Evaluation of Gait and Slip Characteristics
For Adults with Mental Retardation

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ABSTRACT

Adults with mental retardation (MR) experience a greater number of falls than their non-disabled peers. To date, efforts to understand the causes for these falls have primarily involved qualitative studies that use largely subjective measures to quantify stability. Performing a more objective biomechanical gait analysis may better explain the reasons for these fall accidents and provide repeatable measures that can be used for comparison to determine the effectiveness of interventions intended to reduce slip-related falls.

A gait analysis was conducted to quantify normal walking and slip response characteristics for adults with MR as well as a group of non-disabled age- and gender-matched peers. Kinetic and kinematic data were collected and a number of variables relating to gait pattern, slip propensity, and slip severity were calculated to compare the differences between groups. Results showed that adults with MR exhibit slower walking speeds, shorter step lengths, and greater knee flexion at heel contact suggesting that their gait patterns share more similarities with the elderly than with healthy adults of an equivalent age. Unexpectedly, the MR group demonstrated a lower required coefficient of friction (RCOF) and slower heel contact velocity which, alone, would suggest a reduced slip propensity as compared with the healthy group. A greater peak sliding heel velocity and greater slip distance measures, however, indicate greater slip severity for the MR group. The findings of this study suggest that falls in this population may be attributed to delayed response to slip perturbation as measured by slip distances.

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ABBREVIATIONS

General Terms

MR	Mental retardation
TUAG	Timed-Up-And-Go test
ADL(s)	Activity(ies) of daily living

Gait Parameters

WS	Walking speed
SL	Step length
HCV	Heel contact velocity
KA_{HC}	Sagittal knee flexion angle at heel contact
AA_{HC}	Sagittal ankle dorsiflexion angle at heel contact

Slip-Propensity Parameters

RCOF	Required coefficient of friction

Slip Response Parameters

SDI	Initial slip distance; slip distance I
SDII	Slip distance II
PSHV	Peak sliding heel velocity

1.0 INTRODUCTION

1.1 Rationale

Despite the fact that individuals with mental retardation (MR) are known to be more prone to fall injuries than their non-disabled peers (Sherrard et al., 2001 & 2002; Hsieh et al., 2001), there is little biomechanical research available which explores the mechanisms associated with fall accidents. Much of the research conducted with regard to investigating fall propensity in this population has involved physiotherapeutic test methods such as the Berg balance scale and the Timed Up-and-Go (TUAG) test (Bruckner & Herge, 2003; Hale et al., 2006). It is the author's opinion that the disadvantages of using these methods lie in that they provide limited information regarding the movement patterns specific to an individual or group. In the case of the Berg balance scale, a participant performs various activities of daily living (ADLs) while a trained physiotherapist scores their balance on a scale of 0 to 4. While these ratings typically show good inter-rater reliability, the scores themselves represent broad categories which describe, only generally, the quality of the individual's movement. The TUAG test involves the participant rising from a seated position, walking a prescribed distance, and returning to the starting seated position. The primary measure recorded during this test is the time for completion of this sit-walk-sit sequence. Like the Berg balance test, however, the simple time measure does not provide an explanation of the underlying motor control associated with fall accidents or instability in adults with MR.

Biomechanical analysis is advantageous because it allows for the determination of specific, objective measures which are highly repeatable and can quantify specific differences in movement patterns between individuals or groups. Biomechanical analysis has been used to identify stability and gait characteristics for many populations of interest including but not limited to the elderly, individuals with neuromuscular disorders, Alzheimer's and dementia patients, and diabetics (Lockhart et al., 2003 & 2005; Plotnik et al., 2007; Frzovic et al., 2000; Wittwer et al., 2008; Van Dijk et al., 1996). The current study identifies the need for a biomechanical evaluation of gait among the MR population. Utilizing standard gait measures, comparisons were made between the MR population and their non-disabled peers. This information can provide insight into what differences exist and how they may be contributing to an increased fall risk for those with MR. Further, once baseline gait measures are obtained, it is then possible to compare these same parameters following an intervention to determine if it had any effect.

Much of the current research regarding postural and gait stability of individuals with mental retardation employs psychotherapeutic test methods to provide a qualitative perspective on how and why the mentally retarded population exhibits an increased rate of falls. More extensive biomechanical data may be essential to providing quantitative measures which can describe the characteristic behaviors and movement patterns of this population. Acquiring such additional data may help elucidate the mechanisms by which this population is predisposed to suffering fall accidents.

1.2 Objectives

There were two primary goals associated with this study. *1) The first was to use current standards of gait assessment to characterize gait parameters for people with MR and compare them to that of healthy, age- and gender-matched peers during normal walking. 2) Secondly, this study aimed to assess slip propensity characteristics among these two groups in an effort to better understand why adults with MR are more prone to fall accidents.*

1.3 Hypotheses

This study compared the gait of adults with mental retardation to that of healthy age- and gender-matched peers in an effort to quantify differences that may be predisposing the MR population to falls. Specifically, the parameters of walking speed and step length are compared to determine if differences exist among these populations in terms of fundamental gait characteristics. Heel contact velocity and required coefficient of friction measures provide a means to compare the relative likelihood of slip between these two groups. Further, joint angles allow the comparison of body posture during key events of the gait cycle. Understanding the biomechanical differences between people with MR and their healthy peers is an important step in identifying potential factors contributing to their increased occurrence of slip injuries.

A second aim of this study is to determine group differences in slip-propensity and slip severity measures between healthy, non-disabled adults and adults with MR. Required coefficient of friction (RCOF), a commonly accepted measure of slip propensity will be used to assess the relative likelihood of slip for each group. Slip distance measures and peak sliding heel velocity will be used to compare the relative severity of slip for each group.

There are three primary hypotheses associated with this study:
1) Individuals with mental retardation will exhibit significantly different gait patterns than healthy age- and gender-matched peers. Specifically, significant differences are expected for the following gait characteristics: walking speed (WS), step length (SL), heel contact velocity (HCV), and joint angles at heel contact.
2) The MR group will exhibit greater slip propensity by demonstrating a higher required coefficient of friction (RCOF).
3) The number of slip-induced falls as well as slip distance measures and peak sliding heel velocity will suggest a greater slip severity for the MR group as compared to the non-disabled group.

1.4 Implications

Adults with mental retardation are suffering a greater number of accidental falls than their healthy peers (Sherrard et al., 2001 & 2002; Hsieh et al., 2001). Current research on falls in the mentally retarded relies primarily on subjective (Berg Balance scale) or time-based (TUAG test) measures of performance (Bruckner & Herge, 2003; Hale et al., 2006). While these test methods may allow for qualitative comparisons of motor control and stability, they are not useful for determining the mechanisms responsible for these deficits.

The present study is needed as an exploration into the underlying causes of falls in the MR population. A biomechanical gait analysis will quantify fundamental differences in gait patterns between non-disabled and intellectually disabled adults. Biomechanical analysis will also be used to assess slip propensity and slip severity measures to determine how differences in gait characteristics may be translating to an increased fall injury rate for adults with MR. Further, establishing hallmark biomechanical gait characteristics associated with mental retardation provides an objective means of comparison for future research that may wish to assess the effectiveness of interventions intended to reduce slip-induced falls. In other words, having a repeatable and reliable measure of gait and slip parameters for this population will enable future research to determine whether an intervention was successful in improving biomechanical function such that slip-and-fall injuries might be mitigated.

2.0 LITERATURE REVIEW

2.1 Prevalence of Mental Retardation and Fall-Related Injuries

Mental retardation (MR) is a condition which occurs in roughly 2.5-3% of the general population and is the single most common developmental disorder (CDC, 2005). As of the year 2000, the number of Americans living with MR was in excess of 6 million (ADA, 2000). The hallmark of MR is a below-average intelligence quotient (IQ) of less than 70. Other traits associated with MR include limited communications skills, difficulties with social interaction, and an inability to fully care for oneself (CDC, 2005). As a result, these individuals often need lifelong assistive care.

There are four categories which are used to describe the severity of MR: mild, moderate, severe, and profound. Each is defined by a range of IQ scores (shown in Table 2.1) with 'mild' indicating a lesser degree of MR and 'profound' indicating the most substantial intellectual disability (ID).

Table 2.1. Categories of MR.

MR status and corresponding IQ Range	
MR Status	**IQ Range**
Mild	55-69
Moderate	40-54
Severe	25-39
Profound	Below 25

Regardless of MR status, it is well-accepted that this population of individuals with MR experiences a greater number of falls than their non-disabled peers (Sherrard et al., 2001; Sherrard et al., 2002). Epidemiological studies have quantified morbidity and mortality rates for these falls and have tried to identify risk factors which may explain their occurrence (Hsieh et al., 2001; Sherrard et al., 2002). Sherrard reported that roughly 56 of every 1000 people with MR sustain an accidental injury annually. Further, about 150 of every 100,000 mentally retarded individuals perish each year following an accidental injury. With over 6 million Americans living with MR, these statistics suggest that over 9,000 people are dying each year due to accidental injuries in the United States alone. Over 50% of these accidental injuries are due to falls (Hsieh et al., 2001). Moreover, people with MR who live through their thirties are highly likely to survive to old age (Thorpe et al., 2001). When considering fall-risk, this suggests the potential for injury could be compounded by the normal effects of aging.

In a study by Hsieh et al. (2001), a review of medical records as well as surveys from caregivers, indicated that seizure disorders, the use of psychotropic drugs, and destructive behavior increase the overall risk of injury for individuals with developmental disabilities. Displaying destructive behavior, living in a residential care facility, and being ambulatory were also found to be correlated with an increase in accidental injuries. These risk factors were determined by calculating an adjusted odds ratio. When looking at fall injuries specifically, however, this same analysis tool was only able to identify increasing age (≥ 70 years), positive ambulatory status, and seizures as risk factors for falls among the developmentally disabled. It found no significant relation between the risk of falling and other potential factors such as physical health status, level of intellectual disability, or aggressive versus adaptive behavior. The argument could be made that the risk factors reported to have a positive correlation with falls among the developmentally disabled could, and do, also apply to the general population. It's well-accepted that even as non-disabled persons age, their risk of falls increases dramatically. It's also logical that a positive ambulatory status would be associated with falls. Dynamic movement presents greater challenges to balance maintenance. It makes sense then, that those individuals with the ability to ambulate within their community will suffer a greater number of falls than those who are unable to do so. It's also understandable that a seizure disorder would increase the risk of falls for any population of interest. Hsieh et al. (2001) effectively confirmed known risk factors for falls but were unable to distinguish unique risk factors which might explain the increased fall rate among those with MR. This further implies that other factors may influence the occurrence of fall accidents.

Sherrard et al. (2001) compared the injury risk of Australian youths with MR to that of their non-disabled peers. Those with intellectual disabilities were twice as likely to experience an accidental injury. Through a series of questionnaires and behavioral assessments, psychopathology and antisocial temperaments were found to be associated with greater injury risk (Sherrard, 2002). Additionally, age, gender, and IQ had no effect on risk of injury. These findings appear to be largely consistent with those of Hsieh et al. The absence of an age effect in

Sherrard's study is likely attributed to the fact that the participants studied were youths between 4 and 18 years of age.

While Hsieh and Sherrard both reported psychological and behavioral problems to be among the determinants of injury risk for the intellectually disabled, a shortcoming of these studies lies in their qualitative and observational nature. Neither study presented factors specifically related to fall injuries that help explain why the mentally retarded sustain a greater number of falls than their non-disabled peers. Further, those factors that were said to contribute to greater overall accidental injury (psychopathology, behavioral disorders) appear to be factors which lend no means for an intervention. At best, knowledge of these concurrent disabilities may serve a prophylactic purpose by encouraging caregivers to provide more assistance or supervision to those with such disorders. It is suspected, however, that limitations in the number of staff at residential care facilities and the responsibilities of daily life will restrict the one-on-one care these individuals can receive in both assisted-living and at-home dwellings.

2.2 Biomechanical Research and Mental Retardation

Despite its obvious necessity, research regarding biomechanical and balance characteristics of those with MR is limited. Walking is among the most common physical activities performed by those with MR and serves as a primary mode of transportation. Only recently has there been an effort to describe gait and movement performance characteristics for the mentally retarded (Stanish and Draheim, 2005; Sparrow et al., 1998; Bruckner and Herge, 2003; Carmeli et al., 2005; Hale et al., 2007). One study by Stanish and Draheim (2005) used pedometers to measure walking habits. The primary concern of this study was investigating the relationship between physical inactivity and the elevated occurrence of coronary heart disease and stroke among the MR population. Participants in this study were classified as having either mild or moderate MR, and their living environments ranged from institutionalization to group homes to living independently or with family. In general, there were no gender differences with respect to the number of steps taken per day, and the average step counts for both genders were consistent with those reported for typical daily activity (6,000 to 7,000 steps/day) by Tudor-Locke and Bassett (2004). Similarities between the step counts of people with MR and healthy, non-disabled persons might suggest that an increased fall rate is not attributable to physical activity level and that those with MR encounter similar chances of falling during locomotor activities.

A more commonly employed method of assessing movement characteristics associated with MR is to use a Timed-Up and Go (TUAG) test. A TUAG test establishes a starting point and a task to be performed by the participant (usually unassisted, level walking). The data recorded then is simply the time it takes for the participant to execute the task. This test has been used in various forms by several research groups (Bruckner and Herge, 2003; Carmeli et al., 2005; Hale et al., 2007) as a means of describing the physical abilities of those with ID. Bruckner and Herge (2003) attempted to use a modified TUAG test (MUAG) to identify stable and non-stable gait patterns in mentally retarded adults. Their modification to the traditional TUAG test (unassisted level walking) included additional walking trials performed with a rolling walker and a personal assistant. The hypothesis was that more stable walkers would perform better (faster MUAG times) walking without assistance while the unstable walkers would perform better with assistance than without. The method used in the initial identification of stable versus unstable walkers was not described in detail but was presumably decided upon by visual inspection and a review of fall histories. The recorded MUAG scores exhibited good individual reliability but the group scores were not able to distinguish between fallers and non-fallers.

When assessing balance, physiotherapists often employ the Berg Balance scale. The subject is asked to perform a sequence of fourteen everyday tasks and the physiotherapist assigns a score (0-4) accordingly based on the quality of mobility observed. A score of zero indicates minimal mobility while a score of 4 indicates the best mobility; attaining a total score of 45 or over represents safe, stable mobility.

Applications of the Berg Balance scale include a study by Bogle Thorbahn and Newton (1996) who attempted to use these scores as predictors of falls among a group of non-disabled elderly. The study aimed to determine how well the Berg test could detect those with imbalance (*sensitivity*) and how efficiently it is able to correctly classify non-fallers (*specificity*). Considering various factors such as frequency of falls, activity levels, and self-perception of balance, a multiple regression analysis reported that the Berg scores were highly specific (96%)

but only mildly sensitive (53%). In other words, this study suggested that the Berg balance test is efficient at designating non-fallers but is much less efficient at correctly differentiating frequent fallers. The reason for this is that the most frequent fallers were those who were assigned Berg scores close to the cutoff of value of 45 (Bogle Thorbahn and Newton, 1996). It was observed that the most severely unstable participants (i.e. those who scored much lower than 45) had adopted their own strategies for avoiding falls.

In an effort to find a more reliable technique for discerning between fallers and non-fallers, mentally retarded persons with a history of falling were exposed to both physiotherapeutic balance tests (TUAG, Berg Balance scale) as well as biomechanical balance tests (force plates, posturography) (Hale et al., 2006). Hale et al. (2006) concluded that their biomechanical test involving recovery from an external perturbation (forward and backward translations) was the most reliable in characterizing movement patterns of the mentally retarded participants. Translational perturbation tests are known to elicit high inter-subject repeatability because reactionary mechanisms to recover balance are largely reflexic. Here, participants displayed delayed reactions to the external perturbations. Similarly, Frzovic et al. (2000) found that both internal and external perturbation tests elicited the greatest distinction between a healthy control group and a test sample of individuals with multiple sclerosis. Perturbation testing may be a useful tool in describing movement characteristics unique to populations with disabilities.

While most of the balance and movement analyses for the mentally retarded population have occurred in the realm of physical therapy, there have been two studies which employed biomechanical methods to describe the characteristic movements of those with MR (Bodfish et al., 2001; Sparrow et al., 1998). The impetus for the study by Bodfish et al. (2001) was to employ dynamic measurements of postural stability to describe the movement profiles of persons with stereotyped and dyskinetic movement disorders. Those with stereotyped movement disorder exhibit repetitive, non-functional body motions such as body-rocking or hand waving, and this type of movement dysfunction is very often seen in individuals with mental retardation. Dyskinesia refers to similar non-functional body motions, but is exhibited more as tic-like, jerky movements. An important distinction between stereotyped and dyskinetic movement is that dyskinesia is elicited by an existing medical problem or as a side effect to drug treatment.

With the use of force platforms and posturography, Bodfish et al. (2001) compared various postural sway parameters (amount of postural motion; average velocity of motion of center of pressure (COP); variability of resultant motion of the COP from mean location; variability of lateral sway; variability of anterior-posterior (AP) sway) for a control group and each of two test groups displaying stereotypic or dyskinetic movements. The results showed that for most of these parameters the stereotypic movement group exhibited significantly greater amplitudes and greater variability than the control group. Conversely, the dyskinetic group exhibited values significantly less than the control group, implying a definite significant difference in movement profiles between each of the two groups of interest. Also, those with stereotypic movements exhibited greater sway in the AP direction.

A statistical quantity known as *approximate entropy* (ApEn) was used to quantify the regularity of the movement profiles. An ApEn score of 0 indicates perfect regularity while scores greater than 0 are indicative of increasing irregularity. The ApEn scores were significantly different between the control group and each of the movement disorder groups. Bodfish et al. (2001) reported that stereotypic movement patterns exhibited greater regularity than did the dyskinetic group.

Like Bodfish, Sparrow et al. (1998) collected biomechanical data to describe characteristic movement behaviors of individuals with MR. Making mention of "little reliable data of the gait patterns of individuals with MR" in the literature, participants with and without MR were asked to perform tasks that included level, unobstructed walking, stepping over an obstacle, stepping across an obstacle, and climbing stairs. Force plates and video recording were used to assess their performance.

Sparrow et al. (1999) reported that both walking speed and relative speed (walking speed normalized for subject height) were more variable among the participants with MR than for the controls. With regard to negotiating obstacles, those with MR tended to exaggerate or overcompensate their movements to assure safe passage. When stepping over an obstacle in the walking path, the participants with MR had earlier and faster lead-foot crossing times. This means they began to attempt the clear the object sooner in their gait cycle than did the controls. Similarly, when stepping across an obstacle the clearance of each foot was considerably greater for the MR group than for the controls. An additional finding was that the individuals with MR approached the obstacle at their normal gait speed slowing only once they had successfully traversed it. Perhaps this suggests that the overcompensation (high foot clearances, earlier lead-foot crossing times) is a technique adopted by persons with MR to reduce the likelihood of stumbling or falling in the presence of an obstacle. When climbing stairs, the MR group presented with longer gait cycle duration periods than the control group.

2.3 Gait Assessment

Gait assessment may involve the determination of spatial and temporal characteristics of walking as well as the corresponding kinematic and kinetic measures (Winter, 1990 & 1991; Perry, 1992). Spatial and temporal gait analysis identifies the gait cycle as having two primary states – stance phase and swing phase – that are defined by key events such as heel contact and toe-off. A single gait cycle is the period between consecutive heel contacts of the same foot. Stance phase, occurring between the instances of heel contact and toe-off is typically said to last approximately 60% of the gait cycle, where as swing phase, occurring between toe-off and the next heel contact, makes up approximately 40% of the cycle (Perry, 1992).

Within these two primary phases are several sub-phases. Stance phase can be divided into loading phase, midstance, terminal stance, and preswing. Swing phase can be divided into initial swing, midswing, and terminal swing. Additionally, there is a period during the gait cycle in which both feet are in contact with the ground after heel contact of the lead foot but preceding toe-off of the trailing foot known as double support phase. Deviations in the duration and timing of these gait characteristics (i.e. longer stance durations, shorter swing time) may be indicative of pathologic gait.

Gait analysis is often performed by analyzing kinematic data in combination with kinetic data. *Kinematics* describes movement in terms of positions, velocities, and accelerations, neglecting the forces involved. *Kinetics*, on the other hand, quantifies movement with consideration for the forces required to generate the motion. A number of parameters have been developed utilizing these data types that have become gold standards for defining the gait patterns. The parameters of walking speed and step length are among the common measures that are often used to quantify differences in populations (Cham and Redfern, 2002; Lockhart et al., 2005; Sparrow et al., 1998) and are often used to infer whether or not a population of interest has adopted an “adaptive gait pattern.” When considering group differences, reductions in walking speed or step length can often be indicative of an adaptive gait pattern to compensate for some underlying instability (Lockhart et al., 2003; Cham and Redfern, 2002; Sparrow, Shinkfield, and Summers, 1998).

Heel contact velocity describes the horizontal velocity of the heel at the instant of heel contact and may be used as a measure of slip propensity (Lockhart et al., 2003). That is, a person who exhibits a higher heel contact velocity could be at a greater risk for slipping than someone whose horizontal heel velocity is lower. The truest measure of slip propensity, however, is given by a parameter called *required coefficient of friction* (Lockhart et al., 2003; Cham and Redfern, 2002). Required coefficient of friction (RCOF) quantifies the friction demand created by the foot’s contact with the floor. RCOF is calculated as the ratio of the horizontal shear force to the vertical ground reaction force. A higher RCOF value implies that a greater frictional force will be required to keep the foot from slipping during contact with the floor surface. A lower RCOF value implies that the frictional demand is low and slipping is less likely.

Gait may also be characterized by determining joint angles during specific phases of the gait cycle (Begg and Sparrow, 2006; Redfern and DiPaquale, 1997; Cham and Redfern, 2002). Joint angles can provide information pertaining to the relative postures between two groups. Additionally, derivatives of joint angle may be calculated to determine joint angular velocities and accelerations to determine how groups compare in terms of “joint braking” throughout the gait cycle. Slip is suggested to occur between 50-100 ms after heel contact (Perkins, 1978; Lockhart et al., 2003). Additionally, it has been suggested that foot-floor angle at heel contact is related to the occurrence of slip. Specifically, greater foot-floor angles as well as faster foot angular velocity at heel contact have been shown to be predictors of hazardous slips (Moyer et al., 2006). Thus, comparisons of joint angles at heel contact between groups may reveal differences relevant to slip propensity.

In addition to risks for slip propensity, this study is interested in quantifying the relative slip *severity* of a group. Slip severity has been quantified using parameters such as slip distances, peak sliding heel velocity, and sliding heel accelerations with greater values of each parameter suggesting a more hazardous slip (Lockhart et al., 2005; Moyer et al., 2006; Redfern et al., 2001). Further, it has been reported that slips lead to falls if the sliding heel velocity exceeds 0.5 m/s or if the slip distance exceeds 10 cm (Strandberg and Lanshammar, 1981). Thus, comparisons of slip distances and sliding heel velocities provide objective measures of slip severity between individuals or groups and can also be used to differentiate between recoverable slips and slips that ultimately lead to a fall.

Initiation, detection, and recovery are thought to be the three phases of slip-related falls (Lockhart et al., 2005). Initiation refers to initial gait characteristics that may predispose a person to slip (i.e. higher RCOF than the floor surface provides; high heel velocity). Detection describes the phase in which the body begins to recognize the slip perturbation through feedback from the visual, vestibular, and proprioceptive systems. Finally, recovery refers to the physical reaction to slip such as the reflexive muscle contraction to regain balance.

3.0 METHODS

The objectives of this study were: 1) to compare the gait characteristics of individuals with MR to those of healthy, age- and gender-matched peers in an effort to understand what differences may be contributing to an increase in falls in the MR population, and 2) to determine differences in slip propensity and slip severity between these two groups. The hypothesis of this study is that adults with MR will exhibit significantly different gait characteristics and exhibit greater slip propensity and slip severity than their healthy, non-disabled peers.

3.1 Data Collection

3.1.1 Participants

Fifteen participants aged 23 to 62 (11 males, 4 females) were recruited from the Southwestern Virginia Training Center (SWVTC), a residential care facility in Galax, VA. Each participant had been previously diagnosed as having mental retardation, and they were distributed among all four categories of MR severity. Participant information may be seen in Table 3.1.

Table 3.1. Participant information.

Number and ages of subjects with varying degrees of MR		
	n = 15	
MR Status	**No. of Subjects**	**Age Range**
Mild (IQ of 55-69)	1	34
Moderate (IQ of 40-54)	4	23-37
Severe (IQ of 25-39)	7	24-62
Profound (IQ below 25)	3	31-42

This study was approved by the IRB at Virginia Tech and informed consent for participation was obtained by legal guardians, doctors, and staff members from the SWVTC. Participants were excluded if they had any history of surgery on their feet, ankles, knees, hips, neck, or back. Knee or hip replacement surgeries in particular were cause for exclusion. Participants were also screened for arthritis and rheumatoid arthritis, osteoporosis, and vision problems including glaucoma, cataracts, and macular degeneration. Vertigo, peripheral neuropathy, or a history of shortness of breath or fatigue, Parkinson's disease, and dementia were all additional causes for exclusion. At all times during testing, staff members from the SWVTC were present to help the participant become comfortable in the lab environment. If at any time the staff member felt that the participant was becoming distressed or was not able to continue, testing was stopped immediately. No such incidents occurred for the 15 participants used in this study.

For the comparison of MR participants (11 males, 4 females, mean age: 38.5 years ± 10.0 years) to healthy peers, archived data for 15 healthy, age- and gender-matched participants (11 males, 4 females, mean age: 39.2 ± 10.4 years) was used. The average age difference between the matched pairs was 3.2 ± 3.1 years. Each of these 15 control participants had been involved in a prior research study at the Locomotion Research Lab and had experienced the same normal walking and slip perturbation conditions to be described. As with the MR group, the healthy controls were required to wear standard laboratory clothing and shoes, and both kinetic and kinematic data were collected for each test trial.

Objective 1: Characterize gait parameters for people with MR and compare them to that of healthy, age- and gender-matched peers during normal walking.

3.1.2 Apparatus

Gait characteristics were determined by collecting force and motion analysis data while walking trials were performed at a normal, self-selected pace. Walking trials were conducted on a 15-meter linear walking with a vinyl tile floor surface. The track is equipped with 2 force plates (BERTEC #K80102, Type 45550-08, Bertec Corporation, Columbus, OH) embedded consecutively in the center of the walkway (Figure 3.1). Participants were given laboratory clothing and shoes to eliminate any effects due to differences in individual shoe type or wear. A set of 23 retro-reflective markers were positioned over specific anatomical landmarks (head, ears, acromion, acromioclavicular joint, lateral humeral condyle, ulnar stylus, third metacarpal head, anterior superior iliac spine (ASIS), lateral femoral condyle, lateral malleolus, second metacarpal head, and heel). A six-camera Pro-Reflex motion analysis system (Qualysis, East Windsor, CT, USA) collected kinematic data at 120 Hz for each trial. The force plates recorded kinetic data simultaneously via an external trigger at a sampling rate of 1200 Hz. Both the kinematic and kinetic data were acquired using LabVIEW™ system software (National

Instruments, Inc., Austin, TX, USA). An overhead fall-arresting harness, which slides along a track above the walkway, was used at all times during the walking trials to eliminate the possibility of injury from an unexpected fall. For comparison to healthy, age-matched peers, data from a previous study were used. The same protocol was used to collect kinetic and kinematic data for this group.

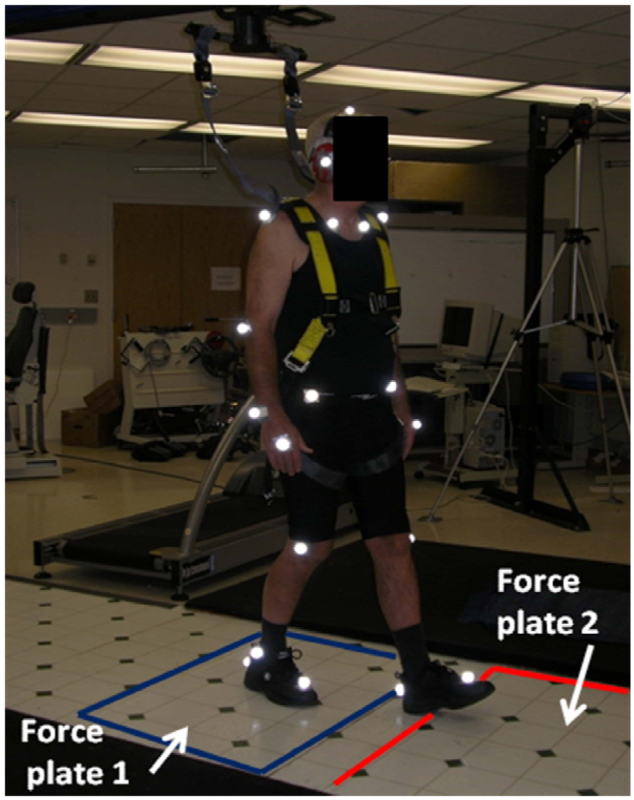

Figure 3.1. Experimental setup (Haynes, C.A., August 2007).

3.1.3 Normal walking

At all times during the walking experiments, participants were secured in a fall-arresting harness that moves overhead on a sliding track. Participants were asked to walk continuously for 10-15 minutes prior to data collection to allow them time to acclimatize to the testing apparatus. After this warm-up period, kinetic and kinematic data were simultaneously recorded for 6 to 10 normal walking trials.

Objective 2: Assess slip propensity and slip severity characteristics among these two groups in an effort to better understand why adults with MR are more prone to fall accidents.

3.1.4 Slip perturbation

During normal walking, a slip perturbation was introduced randomly. A hidden floor coated with a slippery, gel-based solution was placed in the walking path via a sliding floor mechanism located over the second force plate. A second slip perturbation was introduced only when the first perturbation was unsuccessful at eliciting a slip response.

3.2 Dependent Variables

3.2.1 Gait parameters

Walking speed (WS). Walking speed was calculated using the kinematic data recorded from the (ASIS) markers. The change in linear distance is the difference between the initial and final positions of the right ASIS marker in the direction of progression. This distance was then divided by the time it took the participant to traverse it.

Step length (SL). Step length was calculated as the perpendicular distance between the positions (in the direction of progression) of consecutive right and left heel contacts. Recognizing that the heel marker is at its lowest point during heel contact, the heel position data was tracked and the minima (minimal z) were used to identify the instances of heel contact for each foot during the walking trials. Step length was then defined as the linear distance between the positions of the left and right heel contacts along the direction of progression. Figure 3.2 provides an illustration of step length.

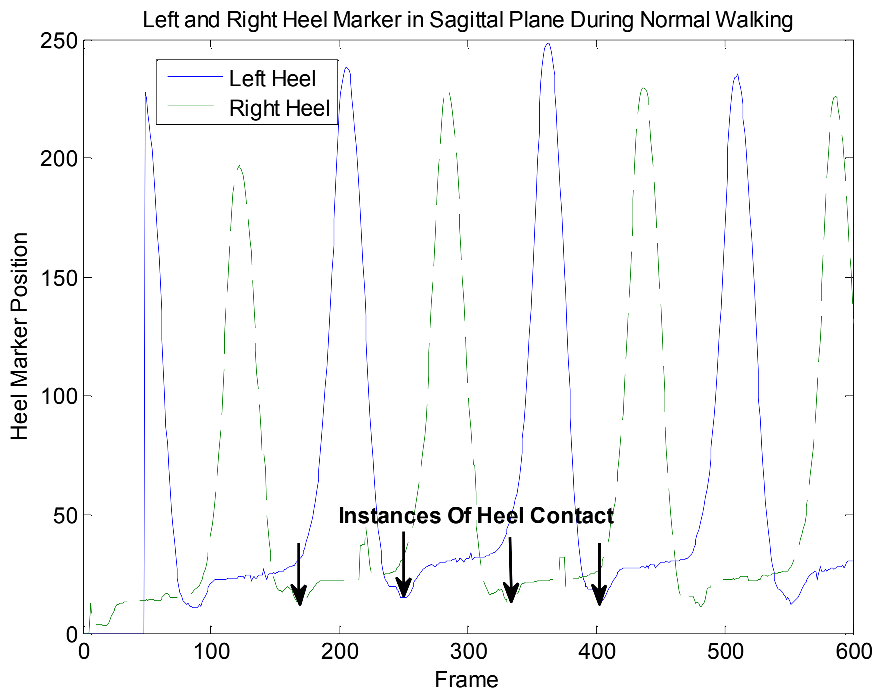

Figure 3.2. Tracking instances of heel contact using kinematic data.

Heel contact velocity (HCV). Heel contact velocity is the instantaneous horizontal velocity of the heel at the moment of heel contact. Heel contact is defined as the instant at which the vertical force on the force plate exceeds 10 N. Processing the heel marker data, HCV was determined by horizontal heel position at 1/60 sec before and after heel contact.

$$\frac{X_{(i+1)} - X_{(i-1)}}{2\Delta t} \tag{3.1}$$

Here, i is the frame index at the moment of heel contact. The variables $X_{(i+1)}$ and $X_{(i-1)}$ represent the horizontal heel positions at the frames occurring 1/60 sec before and after the instant of heel contact, respectively. The time variable Δt is 1/60 sec.

Knee flexion angle. Sagittal joint angles were calculated for one complete gait cycle and the joint angle for each instant of time was normalized as a percent of the total gait cycle. Knee flexion angle is the angle between the thigh and shank segments of the leg. The thigh segment is defined by the vector between the hip joint center and the lateral femoral condyle. The hip joint center (HJC) position was calculated using the ASIS marker data and a pelvic width parameter. Pelvic width (PW) was defined as the perpendicular distance between the two ASIS markers in the frontal plane. Linear equations were then used to project the x, y, and z positions of the HJC as a function of percentage of pelvic width. Specifically, the HJC is located 30% distal, 14% medial, and 24% posterior to ASIS (Seidel, Marchinda, & Dijkers, 1995). The sagittal angle of the thigh segment, θ_{thigh}, can be found with respect to the horizontal by calculating the inverse tangent of the difference between the hip and condyle markers' vertical positions divided by the difference between their horizontal positions in the direction of progression (Equation 3.2)

$$\theta_{thigh} = \tan^{-1}\left(\frac{Z_{hip} - Z_{cond}}{X_{hip} - X_{cond}}\right) \tag{3.2}$$

Here, Z_{hip} and Z_{cond} are the vertical positions of the hip and condyle markers, respectively, and X_{hip} and X_{cond} are their corresponding horizontal positions. Note that the coordinate system for the motion analysis system is oriented such that the participants walk in the –x direction, (+x extends behind them), the +y direction extends to the subjects right, and +z points vertically upward from the floor. For this reason, the Z variable is used to indicate vertical marker position rather than Y.

The next step in calculating the knee flexion angle requires that the angle of the shank segment also be determined with respect to the horizontal. The shank segment is defined by the vector between the lateral femoral condyle and lateral malleolus markers. As with the thigh angle, the shank segment angle, θ_{shank}, is computed as the inverse tangent of the difference in z positions of the markers divided by the difference in their x positions (Equation 3.3).

$$\theta_{shank} = \tan^{-1}\left(\frac{Z_{cond} - Z_{mal}}{X_{cond} - X_{mal}}\right) \tag{3.3}$$

The "mal" subscript in this equation denotes the use of the malleolus marker position data. The knee flexion angle is then the difference between the thigh and shank segment angles (Equation 3.4).

$$\theta_{knee} = \theta_{thigh} - \theta_{shank} \tag{3.4}$$

Ankle dorsiflexion angle. The ankle dorsiflexion angle is defined by the angles of the shank and foot segments. The shank segment is same as described previously. The foot segment is defined by the heel and metatarsal marker. The angle of the foot segment with respect to the horizontal is the inverse tangent of the difference between the vertical marker positions divided by the difference between the corresponding horizontal marker positions (Equation 3.5).

$$\theta_{foot} = \tan^{-1}\left(\frac{Z_{toe} - Z_{heel}}{X_{toe} - X_{heel}}\right) \tag{3.5}$$

The ankle dorsiflexion angle is the difference between the shank and foot segment angles minus an additional 90 degrees to correct for the natural orientation of the foot with respect to the shank (Equation 3.6).

$$\theta_{ankle} = \theta_{shank} - \theta_{foot} + 90° \tag{3.6}$$

3.2.2 Slip-propensity parameter

Required coefficient of friction (RCOF). RCOF is the friction demand placed on the floor by the walker. If the floor surface and shoe tribology are such that the RCOF is met, walking continues uninterrupted. If RCOF is greater than the available friction between the shoe and floor surface, then a foot-slip may occur (as during exposure to the slip perturbation). RCOF is defined as the ratio of the horizontal shear force (F_h) to the vertical ground reaction force (F_v), (F_h/F_v). This analysis, however, is possible only when heel contact occurs precisely on the plate and when there are no other forces exerted on the plate (i.e. from a partial foot fall of the contra-lateral foot) that will corrupt the force profile. Kinetically, the instant of heel contact is defined as when the vertical force exceeds 10 N. The instant of heel contact as determined by the vertical force threshold was compared to the instant of heel contact determined by the minima of the heel marker to verify that RCOF was calculated using forces created purely by heel contact. RCOF was calculated over the duration of the footfall on the plate. If slip is to occur, it begins about 50-100 ms after heel contact (Lockhart et al., 2003). Correspondingly, RCOF also peaks shortly after heel contact as it dictates whether a slip will ensue. The absolute value of this peak represents the RCOF value of interest. Figure 3.3 illustrates the determination of RCOF value.

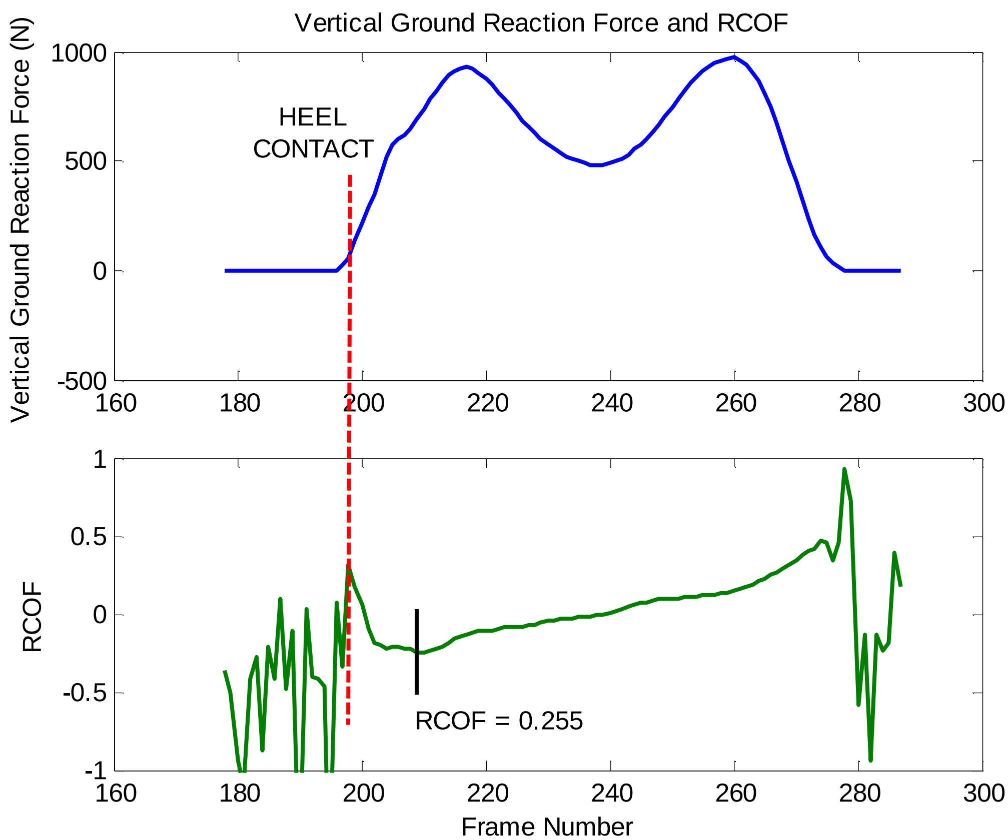

Figure 3.3. Determination of RCOF.

3.2.3 Slip-severity parameters

Initial slip distance (SDI). Initial slip distance begins after heel contact when the first non-rearward positive acceleration of the foot is identified. This SDI is then the distance traveled by the heel from this point of non-rearward positive acceleration (minimum velocity) to the time of the first peak in heel acceleration (Lockhart et al., 2003). The SDI may be calculated using the general distance formula:

$$SDI = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2} \tag{3.7}$$

<u>Slip distance II (SDII)</u>. Slip distance II begins at the slip-stop point of SDI. Slip-stop for SDII is the point at which the first maximum in horizontal heel velocity occurs after the start of SDII. The distance was again calculated using the general distance formula given as equation 3.7. SDI and SDII were used as indices for comparing the severity of slip between non-disabled and intellectually disabled adults. Slip distance measures are shown in Figure 3.4.

<u>Peak sliding heel velocity (PSHV)</u>. Sliding heel velocity is the maximum forward speed of the heel during slipping. This parameter is calculated using the time derivative of heel marker position during the slip.

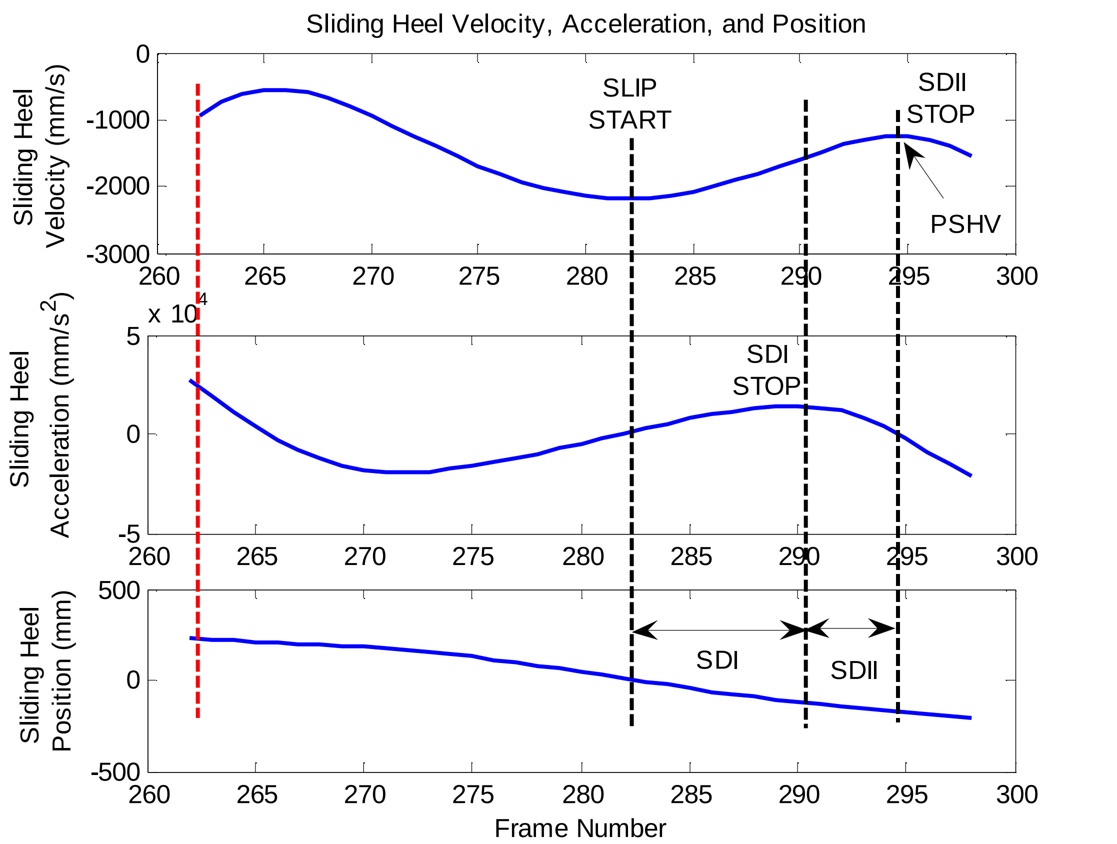

Figure 3.4. Slip distance parameters.

3.3 Statistical Analysis

All statistics were determined using the JMP® 7.0 statistical package (SAS Institute, Inc., 2007).

3.3.1 Normal walking analysis

For statistical analysis there are two test groups (MR and non-disabled). Group differences in WS, SL, HCV, and joint angles were determined using a one-way analysis of variance (ANOVA). Statistical significance was set to $\alpha = 0.05$.

3.3.2 Slip perturbation analysis

Again, there are two test groups (MR and non-disabled). Group differences in PSHV, RCOF, SDI and SDII were determined using a one-way analysis of variance (ANOVA). Statistical significance was again set to $\alpha = 0.05$.

3.3.3 Within-group gait parameter analysis

In order to consider possible relationship between gait parameters and slip characteristics, it's important to check the validity of the assumption that each participant's walking characteristics are equivalent for both the normal walking and slip trials. To verify this assumption, a within-subjects Student's t test was done to compare the walking speeds for the normal walking and slip trials for each group. Significance was set to $\alpha = 0.05$.

4.0 RESULTS

4.1 Normal Walking Parameters

4.1.1 Gait parameters between groups

Table 4.1 provides the comparison of normal walking gait parameters between the healthy and MR groups.

Table 4.1. Normal walking gait parameters between groups (mean(SD)).

	MR n = 15	Age Match n = 15	p-value
WS (cm/s)	61.66 (21.23)	137.15 (15.10)	< 0.0001*
SL (cm)	51.36 (14.45)	76.48 (7.18)	< 0.0001*
HCV (cm/s)	72.67 (35.15)	94.46 (22.98)	0.0541*

* denotes statistical significance.

The MR group exhibited a significantly slower walking speed and shorter step length than their age- and gender-matched peers ($F = 126.01$, $p < 0.0001$; $F = 36.33$, $p < 0.0001$). With a lesser degree of statistical significance, the MR group was also found to have a slower heel contact velocity than the Age Match group ($F = 4.04$, $p < 0.0541$).

4.1.2 Joint angles between groups

Figure 4.1 illustrates the knee flexion and ankle dorsiflexion angles in the sagittal plane for one matched pair over a complete gait cycle. Gait cycle was normalized with respect to the individual's time for consecutive heel contacts of the same foot. Thus, the plots below illustrate the joint angles beginning with the heel contact of one foot and ends with the subsequent heel contact of that same foot. The joint angles at heel contact were selected for analysis in the current study due to their relevance to slip initiation. Measures of knee flexion angle (KA_{HC}) and ankle dorsiflexion angle (AA_{HC}) at the instant of heel contact are presented in Table 4.2.

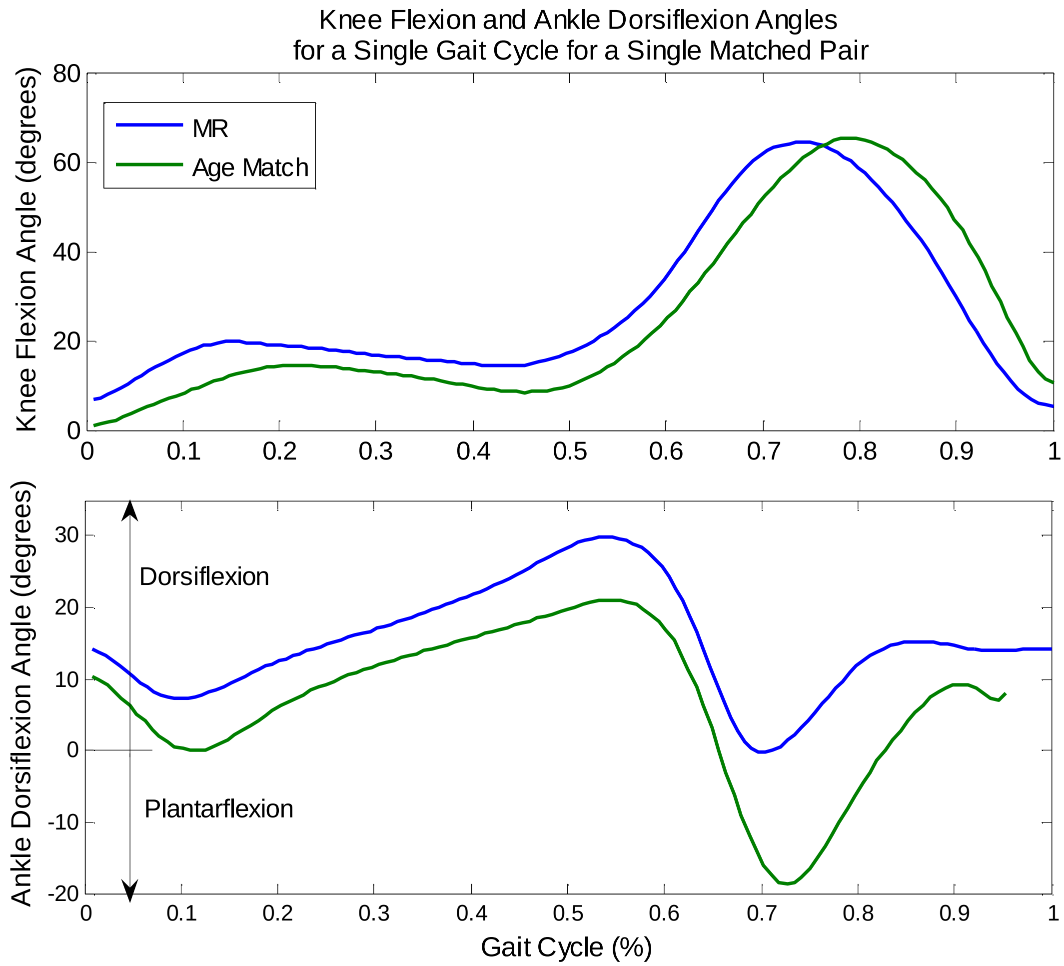

Figure 4.1. Sagittal plane joint angles for a single matched pair during one complete gait cycle.

Table 4.2. Heel contact joint angles between groups (mean(SD)).

	MR	**Age Match**	
	n = 15	n = 15	**p-value**
KA_{HC} (deg)	15.73 (10.41)	9.59 (7.93)	0.0802
AA_{HC} (deg)	12.09 (8.69)	10.55 (3.48)	0.5268

Both joint angles at heel contact failed to reveal significant differences between the groups. Though not statistically significant, the MR group exhibited increased knee flexion ($F = 3.29$, p

< 0.0802) as well as a slight increase in ankle dorsiflexion ($F = 0.4107$, $p < 0.5268$) as heel contact as compared to the age-matched group.

4.1.3 RCOF

Figure 4.2 displays the results of RCOF analysis and Table 4.3 tabulates the results.

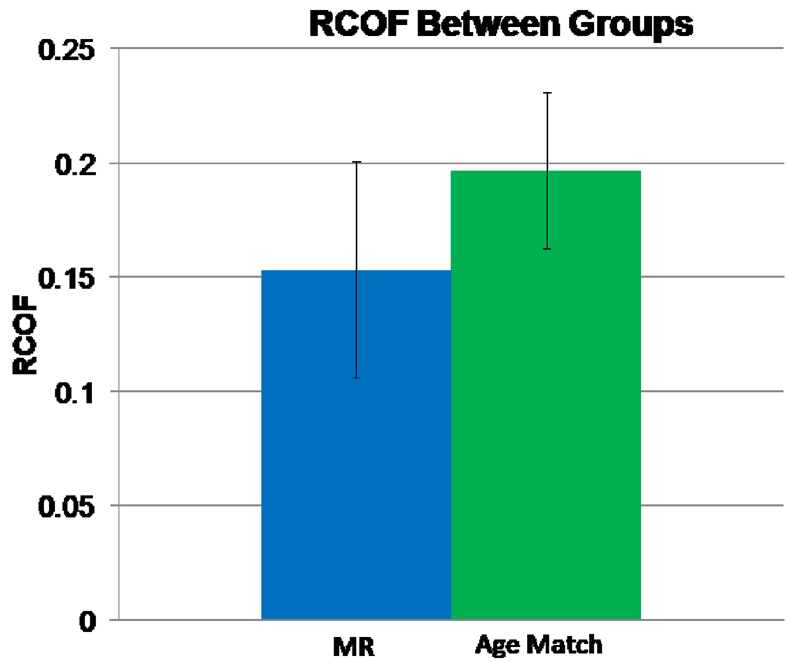

Figure 4.2 RCOF values between groups.

Table 4.3. RCOF between groups (mean(SD)).

	MR n = 15	Age Match n = 15	p-value
RCOF	0.153 (0.047)	0.196 (0.034)	0.0076*

* denotes statistical significance.

The RCOF value proved to be significantly lower for the MR group than for the Age Match group ($F = 8.28$, $p < 0.0076$). A correlation matrix (Table 4.4) was developed to determine if any of the gait parameters might help explain this result.

Table 4.4. Pairwise correlation matrix for gait and slip propensity parameters (R^2).

RCOF	0.2454*	0.3209*	0.0328	0.2458*	0.0803
--	**WS**	0.4692*	0.0852	0.0349	0.0001
--	--	**SL**	0.2684*	0.1709*	0.0881
--	--	--	**HCV**	0.1329*	0.1657*
--	--	--	--	**KA_{HC}**	0.0447
--	--	--	--	--	**AA_{HC}**

* denotes statistical significance.

Significant positive correlations were found between RCOF and WS ($R^2 = 0.2454$, $p < 0.0054$) and SL ($R^2 = 0.3209$, $p < 0.0011$), and a negative correlation with KA_{HC} ($R^2 = 0.2458$, $p < 0.0053$). Other positive correlations exist between WS and SL ($R^2 = 0.4692$, $p < 0.0001$) and HCV and SL ($R^2 = 0.2684$, $p < 0.0034$). Negative correlations exist between KA_{HC} and SL ($R^2 = 0.2458$, $p < 0.0232$), KA_{HC} and HCV ($R^2 = 0.1329$, $p < 0.0477$), and AA_{HC} and HCV ($R^2 = 0.1657$, $p < 0.0256$).

4.2 Slip Parameters

4.2.1 Slip parameters between groups

The slip distance parameters between groups are tabulated in Table 4.5. Despite very large standard deviations, significant group differences were found for both slip distance measures. The MR group was found to have greater SDI and SDII slip distances than their age-matched peers ($F = 6.54$, $p < 0.0163$; $F = 4.70$, $p < 0.0388$). Peak sliding heel velocity, however, failed to reveal significant group differences ($F = 2.20$, $p < 0.1491$).

Table 4.5. Slip parameters between groups (mean(SD)).

	MR	**Age Match**	
	n = 15	n = 15	**p-value**
SDI (cm)	10.04 (6.72)	4.76 (4.35)	0.0163*
SDII (cm)	7.07 (6.80)	2.88 (3.12)	0.0388*
PSHV (cm/s)	137.45 (165.67)	67.27 (78.22)	0.1491

* denotes significant differences.

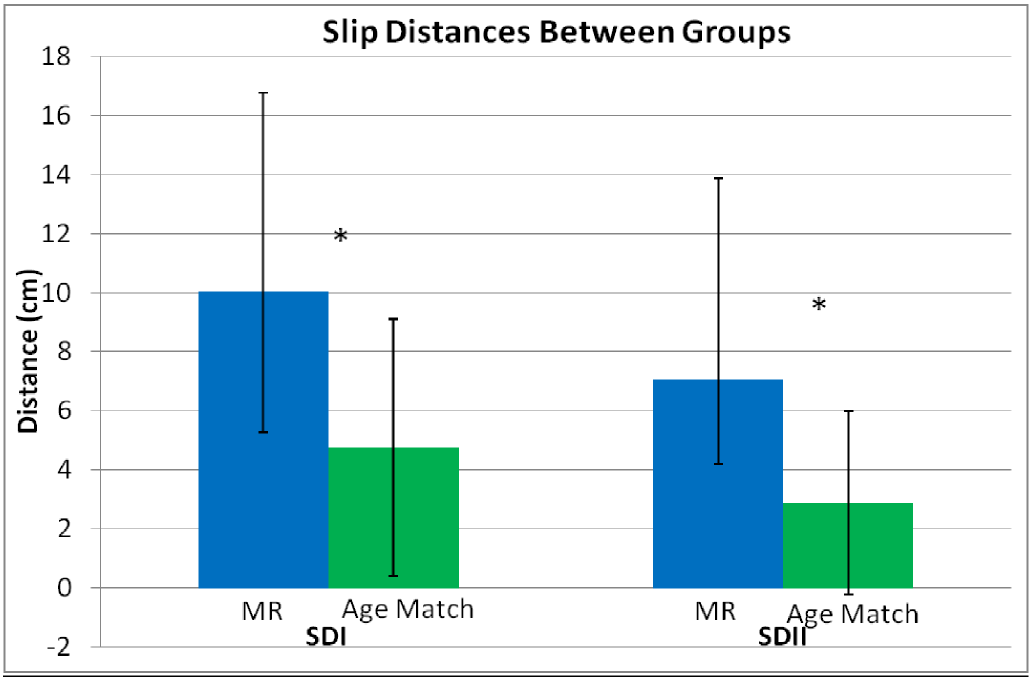

Figure 4.3. Slip distances between groups. '*' denotes significant differences.

4.2.2 Hazardous falls between groups

Overall analysis exhibits large standard deviations within groups presumably due to averaging both hazardous and non-hazardous falls. Therefore, a sub-analysis was performed to compare the slip distances of only the hazardous fallers in each group. Hazardous falls were defined by a SDI of greater than 10 cm. The MR group had 6 hazardous slips while the Age Match group had 3 hazardous slips. The results for these 9 participants can be seen in Table 4.6.

Table 4.6. Comparison of hazardous slips.

	MR	Age Match	
	n = 7	n = 3	**p-value**
SDI (cm)	15.30 (5.89)	12.43 (0.78)	0.3844
SDII (cm)	8.91 (6.44)	4.78 (1.01)	0.3157
PSHV (cm/s)	222.29 (211.08)	171.99 (80.94)	0.7072

Statistics failed to produce any significant results in slip response parameters for the hazardous slips, presumably due to the small sample size from each group. (SDI: $F = 0.85$, $p < 0.3844$; SDII: $F = 1.15$, $p < 0.3157$; PSHV: $F = 1.15$, $p < 0.7072$). Even among the fallers however, the adults in the MR group exhibited greater slip distances and faster PSHV than the age-matched group. Thus, when considering only the hazardous slips, the MR group slipped faster and farther than the group of non-disabled adults.

4.3 Within-Group Analysis

Analysis was conducted to compare basic gait parameters between the normal walking and slip condition trials for each group. This was done to verify the assumption that the gait patterns remained consistent among both testing conditions. Table 4.7 presents the mean walking speed and step length for each group for both the normal walking condition and immediately preceding the slip perturbation.

Table 4.7. Within-group gait parameters between test conditions (mean(SD)).

	Normal Walk n = 15	Slip n = 15	p-value
WS (cm/s)			
MR	61.66 (21.24)	65.35 (20.57)	0.6328
Age Match	137.15 (15.10)	129.94 (21.03)	0.2849
SL (cm)			
MR	51.36 (14.45)	62.30 (32.56)	0.2442
Age Match	76.48 (7.18)	84.71 (24.50)	0.2553

No significant differences between conditions were detected for either group.

4.4 Effects of Walking Speed

It is conceivable that gait parameters may be influenced by choice by gait speed. An analysis of covariance (ANCOVA) was performed, with walking speed as the covariate, to determine statistical significance between groups is affected by their differences in preferred walking speed. Table 4.8 presents the adjusted p-values for each gait parameter when walking speed was specified as a covariate.

Table 4.8. Adjusted p-values for gait parameters between groups.

Gait Parameter	p-value
SL (cm)	< 0.0001*
HCV (cm/s)	0.1506
KA_{HC}	0.0835
AA_{HC}	0.3952
RCOF	0.0205*

* denotes statistical significance.

Factoring in walking speed as a covariate, both step length ($p < 0.0001$) and RCOF ($p < 0.0205$) still demonstrated statistical significance. Thus, given the difference in walking speed between groups, they still presented significantly reduced step lengths as well as a significantly reduced slip propensity as measured by the RCOF parameter. HCV was the only parameter to have shown significance in the original analysis and failed to do so with walking speed as a covariate. This suggests that differences in HCV may only be due to differences in walking speed. The original analysis, however, suggested that HCV was significantly slower for the MR group which suggests a decreased risk of slip as compared to the Age Match group. This ANCOVA analysis now proposes that HCV between groups does not differ significantly when differences in walking speed are considered. Thus, when considering this parameter in terms of predisposal to slip accidents, it may no longer indicate less slip potential for the MR group. Significance of the RCOF parameter, however, still posits that adults with MR are less likely to initiate slip than healthy, non-disabled adults.

5.0 DISCUSSION

There were two primary objectives for this study:

1) The first was to use current standards of gait assessment to characterize gait parameters for people with MR and compare them to that of healthy, age- and gender-matched peers during normal walking.

2) Secondly, this study aimed to assess slip propensity characteristics among these two groups in an effort to better understand why adults with MR are more prone to fall accidents.

5.1 Gait Characteristics and Joint Angle Comparison

5.1.1 Normal walking gait characteristics

The current study found that the MR group had a significantly slower walking speed and a significantly shorter step length than their age- and gender-matched healthy peers. Shorter step lengths and slower walking speeds are also adaptations seen in the elderly and are considered to be compensatory mechanisms to help maintain safe ambulation at a time when our visual, vestibular, and proprioceptive systems begin to lose their acuity (Lockhart et al., 2003; Baloh, Ying, and Jacobson, 2003). With the MR group, age-related degradation of these sensory systems is unlikely as the mean age was 38 years, but perhaps a consequence of mental retardation is developing these altered gait characteristics at a young age during the development of their natural adult gait. Regardless of the cause, however, slower walking speeds are associated with slower center-of-mass (COM) velocities and are typically accompanied by shorter step lengths, particularly when the slower walking speed is the participant's preferred walking speed (Bhatt et al., 2005). It is thought that these shorter step lengths permit the COM to remain in a more forward position with respect to the lead foot and thus provide better protection against a backwards loss of balance during a slip event. A conflicting thought, however, is that the forward displacement of the COM afforded by shorter step lengths may not be sufficient compensation to overcome the slower horizontal transition of the COM when a slip occurs at heel contact (Bhatt et al., 2005; Lockhart et al., 2003). Thus, reductions in walking speed and step length seen within the MR group may be an effort to mitigate slip initiation, but once slipping does begin, their more slowly transitioning COM may contribute to their inability to recover.

One difference between the adaptations seen in the MR and the elderly is that the elderly exhibit higher heel contact velocities compared with younger, healthy adults. Higher heel contact velocity is said to be associated with a greater propensity for slipping (Lockhart et al., 2003). This study revealed that the adults with MR actually exhibited more conservative heel contact velocity than did the adults in the healthy, age-matched group. When walking speed was treated as a covariate, however, no significant group differences in HCV were found. Similar results were reported by Kim, Lockhart, and Yoon (2005) comparing young and elderly adults. This finding suggests again that the increased fall rate is not attributable to greater potential for slip initiation. On the contrary, the results indicate that, on the basis of HCV, healthy adults are as likely to experience slip initiation. This again suggests that perhaps the increased fall rate among adults with MR is not a function of their gait pattern but instead may be a result of a decrement in their ability to recover from a slip perturbation.

5.1.2 Joint angles

Joint angles and angular velocities are another way in which to compare gait patterns between groups (Moyer et al., 2006; Begg and Sparrow, 2006). These measures provide information pertaining to the relative posture and postural control during particular phases of the gait cycle. Arguably, the phase most pertinent to slipping is the instant of heel contact and the transition into single support stance on the lead foot. In relation to slip accidents, Moyer et al. (2006) reported that larger step lengths, larger foot-floor angles and larger foot-floor angular velocities were all associated with hazardous slips.

The present study utilized sagittal-plane knee flexion and ankle dorsiflexion angle to compare posture and posture-related slip potential at heel contact. Velocities were eliminated from the analysis due to the high correlation reported between contact angles and rates-of-change of these angles (Moyer et al., 2006). The present study revealed no statistically significant differences between groups. The ankle dorsiflexion angle was equivalent for both groups indicating that the foot-floor angle did not predict more hazardous slips for either group. Additionally, the knee flexion angle also failed to demonstrate significant differences between groups, although qualitatively knee flexion angle showed a more pronounced difference between groups. The MR group showed a greater knee flexion at heel contact suggesting the use of a knee strategy to ease the transfer of the COM onto the lead leg. Increased knee flexion at heel contact was also observed in the elderly as compared to young adults (Begg and Sparrow, 2006). The present study suggests that the gait of individuals with MR shares more similarities with the elderly than with adults of an equivalent age.

When considering how slip potential may be influenced by gait characteristics, it is important to also notice the standard deviations that accompany the mean absolute values for each group. For nearly every parameter, the standard deviation of gait and slip parameters is considerably higher for the MR group than for the age-matched group. These high standard deviations suggest that the distribution of walking speeds among adults with MR may exhibit not only a slower mean walking speed but also a greater range of possible gait speeds. Casual observation during testing also revealed that this population may have higher intra-subject gait variability than their healthy peers, although additional analysis would be needed to confirm this.

5.2 Slip Propensity and Slip Response Characteristics

5.2.1 RCOF

Greater RCOF is also associated with a higher risk of experiencing a slip (Cham and Redfern, 2002; Lockhart et al., 2003). A surprising result with the current study was that RCOF was found to be significantly lower for the MR group than the healthy group. A higher RCOF implies that a greater frictional force is required to prevent a slip from occurring. A lower value for RCOF among the MR group would suggest that the age-matched healthy group would be more likely to experience a slip because they require a greater frictional resistance. RCOF was found to have a significant positive correlation with walking speed and step length and a negative correlation with KA_{HC}. In other words, as walking speed and step length decrease, RCOF is expected to decrease. Conversely, as KA_{HC} increases, RCOF will again decrease. Lower RCOF may be attributed to the slower walking speeds, shorter step lengths, and greater knee flexion observed for the MR group. Mechanically, gait parameters actually suggest a greater potential for slip initiation among the healthy group. A greater number of slip-related falls among the MR population are likely due to a delay the detection and/or recovery phases of slip.

5.2.2 Slip distances and sliding heel velocity

Slip initiation typically occurs about 50-100 ms after heel contact following an initial backwards acceleration of the heel (Perkins, 1978). SDI, initial slip distance, describes the severity of this slip initiation by quantifying the distance traveled by the foot from the instant slipping begins to the point at which the heel reaches its peak acceleration (Lockhart et al., 2003). In a sense, this slip distance can be thought of as the distance traveled before the sliding heel velocity is beginning to be controlled by the participant's recovery reaction. SDII then describes the remaining slipping distance until the heel reaches its maximum horizontal sliding velocity.

The MR group displayed greater SDI and SDII values than the non-disabled adults. This provides further evidence to support the idea that mental retardation may be accompanied by a delay in the detection and recovery of slip accidents. Surface electromyography (EMG) analysis would be needed to determine if the delay was due to sub-optimal magnitude of muscle contraction or if there was just a greater delay in the development of muscle force (Tang and Woollacott, 1998a & 1998b).

Peak sliding heel velocity did not present significant results when pooling all participants from each group. This was likely due to large standard deviations created by averaging a parameter that has very broad bounds within groups. In an effort to refine the analysis, participants considered to have experienced a "hazardous slip" (using the threshold of SDI > 10 cm) were selected to enable comparisons between fallers in both groups.

This additional analysis also failed to reveal significant differences perhaps due to the small number of participants in each statistical group. The MR group had 7 falls while the age-matched group had only 3. It is interesting to note that in the present study investigating the increased fall rate of mentally retarded adults, over twice the number of hazardous falls was observed in the MR group as compared to the non-disabled group. While no statistical differences were observed, qualitative comparisons again reveal that the slip distances and PSHV were higher in the MR group. Adults with mental retardation slip longer and faster than their healthy peers.

5.3 Repeatability Between Conditions

One important consideration for this study was to determine if significant within-subject variations in gait pattern existed between the normal walking and slip perturbation trials. If gait was shown to be significantly different between testing conditions, it would limit the extent to which the assessment of normal walking gait parameters could be related to the subjects' slip response characteristics. Cham and Redfern (2002) reported a significant decrease in RCOF value when participants anticipated a slippery floor surface even when the participant was asked to walk normally. This reduction was achieved by altering the spatial and temporal characteristics of gait including reducing stride lengths and foot-floor angles at heel contact. Kadaba et al. (1989) investigated the repeatability of gait parameters within and between test days for 40 normal adult subjects. Kadaba and colleagues (1989) reported that as long as participants walked at their preferred speed, kinetic and kinematic gait variables exhibited high intra-subject repeatability when tested on the same day. Between test days, kinetic variables continued to show high repeatability, particularly for the vertical and fore-aft shear forces. Kinematic variables showed poor repeatability in the frontal and transverse plane, but sagittal plane angles also reproduced well between test days (Kadaba et al., 1989).

For the purposes of this study, the all testing was performed on the same day. Statistical analyses revealed no significant differences in step length or walking speed between the normal walking and slip perturbation trials. This result suggests that the participants were not anticipating the slip condition and intra-subject gait pattern was likely well-preserved between test conditions.

5.4 Limitations

One limitation to this study was the availability of participants. Due to the specific population, recruitment was limited and therefore it was difficult to balance the study for gender or MR status. The majority of the participants were classified as having "severe" MR which is one of four MR designations defined by IQ. This study, however, aimed to determine the general effects of mental retardation on gait and was not directly concerned with the subtle differences that may or may not exist due to specific MR status.

Another limitation to the study was that mental retardation is often accompanied by concurrent disorders. Some of the participants in this study also had autism and seizure and impulse control disorders. It is unknown if or how the presence of these maladies may influence measures of gait or slip response characteristics and may be a confounding factor.

An additional limitation could be that the participants were asked to walk for 10-15 minutes to become acclimated to the testing environment. While this was not problematic for the healthy adults, some of the adults with MR did not have the same stamina. If the SWVTC staff noticed the participant becoming fatigued, he or she was allowed to rest until the staff and the participant agreed they could continue. While every effort was made to eliminate the effects of fatigue, it is possible that some of the participants experienced mild fatigue during the testing.

5.5 Future Direction

The present study identified differences in both normal walking and slip response that occur with mental retardation. Generally, the results indicate that a delay in slip detection and recovery are responsible for a greater number of slip-related falls in adults with MR. Although implicated, further study with surface EMG to assess the delay is needed. Specifically, surface EMG analysis would permit the comparison of the timing and relative magnitude of muscle contraction between groups. This data will help determine whether falls for adults with MR are a function of insufficient contraction magnitudes or rather a function of increased reaction times to a slip perturbation.

Future research will involve implementing a training regimen to determine if a routine of weight or balance training can improve the slip propensity among the MR group. Previous studies have reported improved balance and mobility and also decreased fall rates in the elderly following exercise training (Rubenstein et al., 2000; Judge et al., 1993; Weerdesteyn et al., 2006). Among the interventions to be tested are weight and balance training. Weight lifting with Nautilus® fitness equipment is expected to improve strength and, consequently, the magnitude of muscular response during slip. Balance training will be done with Thera-Band® foam therapy pads for practicing one-legged and two-legged stances on unsteady terrain. It is expected that this technique may provide small perturbation training and may improve the adequacy of response to unexpected slip perturbations. The results of the present study provide baseline measures that can be used to compare gait and slip response parameters following exercise training to determine if it improves the ability to recover from a slip perturbation.

Additionally, the results of this study suggest that the increased incidence of slip-induced falls for the MR group is most likely an insufficient attempt at recovery or an actual delay in active recovery. Future analysis should also explore muscular strength capacities during recovery and muscle onset times to determine if the failure to recover is a function of muscle weakness or a physiological delay in slip detection.

6.0 CONCLUSIONS

6.1 Hypothesis 1

Hypothesis 1: Individuals with mental retardation will exhibit significantly different gait patterns than healthy age- and gender-matched peers. Specifically, significant differences are expected for the following gait characteristics: walking speed (WS), step length (SL), heel contact velocity (HCV), and joint angles at heel contact.

Adults with mental retardation were shown to have shorter step lengths, slower walking speeds, and slower horizontal heel contact velocities than healthy age- and gender-matched peers. Significant differences were not found for joint angles, but it is posited by this study that adults with MR exhibit gait patterns that bear greater similarity to the elderly than to their own peers.

As noted, HCV appears to be the primary difference when comparing gait of otherwise healthy mentally retarded adults to elderly adults. Elderly adults are known to demonstrate an age-related reduction in strength (Tang and Woollacott, 1998a). The adults in the present study had a mean age of about 38 years; it is unlikely that they would have experienced age-related strength changes on par with the elderly. It may be differences in strength capacity that permit the younger, mentally retarded adults to brake faster in preparation for COM transfer than the elderly. This is, however, only a hypothesis and such a supposition would need to be verified by comparing relative strength measures and surface EMG profiles between these two populations.

6.2 Hypothesis 2

Hypothesis 2: The MR group will exhibit greater slip propensity by demonstrating a higher required coefficient of friction (RCOF).

Contrary to this hypothesis, the non-disabled, age-matched group showed a higher RCOF than the MR group believed to be due to correlations with walking speed and step length. These results suggest this slip propensity parameter does not indicate a greater predisposition to slip-induced falls for mentally retarded persons.

6.3 Hypothesis 3

Hypothesis 3: The number of slip-induced falls as well as slip distance measures and peak sliding heel velocity will suggest a greater slip severity for the MR group as compared to the non-disabled group.

Adults with MR slipped longer and faster compared to their healthy peers. Considering that these participants demonstrated a more conservative gait, it appears that the best reason for their increased fall rate is insufficient recovery responses.

6.4 Summary

Adults with mental retardation are known to fall more often than their non-disabled peers (Sherrard et al., 2001 & 2002; Hsieh et al., 2001). Slipping is among the modes of falling. Little biomechanical research has been done to explore why adults with MR suffer more fall accidents than their healthy peers.

The present study intended to identify differences in gait characteristics between mentally retarded adults and non-disabled age- and gender-matched peers. This study also sought to investigate the differences, if any, in slip propensity and slip response between these groups.

In summary, the differences in gait characteristics suggest that adults with MR develop an alternative gait strategy similar to that of the elderly, presumably to exert greater control over the COM transitions during gait. Slower walking speeds and shorter step lengths keep the COM located more anteriorly with respect to the base of support (Bhatt et al., 2005), but their slow transition of COM onto the lead foot at heel contact may contribute to their inability to recover from a slip after it has been initiated.

Joint angles at heel contact revealed no statistically significant differences for knee flexion or ankle dorsiflexion angle at heel contact suggesting that body postures between test groups were similar during the critical phase of COM transition. Knee flexion angle, which was nearly significant, suggested a possible knee strategy for transferring weight onto the stance leg.

In regards to slip propensity, RCOF was shown to be higher for the age-matched group. Slip propensity indicated that adults with MR demonstrated longer slip distances and faster peak sliding heel velocity. Taken together with the gait parameters, the findings of this study suggest that healthy adults are as likely or likelier to experience slip initiation. It is during slip recovery, however, that divides the two groups in terms of fall outcomes. Results indicate that the MR are delayed in their efforts to control and recover from a slip allowing themselves to slip farther and longer both before a fall or recovery. EMG analysis may further reveal whether this insufficient recovery response is attributable to differences in muscular contraction magnitude or due to a physiological delay in slip detection or reaction.

Identifying the gait and slip response characteristics of the MR population can help in determining what factors are responsible for their increased fall rate. This could translate to determining appropriate interventions for mitigating falls and reducing personal injury and death. Further, the repeatability of these gait measures will allow for a direct comparison of performance before and after various interventions. Thus, if quantifiable factors leading to falls in this population were understood, interventions could be implemented (i.e. exercise training) and their effectiveness could be measured directly.

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APPENDIX A

Marker Set Reference Sheet