key factor in determining the risk of slips and falls especially in workplaces prone to high traffic and floor contaminants.

To prevent the occurrence of slips and falls in the workplace primary research has focused on the interaction of different footwear materials on surfaces along with different contamination types to try and maintain higher ACOF values. Thus, higher ACOF values will in turn decrease the potential for slipping, minimizing the risk of injury (Beschorner et al., 2007; Li and Chen, 2004; Hanson et al., 1999; Tsai and Powers, 2008). With respect to footwear characteristics much focus has been on the sole material, hardness and tread pattern. Tsai and Powers (2008) examined sole hardness and concluded that compared to hard soles, softer sole material will offer greater available friction on dry floors. It also has been reported that dry smooth polished floors offer sufficient COF values with most footwear soling types, with the exception of hard tipped high-heel shoes. However, if there is any possibility of a contaminant, polished smooth floors become very hazardous. Alternatively, a surface with a higher "microscopic roughness" will allow for higher COF in the events of water or oily contaminants (Manning and Jones, 2001).

Smooth soles tend to give a higher COF on dry smooth floors than a treaded sole, but a treaded sole will allow for a high COF if a contaminant was introduced by channeling the contaminant (Li and Chen, 2004). A higher COF will also be seen with an increase in microscopic soling roughness (Manning and Jones, 2001). Li and Chen (2004) determined that a tread groove pattern of 1.2 cm was most effective for providing proper channeling of water and water-detergent contaminants, but tread groove width and depth are ineffective on oily floor contaminants according to Fong et al., (2008). To address oil contaminants, Manning and Jones (2001) confirmed that the most slip resistant safety footwear soling material is a microcellularpolyurethane, known as AP6603 which has its highest degree of slip resistance following abrasion to obtain maximum roughness. This material has higher COF on oily surfaces as it is oil resistant. Higher COF are also maintained on water contaminated floors compared to other materials. Most rubbers are not oil resistant and although work well on wet surfaces may not be adequate for all work environments (Manning and Jones, 2001).

From this research basic recommendations can be made to determine which surfaces and soling are most slip resistant in the event of certain floor contaminates, but there is no guarantee that these precautions will reduce the incidence of same-level falls. The workplace safety literature demonstrates that even with these recommendations same-level slips and falls are still a serious concern (Lehane and Stubbs, 2001; Cham and Redfern, 2001; Holbein-Jenny et al., 2007; Hamill and Knutzen, 1995; WSIB, 2010; Verma et al., 2008; Maynard, 2002). It is evident that the primary research of the footwear-floor interface is underestimating the individual variability of many biomechanical factors; such as normal forces, footwear contact angle, heel velocity, stride length and loading rates to name a few. Beschorner et al., (2007) and others have reported that a single COF value from slip-meter testing may be insufficient to describe the slipping propensity of a certain footwear-floor interface as each individual has a unique gait pattern (Li and Chen, 2004; Hanson et al., 1999; Tsai and Powers, 2008). It is clear that there are just too many variables to account for when trying to prevent slips focusing on the COF. Therefore, it is necessary to take an alternative approach by determining the biomechanical aspects of a slip. A better understanding of the biomechanics may give insight into how changes to other footwear characteristics (i.e., midsoles, insoles and heel counters) will prevent or minimize the risk of falls from same-level slips.

1.4 The Biomechanics of Normal Gait

Most of the primary research has focused on environmental factors of slips and the footwear-floor interface. This information has been beneficial in making safety recommendations for footwear standards, but has not helped drastically decrease the number of same-level falls from slips in the workplace due to the number of factors involved (WSIB, 2010; Maynard, 2002). There are many biomechanical aspects of gait that may play a role as to whether an individual will slip and/or fall when a perturbation is introduced, how quickly they may detect/respond to a slip and what strategies they employ to regain their balance. All of which are variable across individuals and may degrade with age, making it difficult to predict the occurrence of an unexpected slip (Cham and Redfern, 2001; Redfern et al., 2001). Several studies have investigated many biomechanical aspects involving kinematics (i.e., joint angles, accelerations and velocities), kinetics (i.e., ground reaction forces, joint moments and muscle force) and the centre of mass base of support (COM-BOS) relationship. The most simplistic method to summarize previous literature is through a segmented model (Figure 1.2). This model is comprised of four segments: the first is called "normal gait," representing normal undisturbed gait patterns before an unexpected slip. The second segment is "slip perturbation" outlined from the heel contact of the leading leg until a slip has occurred. The third segment is "slip detection and response" describing the changes to gait as a result of the slipping perturbation along with the primary and secondary responses in attempt to regain balance. The last segment (4^{th}) is "slip outcome"; either balance is recovered or a fall occurs. Each segment will be discussed in turn.

Unexpected Slips Segmental Model

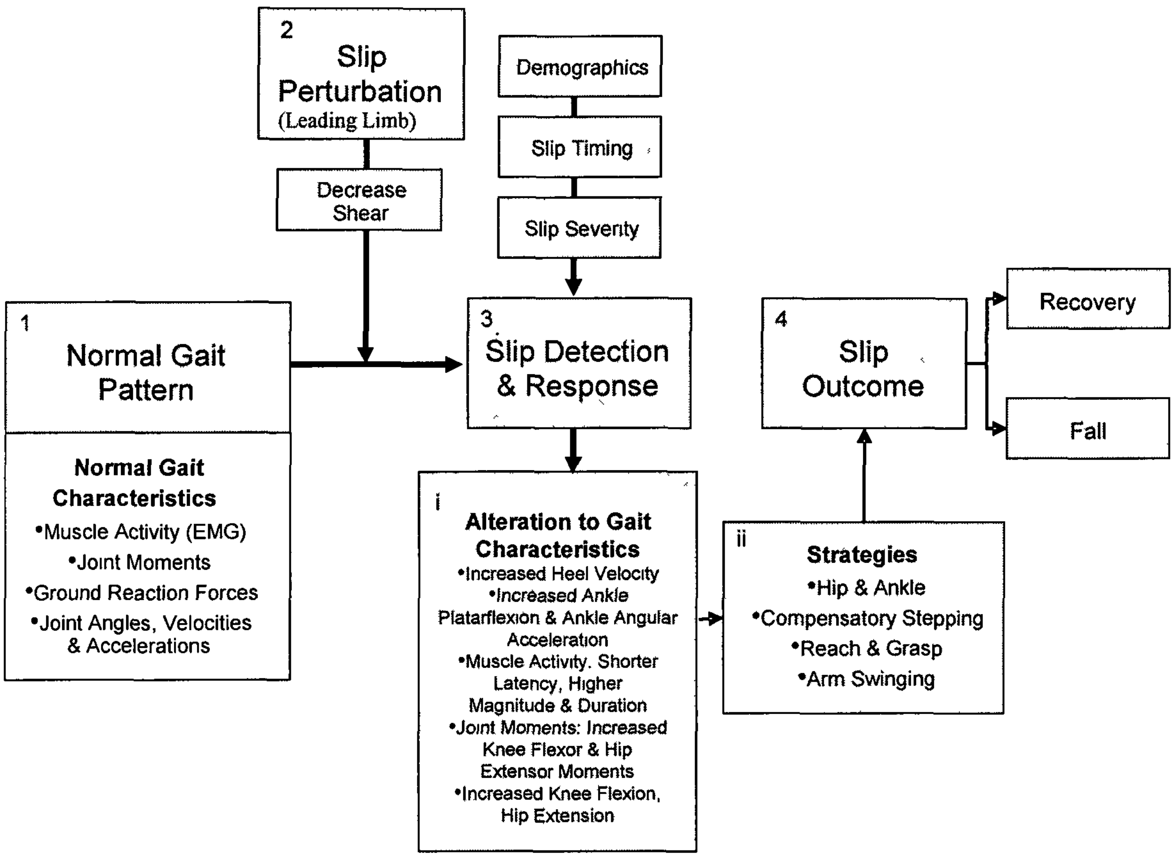


Figure 1.2: **Segmental model of an unexpected slipping perturbation, outlining previous research findings (Cham and Redfern, 2001; Redfern et al., 2001).**

1.4.1 Normal Gait Parameters

To determine disturbances in gait it is crucial to understand what the normal patterns or characteristics of gait are. In the model, the normal gait segment refers to the individual's undisturbed normal walking pattern before a slip has occurred. These patterns are described through stride length, cadence, COM-BOS relationship, normal ground reaction forces, joint angles, velocities and accelerations, joint moments and muscle activity. The normal gait segment does not only serve as a comparison against slipping trials in order to understand what occurred during the slip, but may also give insight into which characteristics make an individual more susceptible to slipping hazards; thereby developing strategies to prevent slips and falls.

Gait Velocity and Stride Length

During normal gait, gait velocity and stride length may be variable within an individual. It has been reported that the average self-chosen gait velocity is between 0.97-1.51 m/s (Redfern et al., 2001). Both gait velocity and stride length will influence an individual's slipping potential. A higher gait velocity will increase stride length and heel velocities. Therefore, greater shear forces are created at heel contact with increased stride length, affecting the COF (ratio of shear to normal force). Conversely, decreased gait velocities and stride lengths have been suggested as strategies to decrease the severity of slips and the risk of falls (Fong et al., 2008; Redfern et al., 2001).

Centre of Mass (COM) - Base of Support (BOS) Relationship

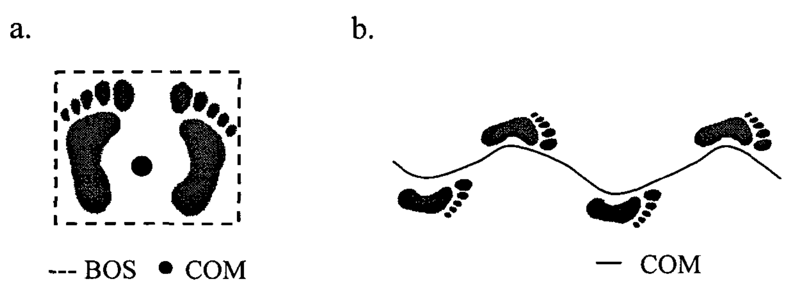


Figure 1.3: **a) depicts the COM and BOS of quiet, double support stance. b) illustrates how the COM moves within the BOS during gait.**

The COM-BOS relationship defines an individual's dynamic balance control. Manipulation of the COM within the BOS allows for everything from upright quiet stance to locomotion (Figure 1.3a) (Hamill and Knutzen, 1995). During normal gait the COM is in a constant state of motion alternating between a double and single BOS (Figure 1.3b). Gait is unstable, as the COM moves very close to the boundaries of a changing BOS. Therefore, dynamic balance during gait is very susceptible to small perturbations such as a heel contact slip.

Normal Ground Reaction Forces (GRF)

In general, the walking vertical GRF normally takes on a bimodal shape with maximum values ranging from 1-1.2 times body weight (BW). After heel contact, the whole body begins to lower until the support leg takes the full weight of the body and accelerates the mass upward again. This is represented by the first peak when the force rises above BW. The dip is a function of a slight knee flexion that occurs at mid-stance, while the shank is rotating over the foot, to continue the COM on a linear path. The forces are lower than that of the individuals BW as the COM drops slightly towards the floor, working with gravity. The last peak is above BW again, as the body actively exerts a force on the ground to allow for push-off (Figure 1.4) (Hamill and Knutzen, 1995; Redfern et al., 2001).

The GRF in the anteroposterior direction (shear force) also exhibits a characteristic shape. Maximum and minimum values usually range from ± 0.15 times BW. When the heel contacts the force plate with a positive velocity in the forward direction, friction creates a 'braking' or shear force, exerting a force back onto the heel to stop its motion. This is usually demonstrated as a negative component for the GRF (Hamill and Knutzen, 1995; Redfern et al., 2001) which peaks roughly 90-150 ms after heel contact; approximately 19% of stance (Redfern et al., 2001). Once the foot has stopped and weight acceptance occurs, the tibia rotates over the foot and force becomes positive as muscles actively propel the foot to toe-off (Figure 1.4) (Hamill and Knutzen, 1995; Redfern et al., 2001). The shear forces are highest just after heel contact and just before toe-off. This is concurrently when the RCOF, discussed earlier, are higher to decelerate the heel and conversely propel the foot forward at toe-off. As a result, an individual is most susceptible to a slip during these periods when shear forces do not meet the demands of peak RCOF. Again, heel contact is more critical as slips occurring at this time are more likely to result in falls (Hanson et al., 1999).

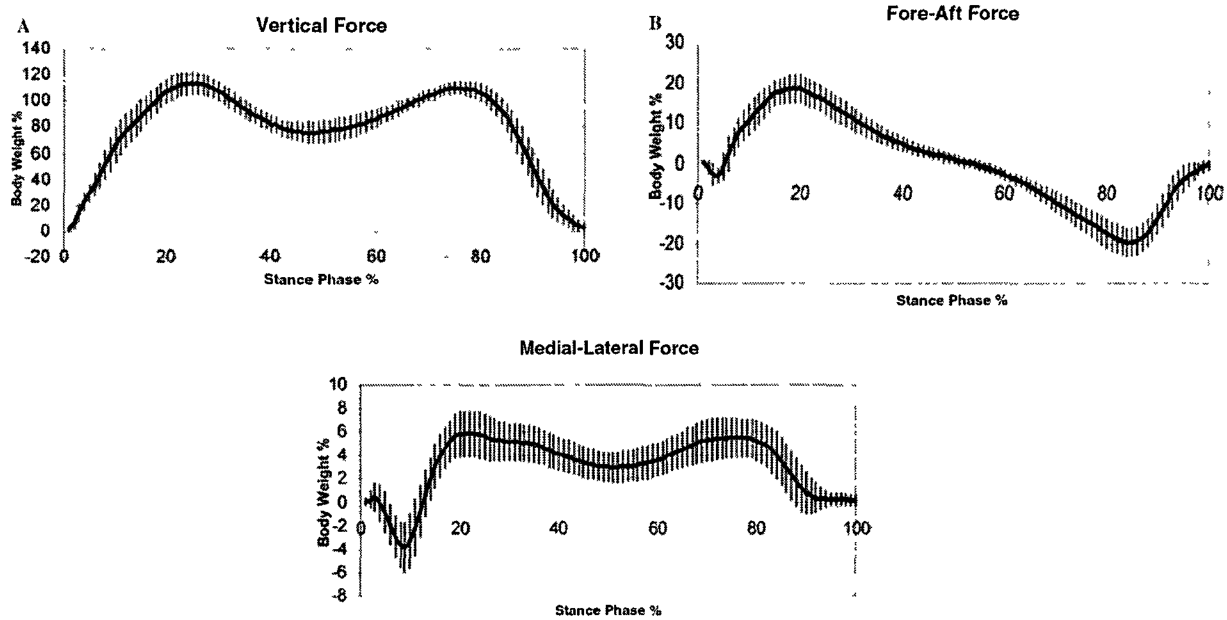


Figure 1.4: **Normal GRF during gait for the (A) vertical, (B) antero-posterior and (C) medio-lateral directions (Modified from Fig. 7, Kitaoka et al.,2006).**

Lastly, the mediolateral GRF is not as consistent as the other two components. These forces are comparatively small; range from ± 0.01 times BW. Foot placement, forefoot adduction and abduction at the ankle will affect how these forces are interpreted. These forces are also considered 'braking' or shear forces as the foot pushes on the ground to ether supinate (a combination of plantarflexion, inversion and adduction) or pronate (a combination of dorsiflexion, eversion and abduction) the foot through the gait cycle. After heel contact, the foot is slightly supinated; therefore, creating a positive mediolateral component. Shortly after heel contact the foot begins to pronate to absorb shock, this may change the mediolateral component to a negative magnitude through midstance. Nearing toe-off the foot begins to supinate again to create a rigid body to propel off of exhibiting a positive mediolateral component (Figure 1.4) (Hamill and Knutzen, 1995; Hanson et al., 1999; Redfern et al., 2001; Kitaoka et al., 2006). Mediolateral ground reaction forces have not been established as significantly effecting heel strike slips.

Ground reaction forces describe how an individual interacts with their environment during gait. Characteristics of normal gait (i.e., loading rates, foot-floor angle at heel contact, and stride length) will affect the normal and shear ground reaction forces in ways that may increase or decrease the likelihood or severity of a slip (Redfern et al, 2001; Cham and Redfern, 2001, 2002).

Normal Joint Angles

During normal gait the upper and lower thigh experience mainly flexion or extension, observed in the sagittal plane, about the hip and knee joint respectively. The torso usually exhibits very little change in orientation during normal gait (Figure 1.5) (Hamill and Knutzen, 1995; Redfern et al., 2001). The foot when viewed from the sagittal plane will also exhibit flexion and extension about the ankle axis (joint between the talus and tibia) of the ankle joint complex (AJC) known as doriflexion and/or plantarflexion, but the movement about the AJC is more complicated. The other axis in the AJC is the subtalar joint which is the articulation between the talus and calcaneous. Movement about the subtalar axis corresponds to supination and pronation of the foot; requiring three-dimensional evaluation. This location of this axis is very difficult to determine as between the calcaneous and talus is hidden within the ankle (Nigg, 1999). Therefore, movement about the ankle has been classified as dorsiflexion/plantarflexion in the sagittal plane, inversion/eversion in the frontal plane and adduction/abduction in the coronal plane, which does not relate directly to anatomical joint axes and is a two-dimensional interpretation. Supination is a combination of plantarflexion, inversion of the forefoot and adduction at the hind-foot where pronation is a combination of dorsiflexion, eversion and abduction of the forefoot (Hamill and Knutzen, 1995; Redfern et al., 2001; Nigg, 1999).

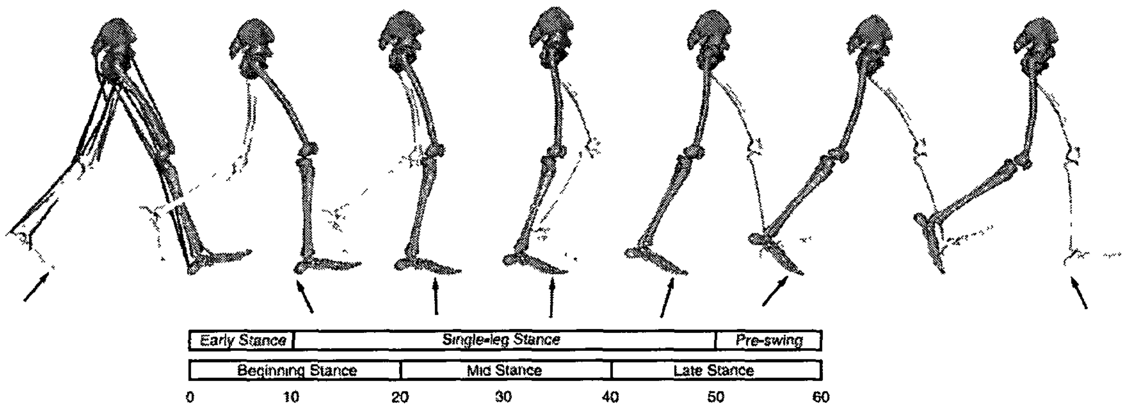


Figure 1.5: **Illustration of normal movement of the lower limb segments during the different phases of gait (Zajac et al., 2003).**

During normal undisturbed gait, the hip is in a slightly flexed position at heel contact as the upper leg is in front of the torso, approximately 165° (or 15°of flexion). During most of the stance phase the hip is in extension as the torso begins to move over the leg (i.e., forward rotation of the thigh), reaching a maximum angle of approximately 193° (or 13° of extension). At the end of stance phase, as the individual is preparing for swing phase, the hip begins to flex to swing the leg after toe-off (TO) (i.e., rearward rotation of the thigh) (Figure 1.6a) (Hamill and Knutzen, 1995; Redfern et al., 2001). The knee is almost in full extension upon heel contact (HC) (172.54°). Flexion of the knee rapidly increases as the shank rotates forward until about 30% stance (160.85°) (Cham and Redfern, 2001). Entering into single support, as the COM moves over the single leg BOS, the knee slightly extends until the last phase of stance (80%). Knee flexion begins again as the COM has moved over the support leg to prepare for toe-off and heel contact of the swing leg (Figure 1.6b) (Cham and Redfern, 2001; Redfern et al., 2001).

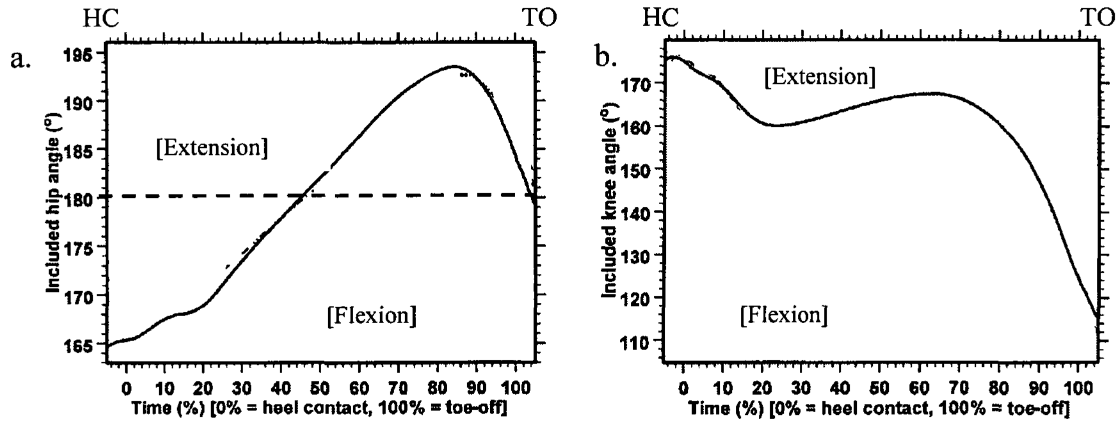


Figure 1.6: **Profiles of the hip (a.) and knee (b.) angles (°) during normal undisturbed gait (Modified from Fig. 4, Redfern et al., 2001).**

In the sagittal plane the ankle is in a neutral to slightly dorsiflexed position at heel contact. Once the heel contacts the ground, the ankle passively plantarflexes until foot flat is reached, approximately 10% stance (Hamill and Knutzen, 1995; Redfern et al., 2001; Kitaoka et al., 2006). Through midstance passive dorsiflexion occurs about the ankle joint as the shank rotates over the foot to a maximum of 6.5° in late stance (Kitaoka et al., 2006). Nearing the end of stance (80%) active plantarflexion begins as the heel comes off the floor to allow for toe-off (Figure 1.7a) (Hamill and Knutzen, 1995; Redfern et al., 2001; Kitaoka et al., 2006). In the coronal plane, the ankle exhibits inversion and eversion about the ankle joint, averaging 10.8° of motion. Along with dorsiflexion, at heel contact the ankle is slightly inverted, everting to absorb shock throughout midstance (20-80%) to a maximum of 4.4°in late stance (Hamill and Knutzen, 1995). Nearing the end of stance phase the ankle begins to invert again to allow for a rigid foot structure for toe-off (Figure 1.7b). Transverse motion is expressed as internal or external rotation (adduction/abduction) about the ankle, averaging 4.8° of motion. At heel contact the foot is slightly abducted or externally rotated, internally rotating through midstance. The foot slightly abducts again at approximately 80%, then adducts until toe-off (Figure 1.7c) (Kitaoka et al., 2006).

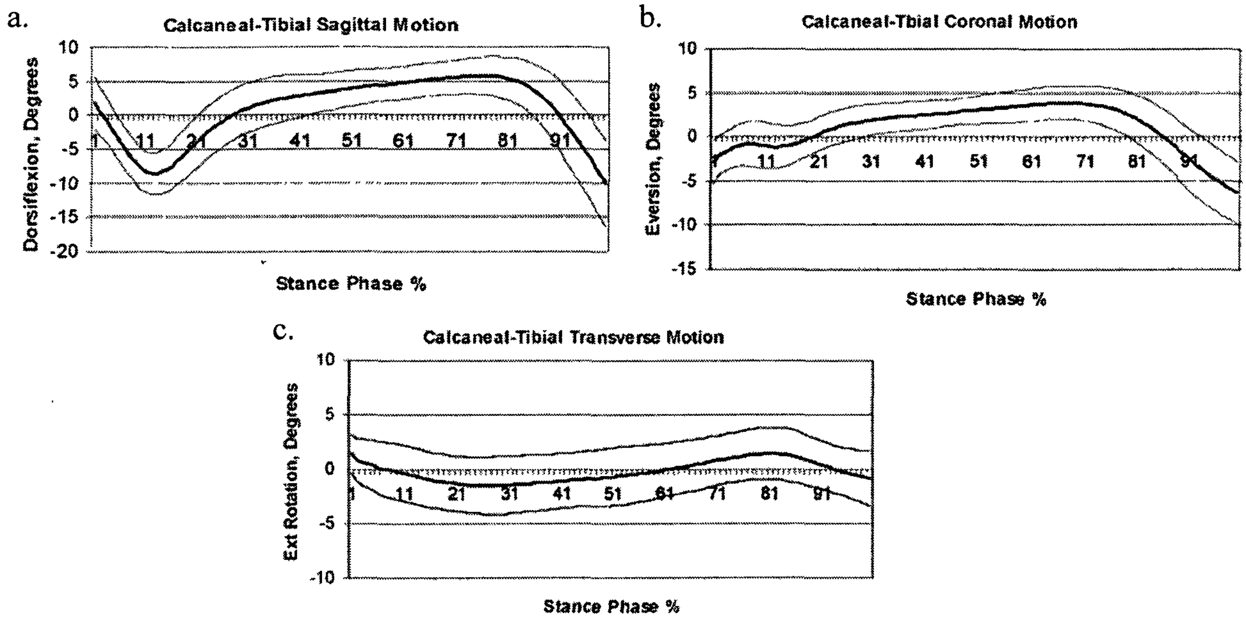


Figure 1.7: **Motion about the ankle joint (tibia and calcaneous) in the a) sagittal , b) coronal and c) tranverse planes. HC at 0%, TO at 100% stance (Modified from Fig. 5, Kitaoka et al., 2006).**

Velocities and Accelerations

With respect to velocities, during normal gait, the heel may be travelling between 0.14 m/s and 0.68 m/s during the 60 ms before heel contact (Strandberg, 1983). The heel has been shown to decelerate (−24.86 m/s) until heel contact and then slides very briefly (< 0.1 m/s, < 1.0 cm) (Redfern et al., 2001). When the heel makes contact (0% stance), the heel impact velocity is positive (forward motion, 0-8%) and may even be slightly negative (rearward motion, 9-11%) before coming to a complete stop (Figure 1.8). At heel contact normal ankle angular velocities average roughly 223.8°/s ± 98.4 (Cham and Redfern, 2001). Heel velocities at heel contact are an important predictor of slips. Higher heel velocities and slower heel decelerations may increase risk of falls when a slip occurs (Redfern et al., 2001, Cham and Redfern, 2001, 2002).

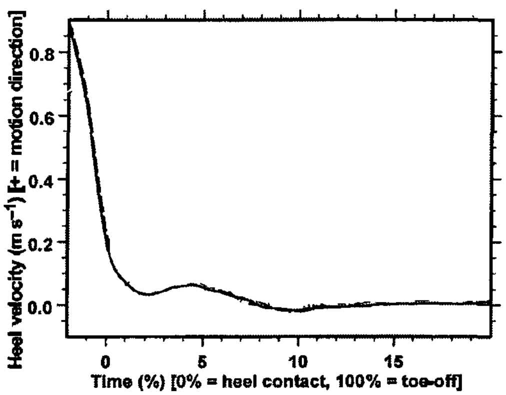


Figure 1.8: **Heel velocity before heel contact until the heel reaches foot flat and comes to a stop around 15% stance. HC at 0% stance. (Modified from Fig. 3, Redfern et al., 2001).**

Muscle Activity and Joint Moments

Intricate coordination and timing of muscles/muscle groups make it possible to achieve movement such as gait. Electromyography (EMG) is used to determine muscle activation timing, duration and magnitude, while inverse dynamics allows for the calculation of joint moments or torques. Together with joint kinematics they create a better understanding of how movements is being produced; which muscle groups are active and whether they are working concentrically, eccentrically or isometrically.

At heel contact (0% stance) the tibialis anterior (TA) switches from actively dorsiflexing the foot at the ankle to working eccentrically (Figure 1.9 d) to oppose plantarflexion (Figure 1.9 ci) (Redfern et al., 2001) creating a dorsiflexor moment (Figure 1.9 cii) (Cham and Redfern, 2001; Zajac et al., 2003). The gluteus maximus (GMAX) is working concentrically along with the hamstrings (HAM) to create an extensor moment at the hip (Figure 1.9 aii) while simultaneously creating a flexor moment at the knee (Figure 1.9 bii) (Cham and Redfern, 2001; Zajac et al., 2003); initiating hip extension and knee flexion after heel contact (Figure 1.9 ai, bi) (Redfern et al., 2001). The vasti group (VAS) mainly works to allow for forward progression of the trunk as well as contributing slowing the forward progression of the lower leg; decelerating knee flexion to help maintain and upright position (Figure 1.9 b). The rectus femoris (RF) of the quadriceps, although active during early stance, is not as important as the VAS and works antagonistically to support hip and knee extension (Figure 1.9 a, b) (Redfern et al., 2001; Zajac et al., 2003).

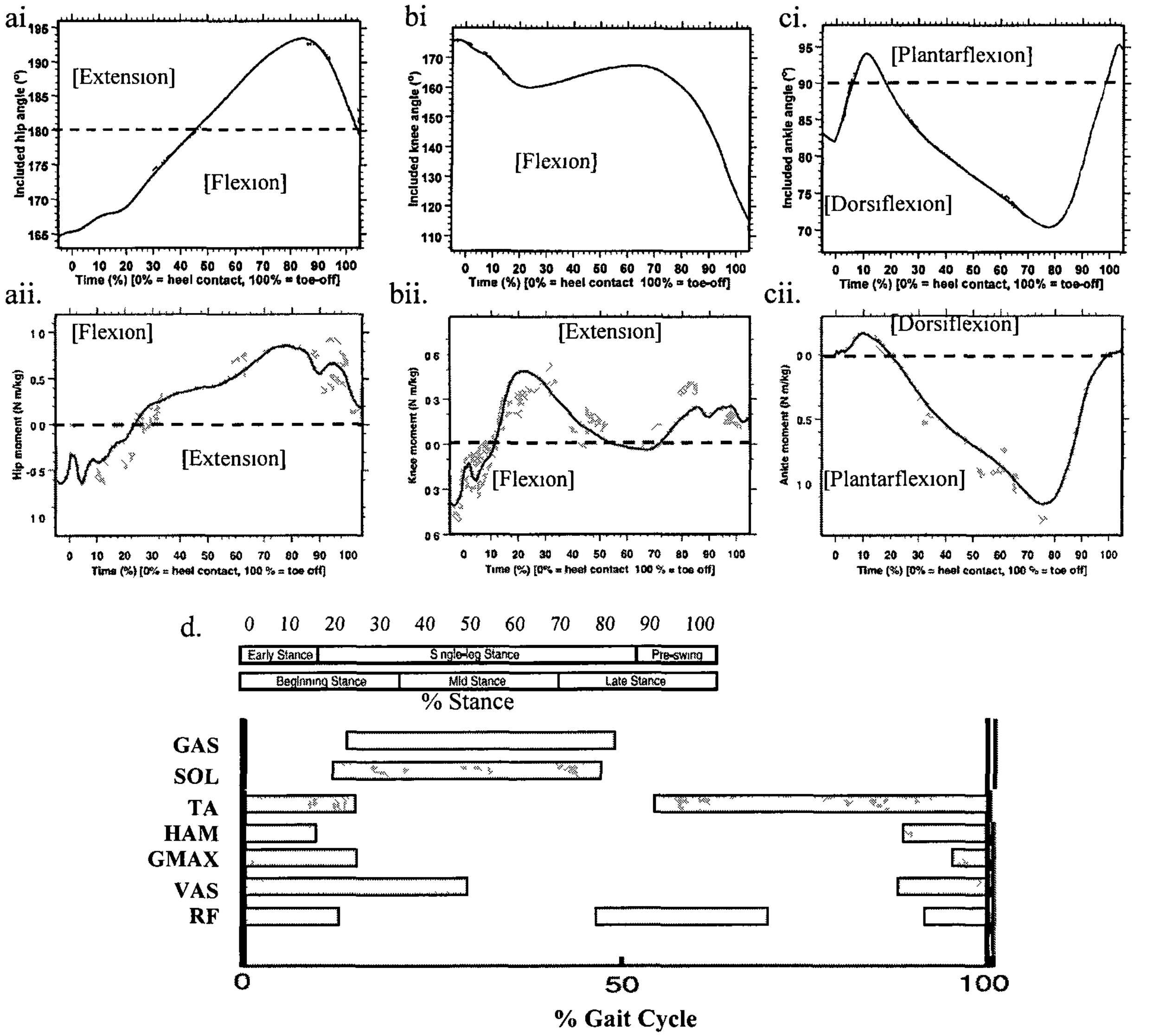


Figure 1.9: **Illustrating a.) hip, b.) knee, and c.) ankle kinematics (i) along with their respective joint moments (ii). Muscle activation is shown in d.) which is given over a whole gait cycle (0-100) refer to % stance above graph (Modified from Fig. 1, Cham and Redfern, 2001; Modified from Fig. 1 and Fig. 2, Zajac et al., 2003).**

During single stance (~25-85% stance), the gastrocnemius (GAS) and soleous (SOL) are active (Figure 1.9 d) generating a strong plantarflexor moment peaking at maximum ankle dorsiflexion, approximately 80% stance (Figure 1.9 ci) (Cham and Redfern, 2001; Hamill and Knutzen, 1995; Redfern et al., 2001; Zajac et al., 2003). The SOL primarily contributes to the forward progression of the trunk, while the GAS works to initiate the swing phase as they both accelerate the foot into plantarflexion by creating upward "intersegmental forces" in both the ankle and knee (Figure 1.9 ci) (Cham and Redfern, 2001; Redfern et al., 2001; Zajac et al., 2003). Just before maximum knee and hip extension is achieved (~80-90% stance) (Figure 1.9 ai,bi), the RF lengthens to accelerate the knee and hip into extension (Figure 1.9 bii) before toe-off (Redfern et al., 2001; Zajac et al., 2003). As toe-off begins to occur (90-100% stance) and body weight begins to transfer to the contralateral leg, the forward progression of the trunk and flexion at hip by the RF allow for the swing phase to occur. The TA is activated at the end of stance to once again (Figure 1.9 d) to dorsiflex the foot at the ankle (Figure 1.9 ci) allowing for clearance of the ground during the swing phase (Cham and Redfern, 2001; Hamill and Knutzen, 1995; Redfern et al., 2001; Zajac et al., 2003).

1.5 The Biomechanics of a Slip

1.5.1 Slip Perturbation

Understanding the biomechanics of normal undisturbed gait has been beneficial in the study of slipping. By having a clear understanding of what is expected during normal gait one can then begin to analyze and compare what happens during a slip to isolate the potential causes. In many slipping situations, the primary reason for the slip is due to a reduction in ground reaction forces available; most importantly shear force. As a function of inappropriate footwear or when the contact surface's available friction decreases due to changes in surface characteristics, most commonly a spill or contaminate, the shear to normal force ratio (COF) decreases (Redfern et al., 2001).

Slipping perturbations that are more likely to result in a fall or severe slip are reportedly occurring at heel strike (Kojima et al., 2008). The severity of the perturbation increases as the 'achievable coefficient of friction' decreases (Hanson et al., 1999) (Figure 1.10). Studies have demonstrated that level-surface slips generally occur 100 ± 150 ms after heel contact. The ACOF during slip-recovery trials is approximately 0.11 (± 0.04) compared to slip-fall trials averaging 0.04 (± 0.02); with ACOF as low as 0.02. The ACOF for grip (or non-slip) trials is approximately 0.17, but mini-slips have been found to occur with ACOF as high as 0.15 (Redfern et al., 2001).

There are also several characteristics of normal gait that affect the COF-GRF relationship and are associated with an increased risk of slipping or falling. Individuals with faster loading rates are at an increased risk of slipping due to a faster transfer of weight to the support limb. This will also be evident with earlier normal force and shear force peak timing. Secondly, individuals who have relatively long stride lengths or larger foot-floor angles at heel contact will increase the amount of shear force present during walking. This will affect the shear to normal force ratio increasing the RCOF to prevent a slip (Redfern et al., 2001). A relationship between higher heel velocities, lower heel decelerations and slower foot angular velocities at heel contact and an increase risk of slipping has also been identified (Cham and Redfern, 2001, 2002; Redfern et al., 2001). It is important to understand that all of these factors interact with each other and therefore, it is not just one individual factor that can predict the severity or likelihood of a fall occurring.

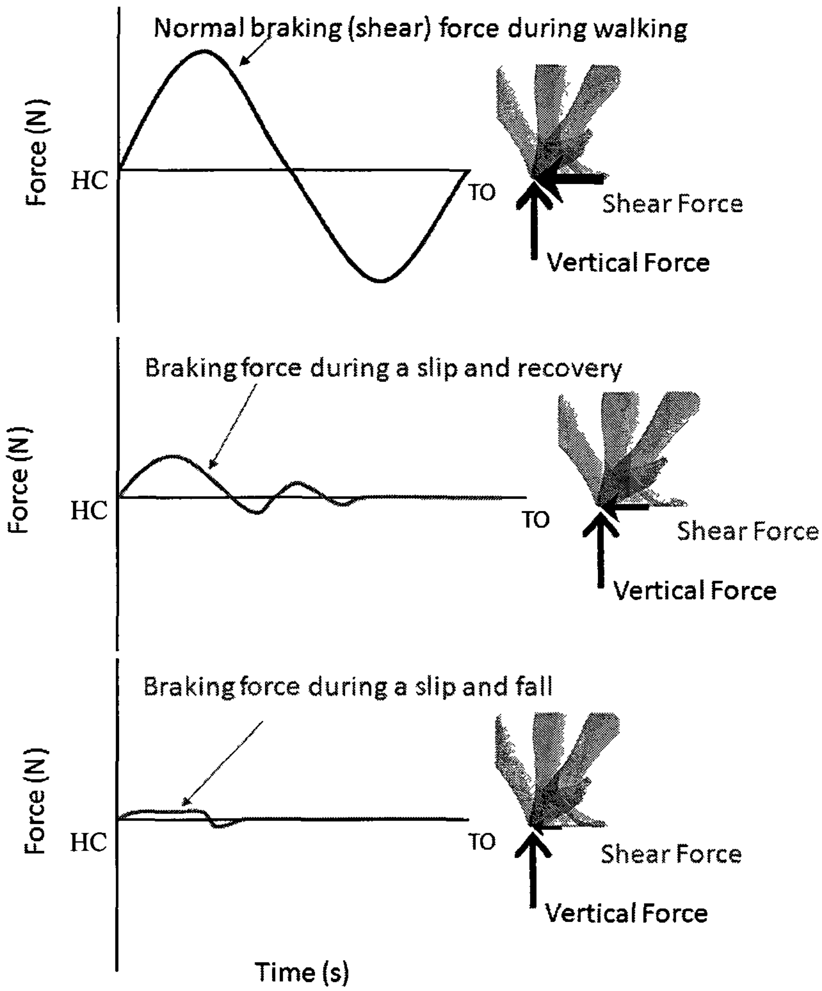


Figure 1.10: **Illustrates the reduction in shear/breaking force as slip severity increases (Hanson et al., 1999; Redfern et al., 2001). Heel contact (HC) and toe-off (TO).**

1.5.2 Slip Detection and Response

With a reduction in normal and shear forces, a slip perturbation changes normal gait characteristics shortly after heel contact (50 ± 100 ms) (Cham and Redfern, 2001). Again, normal gait characteristics have been utilized to identify these changes to determine the natural detection and response customary in active balance recovery attempts. Once these changes in gait occur, they must be detected quickly to generate effective corrective responses. Initial responses are controlled either by 'supraspinal loops' or 'polysynaptic spinal reflex'. This is evident due to short onset muscle latency, occurring approximately 65 ± 110 ms after heel strike (Tang et al., 1998).

The initial response works primarily to bring the BOS back under the COM. The secondary response is a 'compensatory reaction' to assist in the continuation of gait when a fall has been avoided (Redfern et al., 2001; Tang et al., 1998). The compensatory reaction is not limited to the leading limb and studies have investigated strategies of the trailing limb and upper body (Kojima et al., 2008; Moyer et al., 2009; Marigold et al., 2003). How one responds to a slip will depend on how quickly it can be detected and the severity due to low ACOF. The detection and response to a slip is described by changes in ground reaction forces, angles, velocities and accelerations, muscle activity and joint moments in both the leading and trailing limbs.

Leading Limb

Ground Reaction Forces (GRF): As mentioned previously during a slip, the ratio of shear (anteroposterior forces) to normal (vertical forces) GRF decreases with increased severity. The reduction in shear force is due to the footwear-floor interface (i.e., inappropriate footwear, flooring and/or contaminant). Ultimately the decrease in shear or breaking force results in a forward translation of the heel, altering the normal ankle trajectory and pressure under the stance foot. Even small changes in the biomechanics of gait will cause initial corrective response to support the continuation of normal gait (Redfern et al., 2001).

Angles, Velocities and Accelerations

With a decrease in shear force opposing the heel at heel contact, there is an increase in linear heel velocity at impact (Figure 1.11 a) (Redfern et al., 2001). After heel contact there are higher ankle angular velocities as the foot accelerates forward into plantarflexion (Figure 1.11 b) (Cham and Redfern, 2001). This subsequently causes extension of the hip and knee. When the translation of the foot is detected, there is an attempt to regain natural ankle trajectory by slowing down the heel to bring the BOS back under the COM (initial response). This is accommodated by greater knee flexion and hip extension, sometimes causing the heel to slide in the rearward direction (Figure 1.11 a.) (Cham and Redfern, 2001; Redfern et al., 2001). Studies have shown that slips are most likely to result in a fall when peak heel velocities are greater than 0.5 m/s or if the slip distance exceeds 0.1 m (Redfern et al., 2001). If detected quickly the velocity of the heel can be controlled and slowed enough to regain normal joint trajectories to avoid a fall.

a.

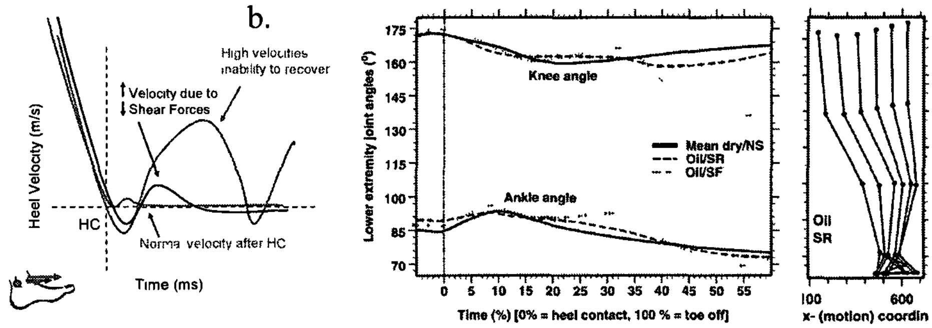


Figure 1.9: **a) Illustrates the linear impact heel velocity and translational heel velocity during a slip. b) Illustrates an increase in plantarflexion, knee flexion and hip extension after heel contact in slip-recovery and slip-fall trials (Modified from Fig. 4 and 5, Cham and Redfern, 2001).**

Muscle Activity and Joint Moments

When a slip occurs, irregular plantarflexion at the ankle and extension at both the hip and knee result. In order to avoid a fall, primary muscles of the lower limb and thigh must work in sequence to generate the quick reactive response described above (Chambers and Cham, 2007). Tang et al., (1998) demonstrated that there is earlier activation of the anterior leg muscles as well as both anterior and posterior thigh muscles during a slipping perturbation compared to normal gait. This is illustrated by relatively shorter latency (90-140 ms), high magnitudes (4-9 times muscles activity during normal gait) and relatively long durations (70-200 ms). Furthermore, this response maintains a distal to proximal activation sequence (i.e., tibialis anterior – rectus femoris – abdominals) relative to the severity of the slip (Tang et al., 1998).

Within slip perturbation literature, movement about the ankle has been classified as dorsiflexion/plantarflexion in the sagittal plane. This two-dimensional interpretation does not relate motion at the ankle directly to an anatomical joint axis. Studies have reported that a slip causes an increase in plantarflexion at the ankle just after heel contact (Kojima et al., 2008). Upon detection of the heel translation, the initial response is for the tibialis anterior to contract, creating a dorsiflexion moment to counteract the plantarflexion (Kojima et al., 2008; Chambers and Cham, 2007; Tang et al., 1998). A maximum dorsiflexion angle (approximately 5.6°) is reached earlier than in normal gait (Kojima et al., 2008). At this time the gastrocnemius is suppressed (Figure 1.12 a) (Chambers and Cham, 2007; Tang et al., 1998). During hazardous slips, the achievement of foot flat was delayed due to greater TA activation. Redfern et al., (2001) reported that foot flat was reached in all non-fall slip trials indicating its importance to carry on with normal gait. It is also important to mention that during hazardous slips there is a null or passive ankle moment which may indicate co-contraction of the ankle muscles, never allowing for the achievement of foot flat and resulting in a fall (Chambers and Cham, 2007).

The forward translation of the ankle due to a heel contact slip causes involuntary knee extension and hip flexion moving the COM more anterior to the BOS. During the initial response the biceps femoris, first contracts concentrically then eccentrically, and the rectus femoris eccentrically activate (Tang et al., 1998) to generate a flexor moment at the knee and an extensor moment at the hip. This opposes the initial movements caused by the slip and allows for increased knee flexion to bring the foot back towards the body in attempt to restore normal joint trajectories (Figure 1.12 b, c). The secondary response is associated with activation of the medial gastrocnemius to create a plantar flexion moment at the ankle (Figure 1.10 a). An extensor moment is generated at the knee along with an extensor moment at the hip to prevent the knee from buckling in attempt to continue with normal gait (Figure 1.10 b, c). Inefficient extensor knee moments later in stance have been associated with falls more commonly seen in elderly individuals (Chambers and Cham, 2007).

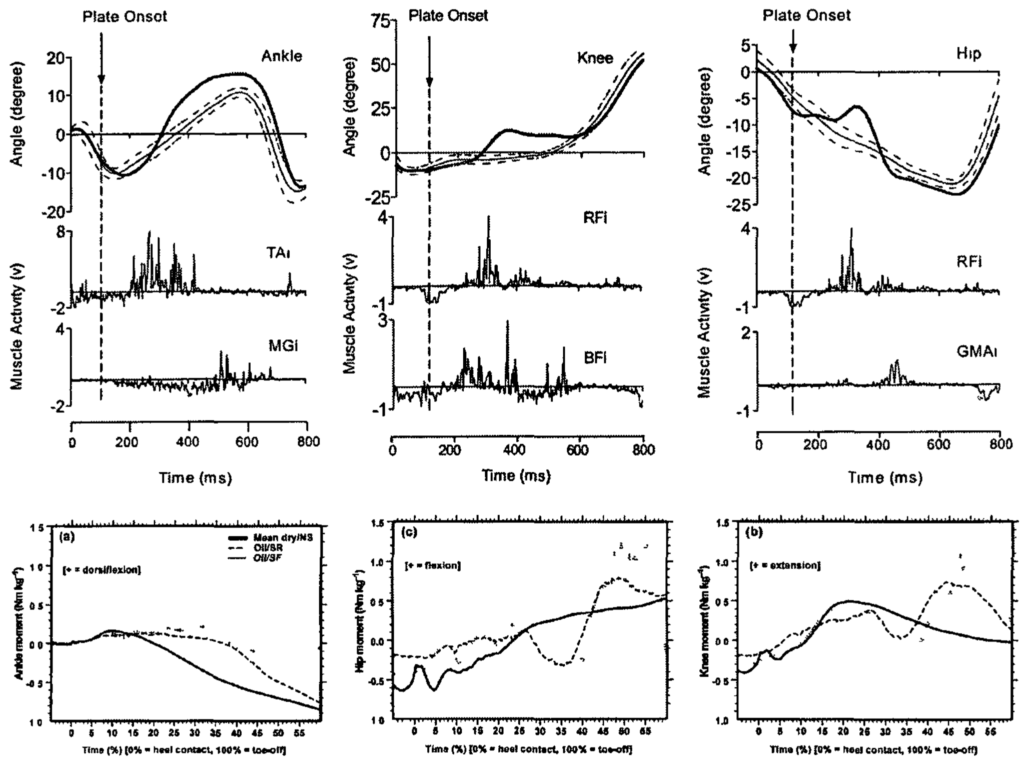


Figure 1.10: Illustrates the joint angle, muscle activation and joint moments for the a) ankle, b) knee and c) hip during normal gait compared to slip-recovery and slip-fall trials (Modified from Fig. 2, Cham and Redfern, 2001; Modified from Fig. 4, Tang et al., 1998).

Trailing Limb

The focus of early slipping research has been on the reactive strategies of the leading limb. More recent studies have identified the importance of the trailing limb in active balance recovery. Compensatory stepping is used mainly to widen the BOS as the trailing limb deviates from its normal gait trajectories. This strategy is used during a forward slip, especially after toe-off of the trailing limb has occurred. The trailing foot is placed on the ground somewhere behind the leading limb (Kojima et al., 2006; Marigold et al., 2003). The extent to which this strategy is utilized depends on the timing of the slip, slip severity and age. Several studies have demonstrated that the trailing limb responses have shown evidence of inter- and intralimb coordination (Kojima et al., 2006; Marigold et al., 2003; Moyer et al., 2009).

Moyer et al., (2009) categorized the trailing limb responses into four categories relating to an increase in slip severity. A 'minimum' (MIN) response occurred with less severe slips where the trailing limbs trajectory was similar to that of normal gait. The 'foot-flat' (FF) response was characterized by the placement of the entire sole of the shoe slightly behind the leading foot. A 'mid-flight' (MID) response was characterized by the forefoot contacting the ground more rapidly and posteriorly that the FF response. Lastly, the 'toe-down' (TD) response involved just the tip of the forefoot contacting the ground more anteriorly than the MID response (Figure 1.11).

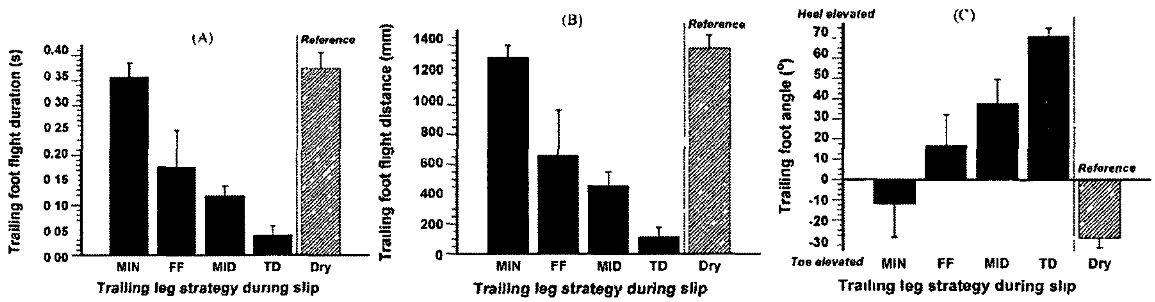


Figure 1.11: **Identifies the differences in foot flight duration, distance and foot angle between compensatory stepping responses (Modified from Fig. 1, Moyer et al., 2009).**

Muscle Activity and Joint Moments

Corrective moments of the trailing limb consisted of flexor and extensor moment occurring simultaneously at the knee and hip respectively at approximately 30% into stance.

These moments occurred in all categories except MIN as the trajectory of the trailing limb is least disturbed (Figure 1.12) (Moyer et al., 2009). These findings are further attenuated, as early activation of the TA, RF and BF have been reported in the trailing limbs response. The activation of the TA while the MG is suppressed allows for dorsiflexion of the trail limb ankle to reduce the risk of tripping. The RF contracts to extend the knee controlled antagonistically by the BF while the hip extends (Marigold et al., 2003). Inter-limb coordination demonstrates that the trailing limb plays an important role in overall active balance recovery and should be incorporated in strategies to decrease the risk of falls (Marigold et al., 2003; Tang et al., 1998; Moyer et al., 2009).

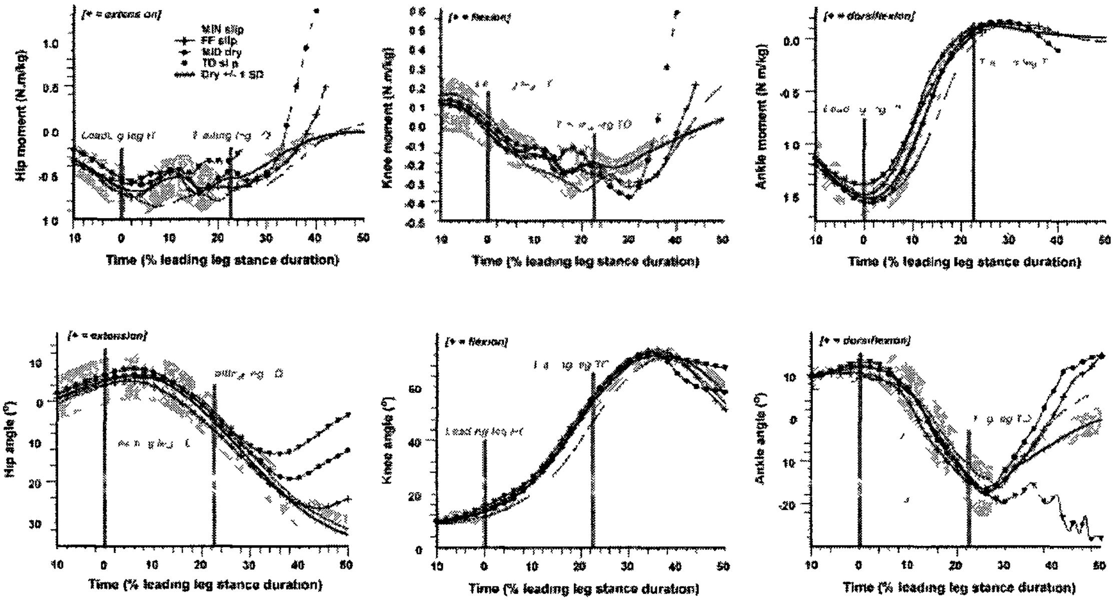


Figure 1.12: **Illustrates the moments and angles of the hip, knee and ankle for the unperturbed trailing limb in slip trials (Modified from Fig. 2, Moyer et al., 2009).**

1.5.3 Slip Outcome

The final segment in the model refers to the outcome of an unexpected slipping perturbation; whether an individual were able to regain their balance or succumb to a potentially hazardous fall. The outcome of an unexpected slip is dependent on several key factors. The characteristics of the individual (i.e., age, reflexes, health, muscle/bone strength, etc.) are major determining factors. Younger individuals may have better reactive abilities as they are generally in good health; have quicker reflexes, stronger muscles and bones allowing for more effective and efficient reactive balance recovery responses (Perry et al., 2007; Son et al., 2009). Furthermore, the risk of severe injury in younger individuals due to a hazardous slip is far less than in an older population (Verma et al., 2008; You et al., 2001; Perry et al., 2007; Son et al., 2009; Menant et al., 2009).

Another key variable that is characteristic of the slip is the function of environmental factors such as the type of contaminant or footwear-floor interface. Most of the primary research has focus on the footwear-floor interface and its contribution to slipping (Li and Chen, 2004; Hanson et al., 1999; Tsai and Powers, 2008; Manning and Jones, 2001). These studies have helped in the development of less slippery floors and soles, but the risk of slipping on a contaminant is still too great. Considering that these innovations have not been able to drastically reduce the number of same level falls in the workplace from slips demonstrates that other factors potentially override the footwear-floor interface when a contaminant is introduced. The risk of a fall is imminent in any situation where the slip distance exceeds approximately 0.1 m. If the slip is not detected quickly enough and the ACOF is too low, a slip will be quicker and farther; allowing the heel velocity to exceed 0.5 m/s which also increases the risk of a fall (Redfern et al., 2001).

Strides have been made in attempt to address the risk of hazardous falls in the workplace. Even with slip resistant floors and appropriate footwear the risk of a fall and severe injury is still too great. It may in fact be other footwear characteristics that effect normal foot motion during the response to the slip that are increasing the risk of a fall when an individual slips (Lehane and Stubbs, 2001; WSIB, 2010; Verma et al., 2008; Maynard, 2002).

As a function of previous research, it is clear that it is difficult to decrease the risk of an unexpected slip due to contaminants. Further investigation is needed to understand how the body detects and responses to unexpected slips. A three dimensional analysis of the tri-planar motion of the subtalar joint and its role in the detection and response to a slip has never been examined. Determining the function of the subtalar joint during an unexpected slip may be important in the prevention of falls. By gaining a better understanding of the subtalar joints role in the response to a slip, footwear characteristics that may ultimately modify its function could affect the response to slips.

1.6 Definition and Function of the Subtalar Joint

1.6.1 Definition of the Subtalar-joint

The ankle joint complex consists of two major axes: the ankle and subtalar axes (Figure 1.15 b) (Nigg and Herzog, 1999). The ankle or talocrural joint is formed by articulations between the tibia and fibula (tibiofibular joint), and the tibia and talus (tibiotalar joint) creating a uniaxial hinge joint. This joint runs medio-laterally through the malleoli, oblique to the tibia, allowing for approximately 50° of plantarflexion and 20° of dorsiflexion (Figure 1.15 e). Normal gait averages 20° of dorsiflexion and 20-25° of plantarflexion (Hamill and Knutzen, 1995). Ankle motion reported in most slipping research has limited the ankle complex to motion in two-dimensions about this axis. This study will expand previous research by investigating motion about the subtalar joint axis in three-dimensions.

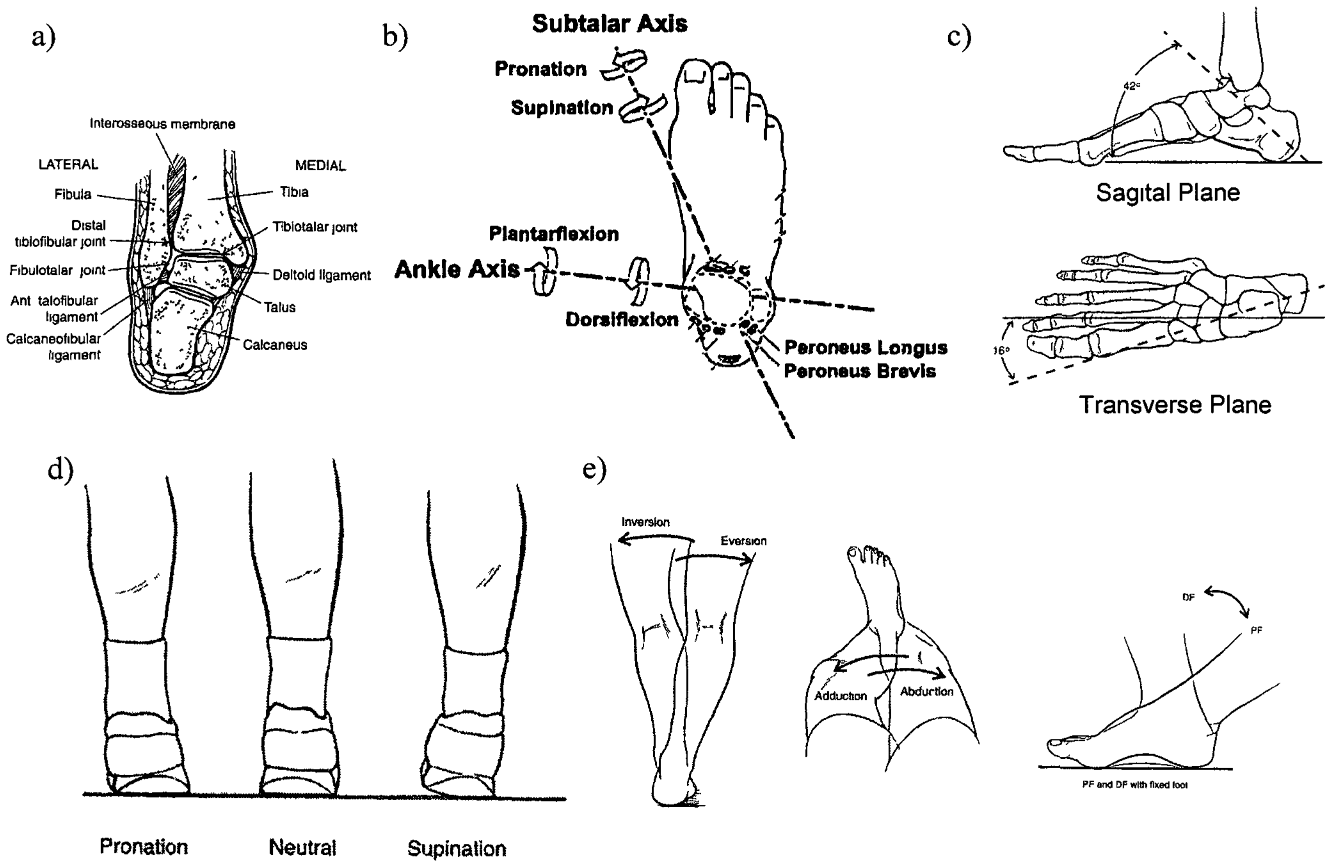


Figure 1.15: **a) illustrates the bones that form the joints of the ankle complex, b) identifies the two axes of the ankle complex, d) illustrates the oblique nature of the subtalar joint axis, d) and e) illustrate the moevemetn associated with the ankle complex and subtler joint (Nigg and Herzogg, 1999; Modified from Fig. 6-33, 6-36 and 6-37, Hamill and Knutzen, 1995).**

The subtalar joint or talocrural joint is formed between the talus and calcaneous (Figure 1.15 a), the largest weight bearing bones of the foot. The convex surface of the talus sits into the concave surface of the calcaneous forming the hind foot, articulating at the anterior, posterior and medial sites. The subtalar joint axis runs obliquely from the 'posterior lateral plantar surface' to the 'anterior dorsal medial surface' (Figure 1.15 b), allowing for tri-axial motion. The axis is slanted approximately 16° antero- medially from the longitudinal axis and inclined 42° antero-superiorly up from the horizontal axis in the sagittal plane (Figure 1.15 c). Motion occurring about this axis is defined as pronation (a combination of dorsiflexion (DF), abduction (AB) and calcaneal eversion (EV)) and supination (a combination of plantarflexion (PF), adduction (AD) and calcaneal inversion (IV)) (Figure 1.15 d) (Nigg and Herzogg, 1999; Hamill and Knutzen, 1995). The motion of the subtalar joint has been difficult to measure due to its oblique axis and that the talus is hidden internally in the ankle. As a result, motion at the ankle is typically defined unrelated to an anatomical joint: plantar-dorsiflexion about medio-lateral, ab-adduction about a superior-inferior and in-eversion about an anterior-posterior axis (Figure 1.15 e) (Nigg and Herzogg, 1999).

1.6.2 Function of the Subtalar-joint

The primary function of the subtalar joint is to absorb internal and external rotation of the femur and tibia during stance by opposing the movement with pronation and supination respectively. Shock absorption is the second major function of this weight bearing joint, achieved through pronation upon heel contact. This allows unlocking at the knee joint as the tibia internally rotates faster than the femur. During normal gait, the foot is in a slight supine position (approximately 3°) before heel contact. As the heel contacts the ground the subtalar joint immediately begins to pronate; the foot is plantarflexed to reach foot flat and the talus rotates medially on the calcaneous. Maximal pronation is normally reached around 35-45% stance phase at a range of 3-10°. Once foot flat has been achieved, the tibia begins to externally rotate as the shank moves of the foot. This results in supination at the subtalar joint (3-10° until heel-off) creating a more rigid body for toe-off (Figure 1.16) (Hamill and Knutzen, 1995, Arndt et al., 2004).

The subtalar joint may play a key role in the reaction to a slip perturbation. Therefore, an investigation of normal subtalar joint motion during a slip perturbation in barefoot individuals in needed. Furthermore, footwear characteristics may change the way the subtalar joint functions during gait (i.e., limiting supination or pronation, changing foot-floor angles or effecting foot angular velocities upon heel contact) which would change its normal function during a slip recovery. Further investigation into how different footwear characteristics affect normal subtalar joint motion is also important.

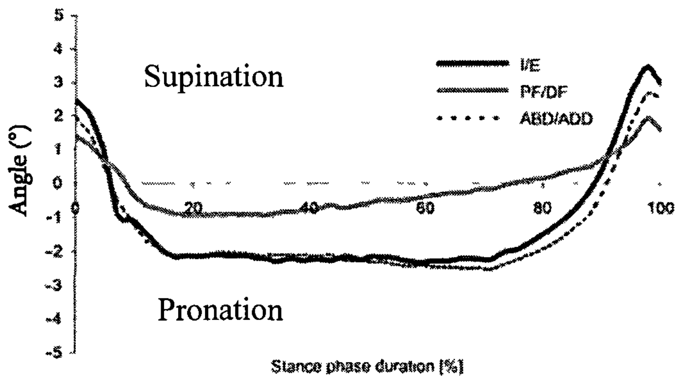


Figure 1.16: **Illustrates the movement about the about the subtalar joint axes. Supination is a combination of inversion, platarflexion and abduction while pronation is the contrary (Modified from Fig. 5, Ardnt et al., 2004).**

1.7 The Interaction of the Footwear Characteristics on Balance Control

It is generally accepted that footwear with treaded soles will afford more traction on most surfaces compared to flat soled footwear (Li and Chen, 2004; Tsai and Powers, 2008). Furthermore, different flooring types and soling material have an effect on the COF (Li and Chen, 2004; Manning and Jones, 2001), but statistics have shown that tread alone will not significantly decrease the risk of hazardous slips when there is a risk of contaminants such as oil, water or ice (WSIB, 2010; Maynard, 2002; Hanson et al., 1999; Manning and Jones, 2001). Investigation of the role of the subtalar joint axis in active balance recovery may be the key in beginning to understand how other footwear characteristics may contribute to the high incidence of falls in the workplace. This study will examine new territory by directing attention to the interaction of the foot and the footwear characteristics (i.e., insole stiffness and heel counter stiffness) during a slip where previous research had focused more on the interaction of the footwear characteristics (i.e., sole material, stiffness and type) and the environment (Figure 1.17).

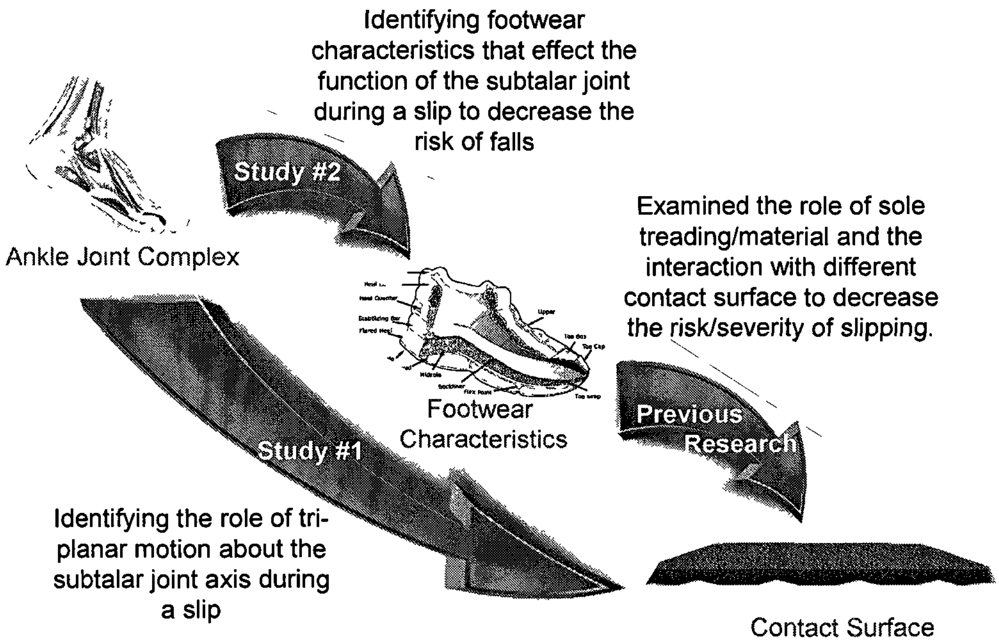


Figure 1.13: **A model outlining the progression of research with respect to previous studies.**

Many footwear characteristics have been investigated in relation to balance and stability during gait, but very little research has explored footwear characteristics and the effect on slip recovery. Dai et al (2006) examined insole friction and the effect of socks on biomechanical responses during gait. Socks with higher friction against the foot tend to decrease the shear force between the foot and the footwear causing slippage within the footwear. The foot has the most potential to slip within the footwear from foot-flat until mid-stance and then again at toe-off. The heel slipping within the footwear my exaggerate the response to minor slips and diminish the ability to respond effectively to more hazardous slips.

Midsole stiffness has been found to play an important role in balance. Softer soles are associated with a reduction in mechanical support to manipulate the COM, requiring larger mechanical responses to balance perturbations compared to barefoot or harder sole conditions. Furthermore, sensory information needed to provide an effective response may be dampened by the softer material (Perry et al., 2007). A softer midsole material may dampen the ability to detect the initiation of a slip as well as decrease the ability of the subtalar joint to respond appropriately.

Sensory information provided by cutaneous feedback from the plantar-surface of the foot has been found to play an important role in balance and corrective strategies. Textured insoles have been found to create significant changes in the activity of both the ankle flexors and extensors, influencing ankle kinematics as well as knee joint moments. Decreased activity in the soleus and tibialis anterior were reported as causing increased plantarflexion at heel contact. Heel contact was associated with a period when the plantar surface is most sensitive to stimuli and may hinder the ability to respond effectively to a slip (Nurse et al., 2005).

On the contrary, Perry et al., (2008) investigated SoleSensor™ inserts and found that they improve balance and stability during normal gait in an older population. Insoles consisting of a raised ridge around the edge of the insole stimulated the cutaneous mechanoreceptors near the periphery of the plantar-surface, areas associated with a loss of balance. These results were further attenuated as stability continued to improve with continued usage of the insoles. During an unexpected slipping perturbation SoleSensor insoles may improve the ability of an individual to detect and appropriately respond to an unexpected slip by improving the ability for an individual to detect the imbalance when there is a cutaneous deficit.

Another footwear characteristic that may be important to investigate is heel counter height and stiffness. Menant et al., (2009) determined that higher collars in footwear provide more stability on both wet and irregular surfaces. However, this may have been attributed to the restriction of subtalar joint motion rather than as a function of increased mechanical and sensory input around the ankle. High, stiff heel counters may also alter normal gait patterns; decreasing stride length. Decreased stride length has been found to be associated with a decreased risk of slipping (Fong et al., 2008), but during even a minor slip, may decrease the ability of the subtalar joint to respond effectively to regain balance.

In most workplaces, safety footwear is mandatory and must be approved by the Canadian Standards Association (CSA). This safety rating will guarantee the footwear can withstand certain amounts of compression and puncture forces. Safety boots and protective footwear have sturdy reinforced soles and higher stiff heel counters for support and protection. Safety boot footwear characteristics that may contribute most to improper subtalar joint function are antero-posterior stiffness and heel collar stiffness. There has been little to no published research at the present time on the effect that anterior-posterior stiffness has on stability and balance.

1.8 Rationale for this Study

Slips in the workplace have lead to high incidences of same-level falls causing serious injuries and even death (WSIB, 2010). Primary research in this area has focused more on the environmental interaction of the floor and soling characteristics of the footwear in order to prevent the occurrence and severity of slips (Li and Chen, 2004; Manning and Jones, 2001). Statistics demonstrate that this approach has not been very effective in reducing the number of hazardous slips due to their unpredictability (WSIB, 2010; Maynard, 2002). As the incidence of unexpected slips is still great, research focusing more on the role of the subtalar joint in detecting and responding to a slip within different footwear conditions may be very beneficial. First, an investigation into the motion of the subtalar joint in barefoot individuals is needed to model the normal response during a slip recovery. This work will supplement the previous "tribological" approaches to the prevention of falls, but instead of trying to prevent unexpected slips, increasing the chance for recovery. Second, an investigation of how different footwear characteristics affect gait variables (and theoretically the subtalar joint motion) during a slip perturbation may lead to recommendations of how to minimize the severity and increase the chances of recovery.

It is generally accepted that pronation (a combination of dorsiflexion, eversion, abduction) and supination (a combination of plantarflexion, inversion, adduction) generated at the subtalar joint, play an important role during the normal gait cycle (Hamill and Knutzen, 1995; Nigg and Herzogg, 1999). However, the tri-planar motion about the subtalar axis has yet to be investigated in responding to a slipping perturbation. Gait characteristics associated with the ankle (e.g. angular velocity at heel contact) are known to effect slip severity and recovery attempts (Redfern et al., 2001, Cham and Redfern, 2001, 2002). Previous research looking at responses to heel contact slipping perturbations have simplified movement within the ankle complex to two dimensions about the ankle axis; reporting the ankle passively plantarflexes in response to an anterior translation in the sagittal plane (Cham and Redfern, 2001; Hughes et al., 1995). This along with the presence of tibialis anterior activity during the slip (Chambers and Cham, 2007) may indicate a role for foot pronation/supination during the reaction. Therefore, further analysis of foot motion should be preformed and evaluated in tandem with muscle activation patterns to understand the potential importance of the interaction between the muscle activity and the motion of foot pronation/supination during a successful slip recovery.

The foot is the first link to our environment during normal upright locomotion. It is here that a slip will first be detected by our somatosensory/kinesthetic systems (cutaneous receptors, golgi tendon organs, muscle spindles and joint receptors) due to changes in pressure under the foot and/or joint trajectories at the ankle. As we age, deficits in cutaneous sensation under the foot (Zehr and Stein, 1999; Perry, Santos and Patla, 2001; Perry, 2006), reaction time (McIlroy and Maki, 1996; Thelen et al., 1997; Maki, Edmondstone and McIlroy, 2000; Tseng, Stanhope and Morton, 2009) and muscle force production in the lower limbs (Thelen et al., 1996; Barry, Rick and Garson, 2005) may make these individuals at higher risk of experiencing a hazardous slip. Therefore, investigation of normal subtalar joint motion during a slip recovery for young individuals free of neurological or musculoskeletal disorders will give insight into its function and how it degrades as we age. From this, one can then hypothesize ways to try and increase chances for recovery and minimize risk of falls due to same-level unexpected slips.

Footwear plays a very important role in how we interact with our environment during ambulation. Certain footwear characteristics have been found to increase frictional properties when they interact with different surfaces (Li and Chen, 2004; Manning and Jones, 2001), but this has not been successful in reducing the incidence of hazardous slips. The effect of different footwear characteristics on slip severity and recovery can be evaluated by comparing how different footwear characteristics affect gait parameters during normal gait and slip perturbations. This will allow recommendations of what footwear characteristics will increase the likelihood of recovery.

1.9 Research Objectives and Hypotheses

The objective of this investigation is two-fold. First, to determine the role of the subtalar joint during a slipping perturbation, by examining the three-dimensional motion around the joints axis and the associated muscle activity in young barefoot individuals free of any neurological or musculoskeletal disorders. This insight may reveal an important function of the subtalar joint in slip recovery. Second, to determine the effect of different footwear characteristics (stiff medio-lateral insoles, stiff heel counters) on normal subtalar joint motion and recovery from unexpected heel contact slip perturbations (including muscle activity) in young individuals free of any neurological or musculoskeletal disorders.

The main hypotheses of this thesis are:

1. In response to a heel contact slip perturbation; there will be early onsets and greater magnitudes in the lead lower limb EMG activity. More specifically earlier onsets (compared to normal walking trials) will occur in the tibialis anterior and peroneus longus of the perturbed limb. There will also be inhibition of the gastrocnemius activity in the perturbed limb. This hypothesis will be examined by analyzing lower limb muscle activity during slip trials in barefoot individuals, timing and magnitudes, compared to normal gait trials collected prior to any slipping.
2. Associated with this muscle activity, there will be a delay in foot pronation (eversion) resulting in the subtalar joint maintaining a supinated (inverted) position. This hypothesis will be examined by analyzing the onset of subtalar joint motion (inversion/eversion) during slip trials in barefoot individuals compared to normal gait trials collected prior to any slipping.

3. There will be an increase in slip severity and inability to recover quickly due to restrictive footwear characteristics. This will be determined by frequency of slip incidences and slip severity within each footwear condition. Condition 4, which is a combination of a stiff heel counter and a stiff medio-lateral insoles will affect normal gait characteristics the most (barefoot as control) and is hypothesized to increase angular velocities at heel contact, increase shear and normal forces, increase rates of loading and decrease the degree of subtalar joint motion resulting in greater slip severities and frequencies. This hypothesis will be examined by comparing kinetic and kinematic variables and EMG timing and magnitudes between all conditions during normal walking trials as well as the frequency and severity of slips across conditions.

Chapter 2: Methodology

2.1 Participants

Forty-two healthy, young adult volunteers were recruited from a university population to participate in this study. Their ages ranged from 18 to 30 years (mean 21.2 years, S.D. ± 2.7 years), weight ranged from 51.2 to 89.8 kg (mean 67.4 kg, S.D. ± 8.9 kg) and height ranged from 1.57 to 1.93 m (mean 1.71 m, S.D. ± 0.1 m). Participant demographic and anthropometric data is presented in Table 2.1. Written informed consent, approved by the Wilfrid Laurier University Research Ethics Board, was obtained prior to participation. Prior to the experimental procedure each participant answered an exclusion questionnaire (Appendix A). Exclusion criteria included any clinically significant history of neurological, orthopedic, cardiovascular or pulmonary abnormality as well as any other difficulties impeding normal gait.

Table 2.1:

Mean (STDev) of demographic information overall and within each condition. Statistical comparison alpha <.05.

	Footwear Conditions						
Study (N=42)	Totals	0 (n=10)	1 (n=8)	2 (n=8)	3 (n=8)	4 (n=8)	p-value*
Males	12	2	1	3	2	4	
Females	30	8	7	5	6	4	
Average Age (yrs)	21.19 (2.7)	22.00 (2.31)	21.63 (3.58)	20.5 (1.07)	20.63 (1.51)	22 (3.89)	0.6461
Average Height (m)	1.71 (0.1)	1.68 (0.09)	1.72 (0.06)	1.76 (0.12)	1.68 (0.11)	1.71 (0.09)	0.4815
Average Weight (kg)	67.43 (8.87)	71.08 (10.71)	64.34 (5.56)	72.07 (9.79)	64.26 (8.64)	69.06 (9.85)	0.2738
Foot Length (m)	0.29 (0.02)	0.25 (0.02)	0.29 (0.01)	0.29 (0.01)	0.28 (0.02)	0.29 (0.02)	*< 0.001

*Condition 0: barefoot; Condition l: soft heel counter, flexible insole; Condition II: stiff heel counter, flexible insole; Condition III: soft heel counter, rigid insole; Condition IV: stiff heel counter, rigid insole. *Foot length was found to be significantly different between the barefoot condition (0) and shoe conditions (1-4) as foot length measurements included the shoe.*

Data collection was performed in two stages. The first ten participants were assigned to a barefoot condition (condition 0). While the remaining 32 participants were randomly assigned to one of four footwear conditions (n=8): condition 1, condition 2, condition 3 or condition 4

(Figure 2.1; Appendix B). The conditions consisted of one of two heel counter stiffness (soft and stiff) crossed with two insole harnesses (flexible and rigid) to create the four conditions:

Condition 1: Flexible insole and soft heel counter
Condition 2: Flexible insole and stiff heel counter
Condition 3: Rigid insole and soft heel counter
Condition 4: rigid insole and stiff heel counter

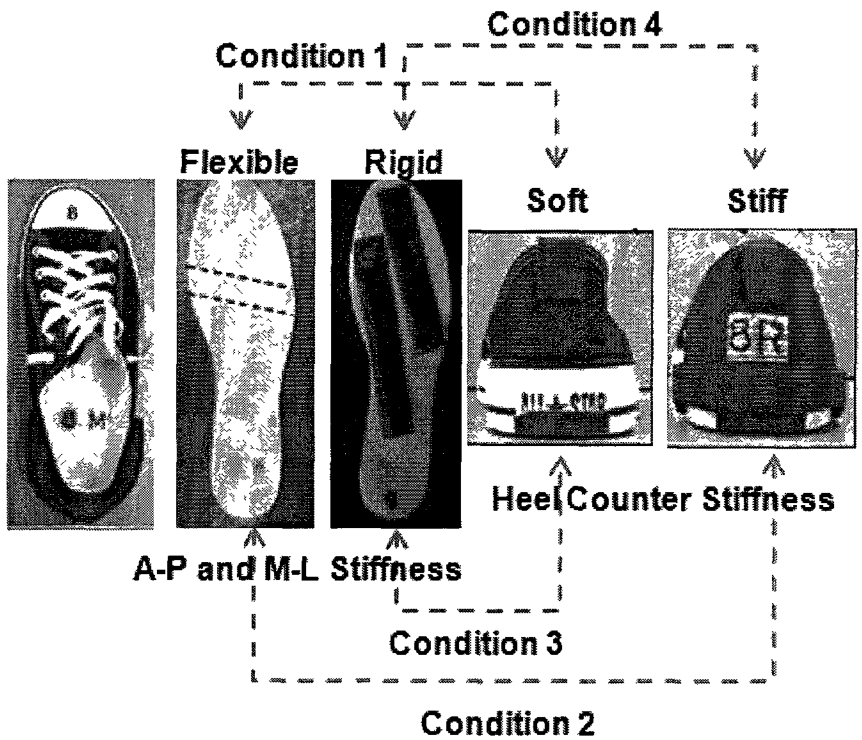


Figure 2.1: **Demonstrates the different footwear characteristics and combinations used within each footwear condition.**

Condition 4 most closely mimicked the rigidity of a work boot which was hypothesized to have the greatest effect on the subtalar joint function during a slip.

2.2 Data Acquisition

The equipment set up is outlined in the following block diagram (Figure 2.2). The Opto Trak motion analysis system (Northern Digital Inc., Waterloo, ON, Canada), electromyography

(EMG) (Bortec Biomedical, Calgary, AB, Canada) and the force plates (Advanced Mechanical TI, Watertown, MA, USA) collections were all controlled through the main collection computer. Both the EMG and force plate signals were passed through amplifiers and sampled (1000Hz) via an analog to digital (A/D) conversion board before reaching the computer. The lab consists of a 10 meter walkway, with three embedded force plates and two Optotrak camera banks (Figure 2.3).

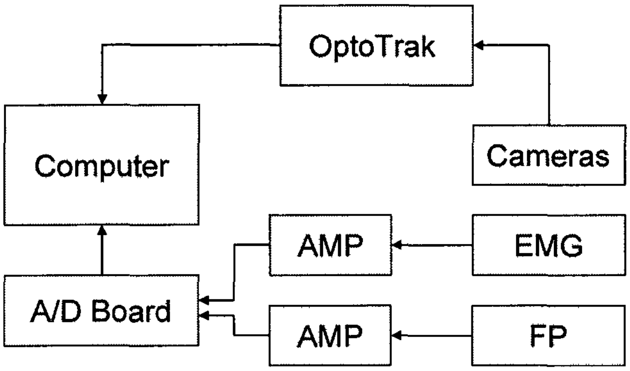


Figure 2.2: **Outlines the system configuration for data collection in the lab. EMG: electromyography, FP: force plates.**

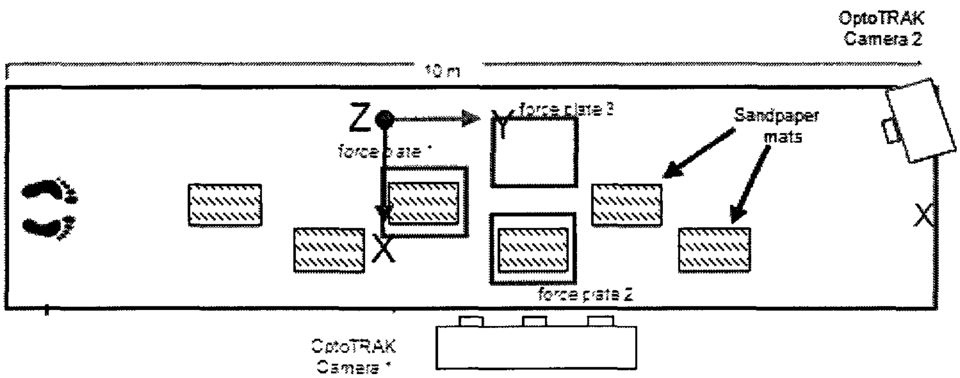


Figure 2.3: **Demonstrates the laboratory set-up: 10m walkway, force plates, OptoTrak cameras, sandpaper mats and global coordinate system.**

2.2.1 Kinetic Data

Ground reaction forces consist of forces acting along antero-posterior, medio-lateral and vertical axes and were recorded by three embedded forces plates (Model: OR-6-2000) within a 10m walkway, along with the moments around each axis. The three force plates are securely mounted within the floor and allowed for the detection of certain events during gait; such as heel contact, peak forces and toe-off. The centre of pressure was also calculated from this data. The force plates are 0.285m apart and staggered, allowing for normal foot contact during gait. The force plate signals were collected using BioSoft collection software (Biodaq v2.0, 1997, Watertown, Ma., USA) at 1000Hz sample rate.

2.2.2 Kinematic Data

A two-camera OptoTrak Motion Analysis System (OptoTrak 3020) were used to collect kinematic data (i.e., COM, joint angles, heel displacement and velocity). Data was sampled at 100Hz using Northern Digital Toolbench software (Northern Digital Inc., Waterloo, ON, Canada). A 20 infrared emitting diod (Ireds) marker set up was used for this experiment (Figure 2.4). Ired markers are numbered and strobe an infrared light that was detected by the Optotrak camera. The cameras use triangulation to determine the markers' location in three dimensions and track its motion during the trial. Twelve Ireds were placed bilaterally on the third metatarsals, ankles, knees, hips, and acromions as well as the xyphoid process and forehead to track the motion of the whole body represented as the centre of mass (COM) (Perry et al., 2007). Tracking markers were placed on the tibia to track tibial motion as well as on the mid-foot and hind-foot to define subtalar joint motion (inversion/eversion) in three-dimensions. The calcaneous (hind-foot) consisted of markers mounted on a plastic dome to create a rigid body.

During the footwear conditions, Ired markers were placed in the same locations as in the barefoot condition, but on top of the canvas shoe.

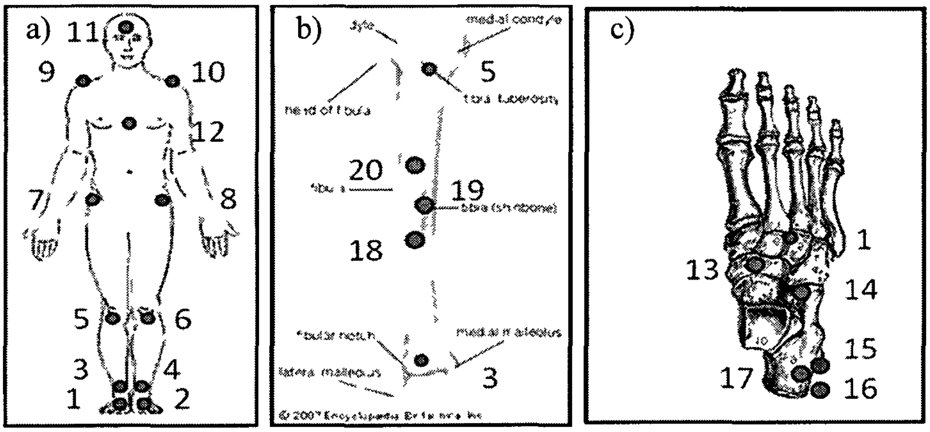


Figure 2.4: **a) the 12 marker set up to examine the COM/BOS relationship, b) illustrates the three tracking markers located on the tibia, c) illustrates the three markers on the calcaneous and two tracking markers on the forefoot to define the subtalar joint axes.**

2.2.3 Electromyography

Muscle activity was collected using surface electromyographical (EMG) electrodes and leads; a Bortec AMT-8 that accepted 8-channels for recording EMG signals were collected at 1000Hz, using AMTI's BioSoft collection software. The collection systems were synchronized by a pulse sent from the Optotrak control unit to the A/D unit where the onset of this pulse triggered the collection of the force plates and EMG data. EMG data was recorded for eight lower limb muscles to determine timing, duration and magnitude of normal gait and the slipping responses. The rectus femoris (RF), bicep femoris (BF), and medial gastrocnemius (MG) were recorded for both the leading and trailing leg. The tibialis anterior (TA) and peroneus longus (PL) were only recorded on the leading leg (Figure 2.5).

Surface EMG electrodes were placed over slightly abraded skin; cleansed with NuPrep gel to remove excess skin and oils. Electrode placement was positioned away from the motor end point and highly tendinous areas so that they were directly located over the muscle belly and oriented in the direction of the muscle fibres (Mesin et al., 2009). Reference of electrode placement was verified by muscle palpation and as indicated by Delagi et al., (1975). The inter-electrode distance was kept consistent at 1cm apart to minimize interference and artifacts. The preamplifiers were adhered to the skin with transpore tape to prevent excessive movement and noise (Moyer et al., 2009; Marigold et al., 2003; Zajac et al., 2003).

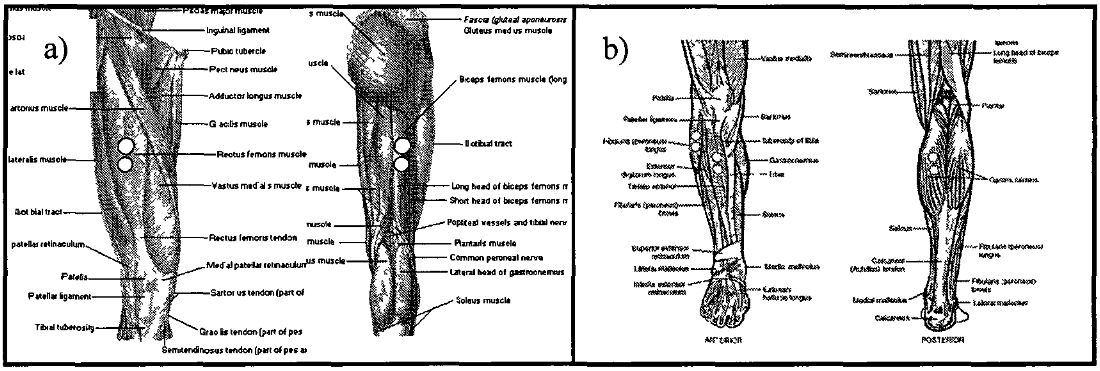


Figure 2.5: **Illustrates the EMG electrode placement on the anterior-posterior a) thigh and b) lower shank muscles.**

2.3 Experimental Protocol

Upon entering the lab participants signed and dated an informed consent letter. Anthropometric data was collected including: height, weight, waist, knee and ankle diameters. Semmes-Westein monofilaments were used to take cutaneous sensation measurements from the bottom of both feet (middle of the heel pad, 5^{th} and 1^{st} metatarsal pad, hallux, medial and lateral arches, and at any callus location) to ensure that participants did not have sensation deficits. Participants were asked to remove their shoes and socks. Each foot was propped up one at a time to allow access to the plantar surface of the foot. Participants were then asked to close their eyes and respond with a verbal ''yes'' whenever they felt pressure on their sole. Each application of the filament was reduced to half its length so as to give a constant pressure (range 0.1–11 g). Filaments were presented in randomized locations from low to high until one was detected consistently over all of the areas. A level of sensation was then assigned to the individual based on this threshold. Any deformation of the great toe (hallux valgus) was also noted as this is known to change normal pressure distributions under the foot during gait (See Appendix B) (Perry et al., 2001). Foot tracings were also taken of both feet for future reference of foot dimensions and toe characteristics.

Participants within the footwear conditions were then put into the appropriate sized canvas shoes outfitted for the condition they were randomly assigned to before EMG and Ired markers were adhered. The eight muscles of the lower limb were cleansed and landmarked for EMG electrode placement. Locations were then tested by using passive resistance to their primary joint motion with the aid of an oscilloscope. Gains were then adjusted on the Bortec unit until each muscle exhibited ± 1 volt during activation. Ired markers were then adhered using sticky discs and transpore tape. Participants were then asked to stand on the second and third force plate; their right foot and ankle were adjusted to align with the anterior-posterior axis of the global coordinate system. Each marker was then checked for congruency and the markers on the feet were measured to identify their specific locations. The participant was then instructed to stand erect; focus on an X on the wall, while a quiet standing calibration trial was recorded for five seconds.

Trials consist of walking along a 10 meter walkway over the force plates while focusing on an X located at eye-level on the perpendicular wall. Participants performed practice trials to determine their starting position, which allowed for consistent force plate contact and a normal gait velocity (0.97-1.51 m/s; Redfern et al., 2001); this was maintained for each trial. Sandpaper sheets were velcroed at equal distances two steps before, on and two steps after the force plates to allow for deception as to the location of the slip mat (Figure 2.6). The slipping apparatus consisted of wax paper adhered to the underside of a sandpaper sheet that was swapped in on the second force plate in an attempt to induce an unexpected slip. The frictional properties of the slip mat are similar to that of ice, averaging a COF value around 0.1 ± 0.01 reported by both Heiden et al., and Siegmund et al., in 2006. Between each trial the participants were asked to face the back wall while the sandpaper sheets on the force plates are swapped or refastened. Similar noises were made to ensure anonymity as to the location of the slip mat.

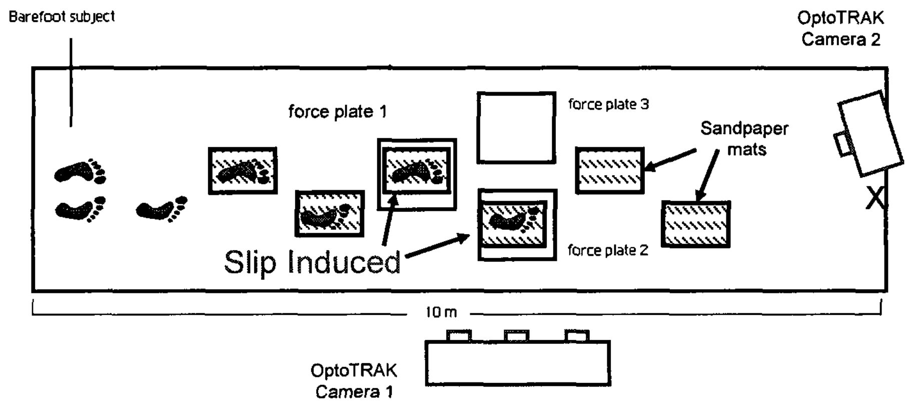


Figure 2.6: **Illustrates the laboratory set-up: the 10 meter walkway with imbedded force plates, sandpaper mats, and camera placement.**

Two research assistants walked alongside the participant in case of a complete loss of balance. One assistant was also responsible for holding the connector cables while the participant walked to prevent the participant from tripping. The assistants were blinded to the trial conditions and faced the back wall with the participant during the adjustments. Participants were allowed to practice walking so that they made contact with the force plates and maintained a consistent gait speed. Before the trial collection began, participants were reminded that they may experience a slip during the collection, but to try and walk as they did during their practice trials (i.e., same speed and stride length). Participants were reminded to increase or decrease their gait speed based on their foot contact with the force plates (i.e., short heel contact with the force plates, asked to increase gait speed; toes off the front of the force plates, asked to decrease gait speed).

In the barefoot collection, the 'trial protocol' consisted of one quiet stance trial, ten normal "control" walking trials, followed by two consecutive slip perturbations on the second force plate in attempt to elicit two slip recovery responses. The first slip attempt was considered as a "true unexpected slip response". After the two consecutive slip trials, fourteen non-slip walking trials were completed to investigate if a normal state of walking was maintained. This was followed by a third and final slip perturbation that was attempted on second force plate for a total of 29 trials (See Appendix B). The slips were always induced on the second force plate with a right heel contact in order to collect subtalar joint motion with the two camera set-up.

In footwear conditions, the trial protocol consisted of a total of 44 trials; ten walking trials for each footwear condition with the addition of one quiet stance at the beginning of each set. The first three sets of trials consisted of the footwear conditions the participant were not assigned to, and were presented in a random order. The last set of ten trials was the condition the participant was randomly assigned to. During trial six and seven of their assigned footwear condition (last set of ten trials); the participant experienced two consecutive slip perturbations followed by the final three non-slip trials for that set (See Appendix B). The randomization of the trial protocol for this collection was done firstly by controlled randomization to ensure the conditions were presented equally among the participants (3-4-3 distribution). The controlled randomization was then randomized using Microsoft Excel and a random number generator to randomize assignment to participants. After all of the trials were completed, participants filled out an exit questionnaire to gather information pertaining to slip and fall experiences (See Appendix C). Results of this questionnaire were not addressed in this paper.

2.4 Data Analysis

2.4.1 Kinetic and Kinematic Variables

From the kinematic and kinetic data, various measurements were calculated (i.e., stride length, stance duration, ground reaction forces, joint angles, heel displacement and velocity). These variables are outlined in detail in Appendix D. Ground reaction forces (GRF) were used to calculate peak forces and loading rates in the anterior-posterior (AP) and vertical axis, and were normalized to body weight. The vertical GRF were used to determine heel contact and toe-off (threshold of 3% bodyweight) that was used to define commencement and termination of stance; stance duration (SD). Joint angles in the sagittal plane (flexion/extension) were calculated for the hip, knee and ankle. Joint angles were normalized to neutral angles collected during quiet stance trials. The foot and ankle markers were used to calculate step width and step length (Perry, 2007). Step width and length were normalized to height.

Slip severity was classified using the heel displacement (m) and the peak heel velocity (peak sliding velocity) determined using the most posterior heel marker located on the calcaneous of the leading foot. The displacement was calculated by taking the placement of the heel marker, along the anterior-posterior axis, upon heel contact to the position of the heel marker when forward movement stopped (0 m/s).

2.4.2 Subtalar Joint Motion

The calculation of the subtalar joint motion was performed using the KinMat program (a collection of Matlab toolboxes written by Christoph Reinschmidt and Ton van den Bogert, 1997) that calculates the intersegmental motion (cardan angles) (Joint Coordinate System; Grood and Suntay, 1983) between two segments. During an initial standing trial the approximate location of the two segments positioned in their anatomical neutral position (tibia, the "lower leg" segment and the foot segment) was used to represent the joint's zero position. Then by tracking the position of these markers during the movement, the relative movements of the foot segment with respect to the tibia segment were calculated. An 'xyz' cardan rotational sequence was chosen for this process ('xyz': first rotation about x fixed in first segment, y floating axis, and last rotation about z fixed in the second segment) (Woltring, 1994). This resulted in the three rotations of the foot relative to the lower leg: plantar/dorsiflexion, inversion/eversion and abduction/adduction. For this investigation, the subtalar joint motion will be focused around foot inversion/eversion as this is the major contributor to supination/pronation and most functionally valuable. As the foot everts/inverts during stance the bones in the foot are relaxed for shock absorption, or rigid to allow for force transference (i.e., toe-off) (Hamill and Knutzen, 1995; Redfern et al., 2001; Kitaoka et al., 2006). Unfortunately, subtalar joint motion was only able to be calculated within the barefoot condition due to large marker errors.

2.4.3 Electromyography

Electromyography (EMG) signals were full wave rectified and filtered using a Bandpass 2nd order butterworth with a frequency cutoff of 10 and 100 Hz, and then normalized to the stance time (0% heel contact, 100% toe-off). Onsets and durations were determined by using a threshold of 5% above activity recorded during a quiet period. Activation that was above this threshold for a minimum of 50ms was considered "on". The muscle was considered "off" when activation fell below the 5% threshold for 50ms or more. Onset and duration timing was normalize to % stance of the right (perturbed) limb.

The magnitude of activity was determined from onset to cessation of the integrated EMG (Chambers and Cham, 2007) and normalized to the average magnitudes during normal walking trials. Activation patterns were characterized into a three burst pattern over the stance phase. EMG activation (onsets) occurring just prior to or just after heel contact (-30 to 10% stance) was classified as "preparatory" activity. Activation occurring during the middle third of stance (20 to 50% stance) was classified as "stabilizing" activity and any activation occurring in the later third of stance (60 to 100% stance) was classified as "transitional" activity (Figure 2.7). Characteristic activation patterns of a given lower limb muscle included activation (onset) either in the preparatory phase and/or the transition phase or only during the stability phase.

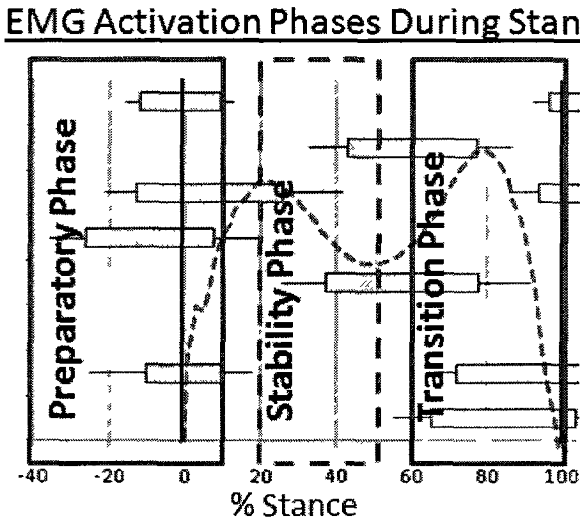


Figure 2.7: **Demonstrates the division of EMG activation patterns into three distinct phases: Preparatory Phase include onsets occurring from -40 to 10% stance, the Stability Phase from 20 to 50% stance and the transition phase from 60 to 100% stance.**

2.4.3 The Slip Perturbation

"Normal walking trials" were considered trials recorded prior to any slip perturbation as they would most resemble normal gait patterns. These trials were used in the analysis across conditions. Post-slip unperturbed trials were not used in this investigation as they may exhibit strategies (i.e., gentler heel strike, short strike length, small foot-floor contact angles, slower heel velocities) that alter normal gait patterns in order to prevent future slipping (Marigold and Patla, 2002; Heiden et al., 2006; Fong, Hong and Li, 2009; Cham and Redfern, 2002; Bhatt and Pai, 2009). The first slip perturbation is potentially the most unexpected and will produce the most realistic slip and slip response. For the purpose of this thesis, the results will focus on reporting variables associated with the first slip perturbation trial to ensure a slip and recovery that is most representative of a 'real life' scenario.

During slip trials participants varied as to the severity of their perturbation and consequently were grouped into four classifications. A '0' was assigned to participants who did not have greater forward heel movement than during normal walking trials (<0.025m, <1.0m/s). In these participants there were no significant changes in normal gait parameters as they did not experience a significant change in heel trajectory. These participants were termed "non-slippers" and their "slip" trials were not included in the analysis. A class '1' slip is defined as a mini-slip. These participants experienced a small slip perturbation (0.025-0.049m, 1.0-1.4m/s) resulting in minor changes in gait parameters as a result of the perturbation. Participants with heel displacements between 0.05-0.10m (1.5-2.0m/s) were termed midi-slips, a class '2' slip. These participants experienced a medium slip perturbation with major changes to gait parameters. A class '3' slip was considered a max-slip perturbation (>0.10m, >2.0m/s). These participants experienced large slips with extreme changes in gait parameters (Table 3.1).

Table 2.2
An outline of the slip classification of the first unexpected slip perturbation assigned to all participants.

Slip Classification Level	Description	Heel Displacement (m)
0	**Non-Slip:** Participants who did not have forward heel movement significantly larger than during normal walking trials.	< 0.025
1	**Mini-Slip:** Participants experienced a small slip perturbation with forward heel displacement slightly larger than during walking trials.	0.025-0.045
2	**Midi-Slip:** Participants experienced a medium slip perturnbation eith forward heel displacement larger than mini-slip trials.	0.05-0.10
3	**Max-Slip:** Participants experienced a large slip perturbation with forward heel displacements exceeding midi-slip trials.	> 0.10

2.5 Statistical Analysis

The results were analyzed using the SAS computerized statistical package. Normal walking trial variables were evaluated using a between-subject, one-factor ANOVA (variables across all conditions 0-4 during normal gait trials) with a priori significance level of $p < 0.05$. Important measures that were examined include: stance duration, step length, heel displacement, heel velocity, ground reaction forces, rate of loading, breaking impulse, the hip, knee and ankle joint angles, and the ankle angular velocity (See Appendix D). Variables were then evaluated using a within-subject, one-way repeated measures ANOVA (three normal walking trials prior to any slip perturbation vs. the first unexpected slip trial within each condition) with a priori significance level of $p < 0.05$. Outliers were investigated and removed if values were due to errors in collection (i.e., participant missed the force plate, error in calculation during processing). During the analysis comparing normal gait to the slip perturbation, only slip trials classified as 1- 3 were used in the comparison; class 1 or 'non-slippers' were removed as the perturbation was not successful.

Chapter 3: Results

3.1Comparison of Normal Walking Trials across Conditions

3.1.1 Kinetic Data

Ground Reaction Forces

During normal walking trials, the average *peak vertical ground reaction forces* (NormF Peak) were 12.41N/kg ± 0.09. Peak normal forces did not significantly differ between footwear conditions during normal walking trials (Condition 0: 12.56N/kg ± 0.81, Condition 1: 12.36N/kg ± 0.88, Condition 2: 12.35N/kg ± 0.95, Condition 3: 12.44N/kg ± 0.95, Condition 4: 12.34N/kg ± 0.84; p = 0.7024) (Table 3.1, Figure 3.3).

The average *rate of vertical loading* ranged from 103.52 – 133.39N/s.kg (111.74N/s.kg ± 12.4). The rate of loading was found to be significantly higher in barefoot individuals (condition 0) compared to shod individuals (condition 1-4) during normal walking trials (Condition 0: 133.39N/s.kg ± 34.18, Condition 1: 107.65N/s.kg ± 21.1, Condition 2: 103.52N/s.kg ± 20.69, Condition 3: 110.14N/s.kg ± 22.13, Condition 4: 104.01N/s.kg ± 19.75; p = 0.0009). A Tukey's post hoc analysis also determined that conditions 1 and 3 had significantly higher loading rates than condition 2 and 4 (Table 3.1, Figure 3.3).

The *average peak shear ground reaction force* (ShearF Peak) was 2.41N/kg ± 0.04. Peak shear forces did not significantly differ between footwear conditions during normal walking trials (Condition 0: 2.36N/kg ± 0.52, Condition 1: 2.40N/kg ± 0.46, Condition 2: 2.44N/kg ± 0.40, Condition 3: 2.46N/kg ± 0.48, Condition 4: 2.38N/kg ± 0.35; p = 0.5091) (Table 3.1, Figure 3.3).

Table 3.1

Repeated measures, within-1 factor ANOVA, comparison of normal walking trials across footwear conditions.

Footwear Condition	0		1		2		3		4				
# of Observations	26		87		88		88		87				
	Mean	STDev	Mean	STDev	Mean	STDev	Mean	STDev	Mean	STDev	P-value	Sig.	Tukey's
Kinetic Data													
NormF Peak (N/kg)	12.56	0.81	12.36	0.88	12.35	0.95	12.44	0.95	12.34	0.84	0.7024		
ROL (N/s.kg)	133.39	34.18	107.65	21.10	103.52	20.69	110.14	22.13	104.01	19.75	0.0009	*	0-((3,1)-(4,2))
UR (N/s.kg)	129.47	23.14	100.05	13.13	98.77	12.81	101.17	12.94	99.26	13.39	0.1666		
LI (N/s.kg)	5.37	1.05	7.19	0.87	7.16	0.87	7.02	0.97	7.03	0.87	0.01	*	0-(1,2,3,4),3-1
ShearF Peak (N/kg)	2.36	0.52	2.40	0.46	2.44	0.40	2.46	0.48	2.38	0.35	0.5091		
BI (N/s.kg)	3.17	0.45	3.58	0.57	3.51	0.49	3.49	0.54	3.37	0.46	0.0873		
PI (N/s.kg)	-3.18	0.45	-3.23	0.44	-3.36	0.38	-3.19	0.52	-3.19	0.41	0.04	*	2-(0,1,3,4)
Kinematic Data													
Stance Duration (s)	0.55	0.05	0.61	0.05	0.62	0.04	0.61	0.04	0.62	0.04	0.0181	*	0-(1,2,3,4)
Step Length	0.38	0.03	0.39	0.02	0.40	0.04	0.39	0.03	0.39	0.02	0.3968		
Step Width	0.07	0.02	0.08	0.02	0.07	0.02	0.07	0.02	0.07	0.02	0.7621		
Gait Speed (m/s)	1.62	0.14	1.78	0.85	1.68	0.13	1.69	0.13	1.67	0.11	0.0771		
Heel Disp (m)	0.018	0.004	0.020	0.004	0.019	0.004	0.020	0.004	0.019	0.004	0.262		
Heel VelHC (m/s)	0.31	0.29	0.72	0.32	0.76	0.32	0.70	0.35	0.81	0.39	0.0326	*	0-(1,2,3,4), 4-3
Heel Vel Peak (m/s)	0.91	0.21	0.90	0.22	0.88	0.22	0.83	0.26	0.89	0.32	0.0224'	*	1-3
Shank AngHC (°)	-16.44	2.40	-21.21	2.73	-21.85	2.63	-21.83	2.40	-21.83	2.40	0.0168	*	0-(1,2,3,4)
FFloor AngHC (°)	17.72	6.95	27.79	6.85	25.86	9.16	28.56	6.55	26.78	8.70	0.196		
NAnkle AngHC (°)	4.45	4.58	-1.46	4.32	-1.36	4.25	-1.35	4.14	-1.16	3.90	0.7247		
Ankle AngVelHC (°/s)	277.24	95.44	46.00	55.08	51.44	61.38	62.84	63.13	60.54	56.52	0.1654		
Knee AngHC (°)	171.21	2.76	172.03	4.40	171.82	4.40	172.24	4.10	171.75	4.11	0.6823		
Hip AngHC (°)	-25.52	5.21	-28.39	2.96	-27.90	3.09	-28.13	2.86	-27.95	2.82	0.547		

(%) Values were normalized to % stance of the right (slipping) limb. Kinetic data was normalized by BW and kinematic data was normalized by height or neutral angle.
Positive ankle and hip angles (+) represent extension, negative angles (-) represent flexion relative to neutral.
'ANOVA performed with a ranked transform to achieve normalcy.
**Significance $p < 0.05$.*

3.1.2 Kinematic Data

Gait Characteristics

The average *stance duration* during all normal walking trials was 0.60s ± 0.03. The barefoot condition (condition '0') had significantly shorter stance durations during normal walking when compared to all other footwear conditions (conditions '1-4') (Condition 0: 0.55s ± 0.05, Condition 1: 0.61s ± 0.05, Condition 2: 0.62s ± 0.04, Condition 3: 0.61s ± 0.04, Condition 4: 0.62s ± 0.04; p = 0.018) (Table 3.1).

Step length and *step width* were normalize to each individual's height. The average step length during all normal walking trials was 0.39m ± 0.01. Step length did not differ significantly during normal walking across all footwear conditions (Condition 0: 0.38 ± 0.03, Condition 1: 0.39 ± 0.02, Condition 2: 0.4 ± 0.04, Condition 3: 0.39 ± 0.03, Condition 4: 0.39 ± 0.02; p = 0.397) (Table 3.4). The average step width across all footwear conditions was 0.07m ± 0.02. There was no significant difference in step width during normal walking trials found between the footwear conditions (Condition 0: 0.07 ± 0.02, Condition 1: 0.08 ± 0.02, Condition 2: 0.07 ± 0.02, Condition 3: 0.07 ± 0.02, Condition 4: 0.07 ± 0.02; p = 0.762) (Table 3.1).

Overall, the average *gait velocity* was 1.69m/s ± 0.06 during normal walking trials. Gait velocities were not found to be significantly different across footwear conditions during normal walking trials, but participants who were in the barefoot condition had slightly slower gait velocities (Condition 0: 1.62m/s ± 0.14, Condition 1: 1.78m/s ± 0.85, Condition 2: 1.68m/s ± 0.13, Condition 3: 1.69m/s ± 0.13, Condition 4: 1.67m/s ± 0.11; p = 0.077) (Table 3.1).

The average forward heel motion *(heel displacement)* during normal walking across all conditions was 0.019m ± 0.004 (p = 0.26) and was not found to be significant. Heel velocities at heel contact were found to be significantly lower in barefoot individuals compared to the shod conditions within normal walking trials (Condition 0: 0.31m/s ± 0.29, Condition 1: 0.72 m/s ± 0.32, Condition 2: 0.76 m/s ± 0.32, Condition 3: 0.70 m/s ± 0.35, Condition 4: 0.81 m/s ± 0.39; p = 0.0326). A Tukey's post Hoc also distinguished that condition 4 had significantly higher heel velocities than condition 3.Overall the average *peak heel velocity* was 0.88 m/s ± 0.03 before coming to a stop (0 m/s). Condition 1 was found to have significantly higher peak heel velocities than condition 3 (Condition 0: 0.91m/s ± 0.21, Condition 1: 0.9m/s ± 0.22, Condition 2: 0.88m/s ± 0.22, Condition 3: 0.83m/s ± 0.26, Condition 4: 0.89m/s ± 0.32, p = 0.0224) (Table 3.1, Figure 3.3).

During normal walking trials participants had an average *heel velocity* at heel contact of 0.66m/s ± 0.20. Heel velocity at heel contact were found to be significantly slower in the barefoot condition (condition 0) (Condition 0: 0.31m/s ± 0.29) compared to the footwear conditions (conditions 1-4) (Condition 1: 0.72m/s ± 0.32, Condition 2: 0.76m/s ± 0.32, Condition 3: 0.70m/s ± 0.35, Condition 4: 0.81m/s ± 0.39; p = 0.0326). A Tukey's post hoc analysis demonstrated further that condition 4 heel velocities at heel contact were significantly faster than condition 3 (Table 3.1, Figure 3.3).

Joint Angles

During normal walking trials, the average *shank angle* (relative to vertical) at heel contact was -20.63° ± 2.36. Barefooted individuals (condition 0) were found to have significantly smaller shank angles than those in the footwear conditions (conditions 1-4) during normal walking trials (Condition 0: -16.44° ± 2.40, Condition 1: -21.21° ± 2.73, Condition 2: -21.85° ± 2.63, Condition 3: -21.83° ± 2.40, Condition 4: -21.83° ± 2.40; p = 0.0168) (Table 3.1).

The average *foot-floor angle* at heel contact was 25.34° ± 4.38. There were no significant differences in foot-floor angles at heel contact during normal walking trials, but barefoot individuals had smaller contact angles than individuals wearing footwear (Condition 0: 17.72° ± 6.95, Condition 1: 27.79° ± 6.85, Condition 2: 25.86° ± 9.16, Condition 3: 28.56° ± 6.55, Condition 4: 26.78° ± 8.70; p = 0.196) (Table 3.1).

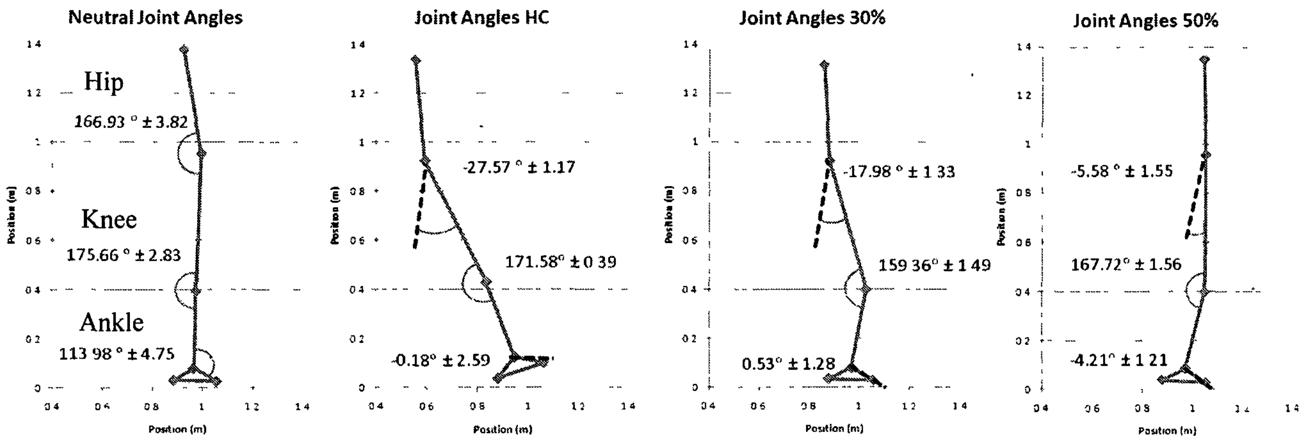


Figure 3.1: **Illustrates neutral joint angles and joint angles during normal walking trails of the hip, knee and ankle (HC, 30% and 50% stance).**

The *ankle angle* averaged 0.176° ± 2.59 of dorsiflexion (negative ankle angle) during normal walking trials. There were no significant differences found between conditions (Condition 0: 4.45° ± 4.58, Condition 1: -1.46° ± 4.32, Condition 2: -1.36° ± 4.25, Condition 3: -1.35° ± 4.14, Condition 4: -1.16° ± 3.90; p = 0.7247) (Table 3.1, Figure 3.1).

During normal walking trails, the average *knee angle* at heel contact was 171.81° ± 0.39 (near full extension). The knee angle at heel contact was relatively consistent across conditions and did not vary significantly (Condition 0: 171.21° ± 2.76, Condition 1: 172.03° ± 4.40, Condition 2: 171.82° ± 4.40, Condition 3: 172.24° ± 4.10, Condition 4: 171.75° ± 4.11; p = 0.6823) (Table 3.1, Figure 3.1).

During normal walking trails, the average *hip angle* at heel contact was -27.58° ± 0.39 (approximately 30° of flexion). The hip angle at heel contact did not vary significantly across conditions, but barefoot individuals had less hip flexion at heel contact than shod individuals

(Condition 0: -25.52° ± 5.21, Condition 1: -28.39° ± 2.96, Condition 2: -27.90° ± 3.09, Condition 3: -28.13° ± 2.86, Condition 4: -27.95° ± 2.82; p = 0.547) (Table 3.1, Figure 3.1).

3.1.3 Electromyography

The eight lower limb muscles exhibited a characteristic three burst pattern during normal unperturbed walking, activity either occurring in both the first and last third of stance or just in the middle third of stance (Whittle, 1996; Rose and Gamble, 2006). This activation was very similar across all footwear conditions (Figure 3.2).

Tibialis Anterior

The right tibialis anterior (RTA) was characteristically active in the ***preparatory phase*** (first third of stance) and the ***transition phase*** (last third of stance). The average onset of activity was -13.18% ± 0.91 and 94.6% ± 1.07 of stance with an average duration of 0.14-0.16s (25.52% ± 2.4 of stance time) and 0.12- 015s (23.54% ± 3.19) respectively. During normal walking trials the onset of activation, duration and magnitude of activity was not significantly different in the *preparatory phase* across all footwear conditions (Condition 0: onset -11.88% ± 3.85, Condition 1: onset -14.22% ± 5.39, Condition 2: onset -13.41% ± 4.63, Condition 3: onset -13.42% ± 4.89, Condition 4: onset -14.00% ± 5.12, p = 0.6431; Condition 0: duration 21.37% ± 3.51, Condition 1: duration 27.34 % ± 7.20, Condition 2: duration 25.74% ± 6.19, Condition 3: duration 26.25% ± 5.37, Condition 4: duration 26.90% ± 6.02, p = 0.4169; Condition 0: magnitude 86,80% ± 20.03, Condition 1: magnitude 103.69% ± 26.50, Condition 2: magnitude 104.68% ± 31.36, Condition 3: magnitude 107.73% ± 33.36, Condition 4: magnitude 110.12% ± 36.62, p = 0. 0.532) (Table 3.1, Figure 3.2; Appendix F).

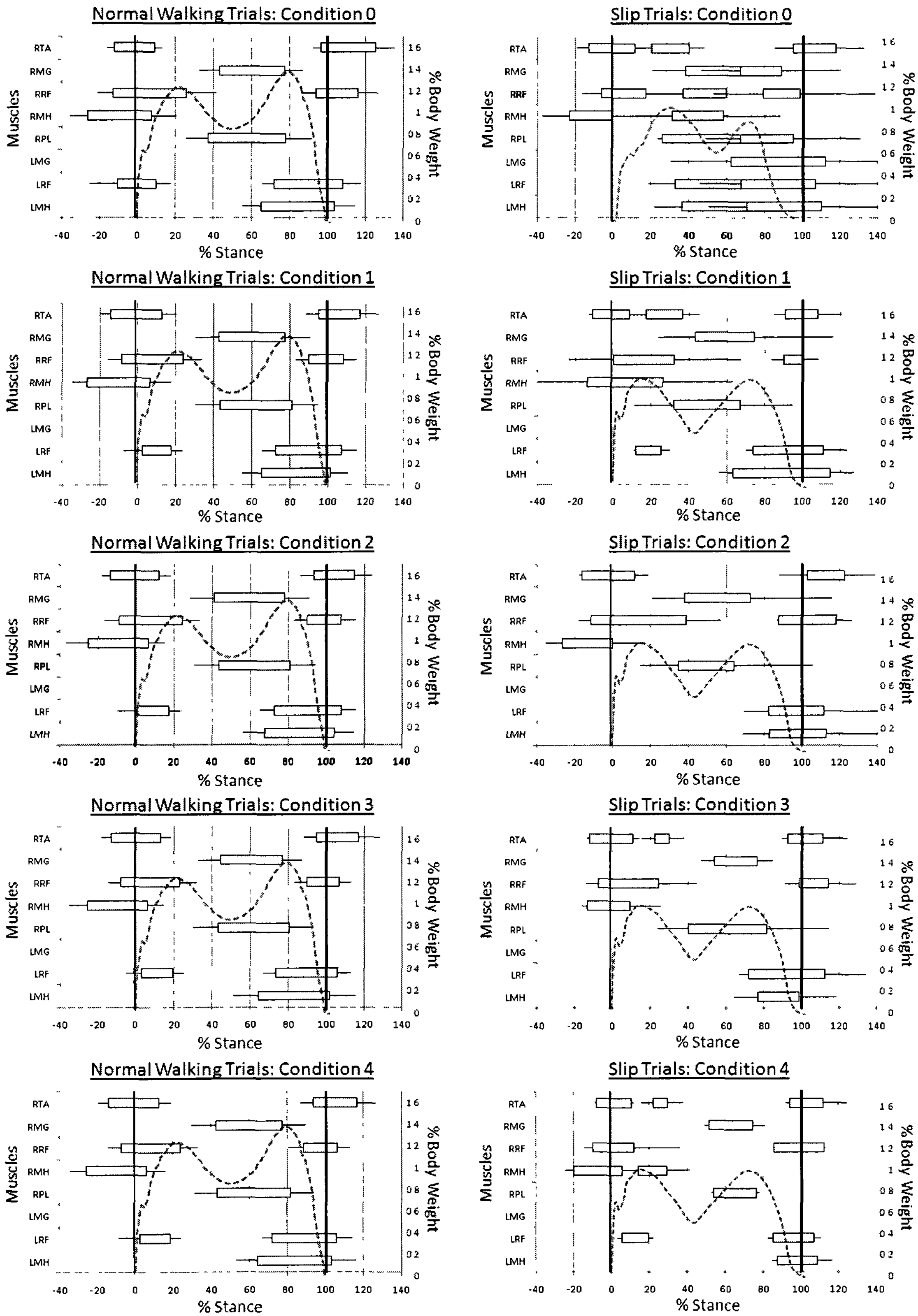


Figure 3.2: **Illustrates the EMG timing of the eight lower limb muscles over the stance of the perturbed limb; a comparison of normal walking trials and slip recovery trials across all five shoe conditions.**

During the *transition phase*, the RTA's durations and magnitudes were not found to be significantly different across footwear conditions (Condition 0: duration 29.09% ± 9.63, Condition 1: duration 21.79% ± 9.81, Condition 2: duration 21.16% ± 9.48, Condition 3: duration 22.60% ± 10.85, Condition 4: duration 23.04% ± 9.65, p = 0.7913; Condition 0: magnitude 95.98% ± 24.82, Condition 1: magnitude 104.28% ± 46.96, Condition 2: magnitude 105.85% ± 36.28, Condition 3: magnitude 104.94% ± 47.22, Condition 4: magnitude 108.69% ± 43.69, p = 0.9798), while EMG onsets were significantly different (Condition 0: onset 96.17% ± 3.97, Condition 1: onset 95.13% ± 6.61, Condition 2: onset 93.61% ± 7.19, Condition 3: 94.44% ± 6.48, Condition 4: 93.67% ± 6.69, p = 0.0411). A Tukey's post hock analysis demonstrated that condition 0 had significantly later onset timing than condition 2, 3 and 4 during the transition phase. Condition 1 also was found to have significantly later onset timing than condition 2 and 4 (Table 3.1, Figure 3.2; Appendix F).

Medial Gastrocnemius

The right medial gastrocnemius (RMG) was characteristically active in the ***stability phase*** (middle third of stance). The average onset of activity was 42.72% ± 1.19 of stance with an average duration of 0.18-0.21s (34.22% ± 1.6 of stance time). During normal walking trials the onset of activation not significantly different across footwear conditions (Condition 0: 43.12% ± 10.25, Condition 1: 42.88% ± 12.26, Condition 2: 41.01% ± 12.26, Condition 3: 44.29% ± 10.90 , Condition 4: 42.48% ± 12.39, p = 0.0626). The duration of the EMG burst was found to be significant; condition 2 had significantly larger durations than condition 3 (Condition 0: 33.94% ± 9.52 , Condition 1: 34.45% ± 13.30, Condition 2: 36.77% ± 13.19, Condition 3: 32.47% ± 10.92 , Condition 4: 34.48% ± 12.65, p = 0.0088). The magnitude of RMG activity was also found to be significant; condition 2 had significantly higher magnitudes than condition

3 and 4 (Condition 0: 102.76% ± 17.31, Condition 1: 100.26% ± 25.99, Condition 2: 107.74% ± 24.21, Condition 3: 96.13% ± 25.34, Condition 4: 99.06% ± 21.41, $p = 0.022$) (Table 3.1, Figure 3.2; Appendix F).

Peroneus Longus

The right peroneus longus (RPL) was also characteristically active in the ***stability phase*** (middle third of stance). The average onset of activity during a slip was 42.13% ± 2.66 of stance with an average duration of 0.21-0.23s (38.27% ± 1.07 of stance time). During normal walking trials the onset of activation, duration and magnitude of activity was not significantly different across all footwear conditions (Condition 0: onset 37.42% ± 11.87, Condition 1: onset 43.42% ± 12.90, Condition 2: onset 43.82% ± 12.77, Condition 3: onset 42.91% ± 12.44, Condition 4: onset 43.08% ± 11.46, $p = 0.9386$; Condition 0: duration 40.03% ± 14.09, Condition 1: duration 37.83% ± 13.56, Condition 2: duration 37.32% ± 13.40, Condition 3: duration 37.68% ± 12.12, Condition 4: duration 38.52% ± 12.04, $p = 0.8707$; Condition 0: magnitude 92.47% ± 25.24, Condition 1: magnitude 100.14% ± 46.86, Condition 2: magnitude 95.54% ± 31.98, Condition 3: magnitude 93.15% ± 37.72, Condition 4: magnitude 95.75% ± 36.70, $p = 0.8124$) (Table 3.1, Figure 3.2; Appendix F).

3.2 Comparison of Normal Walking Trials to Slip Trials within Conditions

3.2.1 Slip Severity and Frequency

Overall, 20 participants experienced a slip (class 1-3). Within the barefoot condition, 80% of the participants experienced an unexpected slip perturbation of class 1-3. The prevalence of slips was not as great within the footwear conditions (Condition1: 37.5%, Condition 2: 37.5%, Condition 3: 50% and Condition 4: 25% respectively). Barefoot individuals experienced a larger percentage of severe slips (midi and max) than shod conditions (75% vs. 30%). Within the footwear conditions, (condition 1 as control) condition 2 had similar risk of slipping to the control (37.5% of participants), condition 3 showed an increased the risk of slipping (50% of participants) and condition 4 showed a decreased risk of slipping (25% of participants) (Table 3.2).

Table 3.2

Demonstrates the severity of the slip perturbation trials across shoe conditions and the total % of incidences within each class of slip severity.

		Footwear Conditions					
Slip Classification	Levels	0	1	2	3	4	%of Total Incid.
	0	2	5	5	4	6	52.4%
	1	2	2	2	2	1	21.4%
	2	3	0	0	1	1	11.9%
	3	3	1	1	1	0	14.3%
	% of Slips	80.0%	37.5%	37.5%	50.0%	25.0%	

3.2.2 Kinetic Data

Ground Reaction Forces

Peak normal ground reaction forces were not found to be significantly different when comparing normal walking trials to slip trials within each footwear condition (Condition 0: normal 12.56N/kg ± 0.81, slip 13.08N/kg ± 3.49, $p = 0.513$; Condition 1: normal 12.22N/kg ± 0.51, slip 12.05N/kg ± 1.03, $p = 0.983$; Condition 2: normal 12.5N/kg ± 0.73, slip 12.45N/kg ± 0.32, $p = 0.9497$; Condition 3: normal 12.07N/kg ± 0.71, slip 11.91N/kg ± 0.59, $p = 0.4521$; Condition 4: normal 12.92N/kg ± 1.13, slip 13.39N/kg ± 0.92, $p = 0.7103$) (Table 3.3- 3.7, Figure 3.3).

Table 3.3

Repeated measures, within-1 factor ANOVA; a comparison of normal to slip trials within footwear condition 0 (barefoot).

Condition 0	Normal		Slip			
# of Observations	26		8			
	Mean	STDev	Mean	STDev	P-value	Significants
Kinetic Data						
NormF Peak (N/kg)	12.56	0.81	13.08	3.49	0.513	
ROL (N/s/kg)	133.39	34.18	120.21	23.10	0.6907	
UR (N/s/kg)	129.47	23.14	130.47	16.52	0.4349	
LI (N/s/kg)	5.37	1.05	5.48	1.30	0.604'	
ShearF Peak (N/kg)	2.36	0.52	3.12	2.37	0.3052	
BI (N/s/kg)	3.17	0.45	4.02	1.52	0.194	
PI (N/s/kg)	-3.18	0.45	-3.28	0.54	0.1413'	
Kinematic Data						
Stance Duration (s)	0.55	0.05	0.51	0.13	0.4808	
Step Length	0.38	0.03	0.38	0.04	0.2924	
Step Width	0.07	0.02	0.08	0.02	0.6917	
Gait Speed (m/s)	1.62	0.14	1.61	0.13	0.5907	
Heel Disp (m)	0.018	0.004	0.107	0.085	0.0011'	*
Heel VelHC (m/s)	0.31	0.29	0.36	0.37	0.8314	
Heel Vel Peak (m/s)	0.91	0.21	1.97	1.33	0.1154	
Shank AngHC (°)	-16.44	2.40	-17.02	2.12	0.9525	
FFloor AngHC (°)	16.97	7.43	17.83	7.68	0.6789'	
FFloor AngVelHC (°/s)	-396.96	162.94	-333.55	249.26	0.4629'	
Ankle AngHC (°)	4.45	4.58	3.51	4.78	0.7708	
Ankle Ang30% (°)	-2.00	3.71	5.43	6.76	0.0462'	*
Ankle Ang50% (°)	-5.19	4.06	-0.99	8.35	0.3378	
Ankle AngVelHC (°/s)	277.24	95.44	281.97	135.07	0.8454	
knee AngHC (°)	171.21	2.76	172.80	3.33	0.4181	
Knee Ang30% (°)	159.00	4.55	163.34	5.27	0.5222'	
Knee Ang50% (°)	168.01	3.35	163.58	7.15	0.0535'	
Hip AngHC (°)	-25.48	5.32	-28.67	2.26	0.0781	
Hip Ang30% (°)	-16.80	3.29	-20.82	3.39	0.0678'	
Hip Ang50% (°)	-3.51	3.09	-14.48	9.01	0.0994	

(%) Values were normalized to % stance of the right (slipping) limb Positive ankle and hip angles (+) represent extension, negative angles (-) represent flexion relative to neutral
'ANOVA performed with a ranked transform to achieve normalcy
**Significance p< 0 05*

Table 3.4

Repeated measures, within-1 factor ANOVA; a comparison of normal to slip trials within footwear condition 1.

Condition 1	Normal		Slip			
# of Observations	21		3			
	Mean	STDev	Mean	STDev	P-value	Significants
Kinetic Data						
NormF Peak (N/kg)	12.22	0.51	12.05	1.03	0.9803	
ROL (N/s/kg)	105.21	11.16	100.21	10.29	0.8833	
UR (N/s/kg)	96.36	7.61	94.97	9.47	0.8577'	
LI (N/s/kg)	7.28	0.82	6.98	1.02	0.9399	
ShearF Peak (N/kg)	2.48	0.34	2.41	0.21	0.9567	
BI (N/s/kg)	3.73	0.46	5.04	2.26	0.1488'	
PI (N/s/kg)	-3.30	0.39	-3.50	0.26	0.102'	
Kinematic Data						
Stance Duration (s)	0.61	0.03	0.64	0.05	0.3863	
Step Length	0.39	0.02	0.40	0.01	0.4878	
Step Width	0.07	0.02	0.08	0.01	0.5921	
Gait Speed (m/s)	1.66	0.06	1.65	0.02	0.8491	
Heel Disp (m)	0.019	0.003	0.068	0.071	0.013'	*
Heel VelHC (m/s)	0.58	0.25	0.56	0.38	0.8177	
Heel Vel Peak (m/s)	0.83	0.13	1.20	0.78	0.4749	
Shank AngHC (°)	-21.35	1.62	-22.07	2.65	0.736	
FFloor AngHC (°)	29.66	2.31	29.86	1.39	0.4186	
FFloor AngVelHC (°/s)	-320.34	31.10	-355.29	52.15	0.4958	
Ankle AngHC (°)	-2.23	4.50	-0.73	0.62	0.518'	
Ankle Ang30% (°)	-0.37	4.44	4.86	4.18	0.3441	
Ankle Ang50% (°)	-4.10	4.44	-2.52	3.46	0.7162'	
Ankle AngVelHC (°/s)	46.73	47.18	71.98	39.15	0.4889'	
knee AngHC (°)	173.04	4.14	174.41	2.91	0.1344	
Knee Ang30% (°)	160.68	5.47	167.13	4.54	0.256	
Knee Ang50% (°)	169.69	4.49	166.52	8.73	0.4265	
Hip AngHC (°)	-27.66	2.43	-26.35	2.85	0.4995	
Hip Ang30% (°)	-16.67	3.42	-15.69	5.38	0.5415	
Hip Ang50% (°)	-3.53	2.41	-7.45	6.40	0.3354	

(%) Values were normalized to % stance of the right (slipping) limb Positive ankle and hip angles (+) represent extension, negative angles (-) represent flexion relative to neutral
'ANOVA performed with a ranked transform to achieve normalcy
**Significance $p < 0.05$*

Table 3.5

Repeated measures, within-1 factor ANOVA; a comparison of normal to slip trials within footwear condition 2.

Condition 2	Normal		Slip			
# of Observations	20		3			
	Mean	STDev	Mean	STDev	P-value	Significants
Kinetic Data						
NormF Peak (N/kg)	12.50	0.73	12.45	0.32	0.9497	
ROL (N/s/kg)	108.25	14.46	103.29	18.36	0.9043	
UR (N/s/kg)	101.70	12.96	107.90	18.46	0.6054	
LI (N/s/kg)	7.39	1.01	7.27	0.63	0.9724	
ShearF Peak (N/kg)	2.61	0.35	2.22	0.12	0.4821	
BI (N/s/kg)	3.39	0.48	3.95	1.56	0.4424'	
PI (N/s/kg)	-3.36	0.44	-3.63	0.47	0.1324	
Kinematic Data						
Stance Duration (s)	0.61	0.05	0.57	0.07	0.1459	
Step Length	0.39	0.03	0.40	0.04	0.1654	
Step Width	0.08	0.01	0.07	0.01	0.9516	
Gait Speed (m/s)	1.73	0.12	1.81	0.12	0.3569	
Heel Disp (m)	0.022	0.004	0.098	0.102	0.478	
Heel VelHC (m/s)	1.01	0.33	1.38	0.80	0.424	
Heel Vel Peak (m/s)	1.06	0.27	1.56	0.77	0.4375	
Shank AngHC (°)	-21.13	5.55	-23.85	1.00	0.9324	
FFloor AngHC (°)	24.79	10.77	18.44	12.38	0.6806	
FFloor AngVelHC (°/s)	-314.39	70.14	-259.41	169.25	0.4329	
Ankle AngHC (°)	-2.09	4.10	1.92	1.66	0.6941	
Ankle Ang30% (°)	-0.10	3.47	2.70	4.82	0.4403'	
Ankle Ang50% (°)	-4.07	2.39	-3.56	0.80	0.9202'	
Ankle AngVelHC (°/s)	30.87	38.36	30.95	50.31	0.7569	
knee AngHC (°)	171.73	6.05	174.87	1.20	0.4268'	
Knee Ang30% (°)	160.95	4.65	161.78	1.94	0.5132'	
Knee Ang50% (°)	168.55	3.70	165.12	9.76	0.5135	
Hip AngHC (°)	-29.02	3.13	-29.26	0.99	0.4462	
Hip Ang30% (°)	-20.02	3.53	-21.46	4.64	0.2431'	
Hip Ang50% (°)	-6.90	4.92	-7.54	5.42	0.5659	

(%) Values were normalized to % stance of the right (slipping) limb Positive ankle and hip angles (+) represent extension, negative angles () represent flexion relative to neutral
'ANOVA performed with a ranked transform to achieve normalcy
**Significance p< 0 05*

Table 3.6

Repeated measures, within-1 factor ANOVA; a comparison of normal to slip trials within footwear condition 3.

Condition 3	Normal		Slip			
# of Observations	22		4			
	Mean	STDev	Mean	STDev	P-value	Significants
Kinetic Data						
NormF Peak (N/kg)	12.07	0.71	11.91	0.59	0.4521	
ROL (N/s/kg)	96.37	15.64	103.30	24.63	0.3625	
UR (N/s/kg)	98.99	17.34	99.71	19.88	0.2236	
LI (N/s/kg)	6.86	1.00	6.33	0.58	0.9556	
ShearF Peak (N/kg)	2.34	0.50	2.47	0.23	0.5143	
BI (N/s/kg)	3.60	0.66	4.22	1.11	0.2832'	
PI (N/s/kg)	-3.35	0.66	-3.34	0.57	0.4816	
Kinematic Data						
Stance Duration (s)	0.63	0.05	0.57	0.12	0.7101	
Step Length	0.40	0.04	0.40	0.05	0.3416	
Step Width	0.07	0.02	0.07	0.02	0.8388	
Gait Speed (m/s)	1.66	0.16	1.71	0.24	0.3281	
Heel Disp (m)	0.017	0.000	0.066	0.043	0.0278'	*
Heel VelHC (m/s)	0.63	0.28	0.77	0.27	0.7925	
Heel Vel Peak (m/s)	0.73	0.23	1.37	0.47	0.1161'	
Shank AngHC (°)	-21.43	2.96	-21.08	3.67	0.63	
FFloor AngHC (°)	29.37	4.62	31.73	5.55	0.108	
FFloor AngVelHC (°/s)	-301.83	75.56	-347.07	40.09	0.8224'	
Ankle AngHC (°)	-2.09	3.56	-5.14	3.41	0.3274	
Ankle Ang30% (°)	-1.46	3.17	-1.10	5.57	0.0916	
Ankle Ang50% (°)	-5.35	3.27	-8.17	3.29	0.2189'	
Ankle AngVelHC (°/s)	55.27	37.70	42.52	54.76	0.6676'	
knee AngHC (°)	172.29	3.73	171.20	3.18	0.2725	
Knee Ang30% (°)	158.84	4.50	155.61	4.49	0.4223	
Knee Ang50% (°)	166.53	4.40	157.33	3.16	0.1509	
Hip AngHC (°)	-28.24	3.27	-29.92	2.21	0.683	
Hip Ang30% (°)	-18.43	2.41	-22.50	2.17	0.0807'	
Hip Ang50% (°)	-6.49	3.15	-11.75	4.19	0.2164	

(%) Values were normalized to % stance of the right (slipping) limb Positive ankle and hip angles (+) represent extension, negative angles (-) represent flexion relative to neutral
'ANOVA performed with a ranked transform to achieve normalcy
**Significance p< 0 05*

Table 3.7

Repeated measures, within-1 factor ANOVA; a comparison of normal to slip trials within footwear condition 4.

Condition 4	Normal		Slip			
# of Observations	19		2			
	Mean	STDev	Mean	STDev	P-value	Significants
Kinetic Data						
NormF Peak (N/kg)	12.92	1.13	13.39	0.92	0.7103	
ROL (N/s/kg)	118.77	23.14	122.89	15.32	0.3428	
UR (N/s/kg)	104.56	10.83	105.82	4.65	0.6879	
LI (N/s/kg)	6.72	0.88	6.28	0.34	0.1881'	
ShearF Peak (N/kg)	2.52	0.38	2.78	0.12	0.6209	
BI (N/s/kg)	3.28	0.40	3.87	0.24	0.1943	
PI (N/s/kg)	-3.02	0.44	-3.50	-	-	
Kinematic Data						
Stance Duration (s)	0.61	0.04	0.62	0.02	0.4482	
Step Length	0.38	0.02	0.37	0.01	0.5152	
Step Width	0.09	0.02	0.10	0.01	0.9131	
Gait Speed (m/s)	1.70	0.11	1.73	0.03	0.7578	
Heel Disp (m)	0.017	0.003	0.061	0.018	0.186	
Heel VelHC (m/s)	0.88	0.47	0.98	0.13	0.6745	
Heel Vel Peak (m/s)	0.95	0.37	1.12	0.07	0.6288	
Shank AngHC (°)	-21.13	2.09	-20.46	3.47	0.6888	
FFloor AngHC (°)	23.46	11.10	5.88	0.12	0.5'	
FFloor AngVelHC (°/s)	-310.75	99.05	-87.04	-	-	
Ankle AngHC (°)	0.76	2.53	-0.73	2.52	0.3666	
Ankle Ang30% (°)	1.30	2.68	4.77	3.37	0.213	
Ankle Ang50% (°)	-2.33	3.12	-0.11	3.44	0.2962	
Ankle AngVelHC (°/s)	83.38	59.46	75.76	67.60	0.2814	
knee AngHC (°)	169.87	5.20	169.69	5.15	0.413	
Knee Ang30% (°)	157.31	9.34	156.95	19.36	0.3194	
Knee Ang50% (°)	165.82	7.90	163.16	15.52	0.8437	
Hip AngHC (°)	-28.33	1.99	-29.62	1.75	0.7004	
Hip Ang30% (°)	-17.36	2.69	-22.34	1.65	0.1257'	
Hip Ang50% (°)	-4.32	1.38	-7.94	0.53	0.1542	

(%) Values were normalized to % stance of the right (slipping) limb Positive ankle and hip angles (+) represent extension, negative angles ( ) represent flexion relative to neutral
'ANOVA performed with a ranked transform to achieve normalcy
**Significance p< 0 05*

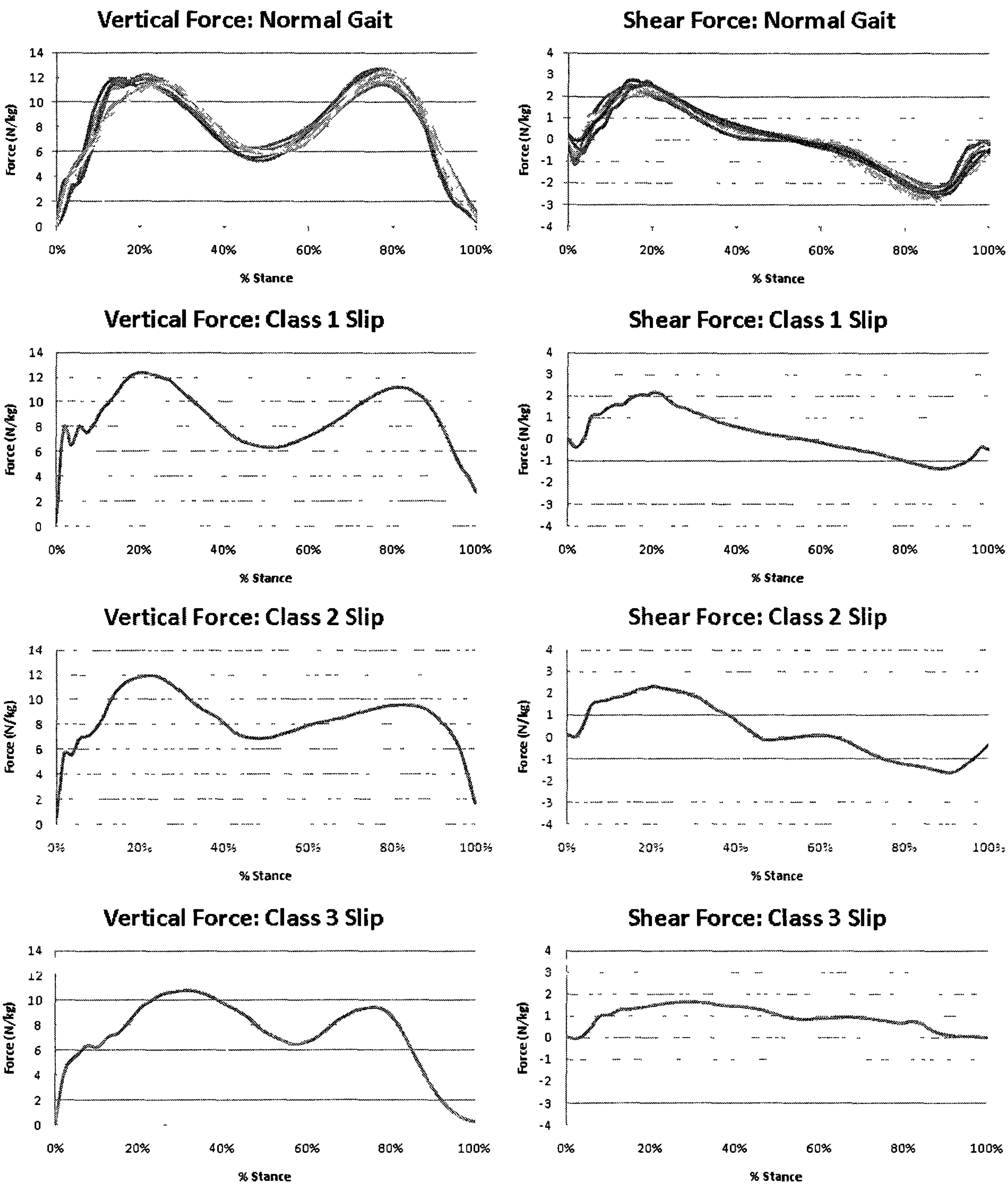


Figure 3.3: **Representative graphs of vertical (Normal) and shear ground reaction forces (N/kg) during normal walking trials (top graphs, several normal trials from three individuals) compared to the three classes of an unexpected slip perturbation (single representative graph from one individual); % stance of the right limb.**

There were no significant differences found when comparing *vertical loading rates* within footwear conditions between normal walking trials and slip trials.(Condition 0: normal 133.39N/s.kg ± 34.18, slip 120.21N/s.kg ± 23.1, p = 0.6907; Condition 1: normal 105.21N/s.kg ± 11.16, slip 100.21N/s.kg ± 10.29, p = 0.8833; Condition 2: normal 108.25N/s.kg ± 14.46, slip 103.29N/s.kg ± 18.36, p = 0.9043, Condition 3: normal 96.37N/s.kg ± 15.64, slip 103.30N/s.kg ± 24.63, p = 0.3625; Condition 4: normal 118.77N/s.kg ± 23.14, slip 122.89N/s.kg ± 15.32, p = 0.3428) (Table 3.3- 3.7).

Peak shear ground reaction forces were not found to be significant when comparing normal walking trials to slip trials within each footwear condition.(Condition 0: normal 2.36N/kg ± 0.52, slip 3.12N/kg ± 2.37, p = 0.3052; Condition 1: normal 2.48N/kg ± 0.34, slip 2.41N/kg ± 0.21, p = 0.9567; Condition 2: normal 2.61N/kg ± 0.35, slip 2.22N/kg ± 0.12, p = 0.4821; Condition 3: normal 2.34N/kg ± 0.5, slip 2.47N/kg ± 0.23, p = 0.5143; Condition 4: normal 2.52N/kg ± 0.38, slip 2.78N/kg ± 0.12, p = 0.6209) (Table 3.3 - 3.7, Figure 3.3).

3.2.3 Kinematic Data

Gait Characteristics

During slip trials, *stance durations* were not significantly different than during normal walking trials when compared within each footwear condition (Condition 0: normal 0.55s ± 0.05, slip 0.51s ± 0.13, p = 0.481; Condition1: normal 0.61s ± 0.03, slip 0.64s ± 0.05, p = 0.386; Condition 2: normal 0.61s ± 0.05, slip 0.57s ± 0.07, p = 0.1459; Condition 3: normal 0.63s ± 0.05, slip 0.57, ± 0.12, p = 0.7101; Condition 4: normal 0.61s ± 0.04, slip 0.62s ± 0.02, p = 0.4482) (Table 3.3 – 3.7).

Step length remained consistent during slip trials compared to normal walking trials as no significant differences were found (Condition 0: normal 0.38 ± 0.03, slip 0.38 ± 0.04, p = 0.292; Condition 1: normal 0.39 ± 0.02, slip 0.40 ± 0.01, p = 0.488; Condition 2: normal 0.39 ± 0.03, slip 0.40 ± 0.04, p = 0.1654; Condition 3: normal 0.40 ± 0.04, slip 0.40 ± 0.05, p = 0.3416; Condition 4: 0.38 ± 0.02, 0.37 ± 0.01, p = 0.5152) (Table 3.5 – 3.9). Similar to step length, *step width* also remained consistent during slip trials as no significant differences were identified (Condition 0: normal 0.07 ± 0.02, slip 0.08 ± 0.02, p = 0.692; Condition 1: normal 0.07 ± 0.02, slip 0.08 ± 0.01, p = 0.592; Condition 2: normal 0.08 ± 0.01, slip 0.07 ± 0.01, p = 0.9515; Condition 3: normal 0.07 ± 0.02, slip 0.07 ± 0.02, p = 0.8388; Condition 4: 0.09 ± 0.02, 0.10 ± 0.012, p = 0.9131) (Table 3.3 – 3.7).

When comparing normal walking trials to slips trials within footwear conditions, no significant differences were found for *gait velocity* (Condition 0: normal 1.62m/s ± 0.14, slip 1.61m/s ± 0.13, p = 0.591; Condition 1: normal 1.66m/s ± 0.06, slip 1.65m/s ± 0.02, p = 0.849; Condition 2: normal 1.73m/s ± 0.12, slip 1.81m/s ± 0.12, p = 0.3569; Condition 3: normal 1.66m/s ± 0.16, slip 1.71m/s ± 0.24, p = 0.3281; Condition 4: 1.70m/ ± 0.11, 1.73m/s ± 0.03, p = 0.7578) (Table 3.3 – 3.7).

Slip trials exhibited significantly greater forward *heel displacements* in conditions 0, 1, and 3 compared to normal walking trials (Condition 0: normal 0.02m ± 0.0, slip 0.11m ± 0.09, p = 0.0011; Condition 1: normal 0.02m ± 0.0, slip 0.07m ± 0.07, p = 0.013; Condition 2: normal 0.02m ± 0.0, slip 0.08m ± 0.10, p = 0.3918; Condition 3: normal 0.02m ± 0.0, slip 0.07m ± 0.04, p = 0.0439; Condition 4: normal 0.02m ± 0.0, slip 0.06m ± 0.02, p = 0.1858). Peak heel velocities were greater during slip trials, but were not found to be significant compared to normal walking trails (Condition 0: normal 0.91m/s ± 0.21, slip 1.97m/s ± 1.33, p = 0.1154; Condition 1:

normal 0.83m/s ± 0.13, slip 1.20m/s ± 0.78, p = 0.4749; Condition 2: normal 1.06m/s ± 0.27, slip 1.56m/s ± 0.77, p = 0.4375; Condition 3: normal 0.73m/s ± 0.23, slip 1.37m/s ± 0.47, p = 0.1161; Condition 4: normal 0.95m/s ± 0.37, slip 1.12m/s ± 0.07, p = 0.6288) compared to normal walking trials (Table 3.3 -3.7, Figure 3.4).

Heel velocities measured at heel contact were not significantly different during the slip perturbation trials compared to normal walking trials within each condition (Condition 0: normal 0.31m/s ± 0.29, slip 0.36m/s ± 0.37, p = 0.8314; Condition 1: normal 0.58m/s ± 0.25, slip 0.56m/s ± 0.38, p = 0.8177; Condition 2: normal 1.01m/s ± 0.33, slip 1.38m/s ± 0.80, p = 0.424; Condition 3: normal 0.63m/s ± 0.28, slip 0.77m/s ± 0.27, p = 0.7925; Condition 4: normal 0.88m/s ± 0.47, slip 0.98m/s ± 0.13, p = 0.6745) (Table 3.3-3.7, Figure 3.4).

Joint Angles

When comparing slip trials to normal walking trials within each condition, no significant differences were found in the *shank angle* at heel contact (Condition 0: normal -16.44° ± 2.40, slip -17.02° ± 2.12, p = 0.9525; Condition 1: normal -21.35° ± 1.62, slip -22.07° ± 2.65, p = 0.736; Condition 2: normal -21.13° ± 5.55, slip -23.85° ± 1.00, p = 0.9324; Condition 3: normal -21.43° ± 2.96, slip -21.08° ± 3.67, p = 0.63; Condition 4: normal -21.13° ± 2.09, slip -20.46° ± 3.47, p = 0.6888) (Table 3.3 - 3.7).

No significant differences were found in the *foot-floor angle* when comparing slip trials to normal walking trials within each condition (Condition 0: normal 16.67° ± 7.43, slip 17.83° ± 7.68, p = 0.6789; Condition 1: normal 29.66° ± 2.31, slip 29.86° ± 1.39, p = 0.4186; Condition 2: normal 24.79° ± 10.77, slip 18.44° ± 12.38, p = 0.6806; Condition 3: normal 29.37° ± 4.62, slip 31.73° ± 5.55, p = 0.108; Condition 4: normal 23.46° ± 11.10, slip 5.88° ± 0.12, p = 0.5) (Table 3.3 – 3.7).

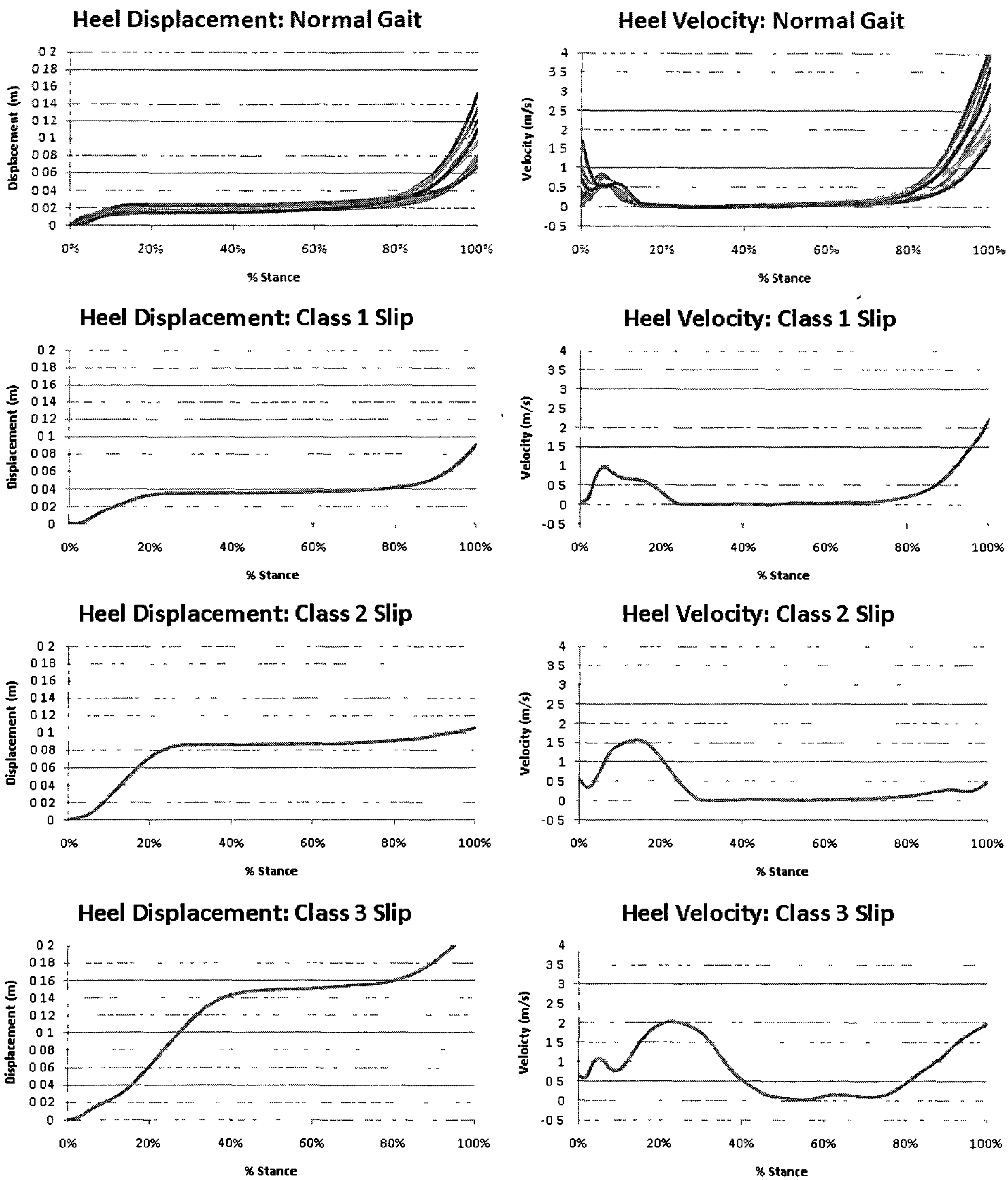


Figure 3.4: **Representative graphs of heel displacement (m) and heel velocity (m/s) during normal walking trials (top graphs, several normal trials from three individuals) compared to the three classes of an unexpected slip perturbation (single representative graph from one individual); % stance of the right limb.**

No significant differences were found in the *ankle angle* when comparing normal walking trails to slip trials within each footwear condition during stance (Condition 0: normal 4.45° ± 4.58, slip 3.51° ± 4.78; p = 0.7708; Conditon1: normal -2.23° ± 4.50, slip -0.73° ± 0.62; p = 0.518; Condition 2: normal -2.09° ± 4.10, slip 1.92° ± 1.66; p = 0.6941; Condition3: normal -2.09° ± 4.10, slip -5.14° ± 3.416; p = 0.3274; Condition 4: normal 0.76° ± 2.53, slip -0.073° ± 2.52; p = 0.3666). Within all of the conditions except for condition 3, individuals averaged greater ankle plantarflexion at *30% stance* during slip trials; significance was found in barefoot individuals (Condition 0: normal -2.0° ± 3.71, slip 5.43° ± 6.76, p = 0.0462; Condition 1: normal -0.37° ± 4.44, slip 4.86° ± 4.18, p = 0.3441; Condition 2: normal -0.10° ± 3.47, slip 2.70° ± 4.82, p = 0.4403; Condition 3: normal -1.46° ± 3.17, slip -1.10° ± 3.57, p = 0.0916; Condition 4: normal 1.30° ± 2.68, slip 4.77° ± 3.37, p = 0.213). At *50% stance* during, no significant differences were identified (Condition 0: normal -5.19° ± 4.06, slip -0.99° ± 8.35, p = 0.3378; Condition 1: normal -4.10° ± 4.44, slip -2.52° ± 3.46, p = 0.7162; Condition 2: normal -4.07° ± 2.39, slip -3.56° ± 0.80, p = 0.9202; Condition 3: normal -5.35° ± 3.27, slip -8.17° ± 3.29, p = 0.2189; Condition 4: normal -2.33° ± 3.12, slip -0.11° ± 3.44, p = 0.2962) (Table 3.3 – 3.7, Figure 3.5).

When comparing the *knee angle* in normal walking trials to slip trials, no significant differences were found during the stance phase. All of the conditions showed relatively similar knee angles at heel contact during both normal walking and slip trials (Condition 0: normal 171.21° ± 2.76, slip 172.80° ± 3.33, p = 0.4181; Condition 1: normal 173.04° ± 4.14, slip 174.41° ± 2.91, p = 0.1344; Condition 2: normal 171.73° ± 6.05, slip 174.87° ± 1.20, p = 0.4268; Condition 3: normal 172.29° ± 3.73, slip 171.20° ± 3.18, p = 0.2725; Condition 4: normal 169.87° ± 5.20, slip 169.69° ± 5.15, p = 0.413) (Table 3.3 – 3.7, Figure 3.5).

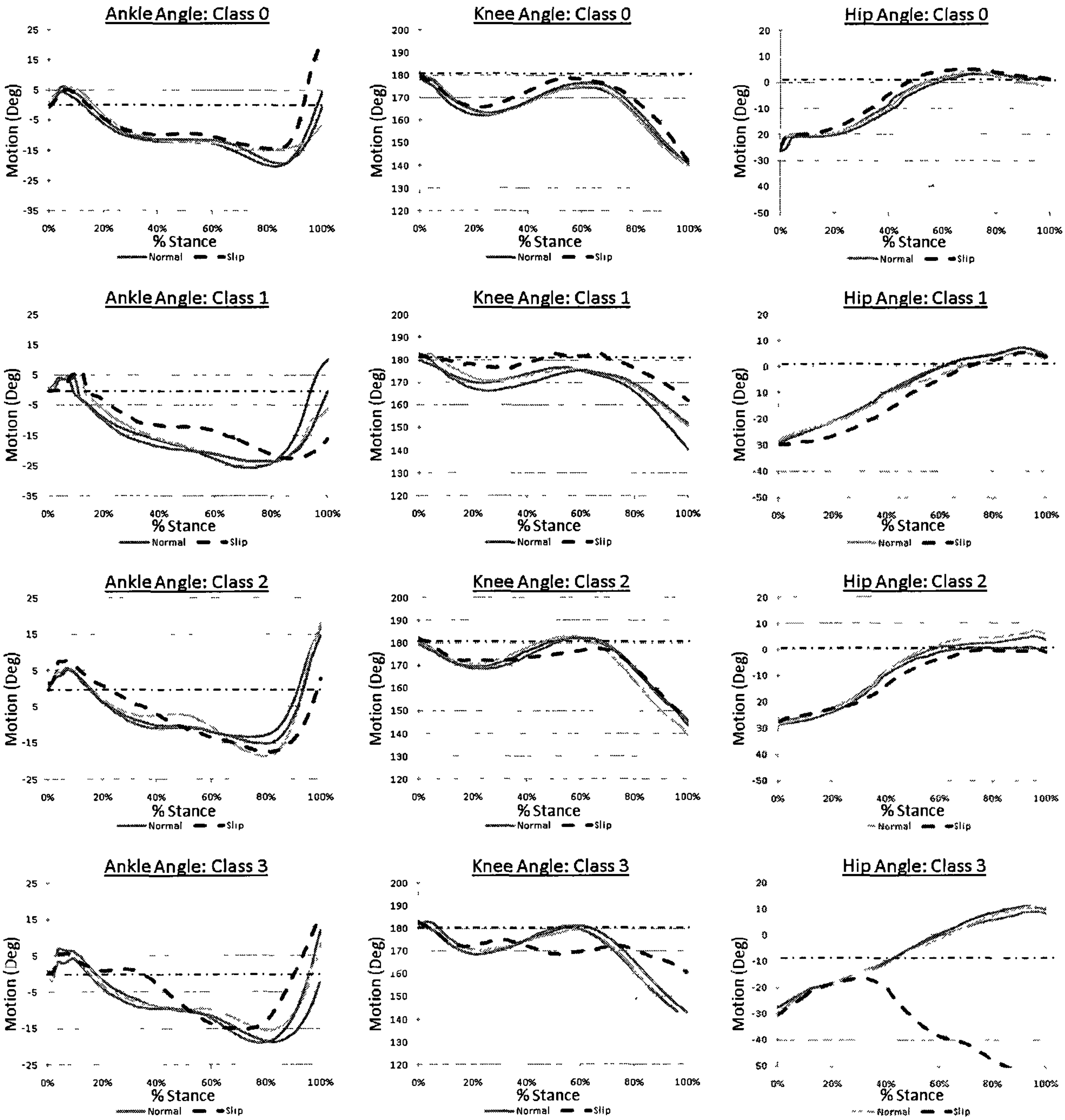


Figure 3.5: **Representative profiles of the ankle, knee and hip joints during normal walking trials (3 normal trials) compared to slip trials (dashed line). The vertical line represents the joints neutral angle. Ankle: (+) plantarflexion, (-) dorsiflexion; Knee: flexion; Hip: (+) extension, (-) flexion.**

At *30% stance*, no significant differences were noted in the *knee angle* (Condition 0: normal 159.0° ± 4.55, slip 163.34° ± 5.27, p = 0.522; Condition 1: normal 160.68° ± 5.47, slip 167.13° ± 4.54, p = 0.256; Condition 2: normal 160.95° ± 4.65, slip 161.78° ± 1.94, p = 0.5132; Condition 3: normal 158.84° ± 4.50, slip 155.61° ± 4.49, p = 0.4223; Condition 4: normal 157.31° ± 9.34, slip 156.95° ± 19.36, p = 0.3149). No significant differences were found within the knee angle at *50% stance*; barefoot individuals averaged greater knee flexion during slip trials (Condition 0: normal 168.01° ± 3.35, slip 163.58° ± 7.15, p = 0.0535; Condition 1: normal 169.69° ± 4.49, slip 166.52° ± 8.73, p = 0.4265; Condition 2: normal 168.55° ± 3.70, slip 165.12° ± 9.76, p = 0.5135; Condition 3: normal 166.53° ± 4.40, slip 157.33° ± 3.16, p = 0.1509; Condition 4: normal 165.82° ± 7.90, slip 163.16° ± 15.52, p = 0.8437) (Table 3.3 – 3.7, Figure 3.5).

When comparing normal walking trials to slip trials, no significant differences were found during the stance phase within the *hip angle*. All of the conditions showed relatively similar hip angles for both the normal and slip trials at heel contact except for the barefoot condition; on average barefoot individuals showed greater hip flexion at HC during the slip trial (Condition 0: normal -25.48° ± 5.32, slip -28.67° ± 2.26, p = 0.0781; Condition 1: normal -27.66° ± 2.43, slip -26.35° ± 2.85, p = 0.4995; Condition 2: normal -29.02° ± 3.13, slip -29.26° ± 0.99, p = 0.4462; Condition 3: normal -28.24° ± 3.27, slip -29.27° ± 2.21, p = 0.683; Condition 4: normal -28.33° ± 1.99, slip -29.62° ± 1.75, p = 0.7004). Although not significant, at *30% stance* all of the conditions exhibited greater hip flexion during the slip trails except condition 2 which remained relatively the same (Condition 0: normal -16.80° ± 3.29, slip -20.82° ± 3.39, p = 0.0678; Condition 1: normal -16.67° ± 3.42, slip -15.69° ± 5.38, p = 0.5415; Condition 2: normal -20.02° ± 3.53, slip -21.46° ± 4.64, p = 0.2431; Condition 3: normal -18.43° ± 2.41, slip

-22.50° ± 2.17, p = 0.0807; Condition 4: normal -17.36° ± 2.69, slip -22.34° ± 1.65, p = 0.1257). Within all of the conditions participants also averaged greater hip flexion at *50% stance* during slip trials, but again this was not found to be significant (Condition 0: normal -3.51° ± 3.09, slip -14.48° ± 9.01, p = 0.0994; Condition 1: normal -3.53° ± 1.41, slip -7.45° ± 6.40, p = 0.3354; Condition 2: normal -6.90° ± 4.92, slip -7.54° ± 5.42, p = 0.56593; Condition 3: normal -6.49° ± 3.15, slip -11.75° ± 4.19, p = 0.2164; Condition 4: normal -4.32° ± 1.38, slip -7.94° ± 0.53, p = 0.1542) (Table 3.3 – 3.7, Figure 3.5).

Subtalar Joint Angle

The subtalar joint angles were only able to be calculated for the barefoot condition (Condition 0). During normal walking trails the subtalar joint averaged 4.8° ± 6.2 of inversion at heel contact which was not found to be significantly different during slip trials (5.7° ± 5.0, p = 0.278). The average onset of eversion during normal walking trails occurred at 5.0% ± 1.0 of stance. During slip trials the average onset of eversion occurred slightly later, but again was not statistically significant (8.1% ± 1.0, p = 0.1014). During normal walking trails, the subtalar joint peaked at an average maximum eversion angle of -3.3° ± 4.6 at 22.0% ± 1.0 of stance. During slip recoveries peak eversion was not found to be significantly different than normal walking trials, but did have slightly lower maximums (-1.8 ° ± 7.0, p = 0.2399) and occurred a little later in stance (24.0% ± 1.0, p = 0.2501) (Table 3.3 – 3.7, Figure 3.5).

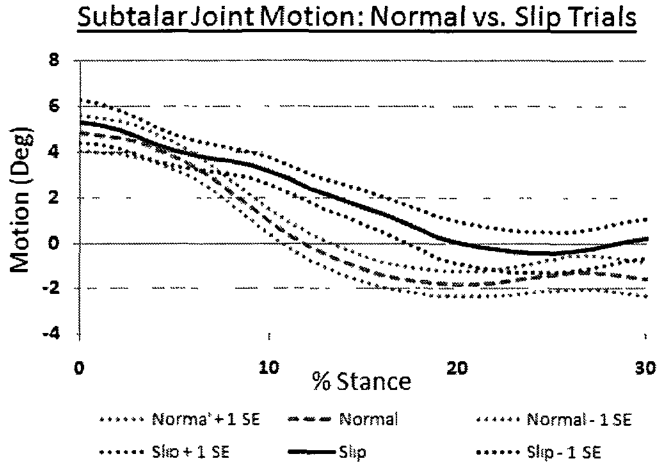


Figure 3.6: **Illustrates average subtalar joint motion (dashed line, dotted represents 1 Stdev) within the first 30% of stance of normal unperturbed walking trials compared to the average joint motion during slip recoveries. *Inversion (+), eversion (-).**

Table 3.8

A comparison of average subtalar joint motion during normal walking trials to slip recovery trials in barefoot individuals (condition 0).

Condition 0	Normal		Slip		
# of Observations: 8	Mean	Stdev	Mean	Stdev	p-value*
Sub AngHC (°)	4.8	6.2	5.7	5.0	0.278
Sub OnsetEv (% stance)	5.0	1.0	8.1	1.0	0.1014
Sub EvPeak (°)	-3.3	4.6	-1.8	7.0	0.2399
Sub EvPeakT (% stance)	22.0	1.0	24.0	1.0	0.2501

**No significant differences were found, p<0 05*
***Subjects 4 and 9 were omitted from the average calculations due to errors in rigid body calculations*
*** *Inversion(+), /eversion(-)*

3.2.4 Electromyography

During slip recovery trials, as a function of slip severity, muscles that did not characteristically activate in the middle part of stance (stability phase) showed activation. Those muscles that were characteristically active during the middle phase of stance elicited earlier onsets and in most cases higher magnitudes as a response to the slip perturbation (Table 3.9, Figure 3.2; refer to Appendix F for full data table). Within barefoot individuals (Condition 0) increased activity of the left medial gastrocnemius (LMG), left rectus femoris (LRF) and left medial hamstring (LMH) were seen as a function of greater slip severities. As this activity was not seen in any of the other footwear conditions, this investigation will be focused on muscles directly affecting the ankle complex of the perturbed limb: the right tibialis anterior (RTA), the right medial gastrocnemius (RMG) and the right peroneus longus (RPL).

Tibialis Anterior

During slip trials, activation patterns within the ***preparatory phase*** were not significantly different than those seen in normal walking trials across all footwear conditions (Condition 0: onset, normal -11.88% ± 3.85, slip -12.99% ± 5.86, p = 0.6057; duration, normal 21.37% ± 3.51, slip 24.74% ± 9.51, p = 0.5723; magnitude, normal 86.80 % ± 20.03, slip 92.09% ± 23.15, p = 0.8427; Condition 1: onset, normal -11.71% ± 4.24, slip -11.29% ± 1.48, p = 0.5382; duration, normal 24.27% ± 5.70 , slip 19.78% ± 3.54, p = 0.7016; magnitude, normal 100.74% ± 29.31, slip 89.56% ± 10.85, p = 0.6613; Condition 2: onset, normal -13.89% ± 5.32, slip -16.34% ± 1.53, p = 0.1104; duration, normal 27.05% ± 7.25, slip 27.90% ± 5.49, p = 0.6779; magnitude, normal 107.04% ± 28.79, slip 97.27% ± 13.25, p = 0.2275; Condition 3: onset, normal -13.71% ± 3.86, slip -12.42% ± 0.82, p = 0.1405; duration, normal 26.86% ± 5.21, slip 22.93% ± 2.59, p = 0.062; magnitude, normal 124.64% ± 41.01, slip 105.73% ± 32.43, p = 0.7039; Condition 4: onset, normal -15.11% ± 5.57, slip -8.13% ± 0.42, p = 0.1727; duration, normal 26.28% ± 4.79, slip 18.84% ± 0.71, p = 0.1823; magnitude, normal 102.88% ± 23.83, slip 89.79% ± 23.00, p = 0.3496) (Table 3.9, Figure 3.2, 3.7; Appendix F).

Table 3.9

Demonstrates EMG activation patterns of the right tibialis anterior (RTA), right medial gastrocnemius (RMG) and right peroneus longus (RPL) during normal walking trials compared to slip trials; repeated measures, within-1 factor ANOVA.

		Preparatory Phase					Stability Phase					Transition Phase				
		Normal		Slip			Normal		Slip			Normal		Slip		
		Mean	STDev	Mean	STDev	P-value*	Mean	STDev	Mean	STDev	P-value*	Mean	STDev	Mean	STDev	P-value*
Condition 0	**RTA**															
	Onset (%)	-11.88	3.85	-12.99	5.86	0.6057	-	-	20.49	2.39	-	96.17	3.97	95.16	9.60	0.5949
	Duration (%)	21.37	3.51	24.74	9.51	0.5723	-	-	19.82	5.38	-	29.09	9.63	22 80	5.17	0.0388*
	Magnitude (%)	86.80	20.03	92.09	23.15	0.8427	-	-	115.43	51.00	-	95.98	24.82	106.62	44.33	0.2745
	RMG															
	Onset (%)	-	-	-	-	-	43.12	10.25	38.36	17.33	0.1409	-	-	67.18	20.37	-
	Duration (%)	-	-	-	-	-	33.94	9.52	38.01	19.17	0.7227	-	-	21.90	10.27	-
	Magnitude (%)	-	-	-	-	-	102.76	17.31	83.75	49.97	0.0172*	-	-	72.45	27.15	-
	RPL															
	Onset (%)	-	-	-	-	-	37.83	11.79	25.99	2.19	0.0778	-	-	67.24	18.40	-
	Duration (%)	-	-	-	-	-	39.68	13.89	60.97	41.55	0.2584	-	-	27.67	5.81	-
	Magnitude (%)	-	-	-	-	-	91.22	25.45	125.94	67.09	0.2164	-	-	78.69	21.53	-
Condition 1	**RTA**															
	Onset (%)	-11.71	4.24	-11.29	1.48	0.5382	-	-	17.42	4.92	-	92.23	10.09	90.72	6.11	0.7333
	Duration (%)	24.27	5.70	19.78	3.54	0.7016	-	-	18.72	4.09	-	25.58	9.16	17.09	6.40	0.5393
	Magnitude (%)	100.74	29.31	89.56	10.85	0.6613	-	-	111.65	106.29	-	99.31	27.60	100.12	64.30	0.994
	RMG															
	Onset (%)	-	-	-	-	-	43.54	14.10	42.98	18.88	0.0681	-	-	-	-	-
	Duration (%)	-	-	-	-	-	32.69	13.72	31.05	23.07	0.7087	-	-	-	-	-
	Magnitude (%)	-	-	-	-	-	99.26	23.04	102.69	22.88	0.8834	-	-	-	-	-
	RPL															
	Onset (%)	-	-	-	-	-	49.70	5.71	31.93	20.47	0.6541	-	-	-	-	-
	Duration (%)	-	-	-	-	-	30.40	3.57	35.27	6.97	0.6474	-	-	-	-	-
	Magnitude (%)	-	-	-	-	-	82.23	22.24	170.16	156.45	0.494	-	-	-	-	-
Condition 2	**RTA**															
	Onset (%)	-13.89	5.32	-16.34	1.53	0.1104	-	-	-	-	-	94.34	5.33	102.44	14.43	0.4269'
	Duration (%)	27.05	7.25	27.90	5.49	0.6779	-	-	-	-	-	16.51	8.48	20.24	1.59	0.6041'
	Magnitude (%)	107.04	28.79	97.27	13.25	0.2275	-	-	-	-	-	109.20	37.13	198.48	116.64	0.2683'
	RMG															
	Onset (%)	-	-	-	-	-	36.54	10.38	37.95	17.14	0.5117	-	-	-	-	-
	Duration (%)	-	-	-	-	-	40.35	11.72	34.22	26.38	0.8749	-	-	-	-	-
	Magnitude (%)	-	-	-	-	-	109.29	20.59	68.62	18.88	0.2409	-	-	-	-	-
	RPL															
	Onset (%)	-	-	-	-	-	45.12	10.85	34.53	19.67	0.3427	-	-	-	-	-
	Duration (%)	-	-	-	-	-	36.68	10.07	29.45	22.18	0.399	-	-	-	-	-
	Magnitude (%)	-	-	-	-	-	95.74	37.96	63.83	59.00	0.1594	-	-	-	-	-
Condition 3	**RTA**															
	Onset (%)	-13.71	3.86	-12.42	0.82	0.1405	-	-	22.08	6.40	-	95.62	3.42	92.19	2.83	0.3789
	Duration (%)	26 86	5.21	22.93	2.59	0 062	-	-	7.69	1.53	-	23.71	10.28	18.85	9.79	0.7098
	Magnitude (%)	124.64	41.01	105.73	32.43	0.7039	-	-	37.10	8.35	-	122.72	71.94	213.23	184.36	0.428
	RMG															
	Onset (%)	-	-	-	-	-	46.93	8.24	53.79	6.88	0.4478	-	-	-	-	-
	Duration (%)	-	-	-	-	-	32.02	9.09	22.38	1 46	0.2841	-	-	-	-	-
	Magnitude (%)	-	-	-	-	-	89.89	21.45	71.41	28.33	0.3406	-	-	-	-	-
	RPL															
	Onset (%)	-	-	-	-	-	44.03	11.85	39.87	15.97	0.7865	-	-	-	-	-
	Duration (%)	-	-	-	-	-	38.90	12.40	41.47	16.77	0.7185	-	-	-	-	-
	Magnitude (%)	-	-	-	-	-	99.17	25.02	128.74	70.89	0.7944	-	-	-	-	-
Condition 4	**RTA**															
	Onset (%)	-15.11	5.57	-8.13	0 42	0.1727	-	-	22.08	6.40	-	93.53	2.22	93.93	2.28	0.1839
	Duration (%)	26.28	4.79	18.84	0.71	0.1823	-	-	7.69	1.53	-	19.99	7.12	17.97	10.12	0.6392'
	Magnitude (%)	102 88	23.83	89.79	23 00	0.3496	-	-	37.10	8.35	-	91.39	25.93	85.26	10.43	0 0146*
	RMG															
	Onset (%)	-	-	-	-	-	48.76	8.27	51.29	2.04	0.3855	-	-	-	-	-
	Duration (%)	-	-	-	-	-	25.69	7.31	23.01	4.26	0.4921	-	-	-	-	-
	Magnitude (%)	-	-	-	-	-	90.42	19.69	82.10	23.64	0.8732	-	-	-	-	-
	RPL															
	Onset (%)	-	-	-	-	-	44.05	11.99	53.68	0.99	0.2271	-	-	-	-	-
	Duration (%)	-	-	-	-	-	35.36	13.21	22.53	0.39	0.2681	-	-	-	-	-
	Magnitude (%)	-	-	-	-	-	97.51	32.59	47.91	2.08	0.0468*	-	-	-	-	-

*Significance, $p<0.05$.

The RTA elicited a burst of activity during the middle phase (***stability phase***) of stance that is typically not seen during normal walking; all conditions except condition 2 (average onset: 20.52% ± 2.20; average duration: 13.48% ± 6.70; average magnitude: 75.32% ± 44.16). This activation had relatively similar onsets across conditions (Condition 0: 20.49% ± 2.39, Condition 1: 17.42% ± 4.92, Condition 3: 22.08% ± 6.40, Condition 4: 22.08% ± 6.40). Condition 0 and 1 had relatively larger durations and magnitudes compared to condition 3 and 4 (Condition 0: duration 19.82% ± 4.38, magnitude 115.43% ± 51.00; Condition 1: duration 18.72% ± 4.09, magnitude 111.65% ± 106.29; Condition 3: duration 7.69% ± 1.53, magnitude 37.10% ± 8.35; Condition 4: duration 7.69% ± 1.53, magnitude 37.10% ± 8.35) (Table 3.9, Figure 3.2, 3.7; Appendix F).

During the ***transition phase***, the RTA *onsets* were not found to be significantly different between normal walking trials and slip trials (Condition 0: normal 96.17% ± 3.97, slip 95.16% ± 9.60, p = 0.5949; Condition 1: normal 92.23% ± 10.09, slip 90.72% ± 6.11, p = 0.7333; Condition2: onset, normal 94.34% ± 5.33, slip 102.44% ± 14.43, p = 0.4269; Condition 3: onset, normal 95.62% ± 3.42, slip 92.19% ± 2.83, p = 0.3789; Condition 4: onset, normal 93.53% ± 2.22, slip 93.93% ± 2.28, p = 0.1839) (Table 3.9, Figure 3.2, 3.7; Appendix F).

The *duration* of RTA activity was only found to be significantly different within condition 0; slip trials had significantly shorter durations than normal walking trials (Condition 0: normal 29.09% ± 9.63, slip 22.80% ± 5.17, p = 0.0388; Condition 1: normal 25.58% ± 9.16, slip 17.09% ± 6.40, p = 0.5393; Condition 2: normal 16.51% ± 8.48, slip 20.24% ± 1.59, p = 0.6041, Condition 3: normal 23.71% ± 10.28, slip 18.85% ± 9.79, p = 0.7098; Condition 4: normal 19.99% ± 7.12, slip 17.97% ± 10.12, p = 0.6392) (Table 3.9, Figure 3.2, 3.7; Appendix F).

The *magnitude* of RTA activity was only found to be significantly different within condition 4; slips trials had significantly lower magnitudes than normal walking trials (Condition 4: 91.39% ± 25.93, slip 85.26% ± 10.43, p = 0.0146). Condition 2 and 3 had higher magnitudes during slip trials (Condition 2: normal 109.20% ± 37.13, slip 198.48% ± 116.64, p = 0.2683; Condition 3: normal 122.72% ± 71.94, slip 213.23% ± 184.36, p = 0.428) while condition 0 and 1 had relatively similar magnitudes during slip trials (Condition 0: normal 95.98% ± 24.82, slip 106.62% ± 44.33, p = 0.2745; Condition 1: 99.31% ± 27.60, slip 100.12% ± 64.30, p = 0.994) (Table 3.9, Figure 3.2, 3.7; Appendix F).

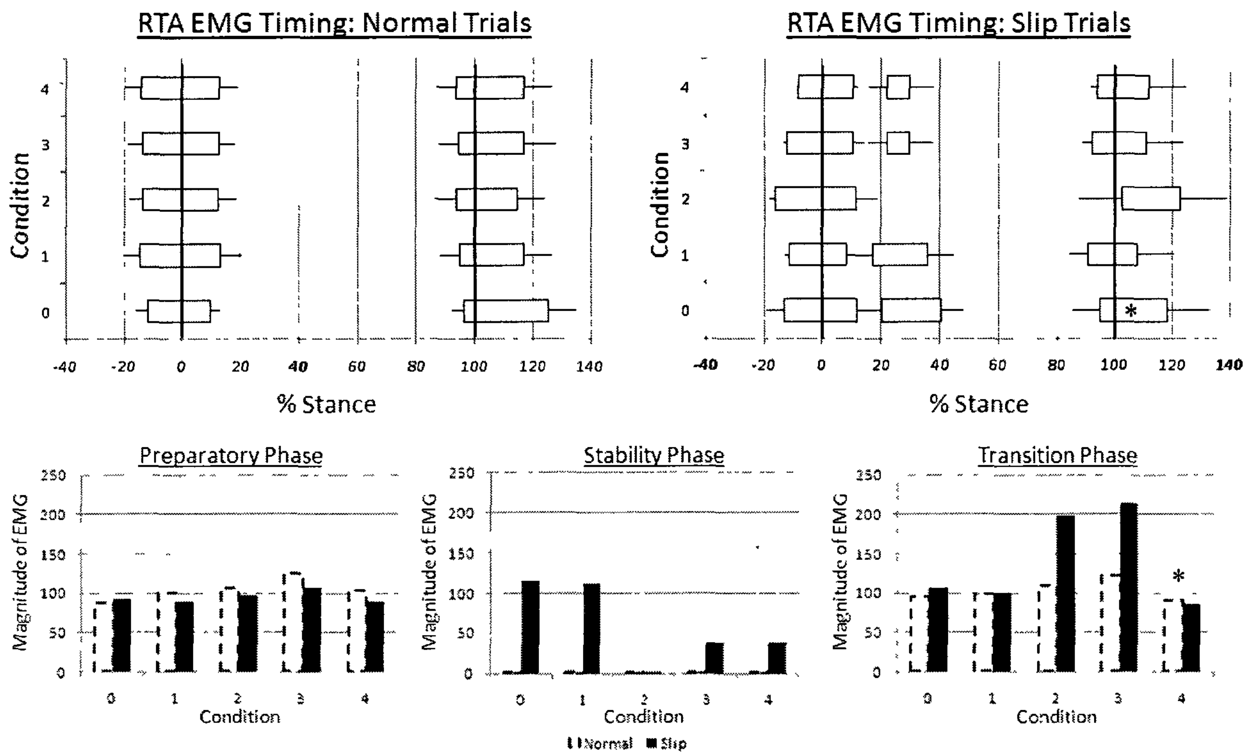


Figure 3.7: **Illustrates EMG timing of the right tibialis anterior (RTA) during normal walking trails compared to slip recovery trials across the five shoe conditions along with the respective magnitudes during the three phases of EMG stance timing: the preparatory phase (first third), stability phase (second third) and transition phase (last third). *Significance, p<0.05.**

Medial Gastrocnemius

During slip trials, the RMG's *onset* was not found to be statistically significant when compared to normal walking trails. The average onset of activity during a slip indicated earlier onsets (34.22% ± 7.32) and shorter durations (0.15-0.17s). Footwear condition 0 and 1 did show earlier activation during slip trials, but again it was not found to be significant (Condition 0: normal 43.12% ± 10.25, slip 38.36% ± 17.33, p = 0.1409; Condition 1: normal 43.54% ± 14.10, slip 42.98% ± 18.88, p = 0.0681; Condition 2: normal 36.54% ± 10.38, slip 37.95% ± 17.14, p = 0.5117; Condition 3: normal 46.93% ± 8.24, slip 53.79% ± 6.88, p = 0.4478; Condition 4: normal 48.76% ± 8.27, slip 51.29% ± 2.04, p = 0.3855) (Table 3.9, Figure 3.2, 3.8; Appendix F).

The *duration* of activity was also not significantly different during slips when compared to normal walking trials within each condition (Condition 0: normal 33.94% ± 9.52, slip 38.01% ± 19.17, p = 0.7227; Condition 1: 32.69% ± 13.72, slip 31.05% ± 23.07, p = 0.7087; Condition 2: normal 40.35% ± 11.72, slip 34.22% ± 26.38, p = 0.8749; Condition 3: normal 32.02% ± 9.09, slip 22.38% ± 1.46, p = 0.2841; Condition 4: normal 25.69% ± 7.31, slip 23.01% ± 4.26, p = 0.4921) (Table 3.9, Figure 3.2, 3.8; Appendix F).

Overall the average *magnitude* during slip trials was found to be lower than during normal walking trials (81.71% ± 13.43). The average magnitude of activity was only found to be significantly different within condition 0; slips trials had significantly lower magnitudes than normal walking trials (Condition 0: normal 102.76% ± 17.31, slip 83.75% ± 49.97, p = 0.0172). Conditions 2, 3 and 4 also showed lower RMG activation during slip trials, but this was not found to be significant (Condition 2: normal 109.29% ± 20.59, slip 68.62% ± 18.88, p = 0.2409; Condition 3: normal 89.89% ± 21.45, slip 71.41% ± 28.33, p = 0.3406; Condition 4: 90.42% ± 19.69, slip 82.10% ± 23.64, p = 0.8732) while condition 1 showed relatively similar magnitudes

(Condition 1: 99.26% ± 23.04, slip 102.69% ± 22.88, p = 0.8834). During slip trials some barefoot individuals had RMG activity during the transition phase of stance (Condition 0: onset 67.18% ± 20.37, duration 21.90% ±10.27, magnitude 72.45% ± 27.15) (Table 3.9, Figure 3.2, 3.8; Appendix F).

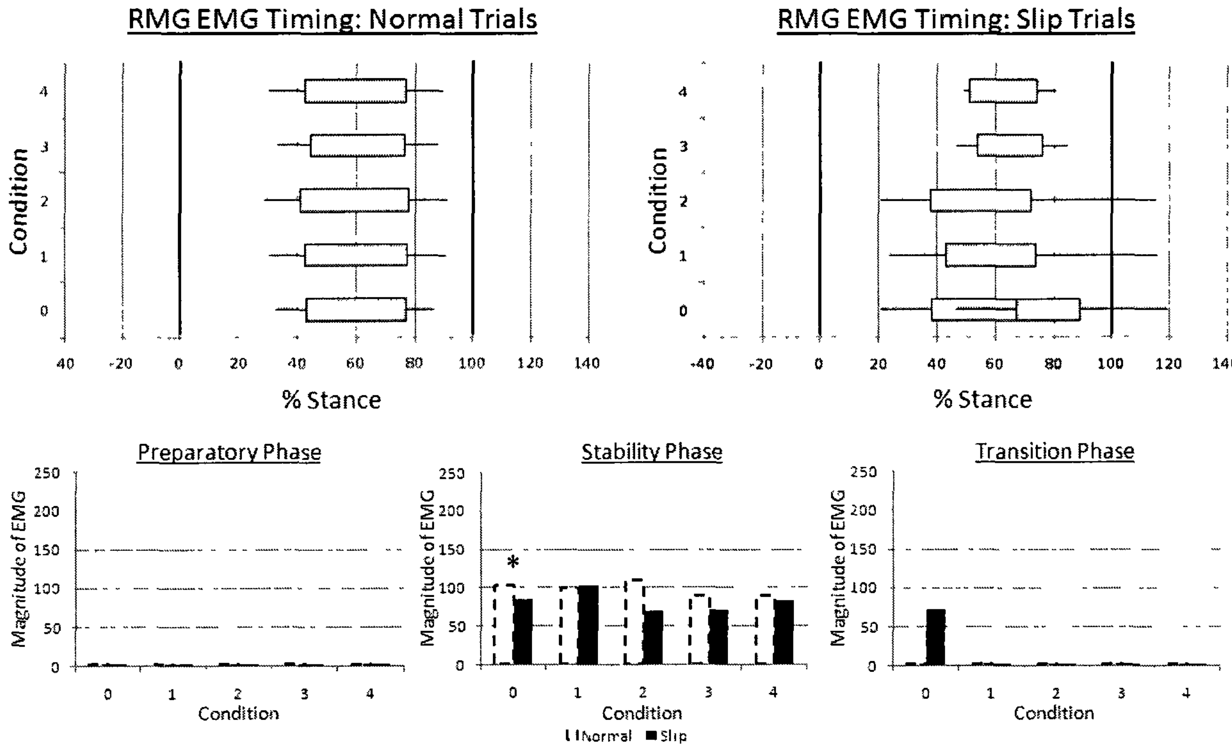


Figure 3.8: **Illustrates EMG timing of the right medial gastrocnemius (RMG) during normal walking trails compared to slip recovery trials across the five shoe conditions; along with the respective magnitudes during the three phases of EMG stance timing: the preparatory phase (first third), stability phase (second third) and transition phase (last third). *Significance, p<0.05.**

Peroneus Longus

During slip trials, the RPL did not have significantly different *onsets* compared to normal walking trials. The average onsets of activity were earlier during the slip trials compared to the normal walking trials; especially within condition 0, but still not significant (Condition 0: normal

37.83% ± 11.79, slip 25.99% ± 2.19, p = 0.0778; Condition 1: normal 49.70% ± 5.71, slip 31.93% ± 20.47, p = 0.6541; Condition 2: normal 45.12% ± 10.85, slip 34.53% ± 19.67, p = 0.3427; Condition 3: normal 44.03% ± 11.85, slip 39.87% ± 15.97, p = 0.7865; Condition 4: normal 44.05% ± 11.99, slip 53.68% ± 0.99, p = 0.2271) (Table 3.9, Figure 3.2, 3.9; Appendix F).

The average *duration* of RPL activity was also not significantly different between slip trials and normal walking trials (Condition 0: normal 39.68% ± 13.89, slip 60.97% ± 41.55, p = 0.2584; Condition 1: normal 30.40% ± 3.57, slip 35.27% ± 6.97, p = 0.6474; Condition 2: normal 36.68% ± 10.07, slip 29.45% ± 22.18, p = 0.399; Condition 3: normal 38.90% ± 12.40, slip 41.47% ± 16.77, p = 0.7185; Condition 4: normal 35.36% ± 13.21, slip 22.53% ± 0.39, p = 0.2681) (Table 3.9, Figure 3.2, 3.9; Appendix F).

The *magnitude* of RPL activity was only found to be significantly different within condition 4; slips trials had significantly lower magnitudes than normal walking trials (Condition 4: normal 97.51% ± 32.59, slip 47.91% ± 2.08, p = 0.0468). Although not significant, conditions 0, 1 and 3 had greater magnitudes during slip trials (Condition 0: normal 91.22% ± 25.45, slip 125.94% ± 67.09, p = 0.2164; Condition 1: normal 82.23% ± 22.24, slip 170.16% ± 156.45, p = 0.494; Condition 3: normal 99.17% ± 25.02, slip 128.74% ± 70.89, p = 0.7944) while condition 2 had slightly lower magnitudes (Condition 2: normal 95.74% ± 37.96, slip 63.83% ± 59.00, p = 0.1594) (Table 3.9, Figure 3.2, 3.9; Appendix F).

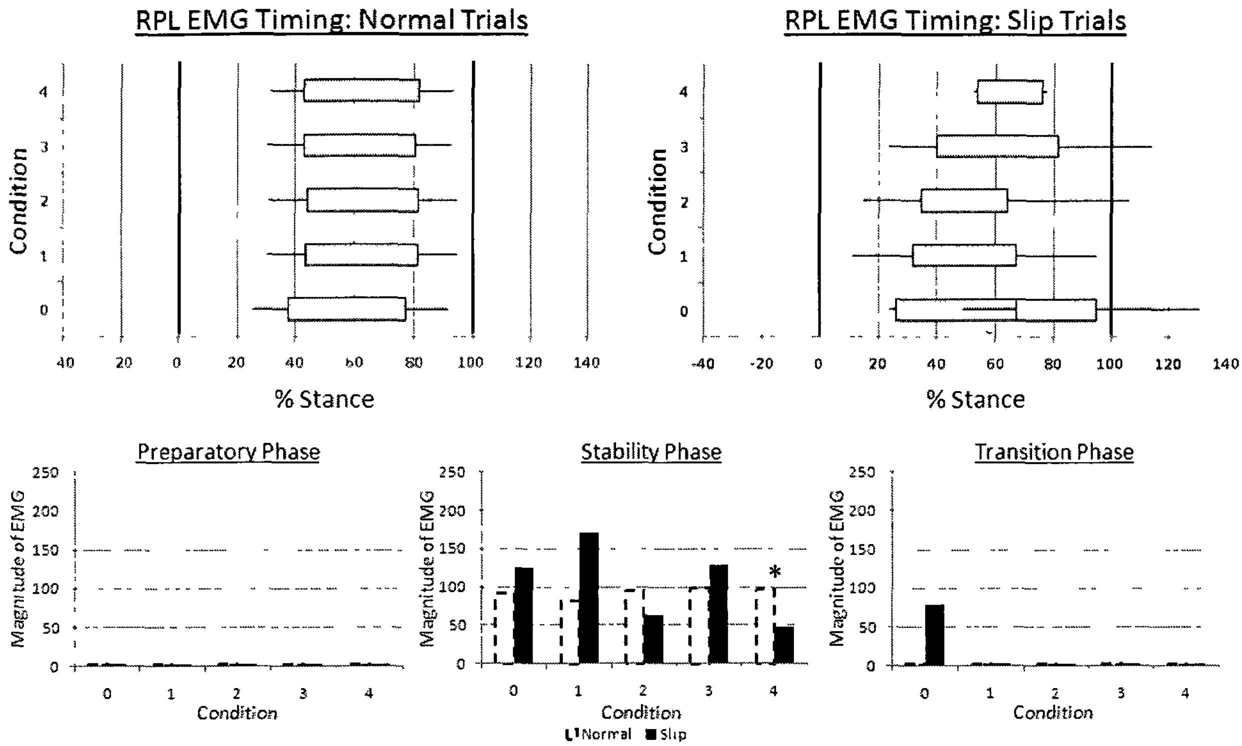


Figure 3.9: **Illustrates EMG timing of the right medial gastrocnemius (RMG) during normal walking trails compared to slip recovery trials across the five shoe conditions; along with the respective magnitudes during the three phases of EMG stance timing: the preparatory phase (first third), stability phase (second third) and transition phase (last third). *Significance, p<0.05.**

Chapter 4: Discussion

4.1 The Effect of Normal Gait Characteristics on the Risk of Slipping

4.1.1 Kinetics

During normal walking trials peak normal forces (12.41N/kg ± 0.09) were very similar to those reported in previous literature; averaging approximately 1.2 times body weight (BW) (Hamill and Knutzen, 1995) (10.9N/kg ± 1.42, Cham and Redfern, 2001; Redfern et al., 2001). Peak normal forces were not found to be significantly different between footwear conditions and may not have contributed to an increased risk of slipping in barefoot individuals. Conversely, high loading rates have been found to be associated with an increased risk of slipping (Cham and Redfern, 2002). Within this study, the average loading rates (111.74N/s.kg ± 12.4) were slightly higher during normal walking trials than the averages reported in previous studies (74.11N/s.kg ± 11.47, Marigold and Patla, 2002; 80.42N/s.kg ± Marigold et al., 2003; 82.7N/s.kg ± 15.4, Cham and Redfern, 2001), but due to the mechanism of the slip perturbation there was a higher incidence of 'non-slippers'; particularly in shod conditions. Furthermore, barefoot individuals averaged significantly higher loading rates (133.39N/s.kg ± 34.18) than their shod counter parts (106.33 N/s.kg ± 3.14). This is consistent with previous findings reported by Lafortune and Hennig (1992), as footwear tends to dissipate the transference of forces; evidence that barefoot individuals were at a high risk of experiencing a greater frequency and severity of slip during the perturbation trials.

Shear forces are highest just after heel contact and just before toe-off. As a result, an individual is most susceptible to a slip during these periods when shear forces do not meet the demands of peak required coefficient of friction (RCOF). Individuals exhibiting higher than normal shear force measures during normal walking trials may contribute to increasing their risk of slipping when the frictional properties are no longer made available by the contact surface (Hanson et al., 1999, Redfern et al., 2001). Peak shear forces (2.41N/kg ± 0.04) were slightly higher during normal walking trials than those previously reported in the literature (± 0.15 times BW, Hamill and Knutzen, 1995; 1.77± 0.61 Redfern et al., 2001). This may have been due to the nature of the contact surface (low grit sandpaper) (Cham and Redfern, 2002); however, peak shear forces were not significantly different between conditions during normal gait trials and therefore, may not have been a contributor to the higher incidence of slips in barefoot individuals. Most participants within the footwear conditions who did not experience successful a heel contact slip, had a high incidence of a slips at push-off.

4.1.2 Kinematics

Stance durations (0.60s ± 0.03) were slightly lower than those reported by Heiden et. al., (2006) (0.66s ± 0.05). Barefoot individuals had significantly shorter stance durations during normal walking than within the shod conditions, but had greater incidence and severity of slips. This finding is contrary to that reported by Cham and Redfern (2002), that longer stance durations would increase the risk of slipping.

High gait velocities have been attributed to increasing the risk of slip due to increased stride length and heel velocities at heel contact; subsequently increasing shear forces required to slow the heel down (Fong et al., 2008; Redfern et al., 2001). The average gait velocity of participants in this study (1.69m/s ± 0.06) was slightly higher than self selected gait velocities reported in other studies (0.97-1.51 m/s, Redfern et al., 2001) and therefore could have contributed to the higher shear forces discussed earlier. Due to the mechanism of the slip perturbation, during the practice trials participants were asked to increase their gait velocity to allow for proper contact with the force plates. As a function of being in a lab setting, participants also tended to walk very stiff with short stride lengths and low velocities prior to practice. It was also important to obtain proper foot contact with the force plates to increase the likelihood of a successful slip perturbation. Increased gait velocities may have increased the risk and severity of the slips, but had a tendency to be higher in the shod conditions compared to barefoot individuals who had greater slip frequency and severity. Therefore, other factors may have attributed to an increased risk of slipping in barefoot individuals (i.e., high loading rates).

Heel velocities at heel contact are an important predictor of slips as higher heel velocities and slower heel decelerations may increase risk of falls when a slip occurs (Redfern et al., 2001, Cham and Redfern, 2001, 2002). During normal walking trials the average heel velocities at heel contact (0.66m/s ± 0.20) were similar to that reported by Strandberg (1983) (0.14 m/s to 0.68 m/s), but are much higher than more recent findings (0.19m/s ± 0.39, Cham and Redfern, 2002). In contrast, barefoot individuals averaged significantly lower heel velocities (0.31m/s ± 0.29) during normal walking trails than those in footwear (0.75 m/s ± 0.05), but had higher incidences and severity of slips. Furthermore, heel displacement after heel contact was comparable across all conditions (0.019m ± 0.004). Therefore, heel displacement and heel velocities were not a major predictor of slips within this study.

Lower limb joint angles had very characteristic profiles during stance and therefore may not have been contributing factors to an increased risk of slipping. The hip angle averaged approximately 28° of flexion at heel contact and reached a maximum of 10-20° of extension during stance. These values were similar to those reported by Redfern et al., (165° or 15°of flexion, max 193° or 13° of extension). Knee angles averaging 172° (near full extension) at heel contact is quite similar to values reported by Cham and Redfern (2001) (172.52° ± 5.83). Ankle motion was also very typical during normal walking trials; neutral to slightly dorsiflexed at heel contact (0.176° ± 2.59) (Hamill and Knutzen, 1995; Kitaoka et al., 2006; 5.02° ± 3.80, Redfern et al., 2001), passively plantarflexing until foot flat is reached, approximately 10% stance and then actively plantarflexing until toe-off (Hamill and Knutzen, 1995; Redfern et al., 2001; Kitaoka et al., 2006). Ankle angular velocities in barefoot participants (277.24°/s) were similar to previous research (223.8°/s ± 98.4, Redfern et al., 2001).

When anticipating a slippery surface, as a mechanism to decrease the risk of slipping, individuals tend to decrease their shank angle (relative to vertical) in order to decrease their foot-floor contact angle (Cham and Redfern, 2002). Significantly lower shank angles were found within barefoot individuals (-16.44° ± 2.4) compared to those in footwear conditions (-21.68° ± 0.31). Although not significantly different, this corresponded with lower foot-floor contact angles in barefoot participants. Again, this is conflicting with previous literature as barefoot individuals had a higher frequency and severity of slips.

4.1.3 Electromyography

Electromyography data also demonstrated typical activation patterns compared to previous research (Cham and Redfern, 2001; Redfern et al., 2001; Zajac et al., 2003; Rose and Gamble, 2006; Whittle, 1996). At heel contact (0% stance) the tibialis anterior was active; switching from actively dorsiflexing the foot at the ankle to working eccentrically to oppose plantarflexion (Redfern et al., 2001). Normal activation also occurred at the end of stance to once again dorsiflex the foot at the ankle allowing for clearance of the ground during the swing phase (Marigold and Patla, 2002; Zajac et al., 2003). The medial gastrocnemius was active during single stance (~25-85% stance) generating a strong plantarflexor moment peaking at maximum ankle dorsiflexion, approximately 80% stance (Cham and Redfern, 2001; Redfern et al., 2001; Zajac et al., 2003; Rose and Gamble, 2006; Whittle, 1996). The Peroneus longus exhibited typical activation patterns (42.13% ± 2.66) (Rose and Gamble, 2006; Whittle, 1996). As EMG during normal walking trails did not have any major differences than those reported in previous research, it is evident that it was not a major contributor to increasing the risk of slipping in barefoot individuals.

Overall, gait characteristics of normal walking trials (trials previous to any slip perturbations) were found to be relatively consistent with previous literature. A higher rate of loading was the only significant finding that would have *increased the risk* of slipping within the barefoot condition; while lower stance durations, gait velocities, heel velocities, and smaller shank and foot-floor angles, compared to shod conditions, would have *decreased the risk* of slipping based on previous literature. These finding would suggest that individuals who were in the shod conditions would have been at a higher risk of slipping than the barefoot condition, resulting in higher incidences and severities; when in fact, contrary to previous findings, the severity of slips was much lower in the shod conditions. Therefore, the footwear, along with decreasing loading rate, must offer a level of stability to the foot and ankle during heel contact that controls foot motion (Morio, et al., 2009). In particular, decreasing the rate of pronation or eversion at the time the slip was detected, which would likely decrease the severity of the slip; evident due to diminished recovery times.

4.2 Muscle Activation: Responses to a Slip Perturbations in Barefoot

In response to the slip perturbation, findings did support our first hypothesis that the TA and PL will activate earlier with higher magnitudes. This was especially evident in barefooted individuals who experienced higher severity and frequency of slips. Although not significant, the anterior muscles (tibialis anterior and peroneus longus) did activate earlier and with higher magnitudes than during normal walking trials; similar to that reported by Tang et al., (1998). The peroneus longus had yet to be investigated as its role during a slipping response. It appears that along with the tibialis anterior, the peroneus longus may activate earlier and with higher magnitudes compared to normal walking trials as an agonist to aid in plantarflexion of the ankle and as an antagonist to control inversion (Hamill and Knutzen, 1995). The gastrocnemius was also found to activate earlier in barefoot conditions, but with lower magnitudes than during normal walking trials. The suppression of gastrocnemius activity during slip recovery was reported in previous findings by Chambers and Cham (2007) to allow for maximum dorsiflexion at the ankle caused by tibialis anterior activation. The EMG response exhibited during the slip perturbation in barefooted individuals was very similar to that reported in previous literature (Tang et al., 1998; Chambers and Cham, 2007) and supports the first hypothesis.

4.3 The Subtalar Joint Model during a Slip Perturbation

The muscle activation patterns exhibited within barefooted individuals during slip recoveries resulted in subtalar joint motion that supported concepts proposed in the second hypothesis; delayed pronation during the slip trials. Average ankle and subtalar joint motion during normal walking trials were comparable to previous literature (Hamill and Knutzen, 1995; Redfern et al., 2001; Kitaoka et al., 2006; Ardnt et al., 2004). Similar to previous findings, there was an increase in plantarflexion at the ankle (sagittal plane) just after heel contact (Kojima et al., 2008) during the slip perturbations. As mentioned previously, the tibialis anterior is the first to respond, creating a dorsiflexion moment to counteract the plantarflexion (Kojima et al., 2008; Chambers and Cham, 2007; Tang et al., 1998). The three dimensional subtalar joint motion demonstrated similar findings and supported the second hypothesis as there was a slight delay in eversion during the response to the slip (within the first 30% of stance). Therefore, an additional function of the tibialis anterior and peroneus longus response during a slip perturbation is to delay eversion, not just counteract plantarflexion. The increased activation around the subtalar joint will work to maintain a more rigid foot structure for the transference of forces to aid in recovery.

4.4 The Effect of Footwear Characteristics on Slip Recovery

Overall, shod conditions experienced less incidence and severity of slip during slip perturbation trials; even though, based on normative gait values supported by previous literature, they would be presumed to be at a higher risk than barefooted individuals. It has been reported that footwear does offer shock absorption properties that may diminish the loading rate (Lafortune and Hennig, 1992); hence higher loading rates within the barefoot condition. However, higher gait and heel velocities, larger foot-floor and shank angles, longer stance durations coupled with similar shear and normal forces and comparable heel displacements during normal gait lead one to believe that shoes offer more stability to the foot and ankle that is not present during barefoot walking. This support may place the foot in a more optimal position for slip avoidance or quick recovery (i.e., delay normal pronation seen in barefoot individuals, which may place them at an increased risk of more hazardous slips). These findings contradicted the third hypothesis. The "restrictive" nature of the footwear actually decreased the risk of slips and slip severity compared to barefoot conditions, opposite of what was originally proposed. It may have in fact been a decrease in subtalar joint motion within the footwear conditions, as proposed, but it came as a benefit to decrease the incidence and severity of slips compared to barefoot individuals. Unfortunately, subtalar joint motion was not able to be calculated for shod conditions so further investigation is needed.

Due to a small sample size, there were no significant differences in slip severity or frequency within shod conditions. Having acknowledged this, slight trends did exist. Condition 2 had very similar slip outcomes, frequency and severity of slips to the control (Condition 1). This demonstrated that footwear with a stiff heel counter alone was very comparable to the unsupportive canvas shoe. While stiff heel counters restrict rear-foot motion, alone it is just as beneficial as a stripped down canvas shoe in decreasing slip severity and incidence compared to barefoot counterparts. Condition 3 had slightly higher incidences and frequencies than the control condition. Therefore, a stiffer insole alone may increase the severity and frequency of slips. Overall, condition 4 had the lowest severity and frequency. This demonstrates that a combination of a stiff heel counter to control rear-foot motion and a stiff insole to assist in providing force transference or restrict subtalar motion may be more optimal in minimized the risk and severity of slips in footwear.

There were also not many significant differences in kinetic, kinematic and EMG variables found between the different footwear conditions during normal walking trials. Condition 1 and 3 had significantly higher loading rates than condition 2 and 4. This demonstrates that a stiff insole alone may increase the risk and/or severity of slipping (Cham and Redfern, 2002). This was supported by a higher number of slips seen in condition 3. Condition 4 was also found to have significantly higher heel velocities at heel contact than condition 3. This finding is similar to that found between barefoot conditions compared to shod conditions; although the heel velocities were higher, the frequency and severity of slips were lower. This further demonstrates that a stiff insole alone may increase your risk and/or severity of slipping. Condition 2 was found to have significantly longer durations and higher magnitudes in medial gastrocnemius activity compared to condition 3. Although significant, the functional role of this muscle activity is unclear.

During slip trials, condition 1 had early activation and higher magnitudes of tibialis anterior activity, similar to that seen in barefoot slips. The other conditions exhibited little or no activity (lower magnitude and relatively small duration). Condition 1 also had comparable finding in the peroneus longus activity; early activation and higher magnitudes. In condition 2, the peroneus longus activated earlier, but with lower magnitudes than normal gait. In condition 3, the activations were not as early, but the magnitudes were relatively higher and in condition 4 the activation was delayed and had significantly lower magnitudes than during normal gait. Condition 1, having the least amount of alterations, exhibited similar responses to the slip perturbation seen in barefoot individuals. Due to the stiff heel counters present in condition 2 and 4, the peroneus longus exhibited lower magnitudes compared to condition 1 and 3 probably attributed to the reduction in rear-foot motion. Within condition 1, the medial gastrocnemius showed similar onsets of activation and magnitudes while in condition two there were similar onsets, but lower magnitudes. Within conditions 3 and 4, there was suppression of the medial gastrocnemius and lower magnitudes.

In general, these findings further illustrate that different footwear characteristics do affect normal foot motion during a slip recovery. The bare canvas shoe most closely resembles the barefoot slip trials and the most restrictive shoe condition (condition 4) having the least amount of EMG activity and the lowest severity and frequency of slips. This demonstrates that the combination of a stiff heel counter and a stiff insole may control rear-foot motion and provide a rigid stable surface to minimize the risk and severity of slips. This may be due to the footwear placing the foot in a less risky position at heel contact and/or restricting foot motion (less inversion and slower pronation at heel contact) compared to barefoot individuals. This would ultimately place these individual at a lower risk of a slip and decrease slip severity by allowing for a diminished response to manipulate the foot into a stable rigid body to all for a successful recovery.

Chapter 5: Conclusions

5.1 Limitations

Sample size was a major limitation in this study. Although a sufficient number of participants was planned to be collected, due to the unpredictable nature of slips and the mechanism of the slip perturbation, it was difficult to collect the large number of slips and level of slip severity needed within each condition. This left the study with very little power to examine the differences within the footwear conditions. In spite of this, significant results were still found and must be interpreted with caution. This limitation also may have increased the risk of type I and II errors occurring during analysis. To account for this, the significance level was set at an appropriate value of 0.05 in order to minimize the risk of a type I error.

Another potential limitation within this study was inherent due to the nature of slip data collection. Once participants experienced the slip perturbation, they adapt gait strategies to successfully overcome subsequent perturbations. This was seen in almost all participants as attempted perturbations post initial perturbation were unsuccessful. This confirms previous studies that experience prevails over knowledge of the perturbation (Marigold and Patla, 2002) and is evident within the next gait trial and prolongs more than fifteen trials. Due to this limitation, the study was designed such that each participant contributed one 'truly unexpected' slip perturbation. Therefore, the number of participants needed for data collection reflected this.

Before collection began participants were informed that they may experience a slip perturbation. The knowledge that they may experience a slip perturbation could have been a limitation by affecting normal gait characteristics during baseline measures. This could have affected the number of participants actually experiencing slips due to strategies to avoid slipping. Participants were encouraged not to concentrate on the perturbation and were reminded to maintain gait velocities similar to practice trials. Normal gait characteristics were found to be very similar to those reported in previous research. Furthermore, 80% of barefoot participants experienced unexpected slip perturbations. Therefore, the knowledge of the perturbation did not negatively affect our collection or findings and the low number of slips exhibited within the footwear conditions was truly a function of the change occurring due to the properties within the footwear and not strategies in gait.

With any marker tracking system there may be errors introduced by markers placed directly on the skin. The markers on the skin may introduce error as they may move independently from the underlying skeletal structure. To try and minimize this, markers were placed on bony prominences where the markers would closely track true skeletal movement. Furthermore, more than three non-collinear markers were used to track the lower limb segments and a rigid body was used to track the calcaneous in an attempt to minimize error associated with marker movement.

Unfortunately, the subtalar joint motion within footwear conditions was unable to be successfully calculated. This was due to large marker errors. Within the footwear conditions, the markers used to track the mid-foot and calcaneous were placed over top of the shoes. This did not represent true skeletal locations and therefore was not accurate at tracking the subtalar joint motion during gait. This was a major limitation as the effects of footwear characteristics on subtalar motion could only be hypothesized and inferred from the subtalar model determined within the barefoot condition and supported by previous research and findings.

5.2 Future Directions

As this study demonstrates, the subtalar joint plays an important role in slip incidence and severity. Further investigation in slip mechanisms is needed within both barefooted and shod individuals to strengthen and confirm these findings. A collection of a greater number of barefoot individual will increase the number of slip trials and slip severities to help strengthen the subtalar model. Furthermore, within footwear conditions, examining rear-foot motion during slips may give more insight as to how different footwear characteristics affect subtalar joint motion.

Secondly, further analysis of the medio-lateral ground reaction forces, the centre-of-pressure base-of-support (COP-BOS) and centre-of-mass base-of-support (COM-BOS) relationships are needed. The medio-lateral ground reaction forces are quite variable between individuals (Hamill and Knutzen, 1995; Redfern et al., 2001). It may be this variability that makes an individual more prone to slipping or better at recovering. Furthermore, the COP-BOS will give insight into how the pressure changes under the foot during a slip and slip recovery. By examining these relationships corresponding to subtalar joint motion will also add strength to the model and further hypotheses can be derived towards beneficial characteristics of footwear.

By examining the effect that an orthotic intervention may have on the role of the subtalar joint during slips may give insight into footwear designs that may decrease the risk and severity of slips and increase the chances of slip recovery. Orthotics may provide added support within footwear to limit the amount of pronation to decrease the severity and frequency of slips.

Lastly, due to the nature of aging, older individuals are inherently at a greater risk of experiencing more severe and hazardous slips. A major contributor to this risk is the loss of cutaneous sensation on the sole of the foot. By freezing the feet (Perry et al., 2001) of young adults free of neurological or musculoskeletal disorders, the role of cutaneous sensation during slips can be evaluated. Investigation of the importance of cutaneous sensation in detection and response to a slip may be important in helping reduce the number of hazardous slips in an aging population.

5.3 Concluding Statements

Barefoot individuals were found to be at a greater risk of slipping and have increased severities compared to other footwear conditions. This appeared to stem from the inability to control the slip early. Barefoot individuals had significantly higher loading rates which may have placed the foot in a more pronated position when the slip is detected. Footwear, although apparently having greater slip risk factors compared to the barefoot condition, showed a decrease in severity and incidence. Footwear, in general, may place the foot in a better position at heel contact (more inverted) and slow the pronation of the foot as a result of significantly slower loading rates. This would decrease the slip severity and make it easier to respond to, evident by faster recovery and lower EMG activity.

In barefoot individuals the primary response to a slip perturbation, seen in the stability phase, was increased tibialis anterior and peroneus longus activity (early onsets and higher magnitudes) and suppression of gastrocnemius (lower magnitudes). This muscle activity works to counteract plantarflexion and reverse or prevent eversion in order to generate a more rigid stable foot structure. It is this objective that will allow for transference of forces to the ground to successfully recover from the slip. If this cannot be achieved quickly enough the individual will risk the chance of experiencing a fall.

Finally, more restrictive footwear conditions (i.e., a combination of a stiff heel counter and stiff insole) may decrease the risk of slipping and allowed for more efficient responses (i.e., lower EMG activity) to perturbations resulting in lower severities. The stiff heel counter controlled eversion while, the stiff insole gave support for the transference of forces. Therefore, findings supported our hypothesis that the subtalar joint does appear to play a very important role in the response to a slip perturbation. The peroneus longus does contribute to controlling subtalar motion alongside the tibialis anterior and finally, footwear characteristics that restrict normal subtalar joint motion seen in barefoot individuals will help decrease the risk of slipping and decrease the severity, improving chances for recovery.

Appendix A: Exclusion Questionnaire

Screening Questionnaire

Subject #:________

VOLUNTEER EXCLUSION CRITERIA **Date: (MM/DD/YYYY): ___, ___, ______**

Name: ____

Address: ____

____

City, Province: ______________, _____ Postal Code ______________

Tel #: (___)-___________ Best time to call: ___________

Age: ____ yrs. Height: ______ cm Weight: _______ kg

Gender: M __ F __

Subject #:________

Age: ____ yrs. Height: ______ cm Weight: _______ kg

Gender: M __ F __

	Yes	**No**	**Both**
Are you left-handed?	☐	☐	☐

Do you have any conditions that limit the use of your arms or legs? Yes / No

If yes, how much does the condition interfere with your activities?

little /or none	moderate	a great deal
☐	☐	☐

Describe: ____

____

____

Do you have or have you ever had: **Yes / No**

a)	paralysis	___
b)	epilepsy	___
c)	cerebral palsy	___
d)	multiple sclerosis	___
e)	Parkinson's disease	___
f)	stroke	___
g)	any other neurological disorder	________________
h)	diabetes	___
i)	vision problem other than corrective glasses	___
j)	cataract surgery	___
k)	a balance or coordination problem	___
l)	an inner ear disorder	___
m)	hearing problems	___
n)	constant ringing in your ears	___
o)	ear surgery	___

Have you ever had any serious problems with your memory? Yes / No
Do you have or ever had recurrent ear infections? Yes / No
Subject #:_______

Have you ever had frostbite in the lower extremities? Yes / No

How much do the conditions that you indicated with a 'yes' below interfere with your activities?

Do you have or have you ever had :		**Y / N**	little or none	moderate	a great deal
a)	problems with your heart or lungs	___	☐	☐	☐
b)	high blood pressure	___	☐	☐	☐
c)	blood circulation problems (generally)	___	☐	☐	☐
	(specifically lower extremities)	___	☐	☐	☐
d)	cancer	___	☐	☐	☐
e)	arthritis	___	☐	☐	☐
f)	rheumatism	___	☐	☐	☐
g)	back problems	___	☐	☐	☐
h)	a joint disorder	___	☐	☐	☐
i)	a muscle disorder	___	☐	☐	☐
j)	a bone disorder	___	☐	☐	☐
k)	spina bifida	___	☐	☐	☐

How much do the conditions that you indicated with a 'yes' below interfere with your activities?

Do you have or have you ever had these <u>foot</u> problems		**Y / N**	little or none	moderate	a great deal
a)	bunions (hallux valgus)	___	☐	☐	☐
b)	hammer toes	___	☐	☐	☐
c)	calluses	___	☐	☐	☐
d)	ulcerations	___	☐	☐	☐
e)	plantar fasciitis	___	☐	☐	☐
f)	any other foot problems (diagnosed or not)				
	____________________	___	☐	☐	☐
	____________________	___	☐	☐	☐
	____________________	___	☐	☐	☐

Have you ever severely injured or had surgery on your					
a)	head	___	☐	☐	☐
b)	neck	___	☐	☐	☐
c)	back	___	☐	☐	☐
d)	pelvis	___	☐	☐	☐
e)	ankle, knee, or hip joints?	___	☐	☐	☐
Have you ever broken any bones?		___	☐	☐	☐

Which ones? : ______________________________

Have you had any recent (specify)

a) illnesses	___	☐	☐	☐
b) injuries	___	☐	☐	☐
c) operations	___	☐	☐	☐

Do you have difficulties performing any daily activities?___ ☐ ☐ ☐

Which activities?: ______________________________

____

Are you currently taking any medications (prescription or over-the-counter), or other drugs?

Medication	Ailment	Frequency of use
____________	____________	____________
____________	____________	____________
____________	____________	____________

Appendix B: Experiment Protocols

An Investigation Of The Role Of The Subtalar Joint And The Influence Of Footwear Characteristics On Foot Function And Dynamic Balance Control During Slip Perturbations

Primary Investigators: Dr. Stephen D. Perry
& Jessica Berrigan

Subject Number: ________

Ht: ___' ___"   Wt: _________N   Gender ______

Dated: (mm/dd/yyyy): ____/____/____

Optotrak:

Sample rate: *100 Hz*   Trial Length: *5 sec*

Marker Strength: *70%*

RMS   Registration______ (< 0.5)   Alignment______ (<0.20)

Force Plate:

Sample rate: *1000 Hz*   Trial Length: *5 sec*

# of Trials: *200*

Foot Sensitivity

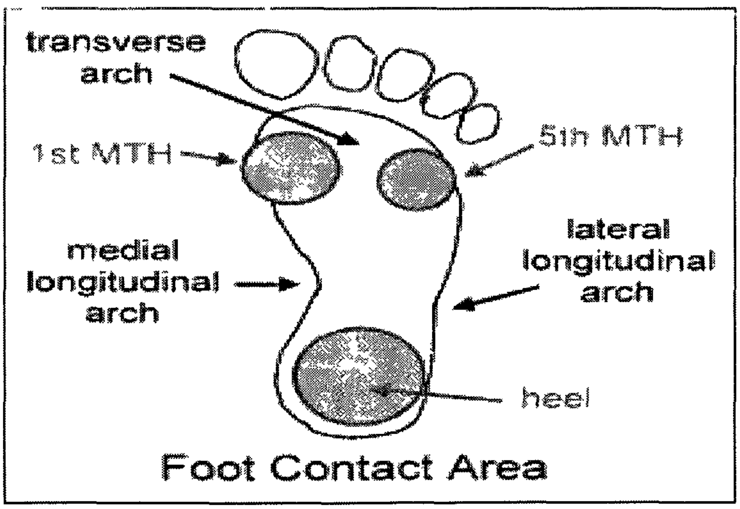
Hallux Valgus		
Circle deformity scenario:	Right	A B C D
	Left	A B C D

Calluses		
Filament Size 1:		Location:
Filament Size 2:		Location:
Filament Size 3:		Location:
Filament Size 4:		Location:
Filament Size 5:		Location:
Filament Size 6:		Location:

Arches	Right	Left
Medial Arch Filament Size:		
Lateral Arch Filament Size:		

Foot Sensation

Touch Thresholds	Right	Left
Great Toe:		
1st MT Head:		
5th MT Head:		
Heel:		



Anthropometrics

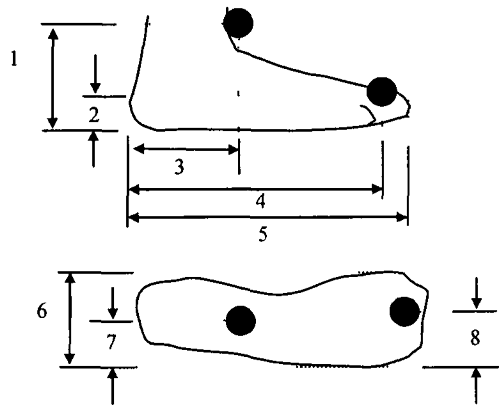
Hip Diameter: ___________cm

Knee Diameter: Left ___________ Right ___________ cm
Ankle Diameter: Left ___________ Right ___________ cm
Heel Diameter: Left ___________ Right ___________ cm

Distance between Tibial tuberosity marker and center of patella:
Left ___________ Right ___________ cm

Distances in cm's

1. Right ______Left _______
2. Right ______Left _______
3. Right ______Left _______
4. Right ______Left _______
5. Right ______Left _______
6. Right ______Left _______
7. Right ______Left _______
8. Right ______Left _______



EMG Collection Information

Right			
	Muscle	Gain	
1	Tibialis Anterior	500	
2	Medial Gastrocnemius	2000	
3	Rectus Femoris (Quad)	2000	
4	Biceps Femoris (Ham)	1000	
5	Peroneus Longus	1000	

Left			
	Muscle	Gain	
6	Medial Gastrocnemius	2000	
7	Rectus Femoris (Quad)	2000	
8	Biceps Femoris (Ham)	1000	

Barefoot Slip Trial Data Sheet

	Trial #	Condition	Y/N Slip	Comments
Non-Slip Control Trials	1		N	Quiet Stance
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
	11			
Slip Trials	12	Plate 2		
	13	Plate 2		
Non-Slip Trials	14			
	15			
	16			
	17			
	18			
	19			
	20			
	21			
	22			
	23			
	24			
	25			
	26			
	27			
	28			
Slip Trial	29	Plate 2		
Non-Slip Trials	30			
	31			
	32			

Shoe Slip Trial Data Sheet

	Trial #	Slip Condition	Y/N Slip	Comments
Quiet Stance	1		N	
Shoe Condition: ——	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
	11			
Quiet Stance	12			
Shoe Condition: ——	13			
	14			
	15			
	16			
	17			
	18			
	19			
	20			
	21			
	22			
Quiet Stance	23			
Shoe Condition: ——	24			
	25			
	26			
	27			
	28			
	29			
	30			
	31			
	32			
	33			
Quiet Stance	34			
Shoe Condition: ——	35			
	36			
	37			
	38			
	39			
	40	Plate 2		
	41	Plate 2		
	42			
	43			
	44			

Shoe Condition Randomization Sheet

Condition I: soft HC, flexible insole
Condition II: stiff HC, flexible insole
Condition III: soft HC, stiff insole
Condition IV: stiff HC and stiff insole

Participant #	Assigned Condition	Condition I	Condition II	Condition III	Condition VI
1	II	1	4	3	2
2	III	3	1	4	2
3	II	3	4	2	1
4	IV	3	2	1	4
5	III	2	3	4	1
6	III	2	1	4	3
7	I	4	1	2	3
8	III	1	2	4	3
9	II	3	4	2	1
10	II	1	4	3	2
11	IV	1	3	2	4
12	III	1	2	4	3
13	II	2	4	1	3
14	III	2	3	4	1
15	II	2	4	1	3
16	I	4	2	3	1
17	IV	2	1	3	4
18	IV	1	3	2	4
19	I	4	2	3	1
20	II	1	4	2	3
21	IV	1	3	2	4
22	I	4	2	3	1
23	I	4	3	1	2
24	III	1	2	4	3
25	I	4	3	1	2
26	IV	2	1	3	4
27	IV	3	2	1	4
28	III	3	1	4	2
29	II	1	4	3	2
30	I	4	3	1	2
31	I	4	2	3	1
32	IV	3	2	1	4
33	II	2	4	1	3
34	I	4	3	2	1
35	III	3	1	4	2
36	IV	1	3	2	4
37	II	2	4	1	3
38	III	2	3	4	1
39	I	4	1	3	2
40	IV	2	1	3	4

Appendix C: Exit Questionnaire

Subject #:_______

	Yes	No
1. Do you regularly walk on slippery surfaces?	☐	☐

☐ Work ☐ Home ☐ Other______________________

If yes, is a slip most likely to occur due to:

	Contaminant	Slippery Floor	Ice	Improper Footwear	Other
Work	☐	☐	☐	☐	☐________________
Home	☐	☐	☐	☐	☐________________
Other	☐	☐	☐	☐	☐________________

	Yes	No
2. Have you experienced a <u>fall</u> due to a slip?	☐	☐

☐ Work ☐ Home ☐ Other______________________

If yes, how frequently have you fallen in the past six months?

☐ More than once a week
☐ Once a week
☐ Once a month
☐ Less than once a month
☐ Other________________________

	Yes	No
3. Have you experienced any injuries from a <u>fall</u> due to a slip?	☐	☐

☐ Work ☐ Home ☐ Other______________________

If yes, what type of injury?

	Work	Home	Other	Briefly Explain
Bruises	☐	☐	☐__________	____________________________________
Cuts/scrapes	☐	☐	☐__________	____________________________________
Sprains	☐	☐	☐__________	____________________________________
Fractures	☐	☐	☐__________	____________________________________
Other	☐	☐	☐__________	____________________________________

	Yes	No
4. Do you feel your injuries/falls from a slip have had any psychological effects (i.e., hesitant on certain floors, cautious when wear certain footwear etc.)?	☐	☐

If yes, please explain

____

____

____

Subject #:_______

5. Can you think of any other situation(s) that you are regularly exposed to that would make you a cautious walker?

Yes	No
☐	☐

If yes, please explain

____
____
____
____
____

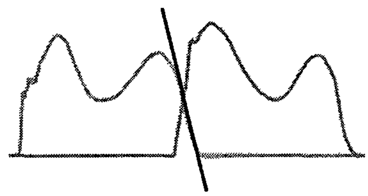
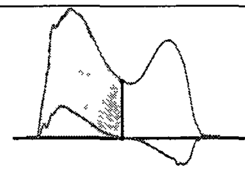
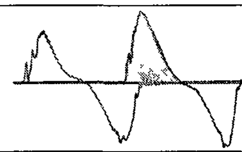
6. Do you feel that due to your experience with slippery surfaces that you are able to respond well to changes in surface slipperiness while walking?

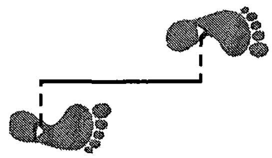
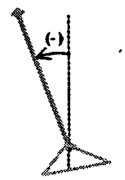
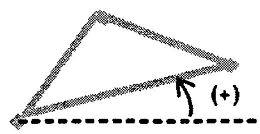
Yes	No
☐	☐

If yes, please explain

____
____
____
____

Appendix D: Variable Definitions

Kinetic Data			
Variable	**Unit**	**Description**	**Specific Measure**
Ground Reaction Forces (GRF's)			
Normal Forces ($F_{vertical}$)	N/kg	Normal GRF curve expressed over % stance for both the perturbed and unperturbed limbs. Normalized to body weight (BW).	**NormPeak:** Normalized peak in the first phase of the normal GRF curve ($F_{vertical}$)
Rate of Loading (ROL)	N/s/Kg	The slope of the vertical ground reaction force curve of the perturbed limb during the double support phase (from heel contact of perturbed limb until toe off of contra lateral limb) when both feet are in contact with the force plates. Normalized to BW.	
Unloading Rate (ULR)	N/s/kg	The slope of the vertical ground reaction force curve of the unperturbed limb during the double support phase (from heel contact of perturbed limb until toe off of contralateral limb) when both feet are in contact with the force plates. Normalized to BW.	
Loading Impulse (LI)	N.s/kg	Integration of the normal GRF curve ($F_{vertical}$) of the perturbed limb from heel contact until the shear force ($F_{anteroposterior}$) crosses zero. Normalized to BW.	
Shear Forces ($F_{anteriorposterior}$)	N/kg	Shear GRF curve expressed over % stance for both the perturbed and unperturbed limbs. Normalized to BW.	**ShearPeak:** Normalized peak in the first phase of the shear GRF curve ($F_{anteroposterior}$).
Braking Impulse (BI)	N.s/kg	Integration of the Shear GRF curve ($F_{anteroposterior}$) of the perturbed limb from heel contact until it reaches zero. Normalized to BW.	
Propulsion Impulse (PI)	N.s/kg	Integration of the Shear GRF curve ($F_{anteroposterior}$) of the unperturbed limb from zero until toe-off. Normalized to BW.	

Kinematic Data			
Variable	**Unit**	**Description**	**Specific Measure**
Stride Length and Cadence			
Stance Duration (SD)	s	Time the foot spends in contact with the ground, calculated from heel contact until toe off.	SD of perturbed and contra-lateral limb during left right contact with the force plates
Normalized Step Length (NSL)	m	Maximum distance between the ankle marker of the left foot and the ankle marker on the right foot during double support normalized to height taken at time of lead HC.	
Gait Velocity	m/s	Walking speed calculated by dividing step length by step time. Also determined using COM velocity.	
Joint Angles/Velocities			
Shank Angle	Deg.	Profile of the absolute Shank-Floor angle of the perturbed limb. Calculated from a line connecting the *knee marker to the ankle marker* relative to vertical during stance (% stance). Neutral angle determined from quiet stance.	**Shank AngHC**: Shank-Floor angle at HC. **Shank Ang30%:** Shank-Floor angle at 30% stance. **Shank Ang50%:** Shank-Floor angle at 50% stance. 
Foot-Floor Angle	Deg.	Profile of the absolute Foot-Floor angle of the perturbed limb. Calculated from a line connecting the heel marker and fifth metatarsal marker relative to the ground during stance (% stance) and normalized to the neutral angle. Neutral angle determined from quiet stance.	**FootF AngHC:** Foot Floor Angle at HC. **FootFAng30%:** Foot-Floor angle at 30% stance. **FootFAng50%:** Foot-Floor angle at 50% stance. 
Foot Angular Velocity	Deg./s	Foot angular velocity profile of the perturbed limb derived from the Foot-Floor angle	**Foot AngVelHC**: Foot angular velocity at HC. **Foot AngVel30%:** Foot angular velocity at 30% stance. **Foot AngVel50%:** Foot angular velocity at 50% stance.
Heel Displacement	m	Displacement of heel during stance of the perturbed limb calculated using markers on the calcaneous from HC until zero velocity.	
Heel Velocity	m/s	Heel velocity profile of the perturbed limb derived using the heel markers positional data.	**HeelVelHC:** Instantaneous velocity at HC. **HeelVelPeak**: Peak heel velocity measured shortly after HC

Ankle Angle	Deg.	Ankle angle profile of the perturbed limb during stance (% stance) determined using relative angle defined by makers on the knee, ankle and 1st metatarsal and normalized to the neutral angle. Neutral angle determined from quiet stance.	**Ankle AngHC:** Ankle angle at HC. **Ankle Ang30%:** Ankle angle at 30% stance. **Ankle Ang50%:** Ankle angle at 50% stance.
Ankle Angular Velocity	Deg./s	Ankle angular velocity profile of the perturbed limb derived from the ankle angle.	**Ankle AngVelHC:** Foot angular velocity at HC.
Knee Angle	Deg.	Knee angle profile of the perturbed limb during stance (% stance) determined using relative angle defined by makers on the hip knee and ankle. Neutral angle determined from quiet stance.	**Knee AngHC**: Knee angle at HC. **Knee Ang30%:** Knee angle at 30% stance. **Knee Ang50%:** Knee angle at 50% stance.
Hip Angle	Deg.	Hip angle profile of the perturbed limb during stance (% stance) determined using a relative angle defined by makers on the shoulder hip and knee and normalized to the neutral angle. Neutral angle determined from quiet stance.	**Hip AngHC:** Hip angle at HC. **Hip Ang30%:** Hip angle at 30% stance. **Hip Ang50%:** Hip angle at 50% stance.
Subtalar Joint Motion	Deg.	Rotations about the subtalar joint axes calculated between two rigid bodies of the perturbed limbs foot over % stance. Calcaneous defined by three markers on the heel. Midfoot defined by three markers on the ventral aspect of the midfoot. Neutral angle determined from quiet stance.	**Sub AngleHC:** Angle of the subtalar joint at HC. **Sub OnsetEv:** Time at which eversion begins to occur. **Sub EvPeak:** Maximum eversion angle during stance. **Sub EvPeakT:** Time of peak eversion.

Electromyography Data

Variable	Unit	Description	Specific Measure
Timing	s	*Timing of muscle onset and cessation calculated using a threshold of 5% of quiet muscle activity. Timing normalized to the stance phase.*	**Onset:** Activation above the 5% threshold of quiet EMG, maintained for 50ms or more. **Cessation:** When activation fell below the 5% threshold of quiet EMG for 50ms or more. **Duration:** Time the muscle was active calculated from time of onset to time of cessation.
Magnitude	A/D Units	Area under the curve from the onset to cessation of muscle activity. Magnitudes during slip trials were normalized to average magnitudes during normal walking for each muscle.	

Appendix E: Subtalar Joint Motion

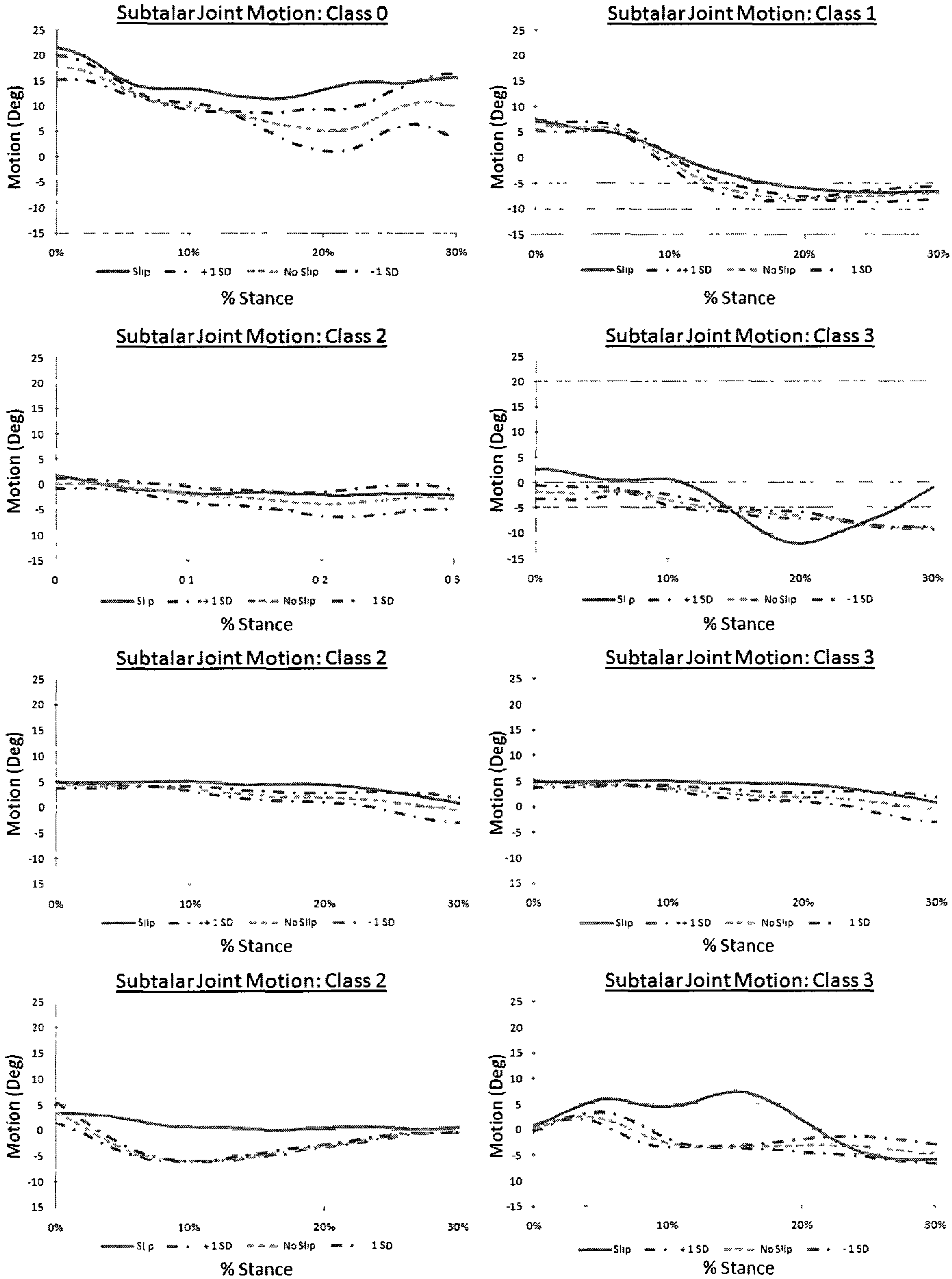


Figure E.1: **Illustrates the subtalar joint motion during normal walking trails compared to different levels of slip severity.**

Appendix F: EMG Result Tables

Table F.1

Demonstrates EMG activation patterns of the lower limb muscles during normal walking trials compared to slip trials; repeated measures, within-1 factor ANOVA.

	Condition	0		1		2		3		4				
	# of Observations	26		87		88		88		87				
		Mean	STDev	Mean	STDev	Mean	STDev	Mean	STDev	Mean	STDev	P-value	Sig.	Tukey's
Preparatory Phase	***RTA***													
	Onset (%)	-11.88	3.85	-14.22	5.39	-13.41	4.63	-13.42	4.89	-14.00	5.12	0.6431		
	Duration (%)	21.37	3.51	27.34	7.20	25.74	6.19	26.25	5.37	26.90	6.02	0.4169		
	Magnitude (%)	86.80	20.03	103.69	26.50	104.68	31.36	107.73	33.36	110.12	36.62	0.532		
	RMG	-	-	-	-	-	-	-	-	-	-	-		
	RRF													
	Onset (%)	-12.74	8.01	-8.55	7.07	-8.81	7.28	-8.15	5.88	-7.25	7.07	0.2199		
	Duration (%)	38.54	16.03	32.63	9.89	33.36	9.18	31.46	8.78	31.30	9.34	0.2682		
	Magnitude (%)	100.25	17.68	105.68	36.28	112.42	43.40	98.98	34.78	100.13	25.72	0.1624		
	RMH													
	Onset (%)	-26.05	9.58	-26.77	7.83	-25.23	11.57	-25.91	9.47	-25.80	8.45	0.5029		
	Duration (%)	33.63	12.63	33.40	11.26	31.98	9.07	32.39	8.16	31.97	9.73	0.8024		
	Magnitude (%)	100.12	22.85	96.59	34.45	92.03	33.65	96.73	32.88	89.80	28.40	0.5471		
	RPL	-	-	-	-	-	-	-	-	-	-	-		
	LMG	-	-	-	-	-	-	-	-	-	-	-		
	LRF													
	Onset (%)	-10.33	14.50	2.63	9.57	0.72	10.36	3.26	8.26	2.35	10.73	0.503		
	Duration (%)	20.50	7.63	15.15	5.72	16.67	6.13	16.52	5.71	16.41	5.07	0.8082		
	Magnitude (%)	95.95	34.38	88.70	36.93	101.73	37.51	104.56	44.19	98.84	27.32	0.0897		
	LMH	-	-	-	-	-	-	-	-	-	-	-		
Stability Phase	***RTA***	-	-	-	-	-	-	-	-	-	-	-		
	RMG													
	Onset (%)	43.12	10.25	42.88	12.26	41.01	12.26	44.29	10.90	42.48	12.39	0.0626		
	Duration (%)	33.94	9.52	34.45	13.30	36.77	13.19	32.47	10.92	34.48	12.65	0.0088	*	2-3
	Magnitude (%)	102.76	17.31	100.26	25.99	107.74	24.21	96.13	25.34	99.06	21.41	0.022	*	2-(3,4)
	RRF	-	-	-	-	-	-	-	-	-	-	-		
	RMH	-	-	-	-	-	-	-	-	-	-	-		
	RPL	37.42	11.87	43.42	12.90	43.82	12.77	42.91	12.44	43.08	11.46	0.9386		
	Onset (%)	40.03	14.09	37.83	13.56	37.32	13.40	37.68	12.12	38.52	12.04	0.8707		
	Duration (%)	92.47	25.24	100.14	46.86	95.54	31.98	93.15	37.72	95.75	36.70	0.8124		
	Magnitude (%)													
	LMG	-	-	-	-	-	-	-	-	-	-	-		
	LRF	-	-	-	-	-	-	-	-	-	-	-		
	LMH	-	-	-	-	-	-	-	-	-	-	-		
Transition Phase	***RTA***													
	Onset (%)	96.17	3.97	95.13	6.61	93.61	7.19	94.44	6.48	93.67	6.69	0.0411	*	0-(2,3,4);4-1
	Duration (%)	29.09	9.63	21.79	9.81	21.16	9.48	22.60	10.85	23.04	9.65	0.7913		
	Magnitude (%)	95.98	24.82	104.28	46.96	105.85	36.28	104.94	47.22	108.69	43.69	0.9798		
	RMG	-	-	-	-	-	-	-	-	-	-	-		
	RRF													
	Onset (%)	93.52	7.64	89.91	6.85	90.04	6.72	89.77	6.03	88.04	7.26	0.2711		
	Duration (%)	22.11	11.06	18.01	6.65	17.80	7.99	16.89	6.67	18.07	6.92	0.5456		
	Magnitude (%)	101.88	25.87	103.33	42.12	96.71	32.59	96.29	44.50	103.02	46.54	0.6287		
	RMH	-	-	-	-	-	-	-	-	-	-	-		
	RPL	-	-	-	-	-	-	-	-	-	-	-		
	LMG	-	-	-	-	-	-	-	-	-	-	-		
	LRF													
	Onset (%)	71.74	5.42	72.21	6.60	72.70	7.05	73.20	6.06	71.97	5.02	0.3895		
	Duration (%)	35.92	9.76	34.77	7.94	34.87	8.12	32.74	6.93	33.64	8.45	0.1532		
	Magnitude (%)	98.55	14.37	102.96	31.28	101.91	25.88	95.02	20.75	97.32	20.54	0.2023		
	LMH													
	Onset (%)	65.33	9.81	65.51	10.47	67.69	11.67	64.49	12.79	64.47	11.11	0.211		
	Duration (%)	38.13	10.94	35.63	9.23	36.28	10.15	37.05	13.85	38.52	12.79	0.4129		
	Magnitude (%)	99.72	18.98	104.22	40.31	98.17	37.09	99.64	39.60	101.31	30.34	0.8114		

**Significance, p<0.05.*

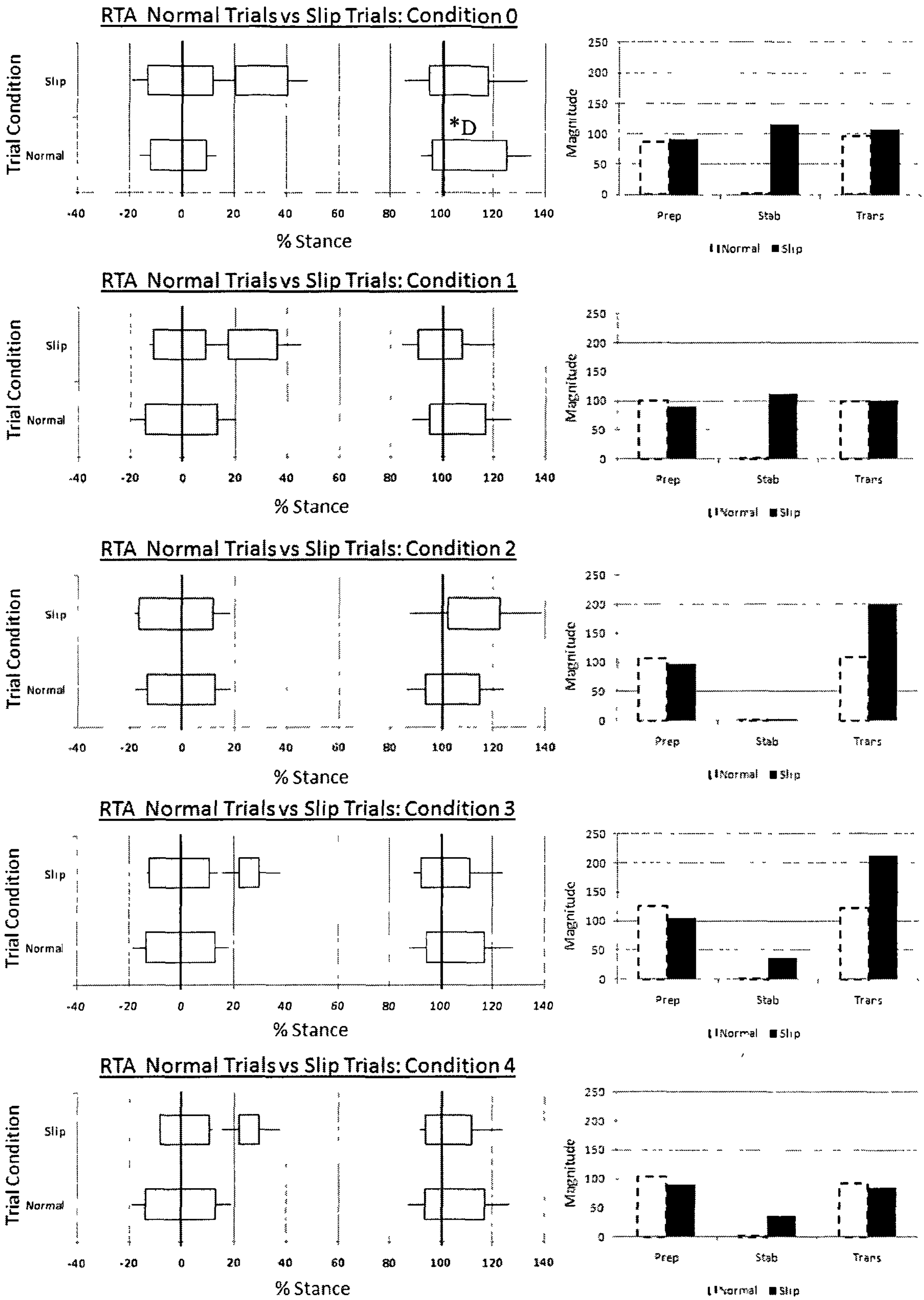


Figure F.1: **Illustrates the activation patterns and magnitudes of the right tibialis anterior (RTA) during normal walking and slip perturbations across the three phases of stance. *Significance, p<0.05.**

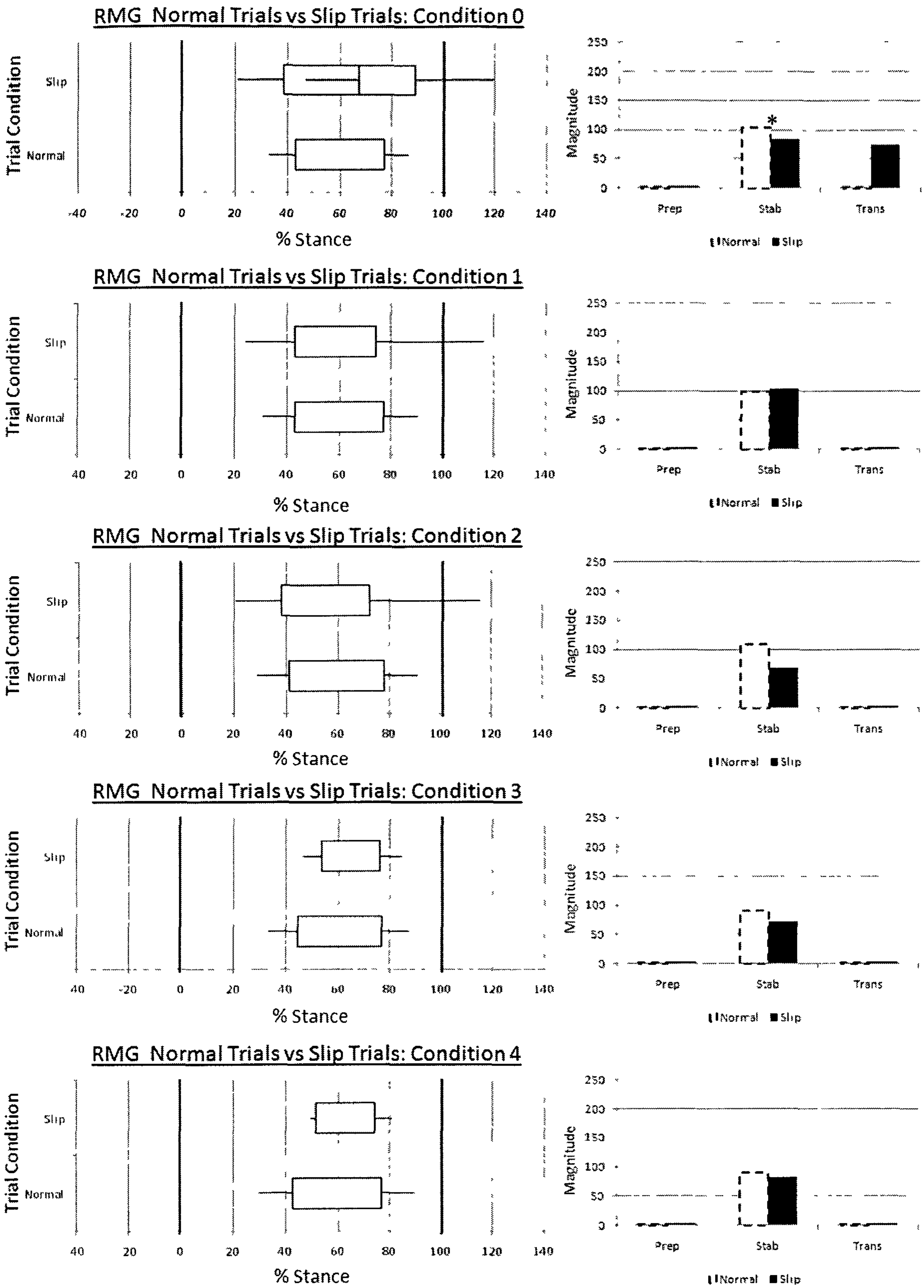


Figure F.2: **Illustrates the activation patterns and magnitudes of the right medial gastrocnemius (RMG) during normal walking and slip perturbations across the three phases of stance. *Significance, $p<0.05$.**

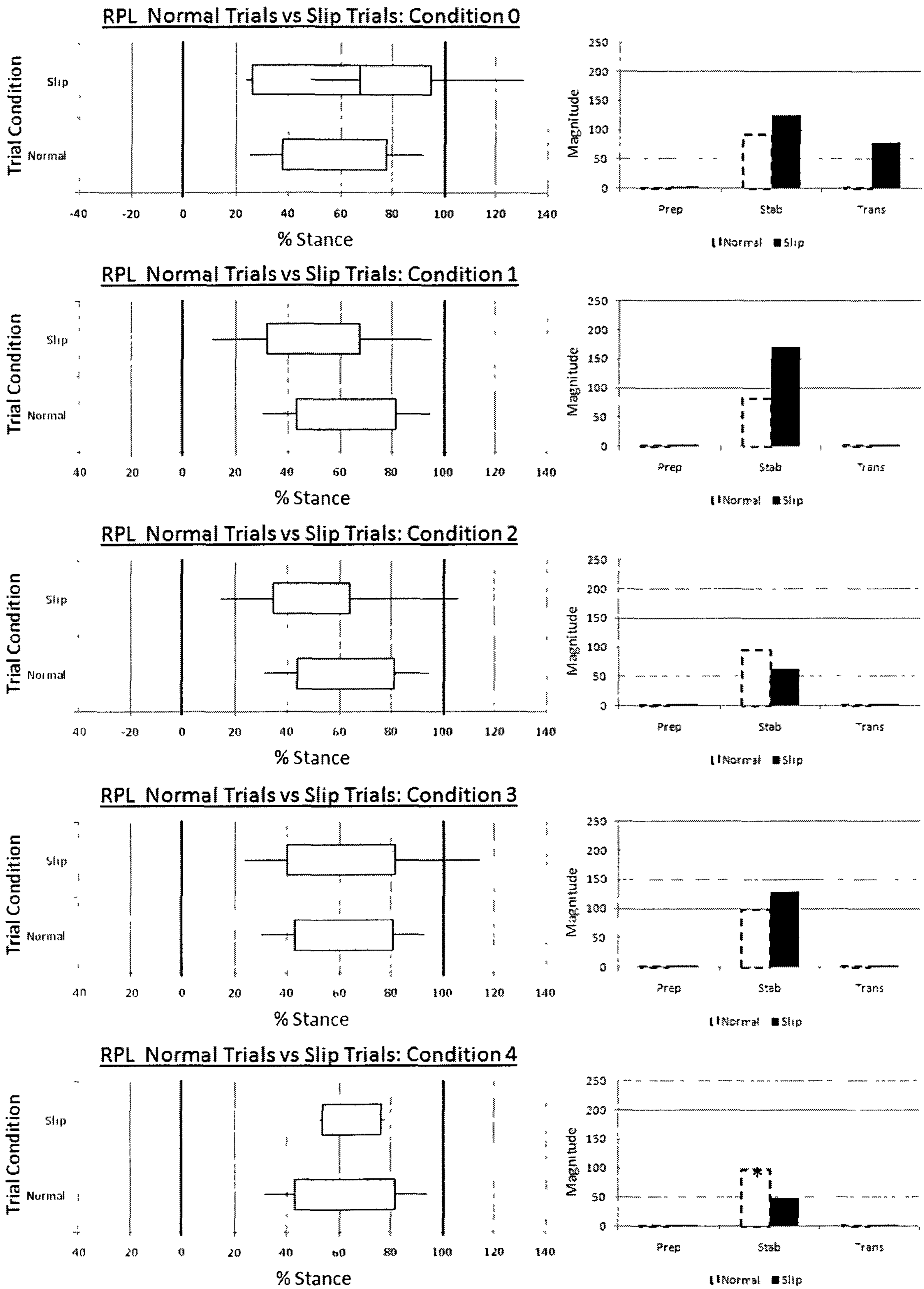


Figure F.3: **Illustrates the activation patterns and magnitudes of the right peroneus longus (RPL) during normal walking and slip perturbations across the three phases of stance.*Significance, $p<0.05$.**

Table F.2

Demonstrates EMG activation patterns of the lower limb muscles during normal walking trials compared to slip trials within condition 0; repeated measures, within-1 factor ANOVA.

	Preparatory Phase					Stability Phase					Transition Phase				
Condition 0	Normal		Slip			Normal		Slip			Normal		Slip		
# of Observations	26		8			26		8			26		8		
	Mean	STDev	Mean	STDev	P-value*	Mean	STDev	Mean	STDev	P-value*	Mean	STDev	Mean	STDev	P-value*
RTA															
Onset (%)	-11.88	3.85	-12.99	5.86	0.6057	-	-	20.49	2.39	-	96.17	3.97	95.16	9.60	0.5949
Duration (%)	21.37	3.51	24.74	9.51	0.5723	-	-	19.82	5.38	-	29.09	9.63	22.80	5.17	0.0388*
Magnitude (%)	86.80	20.03	92.09	23.15	0.8427	-	-	115.43	51.00	-	95.98	24.82	106.62	44.33	0 2745
RMG															
Onset (%)	-	-	-	-	-	43.12	10.25	38.36	17.33	0.1409	-	-	67.18	20.37	-
Duration (%)	-	-	-	-	-	33.94	9.52	38.01	19.17	0.7227	-	-	21.90	10.27	-
Magnitude (%)	-	-	-	-	-	102.76	17.31	83.75	49.97	0.0172*	-	-	72.45	27.15	-
RRF															
Onset (%)	-12 74	8.01	-6.17	9.99	0.2161	-	-	36.81	11 79	-	93.52	7 64	79.20	26.17	0.2316
Duration (%)	38.54	16.03	23.42	7.52	0.1172	-	-	22.93	6.66	-	22.11	11.06	19.55	13.69	0.2087
Magnitude (%)	100.25	17.68	70.63	27.39	0.0304*	-	-	256.38	300.46	-	101.88	25.87	190.67	116.80	0.1287
RMH															
Onset (%)	-26.05	9.58	-22.93	14.32	0.6563	-	-	31.30	10.59	-	-	-	-	-	-
Duration (%)	33.63	12.63	22.49	11.84	0.2617	-	-	27.06	19.14	-	-	-	-	-	-
Magnitude (%)	100.12	22.85	84.02	58.77	0.5382	-	-	202.22	169.51	-	-	-	-	-	-
RPL															
Onset (%)	-	-	-	-	-	37.83	11.79	25.99	2.19	0.0778	-	-	67.24	18.40	-
Duration (%)	-	-	-	-	-	39.68	13.89	60.97	41.55	0.2584	-	-	27.67	5.81	-
Magnitude (%)	-	-	-	-	-	91.22	25.45	125.94	67.09	0.2164	-	-	78.69	21.53	-
LMG															
Onset (%)	-	-	-	-	-	-	-	62.36	31.75	-	-	-	-	-	-
Duration (%)	-	-	-	-	-	-	-	49.97	39.38	-	-	-	-	-	-
Magnitude (%)	-	-	-	-	-	-	-	87.73	41.06	-	-	-	-	-	-
LRF															
Onset (%)	-16.00	17 27	-	-	-	-	-	32.87	13.81	-	71.74	5.42	67.40	21.03	0.1106
Duration (%)	23.47	10.52	-	-	-	-	-	46.34	50.12	-	35.92	9.76	39.71	19.87	0.3615
Magnitude (%)	52.31	23.12	-	-	-	-	-	727.87	1150.77	-	98.55	14.37	128.04	41.13	0.2438
LMH															
Onset (%)	-	-	-	-	-	-	-	36.56	14.65	-	65.33	9.81	70.75	20.05	0 8722
Duration (%)	-	-	-	-	-	-	-	51.01	10.32	-	38.13	10.94	39.52	22.38	0.8229
Magnitude (%)	-	-	-	-	-	-	-	671.43	477.46	-	99.72	18.98	145.64	52.37	0.108

**Significance, p<0 05*

Table F.3

Demonstrates EMG activation patterns of the lower limb muscles during normal walking trials compared to slip trials within condition 1; repeated measures, within-1 factor ANOVA.

	Preparatory Phase					Stability Phase					Transition Phase				
Condition 1	Normal		Slip			Normal		Slip			Normal		Slip		
# of Observations	21		3			21		3			21		3		
	Mean	STDev	Mean	STDev	P-value*	Mean	STDev	Mean	STDev	P-value*	Mean	STDev	Mean	STDev	P-value*
RTA															
Onset (%)	-11.71	4.24	-11.29	1.48	0.5382	-	-	17.42	4.92	-	92.23	10.09	90.72	6.11	0.7333
Duration (%)	24.27	5.70	19.78	3.54	0.7016	-	-	18.72	4.09	-	25.58	9.16	17.09	6.40	0.5393
Magnitude (%)	100.74	29.31	89.56	10.85	0.6613	-	-	111.65	106.29	-	99.31	27.60	100.12	64.30	0.994
RMG															
Onset (%)	-	-	-	-	-	43.54	14.10	42.98	18.88	0.0681	-	-	-	-	-
Duration (%)	-	-	-	-	-	32.69	13.72	31.05	23.07	0.7087	-	-	-	-	-
Magnitude (%)	-	-	-	-	-	99.26	23.04	102.69	22.88	0.8834	-	-	-	-	-
RRF															
Onset (%)	-7.58	4.15	-0.18	23.21	0.6775	-	-	-	-	-	87.20	7.94	89.77	6.49	0.2594
Duration (%)	30.81	5.06	31.93	11.99	0.8455	-	-	-	-	-	14.48	3.00	10.26	1.93	0.2687
Magnitude (%)	104.20	27.74	193.71	150.51	0.4015	-	-	-	-	-	82.20	28.10	69.83	67.54	0.9519
RMH															
Onset (%)	-28.83	4.63	-13.93	30.00	0.4505	-	-	-	-	-	-	-	-	-	-
Duration (%)	29.41	7.98	39.96	6.34	0.0139*	-	-	-	-	-	-	-	-	-	-
Magnitude (%)	87.49	18.40	348.15	409.27	0.3758	-	-	-	-	-	-	-	-	-	-
RPL															
Onset (%)	-	-	-	-	-	49.70	5.71	31.93	20.47	0.6541	-	-	-	-	-
Duration (%)	-	-	-	-	-	30.40	3.57	35.27	6.97	0.6474	-	-	-	-	-
Magnitude (%)	-	-	-	-	-	82.23	22.24	170.16	156.45	0.494	-	-	-	-	-
LMG															
Onset (%)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Duration (%)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Magnitude (%)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LRF															
Onset (%)	2.89	7.58	12.10	1.01	0.4279	-	-	-	-	-	72.88	5.80	73.78	3.77	0.4975
Duration (%)	12.10	3.26	13.25	3.51	0.8991	-	-	-	-	-	32.09	7.89	37.07	8.74	0.7737
Magnitude (%)	74.86	28.11	84.02	23.22	0.7924	-	-	-	-	-	97.04	23.38	98.20	13.79	0.9707
LMH															
Onset (%)	-	-	-	-	-	-	-	-	-	-	63.41	9.93	62.86	6.83	0.0334
Duration (%)	-	-	-	-	-	-	-	-	-	-	35.35	7.62	51.79	5.31	0.3056
Magnitude (%)	-	-	-	-	-	-	-	-	-	-	101.20	39.74	324.19	323.82	0.4636

**Significance, $p<0.05$.*

Table F.4

Demonstrates EMG activation patterns of the lower limb muscles during normal walking trials compared to slip trials within condition 2; repeated measures, within-1 factor ANOVA.

	Preparatory Phase					Stability Phase					Transition Phase				
Condition 2	Normal		Slip			Normal		Slip			Normal		Slip		
# of Observations	20		3			20		3			20		3		
	Mean	STDev	Mean	STDev	P-value*	Mean	STDev	Mean	STDev	P-value*	Mean	STDev	Mean	STDev	P-value*
RTA															
Onset (%)	-13.89	5.32	-16.34	1.53	0.1104	-	-	-	-	-	94.34	5.33	102.44	14.43	0.4269'
Duration (%)	27.05	7.25	27.90	5.49	0.6779	-	-	-	-	-	16.51	8.48	20.24	1.59	0.6041'
Magnitude (%)	107.04	28.79	97.27	13.25	0.2275	-	-	-	-	-	109.20	37.13	198.48	116.64	0.2683'
RMG															
Onset (%)	-	-	-	-	-	36.54	10.38	37.95	17.14	0.5117	-	-	-	-	-
Duration (%)	-	-	-	-	-	40.35	11.72	34.22	26.38	0.8749	-	-	-	-	-
Magnitude (%)	-	-	-	-	-	109.29	20.59	68.62	18.88	0.2409	-	-	-	-	-
RRF															
Onset (%)	-9.68	8.19	-11.44	6.35	0.6269	-	-	-	-	-	86.78	6.95	87.56	0.34	0.5858
Duration (%)	35.30	9.28	50.18	12.33	0.2636	-	-	-	-	-	18.00	8.90	30.62	7.89	0.5269
Magnitude (%)	113.46	48.92	98.12	1.64	0.0247*	-	-	-	-	-	83.63	34.39	170.26	29.35	0.066
RMH															
Onset (%)	-24.27	12.43	-26.71	8.23	0.2591	-	-	-	-	-	-	-	-	-	-
Duration (%)	30.05	8.44	26.69	8.45	0.8087	-	-	-	-	-	-	-	-	-	-
Magnitude (%)	70.85	31.67	70.00	48.53	0.4971	-	-	-	-	-	-	-	-	-	-
RPL															
Onset (%)	-	-	-	-	-	45.12	10.85	34.53	19.67	0.3427	-	-	-	-	-
Duration (%)	-	-	-	-	-	36.68	10.07	29.45	22.18	0.399	-	-	-	-	-
Magnitude (%)	-	-	-	-	-	95.74	37.96	63.83	59.00	0.1594	-	-	-	-	-
LMG															
Onset (%)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Duration (%)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Magnitude (%)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LRF															
Onset (%)	1.30	7.93	-	-	-	-	-	-	-	-	73.64	7.93	82.30	13.25	0.3662
Duration (%)	14.98	6.50	-	-	-	-	-	-	-	-	33.75	7.17	29.07	17.74	0.6643
Magnitude (%)	84.52	41.74	-	-	-	-	-	-	-	-	109.24	19.83	162.68	65.78	0.2319
LMH															
Onset (%)	-	-	-	-	-	-	-	-	-	-	75.32	8.12	82.74	13.99	0.4184
Duration (%)	-	-	-	-	-	-	-	-	-	-	32.38	6.14	29.89	19.62	0.7913
Magnitude (%)	-	-	-	-	-	-	-	-	-	-	80.41	36.85	119.39	26.55	0.2272

**Significance, $p<0.05$*

Table F.5

Demonstrates EMG activation patterns of the lower limb muscles during normal walking trials compared to slip trials within condition 3; repeated measures, within-1 factor ANOVA.

	Preparatory Phase					Stability Phase					Transition Phase				
Condition 3	Normal		Slip			Normal		Slip			Normal		Slip		
# of Observations	22		4			22		4			22		4		
	Mean	STDev	Mean	STDev	P-value*	Mean	STDev	Mean	STDev	P-value*	Mean	STDev	Mean	STDev	P-value*
RTA															
Onset (%)	-13.71	3.86	-12.42	0.82	0.1405	-	-	22.08	6.40	-	95.62	3.42	92.19	2.83	0.3789
Duration (%)	26.86	5.21	22.93	2.59	0.062	-	-	7.69	1.53	-	23.71	10.28	18.85	9.79	0.7098
Magnitude (%)	124.64	41.01	105.73	32.43	0.7039	-	-	37.10	8.35	-	122.72	71.94	213.23	184.36	0.428
RMG															
Onset (%)	-	-	-	-	-	46.93	8.24	53.79	6.88	0.4478	-	-	-	-	-
Duration (%)	-	-	-	-	-	32.02	9.09	22.38	1.46	0.2841	-	-	-	-	-
Magnitude (%)	-	-	-	-	-	89.89	21.45	71.41	28.33	0.3406	-	-	-	-	-
RRF															
Onset (%)	-11.10	5.35	-7.73	6.22	0.3904	-	-	-	-	-	91.85	4.37	98.56	7.48	0.2176
Duration (%)	36.59	6.14	31.99	14.03	0.5801	-	-	-	-	-	13.97	2.93	15.62	7.21	0.6189
Magnitude (%)	110.36	39.04	90.24	18.74	0.8494	-	-	-	-	-	101.78	41.01	165.82	60.70	0.3177
RMH															
Onset (%)	-25.69	6.97	-13.16	3.28	0.423	-	-	-	-	-	-	-	-	-	-
Duration (%)	31.32	7.39	22.67	12.90	0.0429*	-	-	-	-	-	-	-	-	-	-
Magnitude (%)	98.03	18.01	73.52	8.68	0.0488	-	-	-	-	-	-	-	-	-	-
RPL															
Onset (%)	-	-	-	-	-	44.03	11.85	39.87	15.97	0.7865	-	-	-	-	-
Duration (%)	-	-	-	-	-	38.90	12.40	41.47	16.77	0.7185	-	-	-	-	-
Magnitude (%)	-	-	-	-	-	99.17	25.02	128.74	70.89	0.7944	-	-	-	-	-
LMG															
Onset (%)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Duration (%)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Magnitude (%)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LRF															
Onset (%)	2.74	8.06	-	-	-	-	-	-	-	-	71.95	6.79	71.74	4.54	0.7587
Duration (%)	16.74	7.03	-	-	-	-	-	-	-	-	36.04	7.46	40.47	17.32	0.7826
Magnitude (%)	65.41	51.63	-	-	-	-	-	-	-	-	99.59	21.31	137.21	93.87	0.6325
LMH															
Onset (%)	-	-	-	-	-	-	-	-	-	-	59.82	11.61	76.98	12.65	0.043*
Duration (%)	-	-	-	-	-	-	-	-	-	-	41.89	11.69	21.53	7.41	0.0489*
Magnitude (%)	-	-	-	-	-	-	-	-	-	-	99.10	38.48	67.13	5.74	0.0136*

**Significance, $p<0.05$.*

Table F.6

Demonstrates EMG activation patterns of the lower limb muscles during normal walking trials compared to slip trials within condition 4; repeated measures, within-1 factor ANOVA.

	Preparatory Phase					Stability Phase					Transition Phase				
Condition 4	*Normal*		*Slip*			*Normal*		*Slip*			*Normal*		*Slip*		
# of Observations	19		2			19		2			19		2		
	Mean	STDev	Mean	STDev	P-value*	Mean	STDev	Mean	STDev	P-value*	Mean	STDev	Mean	STDev	P-value*
RTA															
Onset (%)	-15.11	5.57	-8.13	0.42	0.1727	-	-	22.08	6.40	-	93.53	2.22	93.93	2.28	0.1839
Duration (%)	26.28	4.79	18.84	0.71	0.1823	-	-	7.69	1.53	-	19.99	7.12	17.97	10.12	0.6392'
Magnitude (%)	102.88	23.83	89.79	23.00	0.3496	-	-	37.10	8.35	-	91.39	25.93	85.26	10.43	0.0146*
RMG															
Onset (%)	-	-	-	-	-	48.76	8.27	51.29	2.04	0.3855	-	-	-	-	-
Duration (%)	-	-	-	-	-	25.69	7.31	23.01	4.26	0.4921	-	-	-	-	-
Magnitude (%)	-	-	-	-	-	90.42	19.69	82.10	23.64	0.8732	-	-	-	-	-
RRF															
Onset (%)	-7.39	7.30	-9.89	4.41	0.6683	-	-	-	-	-	89.12	2.27	85.75	0.42	0.0629
Duration (%)	28.60	9.22	21.92	19.25	0.4663	-	-	-	-	-	20.05	8.12	26.39	0.15	0.9887
Magnitude (%)	85.22	21.40	65.81	60.39	0.8082	-	-	-	-	-	90.29	35.89	84.18	32.63	0.6994
RMH															
Onset (%)	-21.90	8.63	-19.95	4.37	0.9686	-	-	14.03	6.75	-	-	-	-	-	-
Duration (%)	30.13	10.95	25.57	9.51	0.0372*	-	-	15.35	5.11	-	-	-	-	-	-
Magnitude (%)	82.80	34.00	70.76	22.97	0.2904	-	-	67.33	17.99	-	-	-	-	-	-
RPL															
Onset (%)	-	-	-	-	-	44.05	11.99	53.68	0.99	0.2271	-	-	-	-	-
Duration (%)	-	-	-	-	-	35.36	13.21	22.53	0.39	0.2681	-	-	-	-	-
Magnitude (%)	-	-	-	-	-	97.51	32.59	47.91	2.08	0.0468*	-	-	-	-	-
LMG															
Onset (%)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Duration (%)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Magnitude (%)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LRF															
Onset (%)	-0.13	11.16	5.67	2.03	0.5'	-	-	-	-	-	71.27	3.85	85.33	2.75	0.245
Duration (%)	19.66	3.48	13.85	0.75	0.4296'	-	-	-	-	-	33.85	6.18	21.62	0.89	0.4385
Magnitude (%)	88.24	58.87	64.11	54.59	0.5'	-	-	-	-	-	91.67	22.11	59.98	11.46	0.0155'*
LMH															
Onset (%)	-	-	-	-	-	-	-	-	-	-	68.63	9.59	87.32	2.64	0.0441*
Duration (%)	-	-	-	-	-	-	-	-	-	-	35.67	6.31	21.42	5.24	0.0591
Magnitude (%)	-	-	-	-	-	-	-	-	-	-	97.84	28.56	54.46	1.20	0.0808

**Significance, p<0 05*

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