Age-Related Ankle Strength Degradation and Effects on Slip-Induced Falls

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(ABSTRACT)

Each year there is an increasing incidence of slip and fall accidents, especially among the elderly population. Existing evidence has identified several aging effects related to slip and fall accidents, yet, the causes of these accidents with advancing age are still little known. The objective of this research was to investigate the factors influencing the initial phase of unexpected slips and falls in younger and older individuals. More specifically, the relationship between ankle strength, the ankle joint power to transfer the whole body center-of-mass during normal gait, and the likelihood of slip-induced falls was identified.

The walking experiment and the ankle strength tests were conducted in the Locomotion Research Laboratory, Virginia Tech. Fourteen old (67-79 years old) and 14 young (19-35 years old) individuals participated in this study (7 male and 7 female for each age group).Within a subsequent 20-minute session of natural walking on a linear track, kinematic and kinetic data were collected synchronously. A slippery surface was introduced to the participant on the purpose of unexpected slip event. The ankle strength tests were performed using a dynamometer.

The results indicated that ankle strength degradation in older individuals was related to the outcome of slips (i.e., higher frequency of falls). The results also indicated that older individuals' RCOF was less than their younger counterparts. However, older individuals fell more often than younger individuals. It is concluded that friction demand characteristics may not be a total deterministic factor of fall accidents. Thus, the further research should focus not only on the dynamic of slips, but also on the dynamics of falls.

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CHAPTER 1
INTRODUCTION

1.1 Rationale

In 2000, falls in the home and community caused or led to 15,400 deaths (National Safety Council, 2002). All age groups are vulnerable, but older adults are most at risk. Sixty percent of fall-related deaths occur among people 65 and older. The National Council Safety (2002) also reported that falls are the leading cause of injury-related death for males 80 years of age and older and for females 75 years of age and older. One-fourth of individuals who sustain a hip fracture die within one year and another 50% never return to their prior level of mobility or independence (National Council Safety, 2002).

Falling is often initiated by slips (Cham et al., 2001). Numerous researchers have indicated that there is an increasing incidence of slip and fall injuries with advancing age (Campbell et al., 1981; Rice et al., 1989; Rubenstein et al., 1988). In addition, the elderly population is increasing faster than any other age group and is particularly vulnerable to many social and health problems. Falling among older individuals is a major public health concern. To minimize these personal and economic consequences, the causes of slip and fall accidents must be understood and identified.

Multiple mechanisms are involved in slip and fall accidents. The ability to walk safely in the event of slip and fall is dependent upon intact visual, vestibular, proprioceptive, and musculoskeletal systems (Lacour et al., 1983; Nashner, 1982; Tideiksaar, 1990). A variety of physiological changes with advancing age also may affect walking ability and, consequently, the outcome of slips and falls. In general, muscle strength peaks in the mid-twenties and then decreases slowly until after 50 years of age (Astrand et al., 1977; Larsson, 1982). Age-related muscle strength changes have an important effect on initiation of slip and fall accidents (Bonder et al., 1994; Larsson, 1979; Wolfson et al., 1985; Wollacott, 1986). Larsson et al. (1979) suggested that the strength degradation of the quadriceps muscle in older individuals may change the vertical displacement of the center-of-mass of the body suddenly, possibly increasing the likelihood of slipping. Wolfson et al. (1985) reported that ankle muscle strength was significantly lower for those who fall compared to non-fallers, and suggested that ankle muscle strength may be the significant factor in rapidly adjusting the whole body center-of-mass (COM) to prevent falls. Thus, a general decrease in lower extremity muscle strength may impede an older person's ability to recover balance and increase the potential for a slip-induced fall.

A review of the biomechanical literature indicates that there are several differences in gait characteristics between older and younger individuals. Lockhart and his colleagues (2001) found that the deterioration of lower extremity muscular strength among elderly individuals affected the process of initiation and recovery of inadvertent slips and falls. They also reported that an initial friction demand characteristic at the shoe-floor interface was correlated with age-related gait adaptations such as higher heel contact velocity and slower transition of the whole body center-of-mass during the heel contact phase of the gait cycle. Additionally, age-related lower extremity muscle strength was shown to increase the likelihood of slip and fall accidents (Lockhart et al., 2000b).

Initiation of a slip occurs whenever the frictional force ($F\mu$) opposing the movement of the foot is less than the horizontal shear force (F_h) at the foot during the heel contact phase of walking (Perkins et al., 1983). Specifically, at the time of the heel contact, there is a forward horizontal shear force of the ground against the heel. A vertical force (F_v) occurs as the body weight and the downward momentum of the swing foot and leg make contact against the ground.

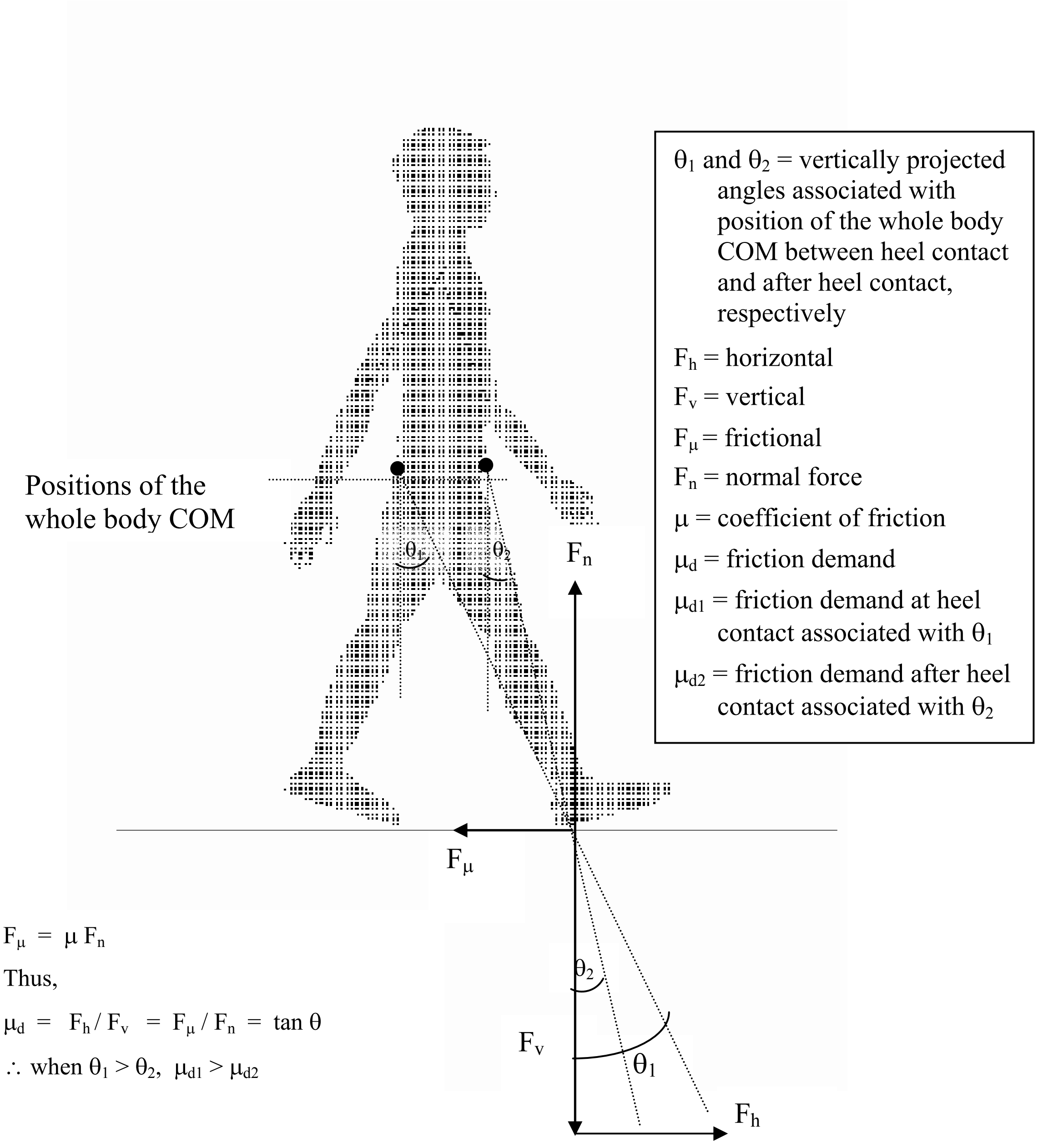
Perkins (1978) identified six peak forces in a normal gait cycle by measuring ground reaction forces exerted between the shoe and ground on a non-slippery floor surface. The ratio of horizontal to vertical foot forces (F_h/F_v) at peak 3 after heel contact indicates where a slip in the walking step is most likely to occur. This ratio at peak 3, the minimum coefficient of friction at the shoe-floor interface to prevent slipping, is called "Required Coefficient of Friction" (RCOF). The RCOF has been related to the tangent of the angle between the leg and a line perpendicular to the floor (Gronqvist et al., 1989). As a result, increasing the step length increases RCOF (Perkins, 1978).

The relationships between gait parameters (walking velocity and step length) and friction demand (RCOF), however, fail to explain why older individuals have a higher likelihood of slip-induced fall accidents. In fact, the existing evidence would imply the opposite. Many studies have shown that in older individuals, their shorter step length and slower walking velocity should decrease initial friction demand, reducing the likelihood of slip and fall accidents. These conflicting findings suggest that there must be factors, besides step length and walking velocity, contributing to the higher frequency of slip-induced fall accidents among elderly individuals (Lockhart et al., 2000b).

Lockhart et al. (2001) found that older participants' horizontal heel contact velocity was significantly faster, and transitional velocity of the whole body COM was significantly slower than their younger counterparts. Consequently, the initial friction demand characteristic, as measured by RCOF, was significantly affected by transitional velocity of the whole body center-of-mass.

Figure 1.1 illustrates a typical slip-grip response with progression of the whole body COM and vertically projected angle (θ) between the instance of the heel contact (θ_1), and shortly after the heel contact (θ_2). As the transfer of the whole body COM progresses forward, projected angle decreases from heel contact (θ_1) to shortly after heel contact (θ_2). At the time of the heel contact (θ_1), force vectors applied by the contacting foot (especially the horizontal foot force) will be greater than the horizontal force vector applied after heel contact (θ_2) as a result of force-angle relationship. In other words, friction demand decreases from θ_1 to θ_2. Additionally, a quicker transition of the whole body COM may be beneficial in terms of reducing friction demand and associated reduced likelihood of slipping. Thus, slower transition of the whole body COM among the elderly may increase friction demand at shoe/floor interface and increase likelihood of slip-induced falls.

A factor influencing transitional velocity of the whole body COM may be the ankle plantar flexors' biomechanical and physiological factors. Plantar flexors produce more than half of the positive work during the push-off phase of the gait cycle (Winter, 1983). The push-off phase, observed between 40% and 60% of the gait cycle, is characterized at the ankle by a shortening (concentric contraction) of the plantar flexor muscles, resulting in power generation [e.g. the whole body COM velocity (Winter, 1991)]. De Vita and Hortobagyi (2000) suggested that a reduction in plantar flexor ankle strength and endurance in older individuals may limit the maximal ankle joint torque and power generation. Consequently, transitional velocity of the whole body COM may be directly reduced and increase older individuals' initial friction demand characteristic at the shoe floor interface of the contacting (swing) foot. Increased initial friction demand would lead to higher likelihood of slips associated with low coefficient of friction at the floor surface.



θ_1 and θ_2 = vertically projected angles associated with position of the whole body COM between heel contact and after heel contact, respectively

F_h = horizontal

F_v = vertical

F_μ = frictional

F_n = normal force

μ = coefficient of friction

μ_d = friction demand

μ_{d1} = friction demand at heel contact associated with θ_1

μ_{d2} = friction demand after heel contact associated with θ_2

$F_\mu = \mu F_n$

Thus,

$\mu_d = F_h / F_v = F_\mu / F_n = \tan\theta$

$\therefore$ when $\theta_1 > \theta_2$, $\mu_{d1} > \mu_{d2}$

Figure 1.1 Positions of the whole body COM and force vectors applied by the left foot during heel contact phase in normal level walking (adapted from Lockhart, 2000a)

1.2 Research Objectives

Injuries associated with slips and falls continue to be the most frequent type of event leading to fatal and non-fatal major accidents. The well-documented reduction in muscle strength with advancing age has been implicated as a cause of increased susceptibility to stability problems such as falls (Berg et al., 2000). However, the mechanisms in which strength declines influence fall risk in older individuals have not been thoroughly explored. One possibility is that decreased lower extremity strength affects the ability of some older individuals to respond to a certain circumstance.

A hypothetical inadvertent slip and fall situation with possible causes and effects is illustrated in Figure 1.2. The process is divided into three distinct phases (environment, initiation, and outcome). The environmental phase considers the effects of contamination. Chaffin et al. (1992) noted that any fluid contaminant between two sliding surfaces provides lubrication and thereby lowers the dynamic coefficient of friction (DCOF) values. Therefore, presence of contamination (oil, water, etc.) will reduce the available dynamic coefficient of friction (ADCOF) of the floor surfaces. Consequently, a slip is initiated by the combination of low DCOF and higher RCOF.

Lockhart et al. (2000a) concluded from their study that older age group's RCOF was not significantly higher than younger counterparts, and the initial gait characteristic, such as heel velocity, did not significantly influence RCOF, suggesting that there might be other variables affecting RCOF. Age-associated declines in muscular strength may have an important effect on initiation of slips as well as torque production at the ankle of the push-off foot. The slower transitional speed of the whole body COM due to less push-off power will increase the horizontal foot force. Consequently, the RCOF will be higher. The outcome of this process will be a higher frequency of slip-induced fall accidents.

In general, the objective of this study was to investigate factors influencing the initial phase of unexpected slips and falls in younger and older individuals by quantifying the relationships between plantar flexor ankle strength and the ankle joint power of the push-off foot on the likelihood of slip-induced falls. Understanding these critical factors will help in developing strategies to reduce the risk of falling. In order to obtain this goal, the primary hypotheses were examined as follow:

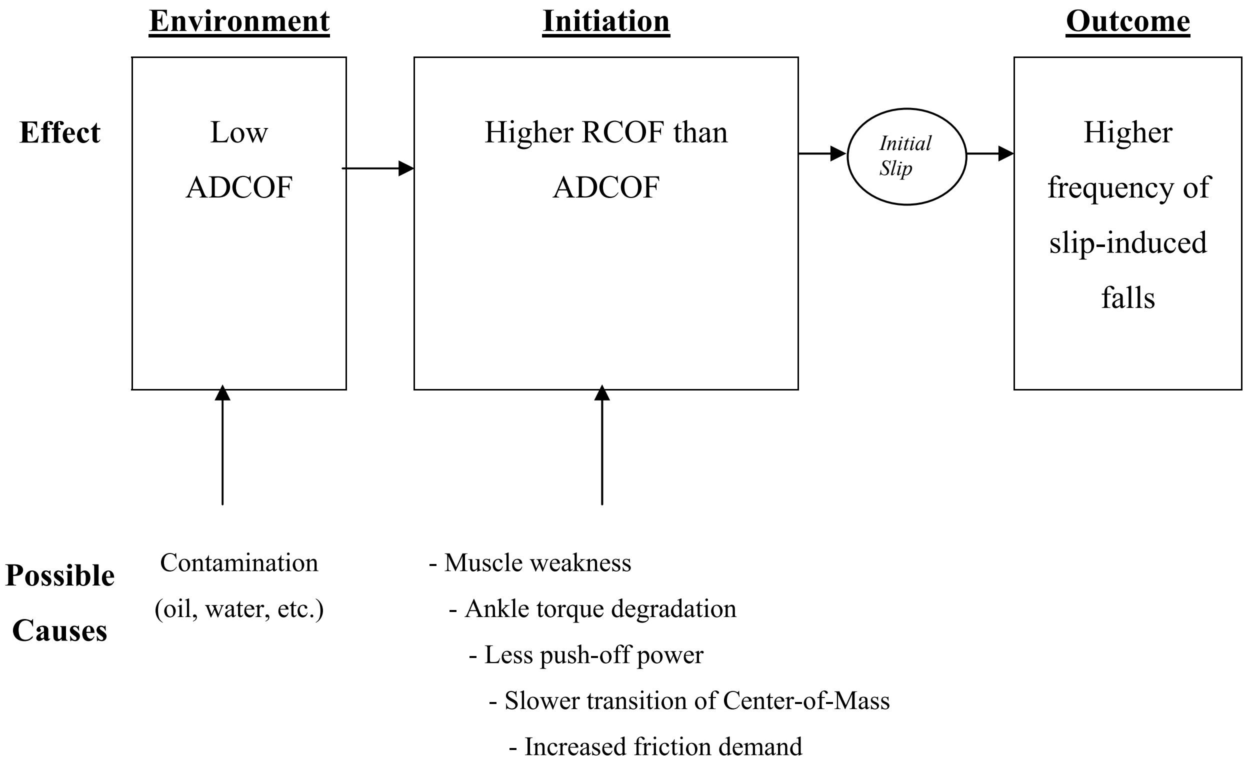


Figure 1.2 The process of initiation and outcome of inadvertent slips and falls with possible causes and effects (adapted from Lockhart, 2000a)

1. Ankle strength in older individuals will be less than their younger counterparts due to musculoskeletal degradation.
2. Ankle joint power of the push-off foot at the heel contact phase of the gait cycle in older individuals will be less than their younger counterparts. It is expected that this reduction is due to the decreased ankle strength in older individuals.
3. Older individuals' transitional velocity of the whole body COM will be slower than younger individuals. It is expected that this reduction is due to the decrease of ankle joint power of the push-off foot in older individuals.
4. Friction demand characteristic (RCOF) in older individuals will be higher than younger counterparts. It is expected that the increase of friction demand is due to the slower transitional velocity of the whole body COM.
5. The slip distance (SD) in older individuals will be longer than younger counterparts.
6. The sliding heel velocity (SHV) in older individuals will be faster than younger counterparts.
7. Frequency of falling in older individuals will be higher than their younger counterparts.

1.3 Need for the Study

This research will provide a better understanding of the initiation phase of the process of inadvertent slips and falls and gait characteristics of two different age groups as they walk on two different types of floor surfaces. Although studies on slip and fall accidents indicate higher rates of fatal injuries in older individuals, the relationship between age-related factors and slip and fall accidents is still unclear. Particularly, the muscular degradation at the lower extremity affecting the initiation of slip has not been well identified in a biomechanical study. In general, the information from this study, such as initial factors leading to slip-induced falls, will help in developing possible fall intervention strategies to protect the elderly population.

CHAPTER 2

LITERATURE REVIEW

The literature review is divided into five sections. The literature investigating the epidemiology of slips and falls is discussed in the first section. The next section presents the biomechanical analysis of human gait. The gait adaptation and musculoskeletal degradation are discussed in the third and fourth section, respectively. Finally, the age-related changes in ankle torque development are discussed in the last section.

2.1 Epidemiology

Epidemiology is a branch of medical science that deals with the rate of occurrence, distribution, and control of diseases in a population including the sum of the factors controlling the presence or absence of a particular disease. A review of slip and fall studies indicate that slipping and tripping are very often the 'trigger event' for the fall accidents (Andersson et al., 1983; Cohen et al., 1982; Manning et al., 1988). Manning et al. (1988), in a study of underfoot accidents in a work population of 10,000 in 1985, reported that a majority of accidents leading to the injury (62%) were due to slipping. Similar findings were reported by Andersson et al. (1983). They searched for the events 'slipping' and 'tripping' among work-related accidents in Sweden in 1979. Of 20,587 cases of falls, the most frequent pre-event was slipping (8,727 cases or about 42%) and 14% or 2,827 cases resulted by tripping event.

The breakdown of fatal occupational injuries by occupation, as reported by the Bureau of Labor Statistics (2000), is shown in Table 2.1. The occupational groups working on a number of different workstation levels have a high percentage of fall-related injuries (such as drywall installers, roofers, or painters). However, cleaning occupations also have high percentage of falls. The most frequent surface where slip and fall accidents occurred was the 'floor' (33%) (Cohen et al., 1982). Other surfaces frequently involved were: ground (outdoors, 11%), stairs (10%), and ladders (6%). Manning et al. (1988) noted two primary features of the underfoot surfaces contributing to slipping accidents; 32.7% of slipping accidents were attributed to floor contaminated by oil and 17.3% were caused by ice or snow. Cohen et al. (1982) also found that 16% of slips occurred on surfaces that were wet (contamination), 8.1% icy, 6.4% oily, and 0.7% muddy.

Table 2.1 Fatal occupational injuries by occupation (BLS, 2000)

Occupation	Total fatalities	Injuries from Falls (percent)
Managerial and professional specialty	642	8.4
Technical, sales, and administrative support	686	5.5
Service occupations	431	12.5
Cleaning and building service occupations, except household	78	35.9
Farming, forestry, and fishing	806	7.4
Precision production, craft, and repair	1,105	28.5
Telephone installers and repairers	9	55.6
Operators, fabricators, and laborers	2,118	9.6
Carpenters and apprentices	91	53.8
Painters, construction and maintenance	45	68.9
Drywall installers	12	75.0
Roofers	65	73.8
Construction laborers	288	29.9

2.1.1 Epidemiology of Slip and Fall Accidents of Older Individuals

Falls and gait instability are among the most serious problems facing the elderly population and constitute a major cause of mortality, morbidity, immobility, and premature nursing home placement (Rubenstein et al., 1988). Both the incidence of falls and the severity of complications resulting from falls increase after middle age (Campbell et al., 1981). Nearly 9,000 people age 65 and older died as a result of a fall in 1997 (National Council Safety, 2002). Sixty percent of fatal falls occur in the home, 30% in public places, and 10% in institutions. The National Safety Council reports that during 1998, "falls" were the second leading cause of unintentional death. Falls are the second leading cause of injury death for ages 55-79, and become even more prevalent for individuals over the age of 80 (National Council Safety, 2002). For all persons age 65 and older, falls account for 50 percent of all injury deaths. Falls are also a major cause of severe non-fatal injuries and a common cause of hospital admissions (CDC, 2000).

2.1.1.1 Causes of Falls in the Elderly

When any group of people has an especially high mortality from a particular injury or disease, the reasons can be classified under one or more of the following three groups of factors: (1) greater exposure to the etiologic agent; (2) lower threshold (greater susceptibility) to the injury or disease; or (3) greater likelihood of a fatal outcome once the injury or disease occurs. High rates of fall injuries and deaths in older individuals are a function of factors in all three categories (Baker et al., 1985).

For many reasons, older individuals are at increased risk of falling and, thereby, of being exposed to an impact. Factors intrinsic to elderly people, the type of activity engaged, and the hazards and demands of the environment contribute to most falls in varying degrees. Causes of a fall can be classified in several ways: by presenting symptom complex (e.g., dizziness, slips, etc.), by a precipitating mechanism (e.g., postural hypotension, environmental hazards, etc.), or by underlying risk factors (e.g., sensory limitations, medical problem, decreased vision, etc.).

2.1.1.2 Fall Injuries in the Elderly

Falls present a serious health risk for millions of older Americans. In the United States, one out of every three people age 65 and older falls each year. According to the American Academy of Orthopaedic Surgeons, most falls happen in the home to people age 65 and older during everyday activities and 90% of the 300,000 hip fractures treated annually in the U.S. occur from falls. Fractures, especially hip fractures, are the most serious fall-related injury. Half of all older individuals hospitalized for hip fractures cannot return home or live independently after their injuries. Centers for Disease Control and Prevention researchers have noted that hip fracture rates among older individuals increased from 1988 to 1996. This trend may partially reflect a rapid increase in the proportion of individuals aged 85 and older in the U.S.; among these oldest-old, the rates of fall-related death and injury increase markedly. The number of people over age 65 is expected to increase from 35 million in 2000 to 70 million by 2030 (Figure 2.1); thus making falls and fall-related injuries an increasingly important public health problem.

2.2 Biomechanics of Human Gait

Locomotion is the process that describes movement of animals from one geographic position to another. Walking can be defined as a method of locomotion involving the use of the two legs, alternately, to provide both support and propulsion (Inman et al., 1981). Lockhart et al. (2000b) have described gait as the manner or style of an individual’s walking pattern. Under normal conditions, walking involves the integrated activity of muscles acting across many joints. Because of the synergistic and antagonistic nature of many of these muscles, the sequence and type of movement of different body parts are essentially the same in all individuals (Steinder, 1977; Winter, 1991). Therefore, it is important to understand dynamic principles of each body segment in locomotion and the translation of the whole body center-of-mass through space.

Information presented in this section describes gait mechanisms involved in walking in both young and older populations. It also describes the translation of the body via the concept of the pathway of the whole body center of mass and the gait parameters of walking.

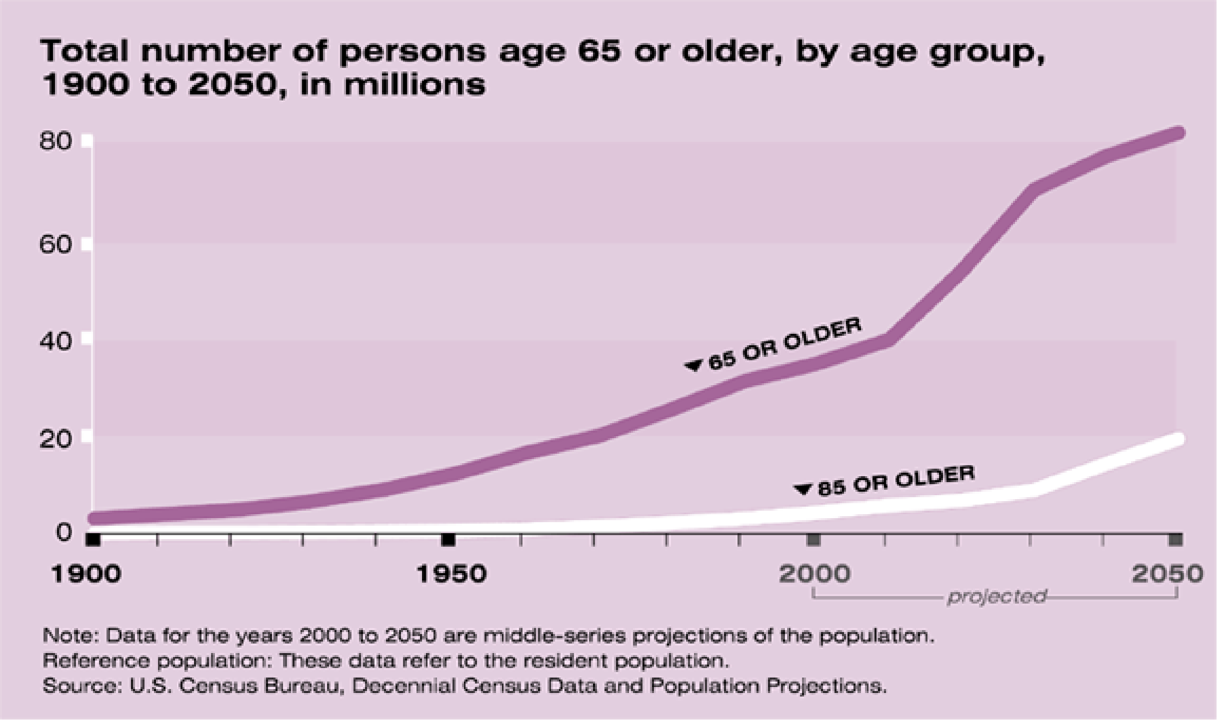


Figure 2.1 The growth of the older American population (age 65 and older) (CDC, 2000)

2.2.1 The Three Dimensional and Cyclic Nature of Gait

The three primary planes of the human body, sagittal, coronal (or frontal), and transverse (Figure 2.2) (Vaughan et al., 1987), have been used to studied human gait. Although the sagittal plane is probably the most important one, where much of the movement takes place, there are pathologies where another plane would yield useful information.

Gait has been studied in forms of the "walking cycle", which is the time interval between the successive floor contact of each foot. The act of walking has two basic requisites: (1) periodic movement of each foot from one position of support to the next, and (2) sufficient ground reaction forces, applied through the feet, to support the body.

This periodic leg movement is the essence of the cyclic nature of human gait. Descriptions of walking are normally confined to a single cycle, with the assumption that successive cycles are approximately the same. Figure 2.3 illustrates a single cycle and the time dimensions of the walking cycle (Inman et al., 1981). There are two main phases in the gait cycle, stance phase and swing phase, during leg movement. During the stance phase, the foot is on the ground, whereas in the swing phase that same foot is no longer in contact with the ground and the leg is swinging through in preparation for the next foot strike.

Forward locomotion is achieved by pushing off on the leg during the stance phase while swinging the other leg forward. The heel contact phase of the gait cycle occurs when the forward moving heel hits the ground, and since the limb is kept relatively straight with the foot, deceleration of the foot converts to acceleration of the hip. In addition, the hip and the knee extend (Cooper et al., 1963; Davis, 1983; Williams et al., 1962). Continued forward movement of the body results in the forefoot coming to ground, and the propulsive part of the support phase begins. At this point, the muscles plantar flex the foot, flex the knee, and extend the hip. The heel is raised and pushes the foot backwards under the body. This is associated with fixation and elevation of the pelvis by the abductors as well as tilting of the body toward the swing leg that allow it to land in a line anterior to the stance leg (Koller et al., 1985). In the swing phase, the leg is flexed and slightly externally rotated at the hip, flexed at the knee, and dorsiflexed at the foot. Throughout the remainder of the swing phase, the limbs move under the influence of gravity alone, and finish in a position which allows direct entry into the next step (Basmajian, 1976; Mochon et al., 1980).

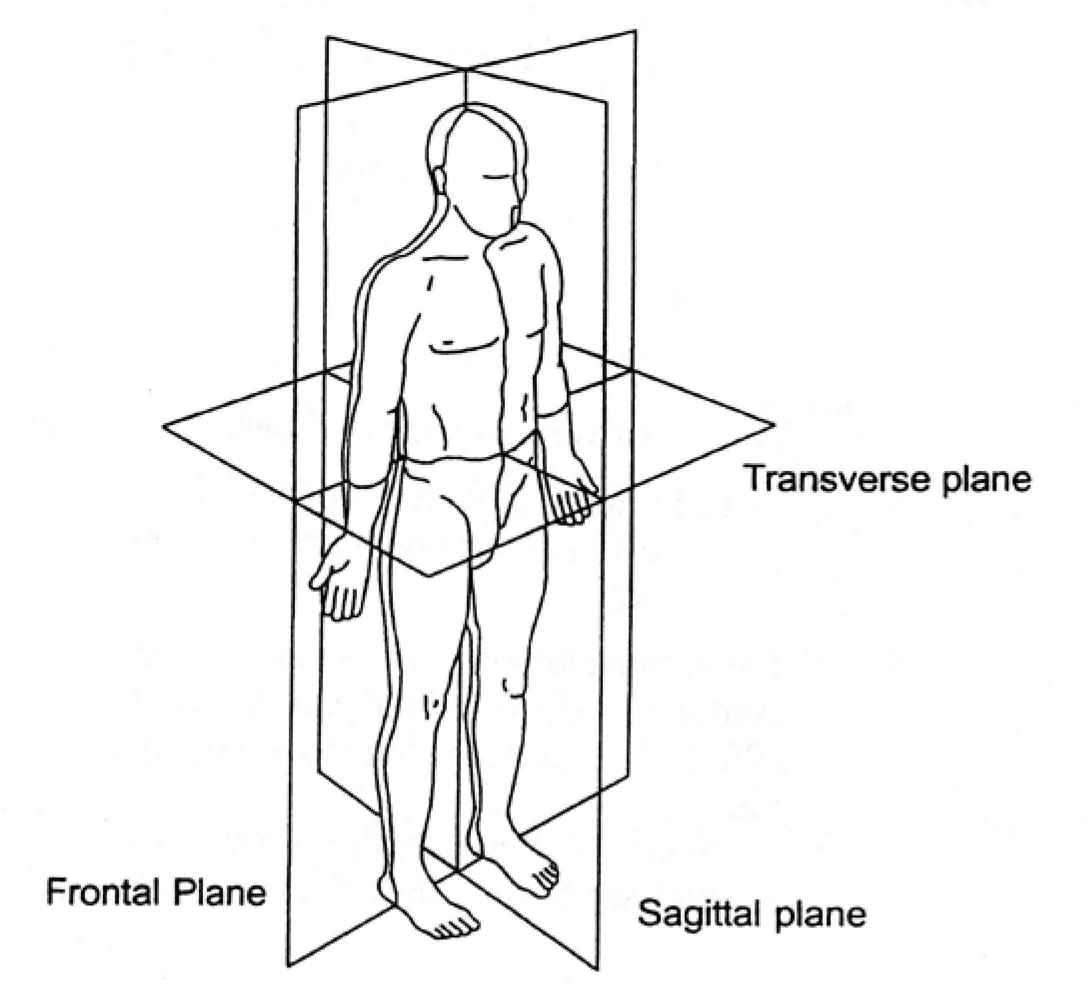


Figure 2.2 The reference planes of the human body in the standard anatomical position (Vaughan et al., 1987)

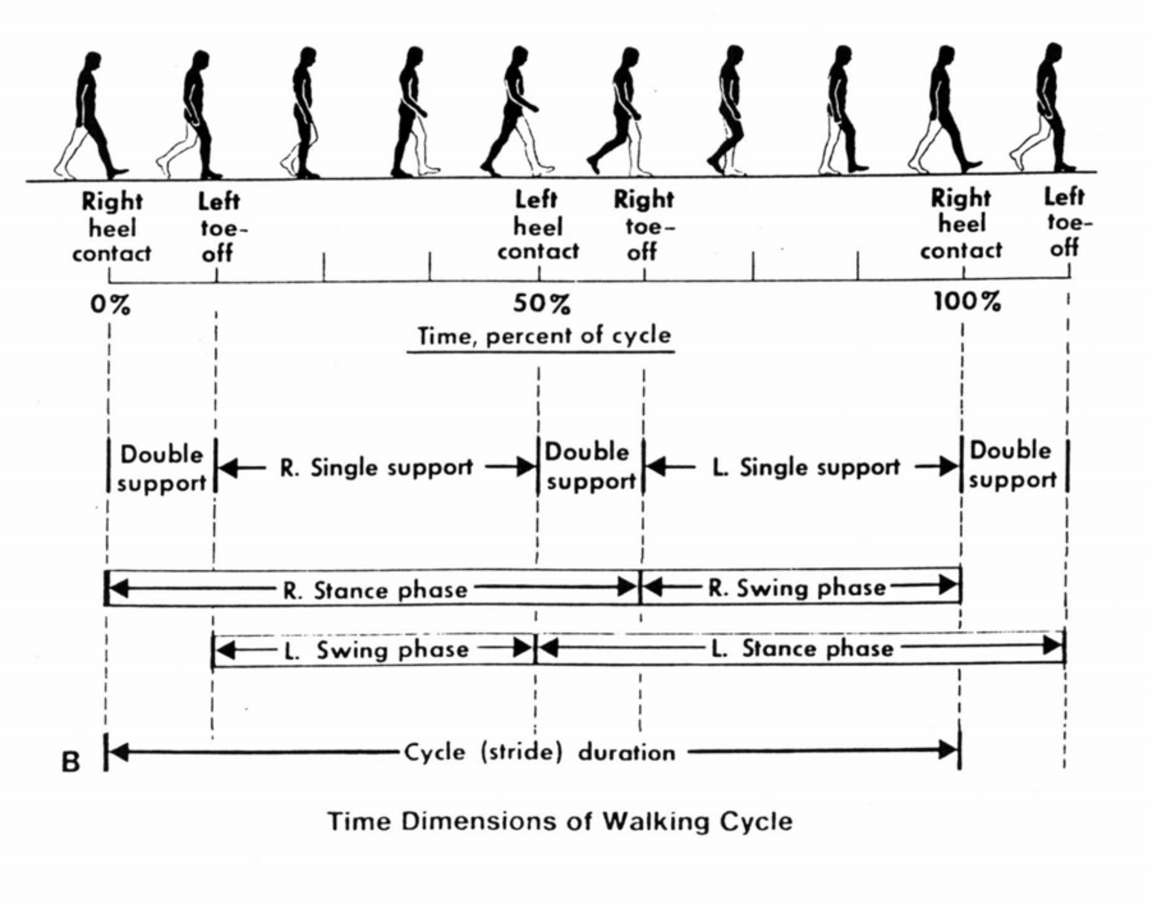


Figure 2.3 The time dimensions of walking cycle (Inman et al., 1981)

2.2.2 Gait Parameters

The cyclic nature of human gait is a very useful feature for reporting different parameters (e.g., heel contact velocity, sliding heel velocity, and required coefficient of friction). The important gait parameters of old and young individuals relevant to the slips and falls investigation will be further reviewed.

2.2.2.1 Heel Contact Velocity

Horizontal velocity builds up gradually after heel-off, reaches a maximum velocity late in the swing phase, and drops rapidly to near zero just prior to heel contact. During the last 10% of swing, the heel is lowered very gently to the ground as horizontal velocity decreases rapidly to near zero. This is significant in that heel velocity prior to heel contact at the end of the swing phase must be reduced sufficiently so that a dangerous slip will not occur. Winter et al. (1990) reported that heel contact velocity in the horizontal direction was significantly higher for older individuals than their younger counterparts even though walking velocity was slower for older individuals. Similarly, Lockhart et al. (2000a) found that the heel contact velocity for different floor surfaces in older individuals was faster than their younger counterparts.

2.2.2.2 Sliding Heel Velocity/Slipping Velocity

The relative sliding velocity between the shoe sole and the floor surface immediately after the heel contact has been one of the essential gait parameter for slip and fall investigations (Leamon et al., 1989; Perkins, 1978; Strandberg et al., 1981). Perkins (1978) and Strandberg et al. (1981) reported that there was some slipping of the heel immediately after heel contact even when participant noticed no loss of balance. The heel often decelerated initially and then began to increase velocity when loss of balance was observed. They concluded that if the sliding heel velocity after heel contact did not decrease to a certain limit, loss of balance or even a fall will result. Lockhart et al. (2000b) reported that there was a significant difference for sliding heel velocities among different age groups. They found that older individuals had faster sliding heel velocities than their younger counterparts in spite of older individuals having slower walking speeds, shorter step lengths, and longer double support times.

2.2.2.3 Required Coefficient of Friction (RCOF)

The ground reaction forces, as measured by a force platform, reflect the vertical and shear forces acting on the surface of the platform (Lockhart et al., 2000a). The required coefficient of friction represents the minimum coefficient of friction that must be available at the shoe-floor interface to prevent forward slipping at the heel contact. Perkins (1978) utilized a force platform to measure the horizontal and vertical components of the force exerted between the shoe and ground during normal walking and calculated the ratio of horizontal to vertical forces as a function of time (Figure 2.4).

Perkins (1978) also found six peak forces in the normal gait cycle. Peaks 1, 3, and 4 are caused by a forward force, whereas peaks 2, 5, and 6 are caused by a backward force on the force platform. Peak 1 is caused by the force of impact of the heel tip against the force platform and has a forward direction as a result of the approach angle of the heel to the ground. However, this peak has been found to be inconsistent due to low vertical force during this phase.

Peak 2 is caused by a backward force exerted on the heel of the shoe shortly after heel contact. Peaks 3 and 4 are caused by the main forward force which retards the motion of the body and leg. During peaks 3 and 4, the vertical force has risen and a significant proportion of the body weight is being applied through the heel tip (less than 0.1 second after heel contact). Therefore, the error in F_h/F_v ratio is relatively small (Perkins, 1978). As more of the body weight is progressively transferred to the striking foot, the whole body center of mass moves over the now stationary foot and the forward force causing peak 4 decreases. During the take-off phase, the F_h/F_v ratio increases due to the force (peaks 5 and 6) exerted by the foot propelling the body forward.

The ratio (F_h/F_v) is significant in that it indicates where in the walking step a slip is most likely to occur. If the magnitude of this ratio exceeds the coefficient of friction (COF) between the two surfaces at a particular moment in time, a slip will occur (Perkins et al., 1983). Lockhart et al.(2000b) studied slips and falls in comparison between older and younger individuals. They found that RCOF was higher for older individuals than their younger counterparts.

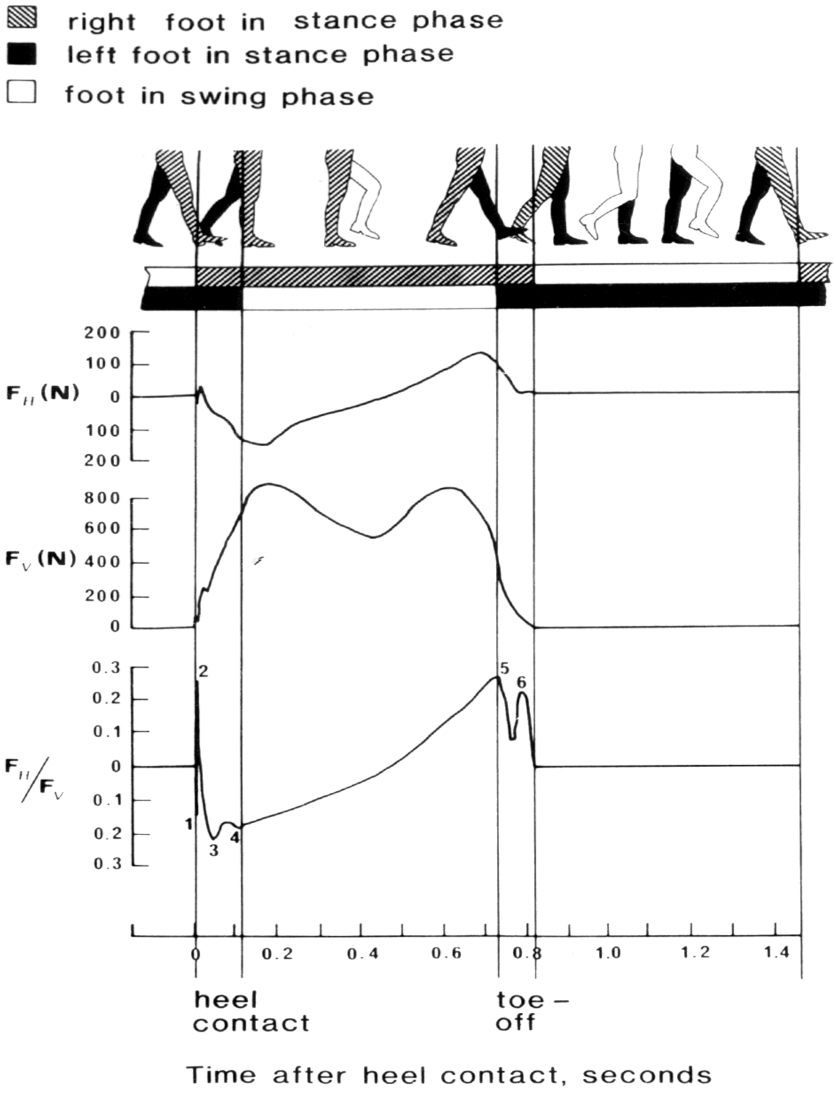


Figure 2.4 Gait phase in normal level walking with typical horizontal, vertical, and their ratio for one step (Perkins, 1978)

2.2.3 Transitional Velocity of the Whole Body Center-of-Mass (COM)

The whole body center of mass (COM) is a key factor in human gait analysis as it reflects the motion of the whole body (Hay, 1973). The center of mass is the theoretical point about which the mass of that body is evenly distributed. In the human body, the location of this theoretical point will depend upon several factors including the distribution of segmental masses, and the location of those segments.

In the standing position, the whole body COM is located centrally in the pelvis, approximately at the level of the second sacral vertebra. However, equilibrium is lost during forward walking (Carlsoo, 1962). When the foot is pushing off, the whole body COM momentarily lies beyond the anterior border of the supporting surface, but returns to neutral when the swinging leg is extended forward and the heel touches the ground (Carlsoo, 1962). In addition, the legs move forward and backward, the arms swing, and the trunk moves up and down and from side to side during walking. Consequently, the whole body COM progresses depending upon the direction of movement.

The transitional velocity of the whole body COM can be defined as the change of the velocity between heel contact phase to shortly after heel contact phase of the gait cycle (Lockhart et al., 2001). Lockhart et al. (2001) indicated that the whole body COM after heel contact always transferred faster than before the heel contact. They also found that the horizontal whole body COM velocity both before and after heel contact was significantly faster in younger individuals than older individuals under normal walking conditions. In other words, younger individuals transfer the whole body COM faster than older individuals. It might be concluded that a slower transitional velocity of the whole body COM increases the horizontal foot force at heel contact, and increases the friction demand at shoe-floor interface. As a result, older individuals slipped longer and faster, and fell more often than younger counterparts.

2.3 Gait Adaptation

There are several differences in gaits between older and younger individuals (Gillis et al., 1986; Imms et al., 1979; Lockhart et al., 2000b; and Murray et al., 1969). Older individuals tend to walk slower, have a shorter step length, and have a broader walking base. This results in a gait cycle with a longer stance or double support time (Gillis et al., 1986; Imms et al., 1979; Murray et al., 1969; Winter et al., 1990).

Normally, people in all ages tend to shorten their step lengths to reduce horizontal foot forces and to reduce the likelihood of slipping on slippery surfaces (Cooper et al., 1963). It is generally believed that the shorter step length and the slower walking velocity of older individuals result in a more stable gait pattern, but these gait changes may also have some important implications for the initiation of slip-induced falls (Lockhart et al., 2000a).

Lockhart et al. (2000b) conducted a laboratory study to examine the gait changes associated with aging and the effect of those changes on initiation of slips, initial friction demand, and frequency of falls. The results indicated that the horizontal heel contact velocity in older individuals was significantly faster, and transitional velocity of the whole body COM was significantly slower than their younger counterparts.

2.4 Musculoskeletal Degradation

The two important biomechanical properties of the intact musculoskeletal system are joint motion and muscle strength (Chaffin et al., 1999). These two properties define an individual's ability to perform a mechanical task. Several studies of strength in different age groups have been conducted (Asmussen et al., 1962; Cathcart, 1927; Chaffin et al., 1977). In general, muscle strength appears to be greatest in the late 20s and early 30s, with a general decline thereafter (Hettinger, 1960). The average population strength at age 40 appears to be approximately 5% less, and at age 60, 20% less, than in the late 20s (Hertzberg, 1972; Roebuck et al., 1975; Shephard, 1995). Most older workers aged between 50 and 60 can produce only about 75-85 % as much muscular strength as persons aged between 20 to 30 (Kroemer et al., 1997).

2.5 Age-Related Changes in Ankle Torque Development

Joint motion is often referred to as joint mobility or joint flexibility. Although joint motion could be defined relative to a specific absolute posture, it is generally conceded that body segments rotate about a joint. Thus, the range of motion (or maximum angular deviation) available at the joint is the best means to express joint mobility. Many investigators indicated that joint torque and joint power at the ankle are directly related to walking velocity (Chen et al., 1997; Winter, 1983, 1991). DeVita and Hortobagyi (2000) reported that older individuals compared with younger individuals generate decreased joint torques and powers in the lower extremity. In addition, a redistribution of joint torques and powers was found among older and younger individuals. The older individuals use more hip extensors, less knee extensors, and less ankle plantar flexors than younger counterparts when walking at the same speed (DeVita et al., 2000).

Strong evidence exists to show that absolute strength exhibits age-related declines in ability to produce appropriate torques to counteract loss of balance (Clarkson et al., 1981; Hakkinen et al., 1991; Larsson, 1978; Thelen et al., 1996). Both isometric and isokinetic strength testing reveal significantly reduced peak torque production about the knee and ankle in older versus younger individuals (Hakkinen et al., 1991; Larsson, 1978; Thelen et al., 1996; Wolfson et al., 1995). Recent studies have shown that the ability to rapidly produce torque declines in older individuals. The rate of knee extensor torque production in an isometric task was significantly slower in older individuals compared to the younger counterparts (Clarkson et al., 1981; Hakkinen et al., 1991). Thelen et al. (1996) also found that the rate of torque production at the ankle was likewise affected by age.

2.5.1 The Ankle and Foot Mechanisms

The foot and ankle are a very complex anatomical structure consisting of 26 irregularly shaped bones, 30 synovial joints, over 100 ligaments, and 30 muscles acting on the segment. The foot moves in three planes with most of the motion occurring in the rear-foot. Also, the foot supports the weight of the body in both standing and locomotion. Finally, when the foot is fixed during stance, it must absorb the rotation of the lower extremity. These functions of the foot all occur during a closed kinetic chain as it is receiving frictional and reaction forces from the ground or another surface (McPoil et al., 1987).

The axis of rotation for the ankle joint is a line between the two malleoli, running oblique to the tibia and not in line with the body (Czerniecki, 1988). Sagittal plane rotation at the ankle occurs both when the foot is moved relative to the lower leg and when the lower leg is moved relative to the foot. Motion bringing the top of the foot toward the lower leg is known as “dorsiflexion”, and the opposite motion is termed “plantar flexion” (Figure 2.5).

The average range of motion in dorsiflexion is 20 degrees, with approximately 10 degrees of dorsiflexion required for efficient gait. The average range of motion in plantar flexion, the movement of the foot away from the leg, is 50 degrees, with 20 to 25 degrees of

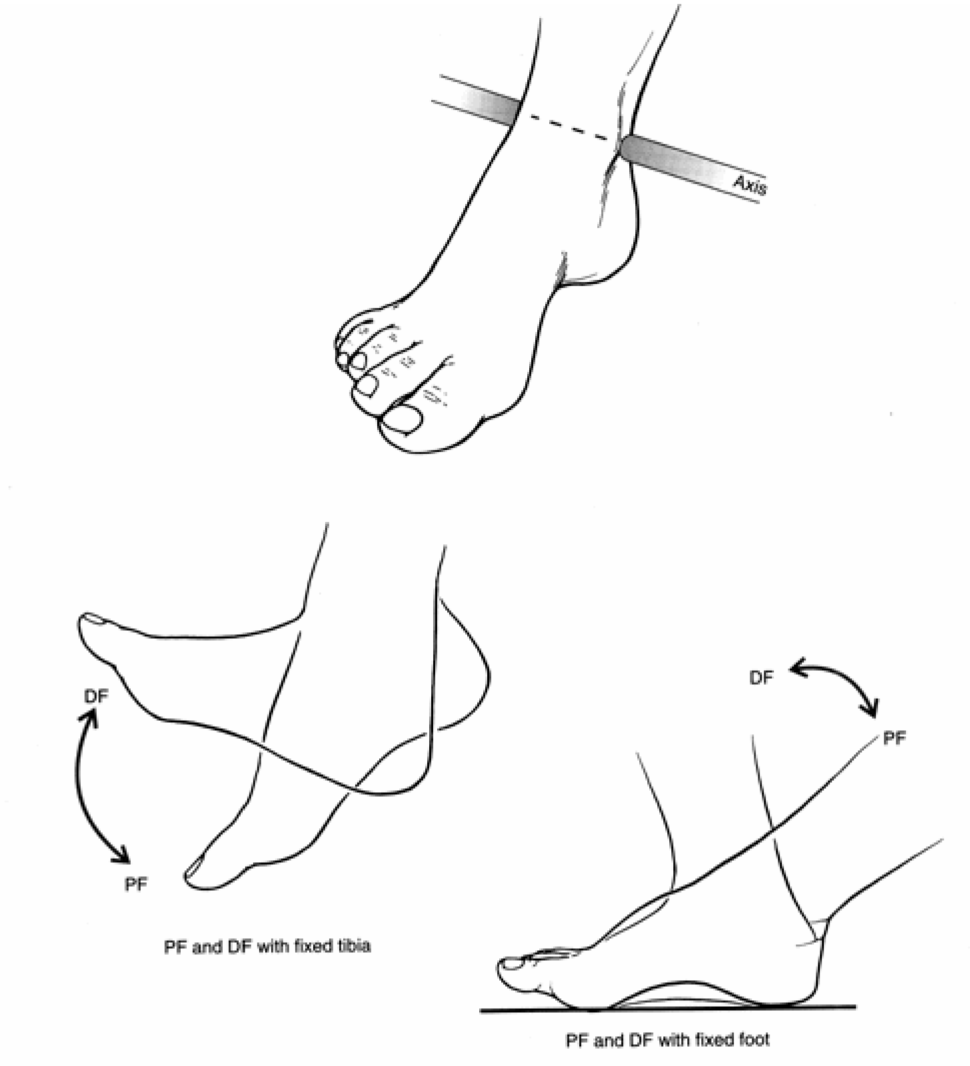


Figure 2.5 Sagittal plane movement of the foot (Hall, 1999)

plantar flexion used in gait (Brown et al., 1987). In the gait, the plantar flexion range of motion is less for both passive and active measurements. The reduction of plantar flexion in gait is substantial due to weak calf muscles (Hamill et al., 1995). Locke et al. (1984) indicated that healthy older individuals do not demonstrate substantial loss in plantar flexion range of motion when compared to younger healthy individuals.

During gait, there is 20 to 40 degrees of total plantar flexion and dorsiflexion movement (Cerny et al., 1990; Murray et al., 1964). The foot strikes the ground with the ankle at 90 degrees, and moves into the loading phase through approximately 10 degrees of plantar flexion to lower the foot to the ground (Perry, 1992). Moving into midstance, the foot moves into approximately 5 degrees of dorsiflexion, increasing to approximately 10 degrees in later stance. At the push-off phase, the ankle rapidly plantar flexes 20 degrees to unload the limb and begin the swing phase (Perry, 1992). In the swing phase of the gait cycle, the ankle dorsiflexes to move back to the neutral position, and to keep the toes up and prepare for the next heel strike (Wright et al., 1964).

2.6 Summary

Reducing slip and fall accidents has been a topic of interest for ergonomics researchers since the 1920's. Epidemiological findings indicate that slip and fall accidents are the leading causes of unintentional death for the elderly populations. There have been many researches trying to determine what causes older individuals to suffer falls. One thread that seems to run through many of the studies is that mobility problems and poor health status are strongly related to the frequency of falls. The biomechanical evaluation of human gait to slips and falls has described relevant gait parameters (e.g., heel contact velocity, sliding heel velocity, and friction demand). Additionally, age-related changes have been reported; such as lower transitional velocity of the whole body center of mass, gait adaptation, and ankle torque degradation; which contribute to falls. In conclusion, many studies suggested that age-related changes in muscle strength and muscle force production have a significant effect on initiation and recovery of slip and fall accidents (Bonder et al., 1994; Campbell et al., 1989; Larsson et al., 1979; Lockhart, 1997; Lockhart et al., 2000b; Wolfson et al., 1985; Woolacott, 1986).

CHAPTER 3
METHOD

3.1 Participants

Fourteen young individuals (19-35 years old) and fourteen older individuals (67-79 years old) participated in this experiment (7 male and 7 female for each age group). The young participants were recruited from the student population at Virginia Tech and the older participants were recruited from the local community. Additionally, the Center of Gerontology at Virginia Tech provided assistance in recruiting older participants. Participants were required to have no restrictions to physical activities and no history of significant musculoskeletal and neurological disease or injury. All participants were compensated for their time and effort ($10 per hour). The average and standard deviation of age, weight, and height of all participants are presented in Table 3.1 and Table 3.2. Additionally, all participants reported that they were right-handed and right-footed.

3.1.1 Sample Size Estimates

Estimation of required sample sizes for the experiment proceeds from estimates of intersubject variability in heel velocity obtained from previous work (Lockhart, 1997). Power calculations are performed by focusing on sample sizes large enough to determine differences between younger and older participants with high probability. The general test statistic for two populations would be the standard two-sided *t* test, for which the power of the test (Neter et al., 1996) is given by:

$$\text{Power} = P\{|t^*| > t(1 - \alpha/2; n\text{-}2 \mid \delta)\}$$

where δ is the noncentrality parameter, or a measure of the distance between the means of A and B (heel velocity of younger and older participants):

$$\delta = |A - B| / \sigma\sqrt{(2/n)}$$

where σ is the standard deviation of the distribution of heel velocity and n is the number of participants in each age group.

The difference between A and B (or the minimum difference which is important to detect with high probability) is assumed to be 15 cm/sec (Lockhart, 1997). Results from a previous study of heel velocity during walking indicated that the standard deviation in heel

Table 3.1 Participant Information (by age)

	Young (19-35 years old) Mean (S.D.)	Old (67-79 years old) Mean (S.D.)
Age (yr)	23.21 (4.41)	72.64 (4.36)
Weight (kg)	71.74 (11.97)	72.59 (16.31)
Height (cm)	172.41 (10.94)	168.49 (9.1)

Table 3.2 Participant Information (by age and gender)

	Young Female Mean (S.D.)	Young Male Mean (S.D.)	Old Female Mean (S.D.)	Old Male Mean (S.D.)
Age (yr)	21.00 (0.82)	25.43 (5.47)	74.71 (4.11)	70.57 (3.78)
Weight (kg)	65.04 (8.02)	78.43 (11.90)	60.09 (10.72)	85.09 (9.84)
Height (cm)	164.64 (8.41)	180.19 (6.90)	160.90 (4.74)	176.09 (4.73)

velocity (σ) was approximately 15 cm/sec. Specifying that $\alpha = 0.05$, 14 participants in each of the age groups should be sufficient to detect the specified differences in heel velocity with risks of Type I error of 0.05 and Type II error of <0.3 (Power > 0.7).

3.2 Apparatus

The experimental setting and definitions of all variables were utilized in the established methods from the earlier studies (Lockhart et al., 2000a, 2000b). Figure 3.1 shows the field layout of the experiment. The overall function of the system is to control the experimental conditions without the participant being aware of any floor surface change.

3.2.1 Simulated Floor

Walking trials were conducted on a linear walking track (1.5 m x 15.5 m) in the Virginia Tech Locomotion Research Laboratory. The entire walking track was covered with the non-slippery vinyl floor tile (Armstrong) to represent a realistic environmental setting. The slippery surface was covered with a soap-water contaminant, 43% soap (Ultra Ivory® concentrated dishwashing liquid (Procter&Gamble, Cincinnati, OH) and 57% water, to reduce the available dynamic coefficient of friction (ADCOF) of the floor surface. Both of the test surfaces (slippery and non-slippery) were mounted on a wooden platform, which was connected to a gliding shaft, and was attached to two force plates.

3.2.2 Force Plate and LabVIEW Interface

The ground reaction forces of the participants were collected by two force plates for left and right feet (force plate 1: 24”x 48”, Advanced Mechanical Technology (AMTI), Inc., Watertown, MA and force plate 2: 18.25”x 20”, Bertec Corporation, Columbus, OH). Both force plates were connected to an analog-to-digital converter and amplifier interfaced with LabVIEW data collection software (LabVIEW 6i, National Instruments™, July 2000 Edition).

3.2.3 Motion Analysis System

Six infrared cameras in the ProReflex system (Qualisys Inc., East Windsor, CT) were used to collect the three-dimensional movement data of the participants as they walked over the test surfaces. The coordinates of the 26 reflecting markers (Qualisys Inc., East Windsor, CT) on

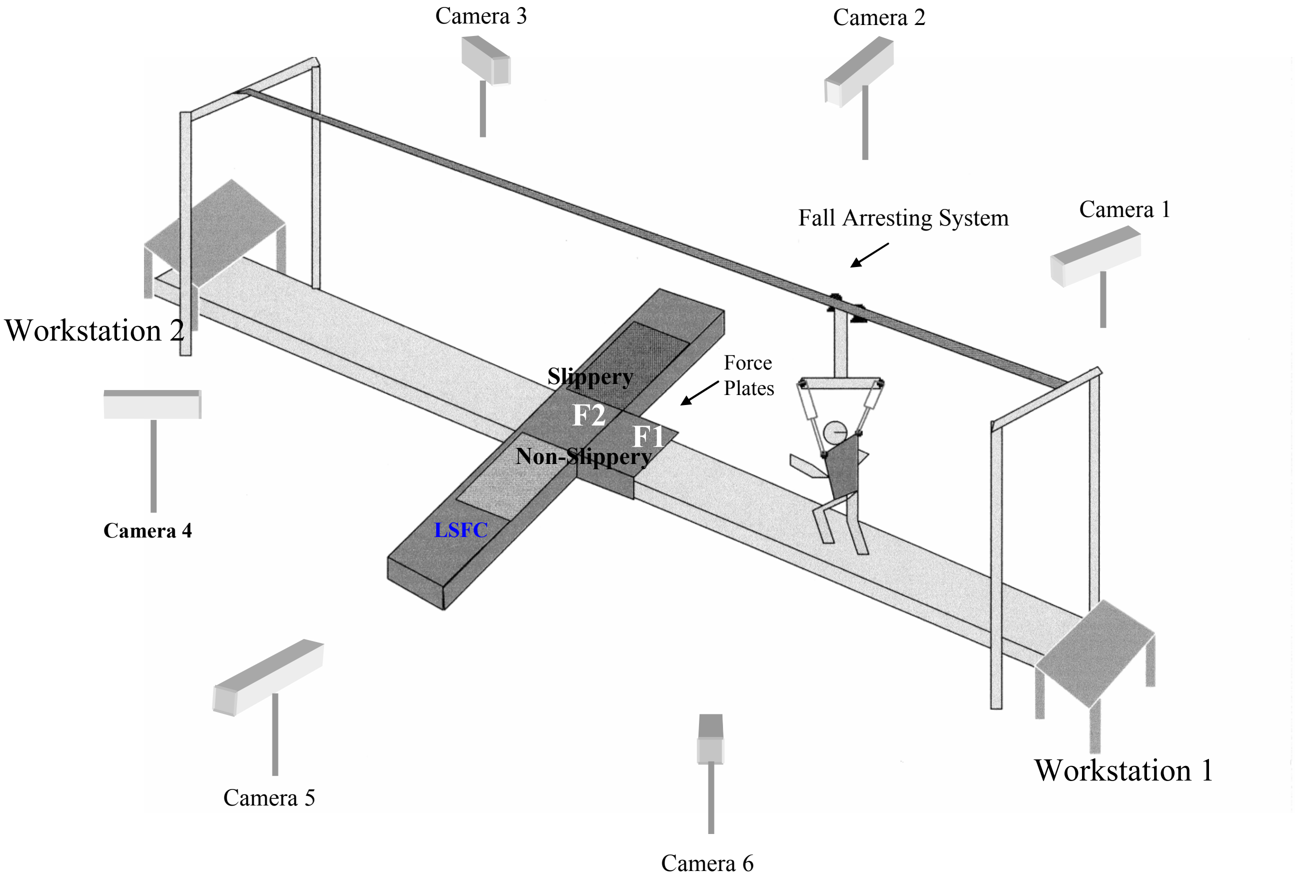


Figure 3.1 Field layout of the experiment including: fall arresting system, six infra-red cameras for motion capture, linear sliding floor changer (LSFC) with force plate (F2) and hidden slippery and non-slippery test floor surfaces, fixed force plate (F1), and two workstations

a participant’s anatomical landmarks were transferred from all six cameras with QTrac motion analysis software (Qtrac software version 2.5, Qualisys Inc., East Windsor, CT). Movement data were sampled and recorded at a rate of 120 Hz when participants walked over the test surfaces.

3.2.4 Fall Arresting Harness System

A fall arresting harness system was used to protect the participants from falling during the experiment. The harness system consisted of a full-body harness and an overhead rotational suspension system. The full-body harness allowed a participant to walk under experimental conditions with minimal restrictions and provided self paced control of the fall arresting system.

3.2.5 Linear Slide Floor Changer (LSFC)

A lab-produced linear slide floor changer were used to change the test floor surfaces manually to provide unexpected slippery conditions to the participants.

3.2.6 Experimental Shoes

The experimental shoes were provided to all participants to control the same resistance of shoe soles and underfoot surfaces.

3.2.7 Dynamometer

BioDex dynamometer (Biodex Medical Systems, Inc., Shirley, NY) were used to collect isometric and isokinetic strength at the participant’s ankles. The data from dynamometer were collected by interfacing with LabView data collection software.

3.3 Procedure

Participants were scheduled to participate in two testing sessions: Walking Experiment session and Strength Test session. At the first session, participants were asked to fill out the personal data and medical history questionnaire (Appendix A). After each participant completed an informed consent procedure approved by the Virginia Tech Internal Review Board (IRB) (Appendix B), the walking experiment was served to collect the participant’s gait parameters. The strength test session was scheduled within two weeks. Due to schedule conflicts, two participants completed the second session four weeks later. All participants were asked if any injury occurred during the time between the first session and the second session. They all reported no injury occurred during the period of time between two sessions.

3.3.1 Walking Session

Prior to performing the walking experiments, all participants were fitted with the experimental shoes in order to minimize possible variations due to footwear. Participants were asked to walk on the track as natural as possible to measure their natural cadence. Twenty-six reflective markers were attached to the anatomically significant positions (Figure 3.2).

All participants wore a full-body safety harness suspended with double cables to a single overhead track. The length of the harness suspension cable was adjusted for each participant so that their hands would not contact the floor in the event of a failure to regain balance. It was assumed that the full body harness did not interfere with upper or lower extremity motions, and all support cables were attached to the shoulders out of the participants' field of vision. Participants were instructed how to turn around with the harness during walking on the linear track.

During the walking trials, participants were asked to walk at the same speed as their own natural cadence. Participants were also instructed to focus the eyes on TV monitors located approximately 2 meters above the workstations at both ends of the walking track to ensure that they did not look at the test floor surface. A secondary task required them to count out the images displayed (3 color dots: blue, green, and red) to ensure that they attended to the TV monitors. As participants walked back and forth from each end of the track, foot placements of the participants were monitored and adjusted (by adjusting the starting step after turning around) to hit the target force plate. The target was designed for left foot on the first force plate and right foot on the second force plate. Participants were also supplied with a portable CD player listening to a comedy during the walking experiment to conceal any noises associated with laboratory activities (e.g., noises from changing the floor surface).

Within a subsequent 20-minute session walking on the non-slippery surface, the participant's posture and ground reaction forces were recorded with motion analysis system and force plates, respectively. A slippery surface was randomly introduced to the participant after

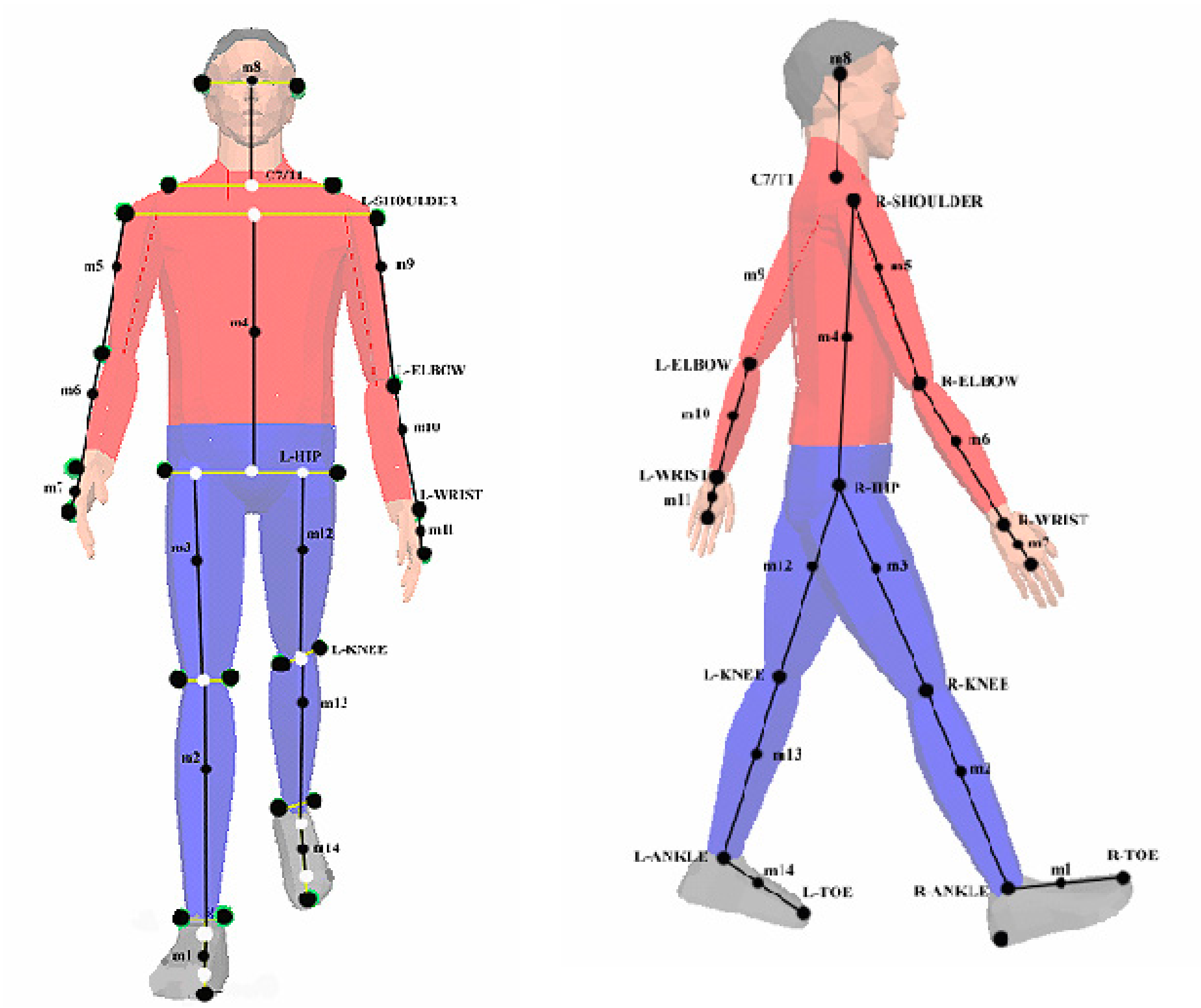


Figure 3.2 Reflective markers placements and internal landmarks (Lockhart et al., 2000b)

all kinetic (i.e. forces) and kinematic (i.e. dimension) profiles of walking pattern on non-slippery surface were collected. The slippery surface was introduced only once to the participant for the purpose of initiating an unexpected slip event. The kinetic and kinematic data for the slip test were also collected. Discrepancies between the appearance of the slippery and non-slippery surfaces were minimized (same vinyl tile and orientation).

3.3.2 Strength Session

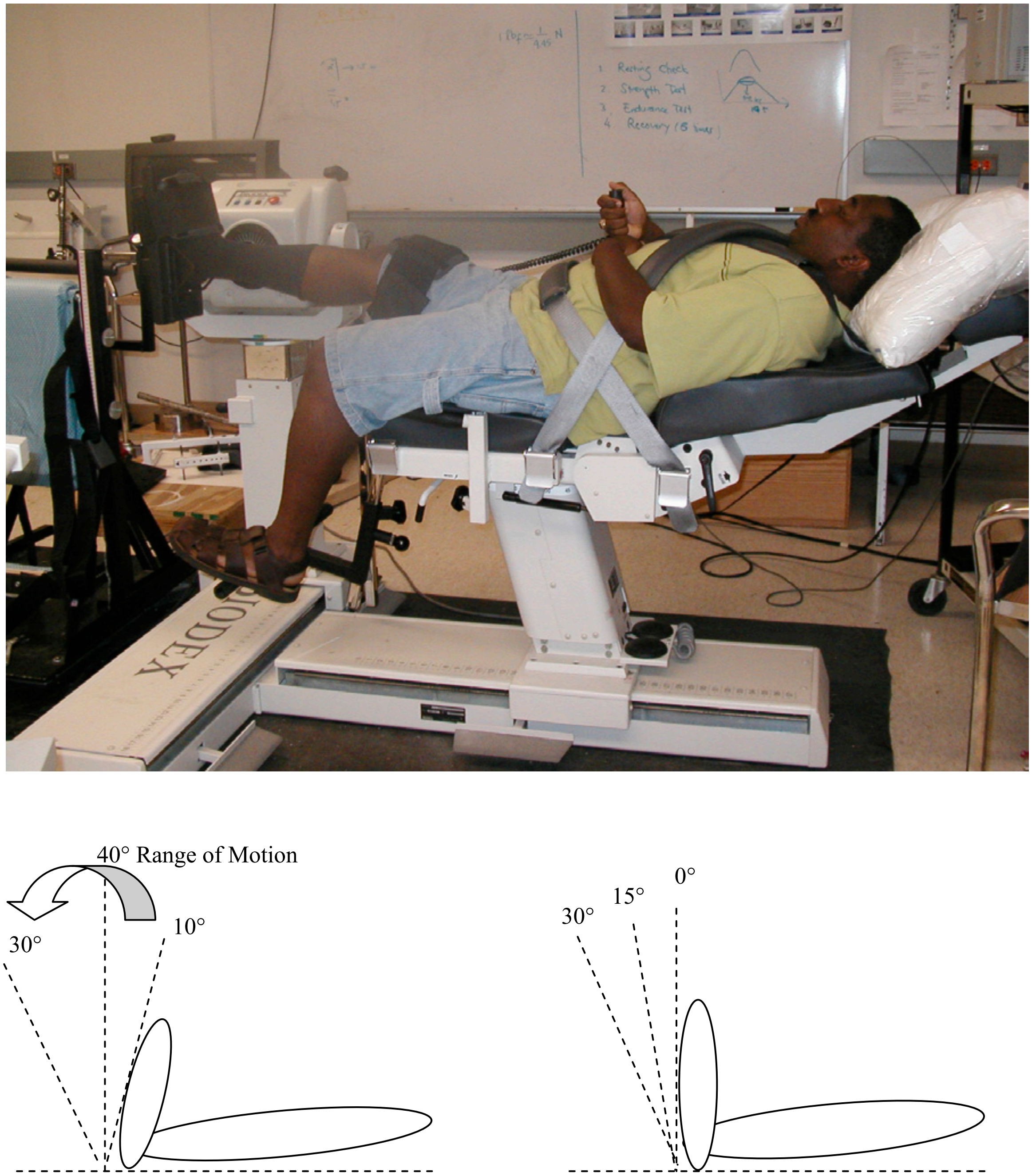
Anthropometric data of the participants (body weight and height with experimental shoes) were measured in this session. Participants were asked to walk on the track for 2-3 minutes before starting the strength test to warm up their muscles. The isokinetic and isometric strength test were measured for the participants' left and right ankles. Participants were moved into a recumbent position and the ankle axis of rotation was aligned with the dynamometer shaft by vertically adjusting the footplate. Figure 3.3 illustrates the BioDex dynamometer setup and position for ankle strength test.

3.3.2.1 Isokinetic Ankle Strength Test

The footplate was adjusted at 40 degrees for the total range of motion at the ankle joint axis: 10 degrees of dorsiflexion (flexion) and 30 degrees of plantarflexion (extension). Participants were instructed to push down against the footplate and pull back up "as hard as you can" continuously for approximately 5 seconds after a spoken cue. Participants were allowed to practice at least one trial before collecting data. Participants were asked to apply two dynamic maximum exertions at each of three levels randomly (30, 60, and 120 degrees per second). The rest periods were given after each exertion for 45 seconds. If the second exertion was different more than 10% of the first exertion, participants were asked to apply the third exertion. The highest plantar flexion torque of the two close torques in each testing level was recorded as the isokinetic strength.

3.3.2.2 Isometric Ankle Strength Test

The plantar flexor isometric ankle strength in participants' both feet, usually occurring at the heel contact phase of gait cycle, was tested. Participants were instructed to push "as hard as you can" for approximately 3 seconds after a spoken cue. Participants were allowed to



(a) Isokinetic at 30°/s, 60°/s, and 120°/s

(b) Isometric at 0°, 15°, and 30°

Figure 3.3 BioDex dynamometer setup and position for ankle strength test
(a) Isokinetic
(b) Isometric

practice at least one trial before collecting data. Participants were asked to apply two maximum voluntary exertions at each of three fixed angles randomly (0, 15, and 30 plantarflexed degrees). The rest periods were given after each exertion for 45 seconds. If the second exertion was different more than 10% of the first exertion, participants were asked to apply the third exertion. The highest plantar flexion torque of the two close torques in each tested angle was recorded as the isometric strength.

3.4 Experimental Variables

3.4.1 Independent Variables

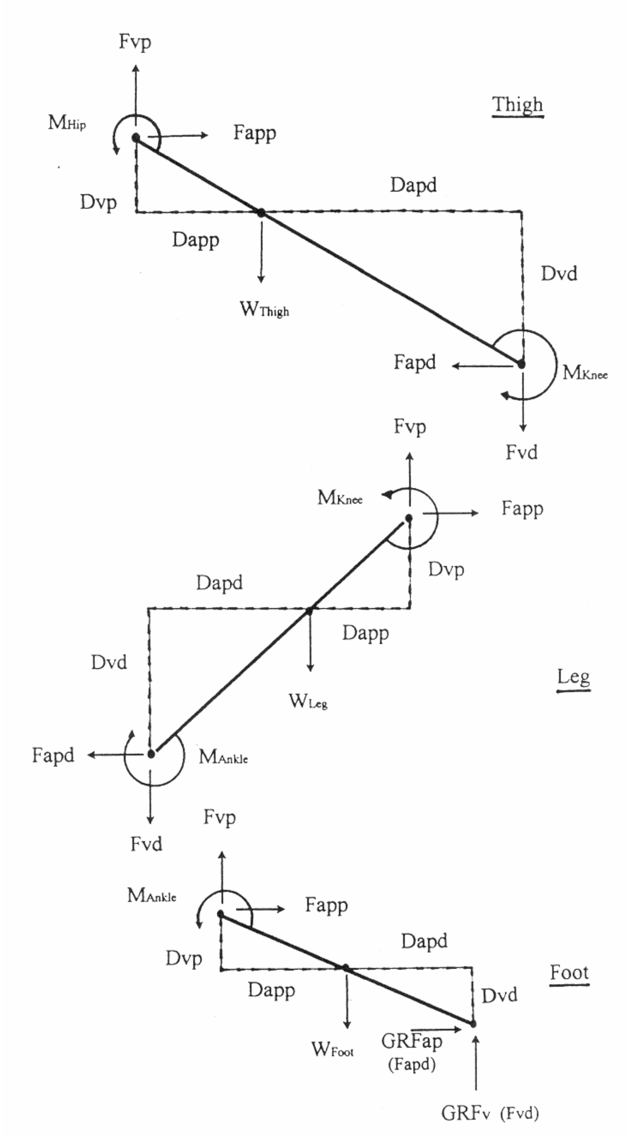
Two age groups (Between-Subjects) and gender (Between-Subjects) were independent variables in this study. Two age groups of participants consisted of younger age group (19-35 years old) and older age group (67-79 years old). Gender variable consisted of female group and male group.

3.4.2 Dependent Variables

3.4.2.1 Ankle Joint Power

The mathematical model from Winter et al. (1990) was utilized in this study to estimate the inertial characteristics of the lower extremity body segments. The model used the four-component-like-segment system defined by the reflective markers and the anthropometric model (Dempster, 1955; Hanavan, 1964) to compute joint reaction forces and net joint moments (torques) during walking via an inverse dynamic approach. Afterwards, joint powers were calculated as the product of the joint torques and angular velocities. The model has been described in detail by Winter et al. (1990). A free body diagram of the ankle segment was used to compute the ankle joint power (Figure 3.4). The ankle joint torques and powers exerted during a successful step (from heel contact phase to push-off phase) were compared between age groups and gender and were used to determine the relationship, if any, between ankle strength, ankle joint powers, and transitional velocity of the whole body center-of-mass. This comparison allowed for an estimation of the relative effort necessary for young and old participants to push their bodies forward during the experimental trials.

Several assumptions were required to compute estimates of ankle joint torque. These assumptions are necessary in order to solve the dynamic equations in the presence of multiple



From the information shown in the free body diagram, the equation for the net joint moment at each joint is given by:

$$M = (I * \alpha) + (Fvd * Dapd) + (Fapd * Dvd) + (Fvp * Dapp) + (Fapp * Dvp) + Md$$

M = net moment of force acting about the joint,
I = moment of inertial of the segment,
α = angular acceleration of the segment,
Fvd = vertical force at the distal end of segment (GRF or JRF),
Dapd = horizontal distance of Fvd from segment center of mass,
Fapd = horizontal (anterior-posterior) force at the distal end of segment (GRF or JRF),
Dvd = vertical distance of Fapd from segment center of mass,
Fvp = vertical JRF at the proximal end of segment,
Dapp = horizontal distance of Fvp from segment center of mass,
Fapp = horizontal (anterior-posterior) JRF at proximal end of segment,
Dvp = vertical distance of Fapp from segment center of mass,
Md = net moment computed from the preceding (distal) joint,
GRFv = vertical ground reaction force,
GRFap = anterior-posterior ground reaction force,
W = weight of the segment
COPap = anterior-posterior center of pressure.

Thus,

$$\boldsymbol{P = M\omega}$$

where, P = joint power (W)
M = net joint moment (Nm)
ω = joint angular velocity (rad/s)

Figure 3.4 Free body diagram of the foot (Adapted from Lockhart et al., 2001) indeterminacies which result from incomplete anthropometric information. The assumptions (Winter et al., 1990) included:

(a) The center of mass of each segment is represented by a single point (3-D coordinates) and its location remained fixed relative to the segment;
(b) Joints will be considered to have three dimensional rotation (frictionless hinge joints);
(c) The length and moment of inertia of each segment will remain constant throughout the movement; and
(d) Vertical ground reaction force (GRFv) and anterior-posterior ground reaction force (GRFap) acted through the calculated anterior-posterior center of pressure (COPap).

As computed, the sign polarity of the torque was based on a standard right-hand coordinate system, where counter clockwise torque was positive in sign. Generally, in order to improve the association of the torque signs with joint functions, the signs were converted to positive signs for plantar flexor torques.

Summary of Inverse Dynamics Procedure

1. Find the position of ankle joint in 3-D global coordinates.
2. Find the position of the center of mass of foot.
3. Calculate joint reaction forces at the ankle in global coordinates using Newton's second law of motion.
4. Transform joint reaction forces into local coordinates using the [R] matrix of the segment (for foot segment, use reaction forces-F_1 (Fx, Fy, Fz) collected from force plate and F_2 (Fx, Fy, Fz) calculated from weight of foot).
5. Determine distance r_1 (r_x, r_y, and r_z), a vector from joint reaction forces to joint center, and determine distance r_2 (r_x, r_y, and r_z), a vector from the segment center of mass to the joint center.
6. Transform distance vectors into local coordinates using the [R] metrix of the segment.
7. Calculate torques at the ankle joint by using the vector cross product of the joint reaction forces (F_1 and F_2) and the moment arms (distance r_1 and r_2).
8. Calculate net moment (M_x, M_y, M_z). The plantar flexion torque at the ankle joint is considered as M_y.

The ankle joint angular velocity was calculated by using the angle between knee-ankle axis (point from the middle of medial-lateral condyle to the middle of medial-lateral malleolus) and ankle-toe axis (point from the middle of medial-lateral malleolus to the toe) (Figure 3.5). The angular velocity utilized the linear finite difference equation during a successful step (from heel contact phase to push-off phase). The rotational velocity formula is as followed:

$$\omega = \Delta\theta / \Delta t$$

$$\omega_i = (\theta_{i+1} - \theta_{i-1}) / 2\Delta t$$

where θ is an ankle angle at frame i, ω is an angular velocity, and t is 1/120 second per frame.

3.4.2.2 Transitional Velocity of the Whole Body Center-of-Mass

The transitional velocity of the whole body COM was defined as the change of the horizontal COM velocity between heel contact phase to shortly after heel contact phase of the gait cycle (Lockhart et al., 2001). This change was calculated from the average whole body COM velocity 10 frames (1/12 second or approximately 83 ms) right after the heel contact to the average whole body COM velocity 10 frames (1/12 second or approximately 83 ms) right before the heel contact.

A 3-D link (14) segment model was used to calculate position and velocities of the whole body center of mass. The anatomical reflective markers locations, as shown in Figure 3.2, illustrate the frontal and sagittal models utilizing the 14 component-link-segment system defined by the reflective markers and the anthropometric model (Winter et al., 1990; Zatsiorsky et al., 1983, 1985). Body segment COM locations are based on data obtained from cadaveric studies, which are comprised of primarily elderly individuals. Each center-of-mass location may differ significantly between younger and older individuals due to physiological changes associated with aging (decreased in bone density, bone mass, muscle mass, etc.). Additionally, data on potential different COM locations for various age groups are currently unavailable. As a result, parameters dependent upon COM locations (such as the whole body COM location) therefore, may be affected. However, the transitional velocity of the whole body COM was aimed to compare the velocity changes right after and before the heel contact at the whole body COM location. It was assumed that the whole body COM in each individual was approximately calculated by the same 14 component-link-segment system.

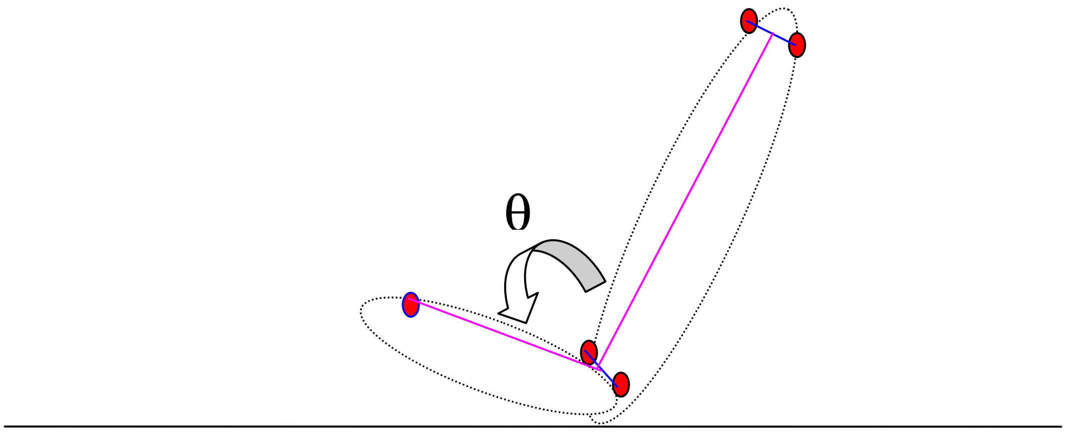


Figure 3.5 Ankle Angle

Generally, several assumptions are required to compute estimates of the whole body center of mass. The assumptions includes: (a) the human body can be represented by a set of 14 rigid bodies; (b) the center of mass of each segment is represented by a single point and its location remains fixed relative to the segment; (c) the anthropometric information used for the segment weights are representative of the body weights of interest; (d) the limbs move about fixed points when the body changes position; and (e) the limbs are connected by massless hinge joints. The basic theory is briefly introduced below:

Definition of Center-of-Mass: The centroid of an assemblage of n similar quantities, Δ_1, Δ_2,…, Δ_n, situated at points P_1, P_2, …, P_n, and having the position vectors r_1, r_2, …, r_n, has a position vector r:

$$r = \frac{\sum_{i=1}^{n} r_i \Delta_i}{\sum_{i=1}^{n} \Delta_i}.$$

The center of mass of an object is the location of the centroid of all mass elements, dm:

$$r_{COM} = \frac{\int r dm}{\int dm}.$$

Thus, the center-of-mass of an object is the location of the centroid of all gravitational forces, G, of its mass elements, dG:

$$r_{COG} = \frac{\int r dG}{\int dG}.$$

Utilizing the above definition, a whole body center-of-mass can be calculated by summing the moment of the whole body about the same axis assuming uniform density:

$$\mathrm{M\,x} = \sum_{i=1}^{14} m_i x_i$$

where m_1, m_2, …., m_{14} are the weights of the 14 segments; M is the weight of the body; and x_1, x_2, …., x_{14} are the respective distances of the center-of-gravity of the segments and whole body from the reference point (Table 3.3). Therefore,

$$X = \frac{1}{M}\sum_{i=1}^{14} m_i x_i .$$

Similar computations for the moments about the second axis (Y) and the third axis (Z) were performed to locate the 3-D whole body center of mass. Twenty-six reflective markers were used to define a whole body model. The locations of the external and extrapolated internal landmarks are shown in Figure 3.2. The internal and external 3-D landmarks allowed definition of a 14-segment whole body model which includes; foot, lower leg, thigh, trunk, upper arm, forearm, hand and head and neck segments in Table 3.3.

3.4.2.3 Friction Demand Characteristics

The required coefficient of friction (RCOF) was obtained by dividing the horizontal ground reaction force by the vertical ground reaction force after heel contact on the non-slippery surface (peak 3 as defined by Perkins and Wilson, 1983). Both vertical and horizontal forces were directly collected from two force plates during the heel contact phase of the gait cycle. Heel contact was defined as the time when the vertical ground reaction force exceeded 10 N. Generally, friction demand indicated where in the walking step a slip is most likely to occur. If the magnitude of this ratio exceeds the coefficient of friction between the two surfaces at a particular moment in time, a slip will occur (Perkins et al., 1983).

3.4.2.4 Slip Distance

Figure 3.6 illustrates a typical slip behavior starting from the heel contact phase (Gronqvist et al., 1989; Lockhart et al., 2000b). Initially, the horizontal heel position (Figure 3.6c) indicates that the heel does not slip forward. Shortly after heel contact (approximately 60 ms), the heel starts slipping forward. Figure 3.6b illustrates that the horizontal heel velocity decreases as the heel quickly decelerates (Figure 3.6a). The slip distance is the resultant slip distance traveled by the foot after the heel contact phase of the gait cycle.

Utilizing existing methods (Lockhart et al., 2000a, 2000b), slip distance was obtained using the heel coordinates between the slip-start (x_1, y_1) and slip-stop (x_2, y_2) points on the slippery floor surface. The x and y components represent the horizontal and lateral directions. The slip-start point was defined as the time where the first minimum of the vertical heel

Table 3.3 Definition of the 14 segments and the location of center-of-mass of the segments employed in 3-D (adapted from Lockhart et al., 2000b)

Segment	Segment Definition	Total Weight (% of Body Weight)	COM Location
Foot (m1, m14)	Extrapolating down 1.9 cm and perpendicular to the midpoint of the line between midpoint of markers placed on the lateral and medial malleolus (Subtalar) and the head metatarsal II	0.0145	Midpoint of the line between midpoint of markers placed on the lateral and medial malleolus and the head metatarsal II
Leg (m2, m13)	Mid point between medial and lateral femoral condyles / Subtalar	0.0465	43.3 % below femoral condyle markers
Thigh (m3, m12)	Extrapolating medially 19.7% of the distance between the right and left greater trochanter (HIP)/ Mid point between medial and lateral femoral condyles	0.1000	43.3 % below hip markers
Trunk (m4)	Mid point between the right and left hip markers/Mid point between the right and left shoulder markers	0.497	Midpoint between the line intersecting hip and shoulder
Upper arm (m5, m9)	Glenohumeral axis/elbow axis	0.028	43.6 % below glenohumeral axis
Forearm (m6, m10)	Elbow axis /ulnar styloid	0.016	43.0% below elbow axis
Hand (m7, m11)	Wrist axis / knuckle II middle finger	0.006	49.4 % above knuckle II middle finger
Head and Neck (m8)	Mid point between the right and left acromion of scapula (C7/T1)/ Mid point between the right and left 1st rib/ear markers	0.081	At the 1st rib/ear canal

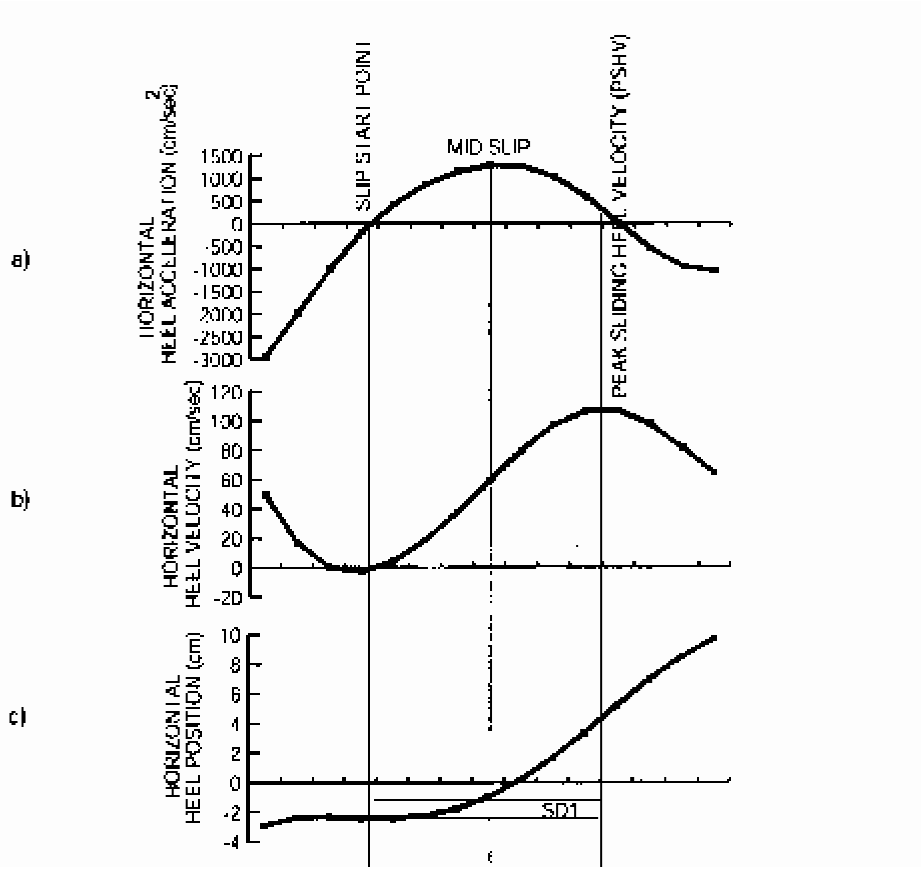


Figure 3.6 A typical slip behavior starting from the heel contact phase

velocity after the heel contact occurred. The mid-slip point was defined as the time where the first maximum horizontal heel acceleration occurred. Finally, the slip-stop point was defined as the time where the first maximum horizontal heel velocity occurred.

To investigate the initiation phase of the unexpected slip event, the slip distance was considered in two phases: the initial slip distance and the slip distance after peak acceleration. Initial slip distance (SD1) was defined as the resultant distance from the slip-start point to the mid-slip point. The slip distance after peak acceleration (SD2) was defined as the resultant distance from the mid-slip point to the slip-stop point. The resultant slip distance was calculated by utilizing the formula:

$$\mathrm{SD} = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}\,.$$

3.4.2.5 Sliding Heel Velocity

Relative sliding heel velocity (SHV) after heel contact was calculated to assess severity of slips and falls. Sliding heel velocity was calculated by averaging the instantaneous sliding heel velocity during the slip-start point to slip-stop point. The horizontal heel velocity (V) was obtained using finite difference methods. The linear finite difference equation uses the difference of the foot displacements of last 1/120 second (Δt) before and after the heel contact divided by the elapsed time (2Δt) using the following formula:

$$V = \Delta x / \Delta t$$

$$V_i = (X_{i+1} - X_{i-1}) / 2\Delta t$$

where x is a horizontal distance at frame i, V is a horizontal velocity, and t is 1/120 second per frame.

Relative horizontal heel acceleration (A) was also calculated by using finite difference formula with the same concept as the heel velocity. The linear finite difference equation uses the difference of the heel velocity of last 1/120 second (Δt) before and after the heel contact divided by the elapsed time (2Δt) using the following formula:

$$A = \Delta V / \Delta t$$

$$A_i = (V_{i+1} - V_{i-1}) / 2\Delta t$$

where V is a horizontal velocity at frame i, A is a horizontal acceleration, and t is 1/120 second per frame.

3.4.2.6 Frequency of Falls

In this study, frequency of falling was defined by using two gait parameters: slip distance and sliding heel velocity. A fall occurred when the total slip distance (slip-start point to slip-stop point) exceeds 10 centimeters and when the sliding heel velocity exceeds the whole body COM velocity during slipping (Lockhart et al., 2001).

3.5 Data Analyses

3.5.1 ANOVA

The effects of age and gender were evaluated using 2 x 2 two-way repeated measures analyses of variance (ANOVA) on each dependent variables with $\alpha = 0.05$. For these analyses, both age groups and gender were treated as between-subject effects. Effects were considered significant when $p \leq 0.05$.

The statistical structural model for this design was;

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_{k\,(ij)} + \alpha\beta_{ij} + \varepsilon_{l\,(ijk)}$$

(i [age] = 1 to 2; j [gender] = 1 to 2; k [subject] = 1 to 7) where,

α_i = fixed effect of the age groups (factor A);

β_j = fixed effect of gender (factor B);

$\gamma_{k\,(ij)}$ = effect of the subjects (random) in each group (7 subjects in 4 groups; old male, old female, young male, and young female);

$\alpha\beta_{ij}$ = interaction effects of the age groups and gender (A x B);

$\varepsilon_{l\,(ijk)}$ = random effect of the variables.

3.5.2 Correlation Analysis

Bivariate correlation analyses were performed to describe the relationships between independent variable and dependent variables (e.g., ankle strength, ankle joint power, transitional velocity of the whole body center-of-mass, friction demand, slip distance, sliding heel velocity).

CHAPTER 4
RESULTS

4.1 Treatment of Data

The ankle strength was analyzed by 2 x 2 two-way (age x gender) multivariate analyses of variance (MANOVA). In addition, independent measures (e.g., ankle joint torque, ankle joint power, transitional velocity of the whole body center-of-mass, friction demand, slip distance, and sliding heel velocity) were analyzed by 2 x 2 two-way repeated measures analyses of variance (ANOVA). Bivariate correlation analyses were performed to describe the relationships between independent and dependent variables. Post-hoc means separation test (Tukey-Kramer) was performed on all significant differences (age, gender, interactions). The statistical package, JMP, was utilized for all data analyses. Results were considered significant at $\alpha \leq 0.05$.

4.2 MANOVA Results

The findings from MANOVA analyses are summarized under the following headings: overall means, age comparisons, gender comparisons, and interactions. All different levels of ankle strength tests were analyzed in four categories: isokinetic-right ankle, isokinetic-left ankle, isometric-right ankle, and isometric-left ankle. Post-hoc means separation test (Tukey-Kramer) utilizing one-way ANOVA was performed on all significant differences (age, gender, interactions). Summary of the MANOVA results are listed on Table 4.1.

Table 4.1 Summary of MANOVA Results

Variables (unit)	Young Mean (S.D.)	Old Mean (S.D.)
*ISOK$_{right}$ - 30°/s (Nm)	70.57 (19.20)	50.57 (16.40)
- 60°/s (Nm)	52.67 (15.66)	41.09 (12.13)
- 120°/s (Nm)	35.66 (9.06)	30.91 (10.11)
ISOK$_{left}$ - 30°/s (Nm)	56.33 (14.74)	52.20 (15.63)
- 60°/s (Nm)	47.02 (16.50)	43.06 (17.21)
- 120°/s (Nm)	34.98 (11.47)	33.02 (10.98)
*ISOM$_{right}$ - 0° (Nm)	73.15 (11.99)	60.75 (16.68)
- 15° (Nm)	52.45 (8.11)	40.32 (8.57)
- 30° (Nm)	40.32 (7.75)	25.60 (5.80)
ISOM$_{left}$ - 0° (Nm)	69.84 (25.09)	68.22 (22.19)
- 15° (Nm)	49.61 (11.61)	48.54 (15.01)
- 30° (Nm)	35.05 (9.98)	26.30 (8.04)

* significant difference between age groups

4.2.1 Isokinetic Right Ankle Strength ($ISOK_{right}$)

4.2.1.1 Overall Means

The results indicated statistically significant differences ($F_{3, 24} = 7.4796$, $p = 0.0053$) between each level: 30°/s, 60°/s, and 120°/s. The average of $ISOK_{right}$ at 30°/s was 60.57 Nm (20.18 Nm); the average of $ISOK_{right}$ at 60°/s was 46.88 Nm (14.87 Nm); and the average of $ISOK_{right}$ at 120°/s was 33.29 Nm (9.66 Nm) (Figure 4.1). Furthermore, Tukey-Kramer post-hoc test indicated that there was a significant difference between each level ($p < 0.05$). In general, $ISOK_{right}$ at 30°/s was significantly higher than $ISOK_{right}$ at 60°/s and $ISOK_{right}$ at 120°/s. $ISOK_{right}$ at 60°/s was also significantly higher than $ISOK_{right}$ at 120°/s.

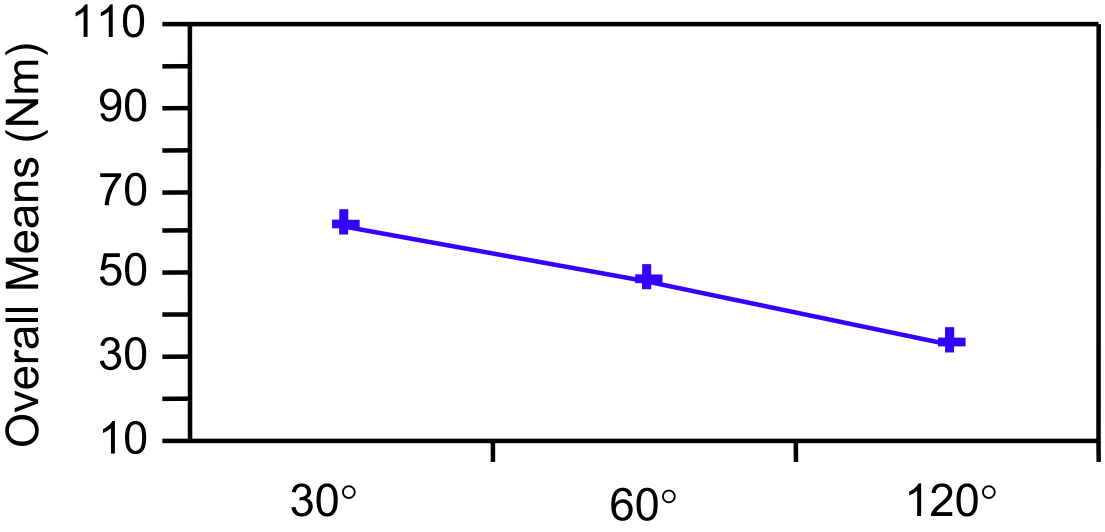


Figure 4.1 Overall means of $ISOK_{right}$ at 30°/s, 60°/s, and 120°/s

4.2.1.2 Age Comparisons

The results indicated statistically significant differences ($F_{1,24} = 5.2839$, $p = 0.0421$) between the two age groups. In general, younger individuals' $ISOK_{right}$ at all levels were higher than their older counterparts (Table 4.2 and Figure 4.2). Furthermore, Tukey-Kramer post-hoc test indicated that there was a significant difference between $ISOK_{right}$ at 30°/s and $ISOK_{right}$ at 120°/s ($p < 0.01$). In general, $ISOK_{right}$ at 30°/s was significantly higher than $ISOK_{right}$ at 120°/s for both age groups. There were no significant differences between $ISOK_{right}$ at 30°/s and $ISOK_{right}$ at 60°/s and between $ISOK_{right}$ at 60°/s and $ISOK_{right}$ at 120°/s.

Table 4.2 Descriptive summary of $ISOK_{right}$ (Nm) on main effect age

Age	Count	30°/s	60°/s	120°/s
Old	14	50.57 (16.40)	41.09 (12.13)	30.91 (10.11)
Young	14	70.57 (19.20)	52.67 (15.66)	35.66 (9.06)

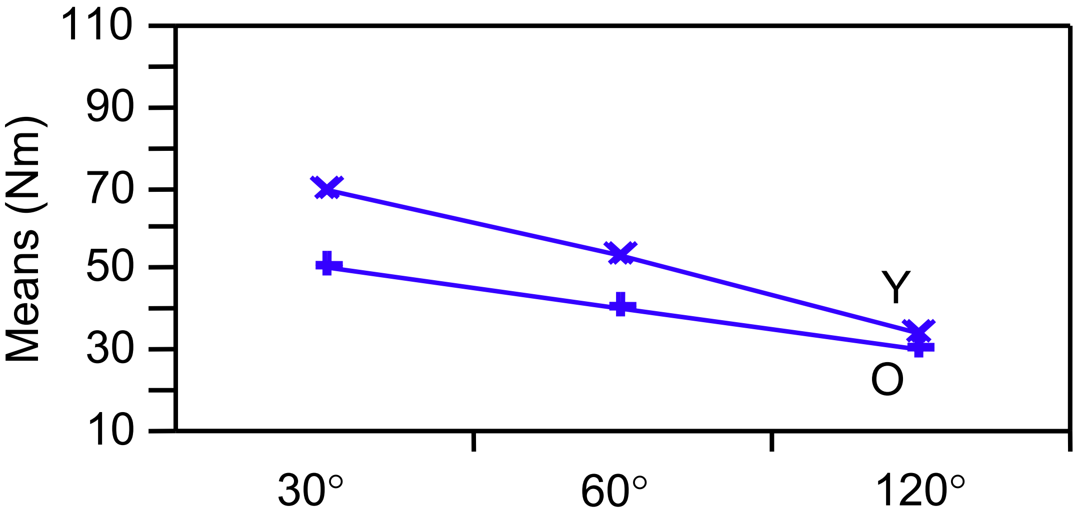


Figure 4.2 Age effect on $ISOK_{right}$ at 30°/s, 60°/s, and 120°/s

4.2.1.3 Gender Comparisons

The results indicated statistically significant differences ($F_{1, 24} = 10.9618$, $p = 0.0069$) between female and male participants. In general, male individuals' $ISOK_{right}$ at all levels were higher than their female counterparts (Table 4.3 and Figure 4.3). Furthermore, Tukey-Kramer post-hoc test indicated that there was a significant difference between $ISOK_{right}$ at 30°/s and $ISOK_{right}$ at 120°/s ($p < 0.05$). In general, $ISOK_{right}$ at 30°/s was significantly higher than $ISOK_{right}$ at 120°/s for both gender groups. There were no significant differences between $ISOK_{right}$ at 30°/s and $ISOK_{right}$ at 60°/s and between $ISOK_{right}$ at 60°/s and $ISOK_{right}$ at 120°/s.

Table 4.3 Descriptive summary of $ISOK_{right}$ (Nm) on main effect gender

Gender	Count	30°/s	60°/s	120°/s
Male	14	72.26 (19.49)	56.83 (14.27)	40.07 (8.41)
Female	14	48.88 (13.29)	36.93 (6.57)	26.50 (4.89)

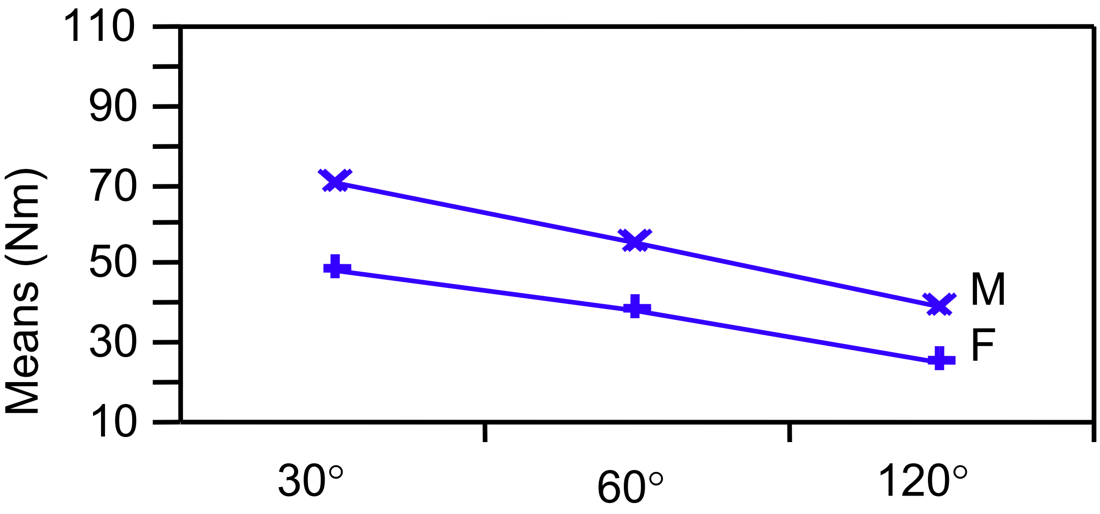


Figure 4.3 Gender effect on $ISOK_{right}$ at 30°/s, 60°/s, and 120°/s

4.2.1.4 Interactions

The results indicated no statistically significant age and gender interactions ($F_{1, 24}$ = 0.7113, p = 0.4169) (Table 4.4).

Table 4.4 Descriptive summary of $ISOK_{right}$ (Nm) on age and gender interactions

Interactions	Count	30°/s	60°/s	120°/s
Old Male	7	60.99 (17.45)	48.09 (12.52)	37.93 (9.24)
Old Female	7	40.14 (5.36)	34.09 (7.19)	23.88 (4.60)
Young Male	7	83.51 (15.28)	65.56 (10.53)	42.21 (7.89)
Young Female	7	57.63 (13.32)	39.78 (5.02)	29.12 (3.94)

4.2.2 Isokinetic Left Ankle Strength (ISOK$_{left}$)

4.2.2.1 Overall Means

The results indicated statistically significant differences ($F_{3, 24} = 4.2830$, $p = 0.0312$) between each level: 30°/s, 60°/s, and 120°/s. The average of ISOK$_{left}$ at 30°/s was 54.26 Nm (14.94 Nm); the average of ISOK$_{left}$ at 60°/s was 45.04 Nm (16.53 Nm); and the average of ISOK$_{left}$ at 120°/s was 33.99 Nm (10.97 Nm) (Figure 4.4). Furthermore, Tukey-Kramer post-hoc test indicated that there was a significant difference between each level ($p < 0.05$). The result indicated that ISOK$_{left}$ at 30°/s was significantly higher than ISOK$_{left}$ at 120°/s. There were no significant differences between ISOK$_{left}$ at 30°/s and ISOK$_{left}$ at 60°/s and between ISOK$_{left}$ at 60°/s and ISOK$_{left}$ at 120°/s.

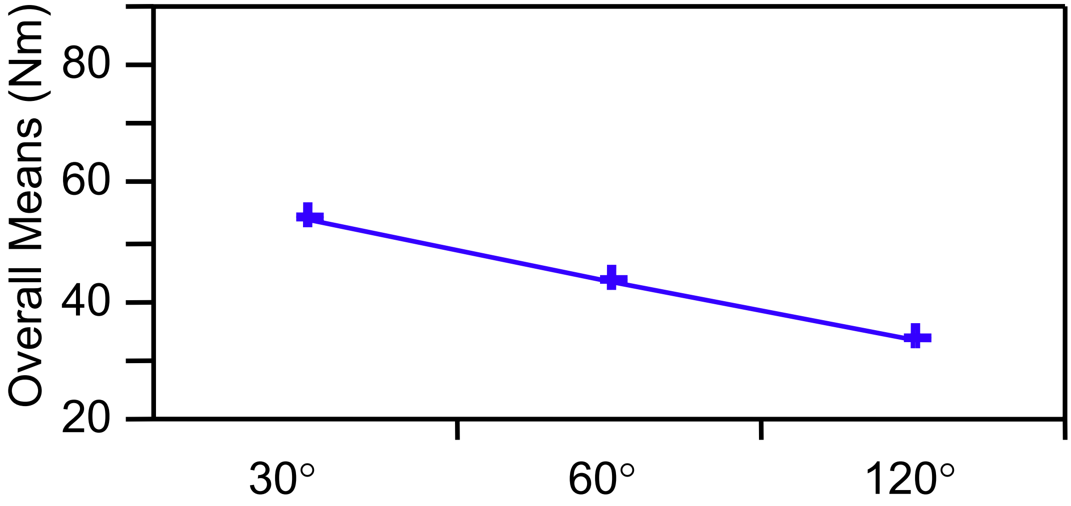


Figure 4.4 Overall means of ISOK$_{left}$ at 30°/s, 60°/s, and 120°/s

4.2.2.2 Age Comparisons

The results indicated no statistically significant differences ($F_{1,24} = 2.7171$, $p = 0.1275$) between the two age groups (Table 4.5 and Figure 4.5).

Table 4.5 Descriptive summary of $ISOK_{left}$ (Nm) on main effect age

Age	Count	30°/s	60°/s	120°/s
Old	14	52.20 (15.63)	43.06 (17.21)	33.02 (10.98)
Young	14	56.33 (14.74)	47.02 (16.50)	34.98 (11.47)

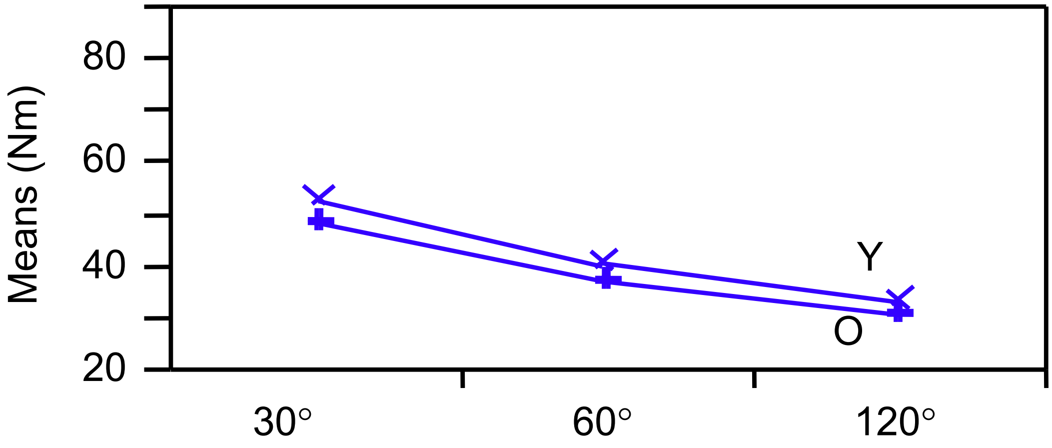


Figure 4.5 Age effect on $ISOK_{left}$ at 30°/s, 60°/s, and 120°/s

4.2.2.3 Gender Comparisons

The results indicated statistically significant differences ($F_{1, 24} = 9.3645$, $p = 0.0108$) between female and male participants. In general, male individuals' $ISOK_{left}$ at all levels were higher than their female counterparts (Table 4.6 and Figure 4.6). Furthermore, Tukey-Kramer post-hoc test indicated that there was a significant difference between $ISOK_{left}$ at 30°/s and $ISOK_{left}$ at 120°/s ($p < 0.01$). In general, $ISOK_{left}$ at 30°/s was significantly higher than $ISOK_{left}$ at 120°/s for both gender groups. There were no significant differences between $ISOK_{left}$ at 30°/s and $ISOK_{left}$ at 60°/s and between $ISOK_{left}$ at 60°/s and $ISOK_{left}$ at 120°/s.

Table 4.6 Descriptive summary of $ISOK_{left}$ (Nm) on main effect gender

Gender	Count	30°/s	60°/s	120°/s
Male	14	63.20 (13.46)	55.04 (17.85)	40.75 (10.74)
Female	14	45.32 (10.60)	35.04 (6.04)	27.24 (6.12)

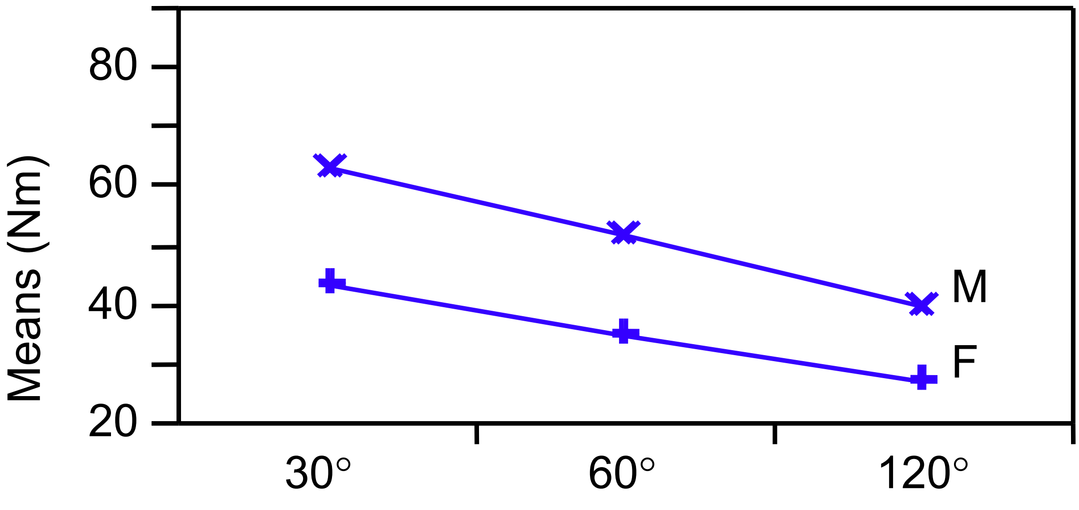


Figure 4.6 Gender effect on $ISOK_{left}$ at 30°/s, 60°/s, and 120°/s

4.2.2.4 Interactions

The results indicated no statistically significant age and gender interactions ($F_{1,24}$ = 0.3117, p = 0.5878) (Table 4.7).

Table 4.7 Descriptive summary of $ISOK_{left}$ (Nm) on age and gender interactions

Interactions	Count	30°/s	60°/s	120°/s
Old Male	7	61.68 (12.14)	53.91 (18.23)	40.50 (10.03)
Old Female	7	42.72 (13.32)	32.22 (6.33)	25.53 (5.51)
Young Male	7	64.73 (15.94)	56.17 (19.52)	41.00 (12.59)
Young Female	7	47.93 (7.63)	37.87 (4.71)	28.95 (6.83)

4.2.3 Isometric Right Ankle Strength (ISOM$_{right}$)

4.2.3.1 Overall Means

The results indicated statistically significant differences ($F_{3, 24} = 10.5822$, $p = 0.0011$) between each level: 0°, 15°, and 30°. The average of ISOM$_{right}$ at 0° was 66.95 Nm (15.50 Nm); the average of ISOM$_{right}$ at 15° was 46.38 Nm (10.23 Nm); and the average of ISOM$_{right}$ at 30° was 32.96 Nm (10.07 Nm) (Figure 4.7). Furthermore, Tukey-Kramer post-hoc test indicated that there was a significant difference between each level ($p < 0.0005$). ISOM$_{right}$ at 0° was significantly higher than ISOM$_{right}$ at 15° and ISOM$_{right}$ at 30°. ISOM$_{right}$ at 15° was also significantly higher than ISOM$_{right}$ at 30°.

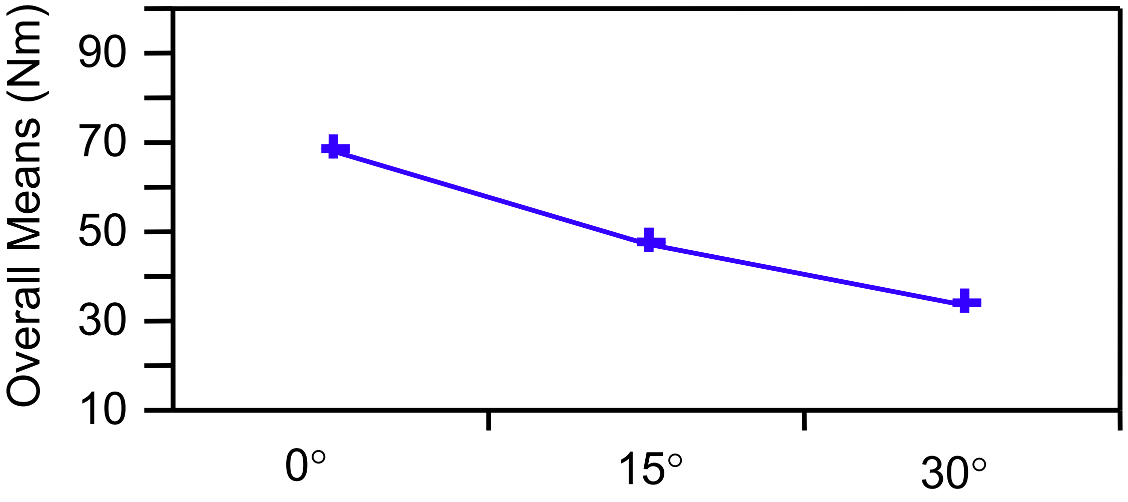


Figure 4.7 Overall means of ISOM$_{right}$ at 0°, 15°, and 30°

4.2.3.2 Age Comparisons

The results indicated statistically significant differences ($F_{1, 24} = 18.8417$, $p = 0.0010$) between the two age groups. In general, younger individuals' $ISOM_{right}$ at all levels were higher than their older counterparts (Table 4.8 and Figure 4.8). Furthermore, Tukey-Kramer post-hoc test indicated that there was a significant difference between each level ($p < 0.0001$). In general, $ISOM_{right}$ at 0° was significantly higher than $ISOM_{right}$ at 15° and $ISOM_{right}$ at 30° for both age groups. Additionally, $ISOM_{right}$ at 15° was also significantly higher than $ISOM_{right}$ at 30°.

Table 4.8 Descriptive summary of $ISOM_{right}$ (Nm) on main effect age

Age	Count	0°	15°	30°
Old	14	60.75 (16.68)	40.32 (8.57)	25.60 (5.80)
Young	14	73.15 (11.99)	52.45 (8.11)	40.32 (7.75)

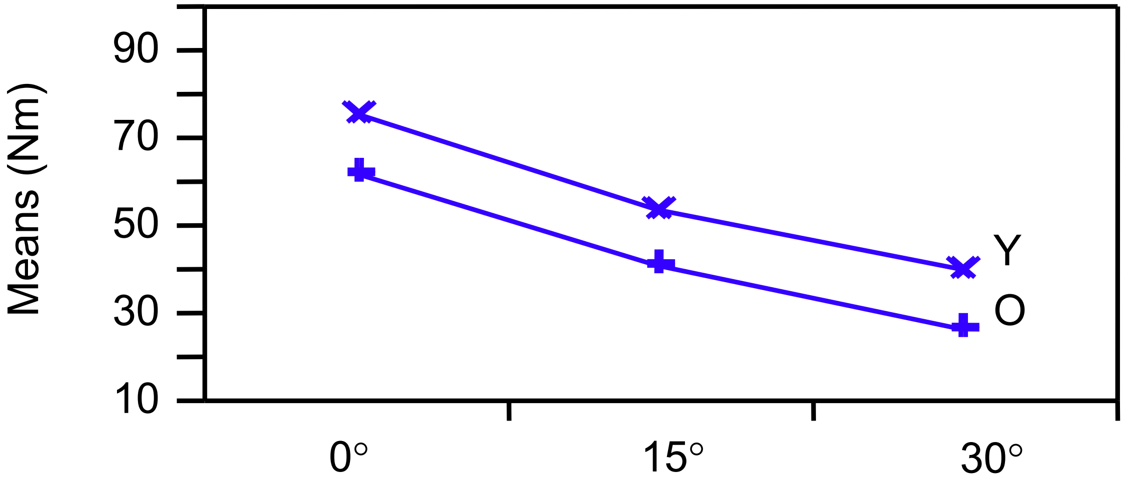


Figure 4.8 Age effect on $ISOM_{right}$ at 0°, 15°, and 30°

4.2.3.3 Gender Comparisons

The results indicated statistically significant differences ($F_{1, 24} = 9.8160$, $p = 0.0086$) between female and male participants. In general, male individuals' $ISOM_{right}$ at all levels were higher than their female counterparts (Table 4.9 and Figure 4.9). Furthermore, Tukey-Kramer post-hoc test indicated that there was a significant difference between each level ($p < 0.0005$). In general, $ISOM_{right}$ at 0° was significantly higher than $ISOM_{right}$ at 15° and $ISOM_{right}$ at 30° for both age groups. Additionally, $ISOM_{right}$ at 15° was also significantly higher than $ISOM_{right}$ at 30°.

Table 4.9 Descriptive summary of $ISOM_{right}$ (Nm) on main effect gender

Gender	Count	0°	15°	30°
Male	14	74.94 (13.54)	49.97 (11.24)	36.65 (11.26)
Female	14	58.95 (13.48)	42.79 (8.13)	29.27 (7.55)

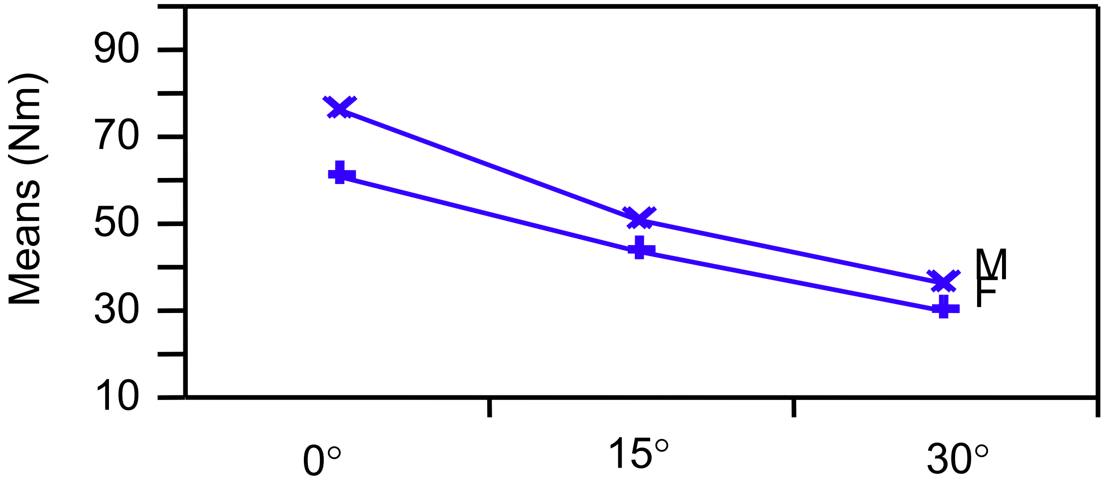


Figure 4.9 Gender effect on $ISOM_{right}$ at 0°, 15°, and 30°

4.2.3.4 Interactions

The results indicated no statistically significant age and gender interactions ($F_{1, 24}$ = 2.5715, p = 0.1348) (Table 4.10).

Table 4.10 Descriptive summary of $ISOM_{right}$ (Nm) on age and gender interactions

Interactions	Count	0°	15°	30°
Old Male	7	70.22 (12.83)	42.72 (8.91)	27.06 (6.44)
Old Female	7	51.28 (15.39)	37.91 (37.92)	24.14 (5.37)
Young Male	7	79.67 (13.86)	57.22 (57.22)	46.25 (3.67)
Young Female	7	66.63 (4.99)	47.67 (4.24)	34.39 (5.82)

4.2.4 Isometric Left Ankle Strength ($ISOM_{left}$)

4.2.4.1 Overall Means

The results indicated no statistically significant differences ($F_{3, 24} = 1.0478$, $p = 0.4070$) between each level: 0°, 15°, and 30°. In general, the average of $ISOM_{left}$ at 0° was 67.53 Nm (23.06 Nm); the average of $ISOM_{left}$ at 15° was 49.07 Nm (13.07 Nm); and the average of $ISOM_{left}$ at 30° was 30.67 Nm (9.89 Nm) (Figure 4.10).

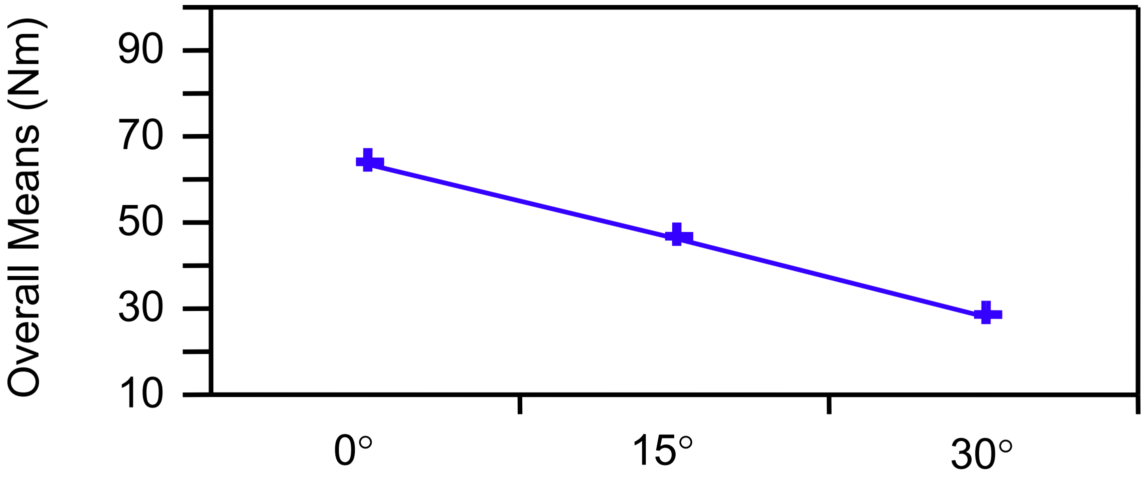


Figure 4.10 Overall means of $ISOM_{left}$ at 0°, 15°, and 30°

4.2.4.2 Age Comparisons

The results indicated no statistically significant differences ($F_{1, 24} = 0.0392$, $p = 0.8464$) between the two age groups (Table 4.11 and Figure 4.11).

Table 4.11 Descriptive summary of $\text{ISOM}_{\text{left}}$ (Nm) on main effect age

Age	Count	0°	15°	30°
Old	14	68.22 (22.19)	48.54 (15.01)	26.30 (8.04)
Young	14	69.84 (25.09)	49.61 (11.61)	35.05 (9.98)

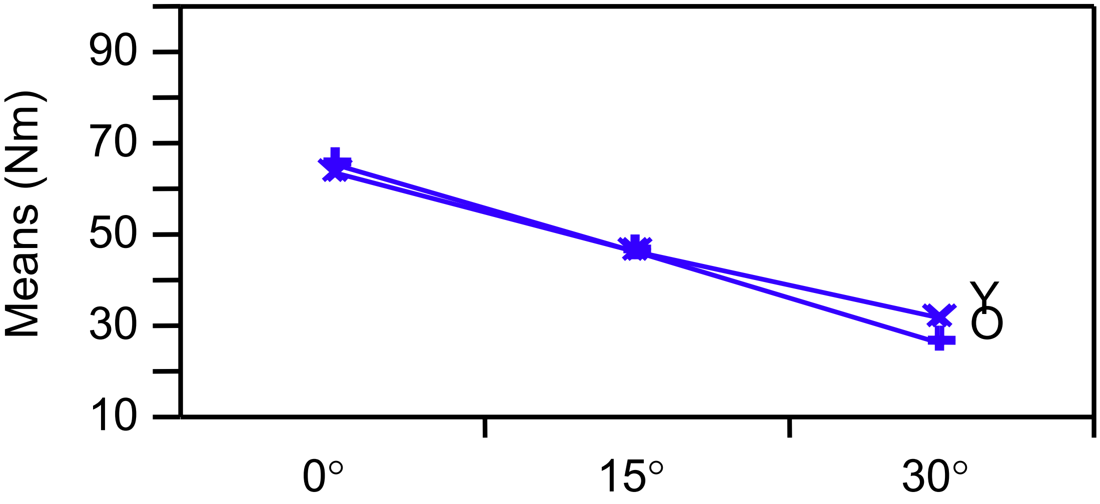


Figure 4.11 Age effect on $\text{ISOM}_{\text{left}}$ at 0°, 15°, and 30°

4.2.4.3 Gender Comparisons

The results indicated no statistically significant differences ($F_{1, 24}$ = 2.7398, p = 0.1238) between female and male participants (Table 4.12 and Figure 4.12).

Table 4.12 Descriptive summary of $\text{ISOM}_{\text{left}}$ (Nm) on main effect gender

Gender	Count	0°	15°	30°
Male	14	77.76 (26.35)	55.29 (14.43)	33.20 (11.59)
Female	14	57.30 (14.05)	42.86 (8.16)	28.15 (7.63)

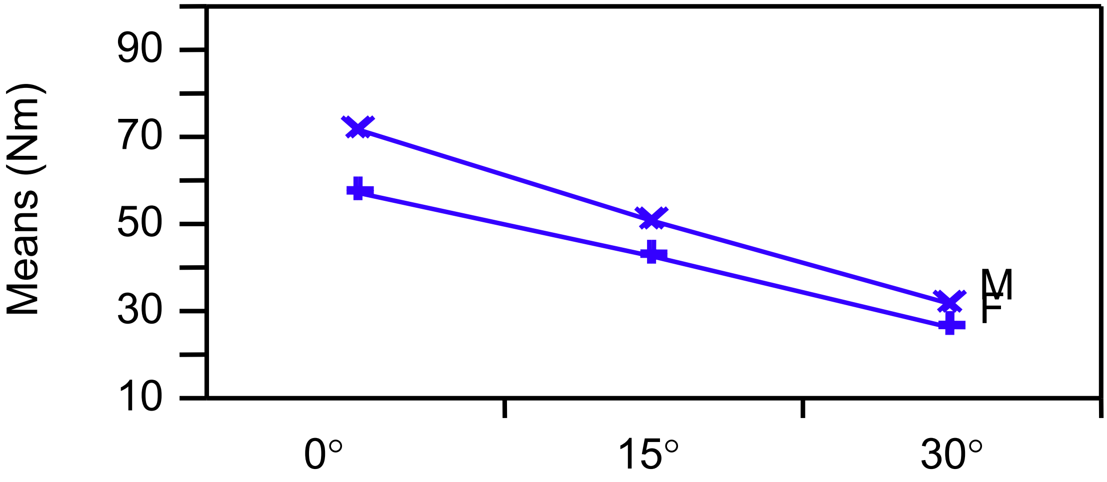


Figure 4.12 Gender effect on $\text{ISOM}_{\text{left}}$ at 0°, 15°, and 30°

4.2.4.4 Interactions

The results indicated no statistically significant age and gender interactions ($F_{1, 24}$ = 0.1420, p = 0.7129) (Table 4.13).

Table 4.13 Descriptive summary of $\text{ISOM}_{\text{leftt}}$ (Nm) on age and gender interactions

Interactions	Count	0°	15°	30°
Old Male	7	76.43 (22.09)	54.87 (14.61)	28.19 (9.52)
Old Female	7	58.83 (19.99)	39.66 (9.81)	24.37 (6.74)
Young Male	7	81.54 (32.77)	56.92 (15.61)	38.16 (12.24)
Young Female	7	66.29 (6.22)	52.06 (5.29)	31.93 (7.06)

4.3 ANOVA Results

The findings from ANOVA analyses are summarized under the following headings: age comparisons, gender comparisons, and interactions. All dependent variables in this study were analyzed with 2 x 2 two-way repeated measures (age x gender) analysis of variance. Summary of the ANOVA results are listed on Table 4.14.

Table 4.14 Summary of ANOVA Results

Variables (unit)	Young Mean (S.D.)	Old Mean (S.D.)
*Ankle Joint Torque (Nm/kg)	1.06 (0.07)	0.98 (0.06)
*Ankle Joint Power (W/kg)	1.10 (0.26)	0.93 (0.11)
COM_{Before} (mm/s)	1293.24 (125.90)	1192.25 (182.49)
COM_{After} (mm/s)	1365.37 (129.45)	1242.53 (183.15)
*COM_{Diff} (mm/s)	72.13 (16.38)	50.27 (28.28)
*RCOF	0.18 (0.02)	0.15 (0.02)
SDI (mm)	25.17 (13.52)	26.88 (35.57)
SDII (mm)	83.39 (54.40)	103.96 (157.05)
Total SD (mm)	108.56 (60.61)	130.84 (192.47)
SHV (mm/s)	681.47 (314.55)	576.92 (522.89)
*COM_{Slip} (mm/s)	1460.56 (126.77)	1259.99 (199.58)

* significant difference between age groups

4.3.1 Ankle Joint Torque

4.3.1.1 Age Comparisons

The results indicated statistically significant differences ($F_{1, 24} = 12.2503$, $p = 0.0030$) between the two age groups. In general, younger individuals' ankle joint torque was higher than their older counterparts (Table 4.15 and Figure 4.13).

Table 4.15 Descriptive summary of ankle joint torque (Nm/kg) on main effect age

Age	Count	Mean	Std. Dev.
Old	14	0.976592914	0.059946002
Young	14	1.062687117	0.07073801

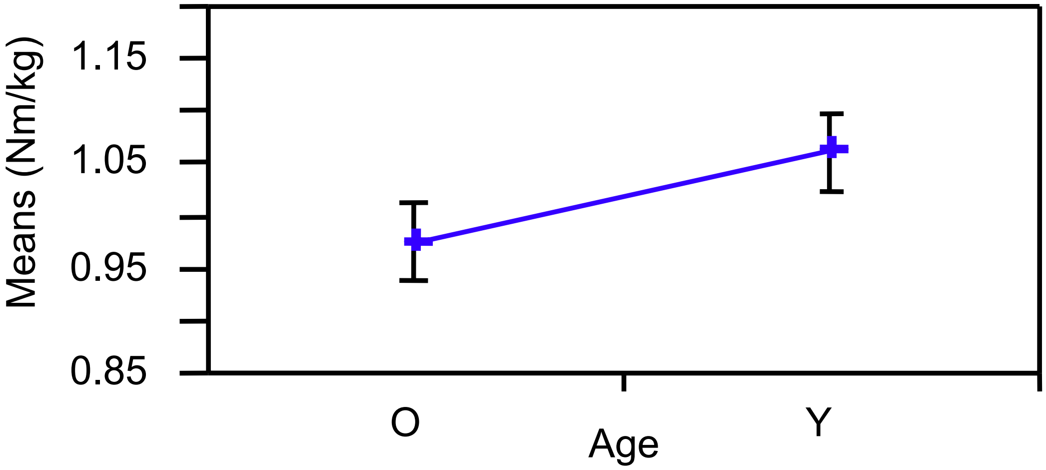


Figure 4.13 Age effect on ankle torque

4.3.1.2 Gender Comparisons

The results indicated statistically significant differences ($F_{1,24} = 9.5074$, $p = 0.0071$) between female and male participants. In general, male individuals' ankle joint torque was higher than their female counterparts (Table 4.16 and Figure 4.14).

Table 4.16 Descriptive summary of ankle joint torque (Nm/kg) on main effect gender

Gender	Count	Mean	Std. Dev.
Male	14	1.057562882	0.060527272
Female	14	0.981717149	0.076523584

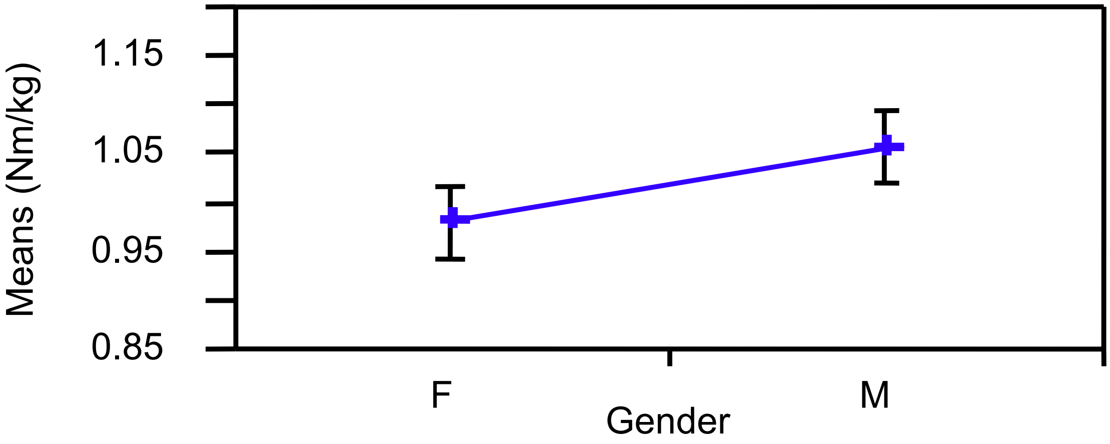


Figure 4.14 Gender effect on ankle joint torque

4.3.1.3 Interactions

The results indicated no statistically significant age and gender interactions ($F_{1, 24}$ = 0.0689, p = 0.7962) (Table 4.17 and Figure 4.15).

Table 4.17 Descriptive summary of ankle joint torque (Nm/kg) on age and gender interactions

Interactions	Count	Mean	Std. Dev.
Old Male	7	1.011286265	0.036883724
Old Female	7	0.941899563	0.060958563
Young Male	7	1.103839499	0.039099444
Young Female	7	1.021534735	0.074135928

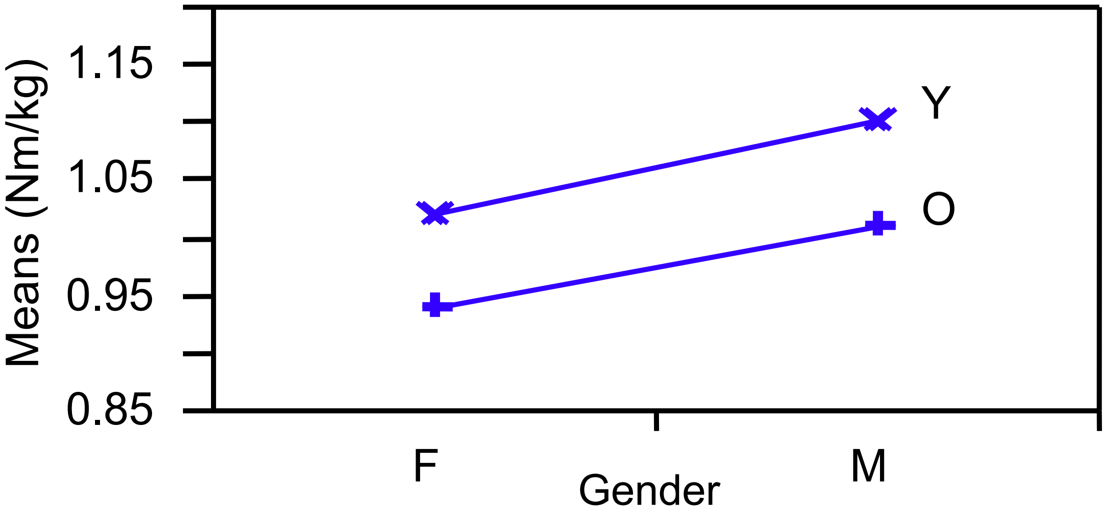


Figure 4.15 Interactions effect on ankle joint torque

4.3.2 Ankle Joint Power

4.3.2.1 Age Comparisons

The results indicated statistically significant differences ($F_{1,24} = 4.6431$, $p = 0.0505$) between the two age groups. In general, younger individuals' ankle joint power was higher than their older counterparts (Table 4.18 and Figure 4.16).

Table 4.18 Descriptive summary of ankle joint power (W/kg) on main effect age

Age	Count	Mean	Std. Dev.
Old	14	0.926712296	0.113020705
Young	14	1.102626463	0.259204347

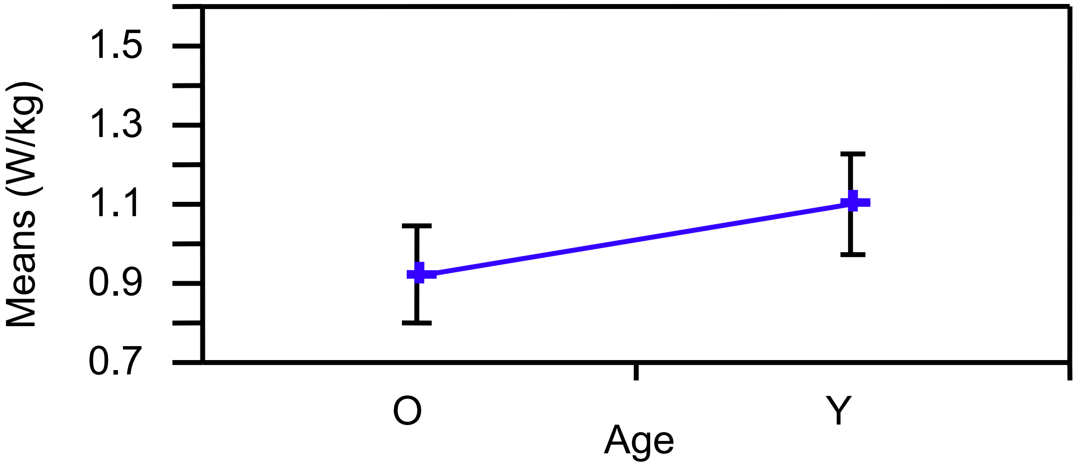


Figure 4.16 Age effect on ankle joint power

4.3.2.2 Gender Comparisons

The results indicated no statistically significant differences ($F_{1, 24} = 1.8702$, $p = 0.1904$) between female and male participants (Table 4.19 and Figure 4.17).

Table 4.19 Descriptive summary of ankle joint power (W/kg) on main effect gender

Gender	Count	Mean	Std. Dev.
Male	14	0.956950646	0.190914301
Female	14	1.072388113	0.230870491

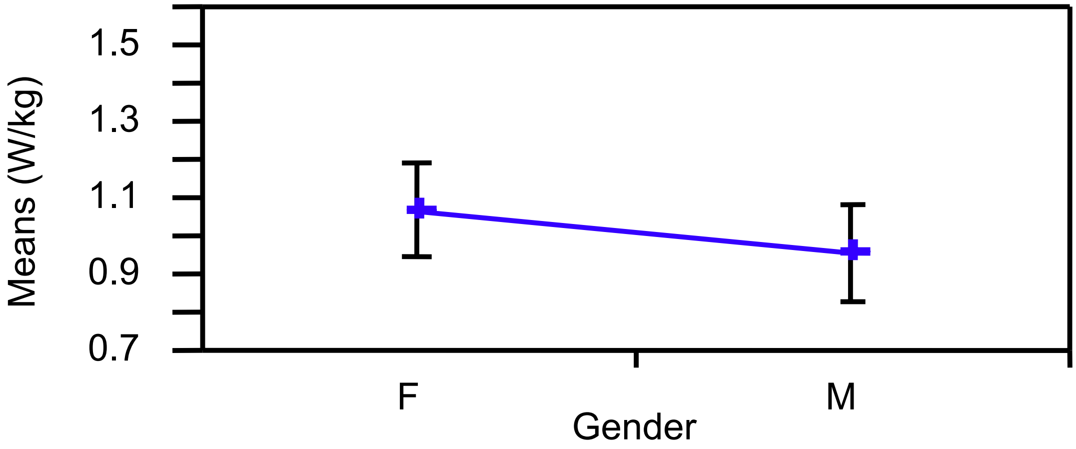


Figure 4.17 Gender effect on ankle joint power

4.3.2.3 Interactions

The results indicated no statistically significant age and gender interactions ($F_{1, 24}$ = 2.3297, p = 0.1465) (Table 4.20 and Figure 4.18).

Table 4.20 Descriptive summary of ankle joint power (W/kg) on age and gender interactions

Interactions	Count	Mean	Std. Dev.
Old Male	7	0.93341296	0.138218366
Old Female	7	0.920011632	0.097592088
Young Male	7	0.980488332	0.248030713
Young Female	7	1.224764594	0.228816451

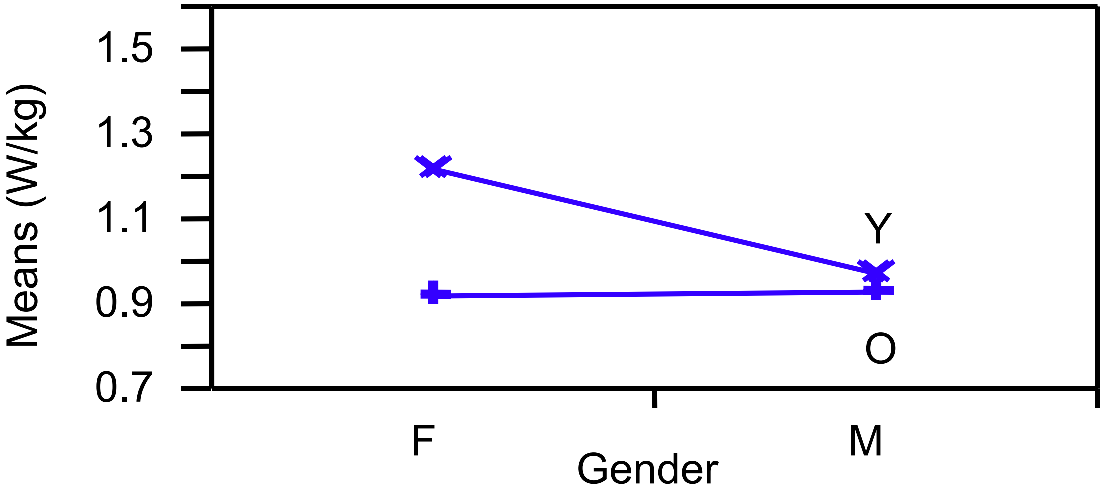


Figure 4.18 Interactions effect on ankle joint power

4.3.3 Horizontal Velocity of the Whole Body COM Before Heel Contact (COM_{Before})

4.3.3.1 Age Comparisons

The results indicated no statistically significant differences ($F_{1, 24} = 2.7565$, $p = 0.1163$) between the two age groups (Table 4.21 and Figure 4.19).

Table 4.21 Descriptive summary of COM_{Beofre} (mm/s) on main effect age

Age	Count	Mean	Std. Dev.
Old	14	1192.251164	182.491073
Young	14	1293.241818	125.9037068

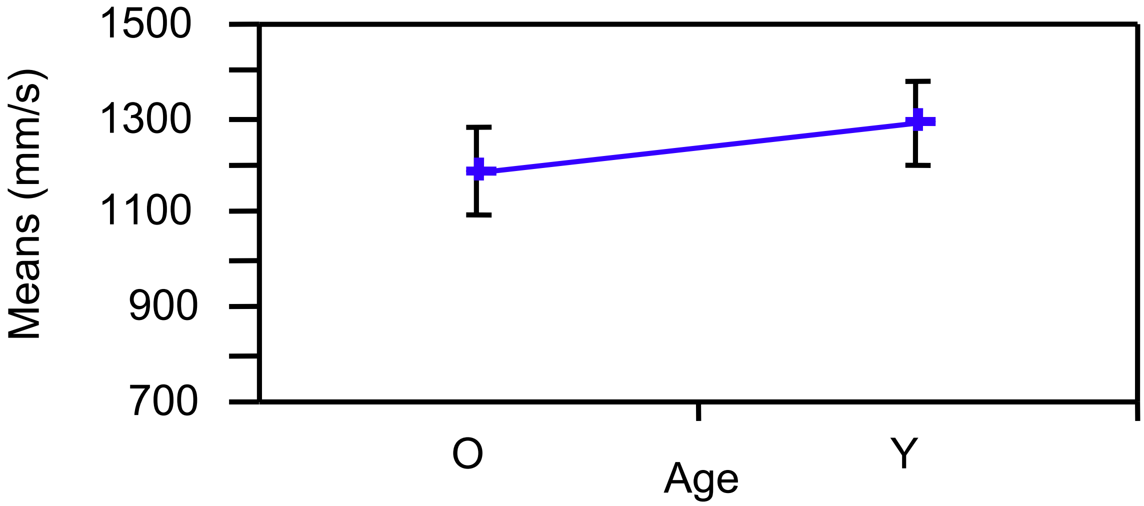


Figure 4.19 Age effect on COM_{Before}

4.3.3.2 Gender Comparisons

The results indicated statistically significant differences ($F_{1, 24} = 7.9107$, p = 0.0125) between female and male participants. In general, female individuals' COM_{Before} was higher than male individuals (Table 4.22 and Figure 4.20).

Table 4.22 Descriptive summary of COM_{Before} (mm/s) on main effect gender

Gender	Count	Mean	Std. Dev.
Male	14	1157.203709	165.1354909
Female	14	1328.289273	106.2540215

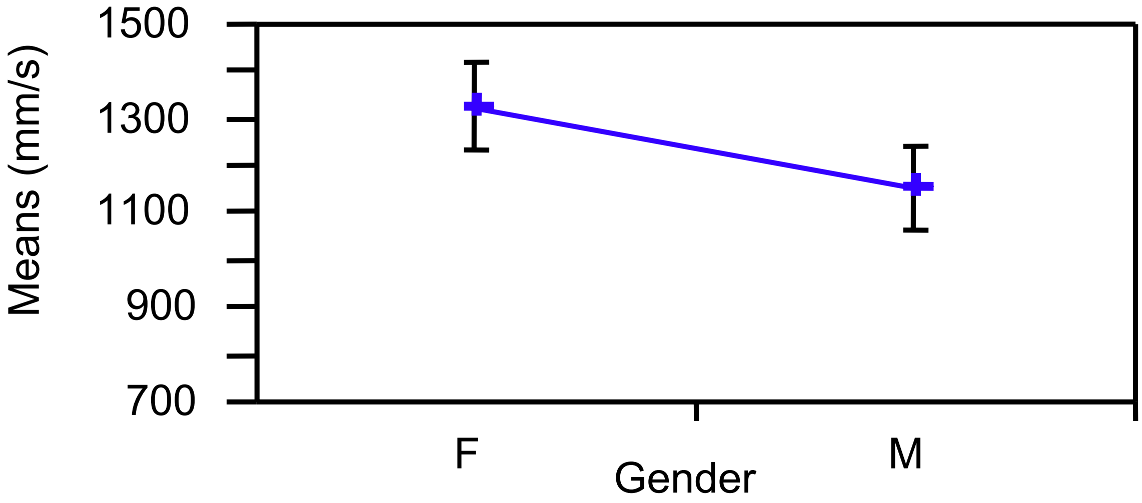


Figure 4.20 Gender effect on COM_{Before}

4.3.3.3 Interactions

The results indicated no statistically significant age and gender interactions ($F_{1, 24}$ = 0.0019, p = 0.9662) (Table 4.23 and Figure 4.21).

Table 4.23 Descriptive summary of COM_{Before} (mm/s) on age and gender interactions

Interactions	Count	Mean	Std. Dev.
Old Male	7	1105.399418	205.149908
Old Female	7	1279.102909	118.2674189
Young Male	7	1209.008	112.0767468
Young Female	7	1377.475636	73.25902769

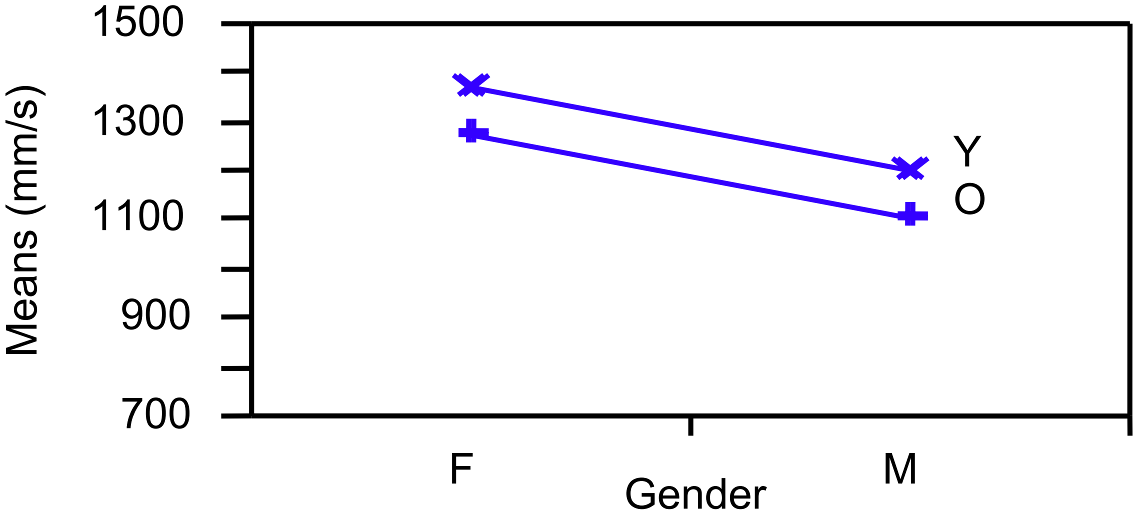


Figure 4.21 Interactions effect on COM_{Before}

4.3.4 Horizontal Velocity of the Whole Body COM After Heel Contact (COM_{After})

4.3.4.1 Age Comparisons

The results indicated no statistically significant differences ($F_{1, 24} = 3.7048$, $p = 0.0722$) between the two age groups (Table 4.24 and Figure 4.22).

Table 4.24 Descriptive summary of COM_{After} (mm/s) on main effect age

Age	Count	Mean	Std. Dev.
Old	14	1242.5258	183.1548943
Young	14	1365.3726	129.451876

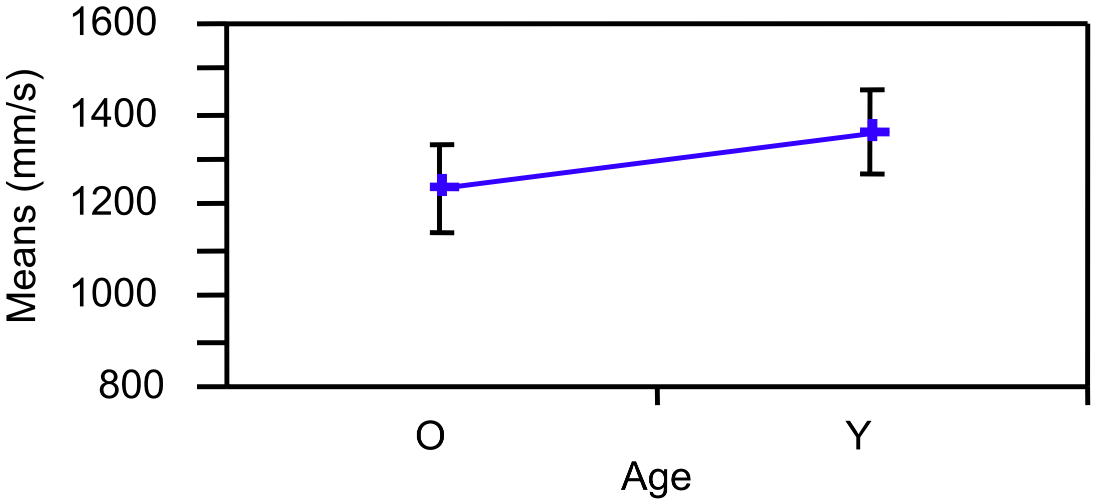


Figure 4.22 Age effect on COM_{After}

4.3.4.2 Gender Comparisons

The results indicated statistically significant differences ($F_{1,24} = 6.2052$, $p = 0.0241$) between female and male participants. In general, female individuals' COM_{After} was higher than male individuals (Table 4.25 and Figure 4.23).

Table 4.25 Descriptive summary of COM_{After} (mm/s) on main effect gender

Gender	Count	Mean	Std. Dev.
Male	14	1224.456	174.2657327
Female	14	1383.4424	119.4840415

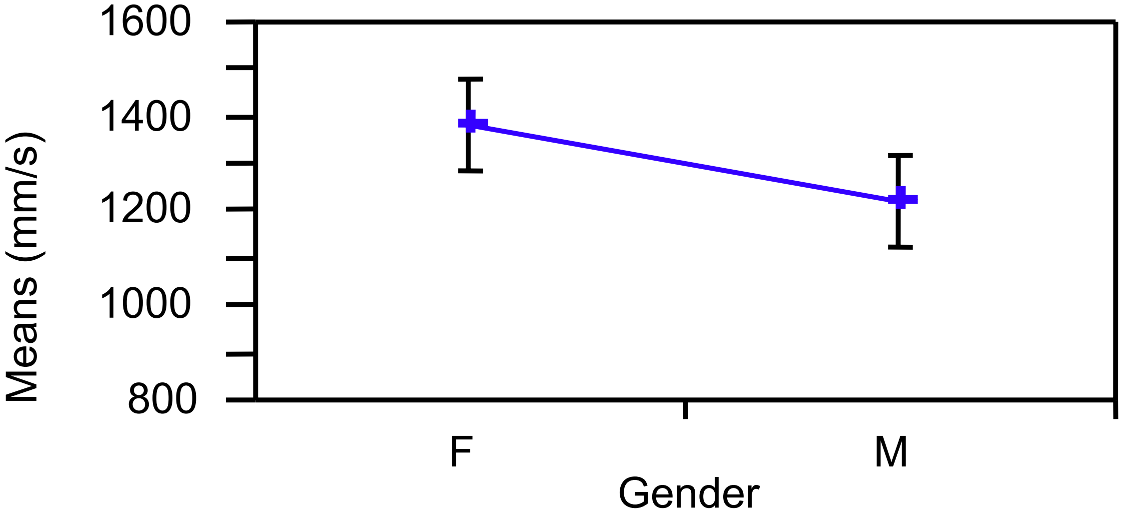


Figure 4.23 Gender effect on COM_{After}

4.3.4.3 Interactions

The results indicated no statistically significant age and gender interactions ($F_{1, 24}$ = 0.0231, p = 0.8810) (Table 4.26 and Figure 4.24).

Table 4.26 Descriptive summary of COM_{After} (mm/s) on age and gender interactions

Interactions	Count	Mean	Std. Dev.
Old Male	7	1167.8868	215.3617043
Old Female	7	1317.1648	123.1655185
Young Male	7	1281.0252	118.1032512
Young Female	7	1449.72	77.2685952

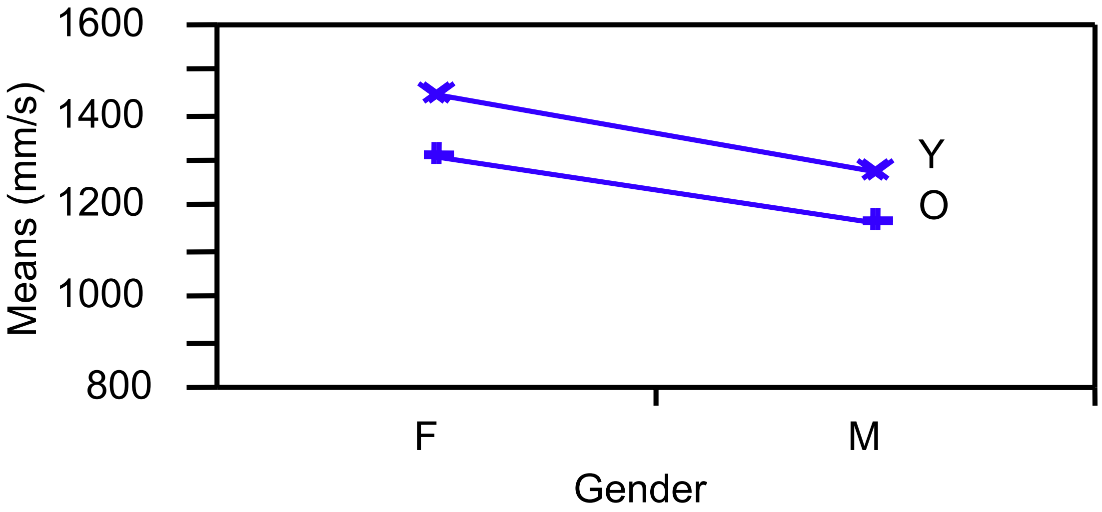


Figure 4.24 Interactions effect on COM_{After}

4.3.5 Transitional Velocity of the Whole Body COM (COM_{Diff})

4.3.5.1 Age Comparisons

The results indicated statistically significant differences ($F_{1, 24} = 4.7046$, $p = 0.0455$) between the two age groups. In general, younger individuals' transitional velocity of the whole body center-of-mass (COM_{Diff}) was higher than their older counterparts (Table 4.27 and Figure 4.25).

Table 4.27 Descriptive summary of COM_{Diff} (mm/s) on main effect age

Age	Count	Mean	Std. Dev.
Old	14	50.27463636	28.28248289
Young	14	72.13078182	16.38260439

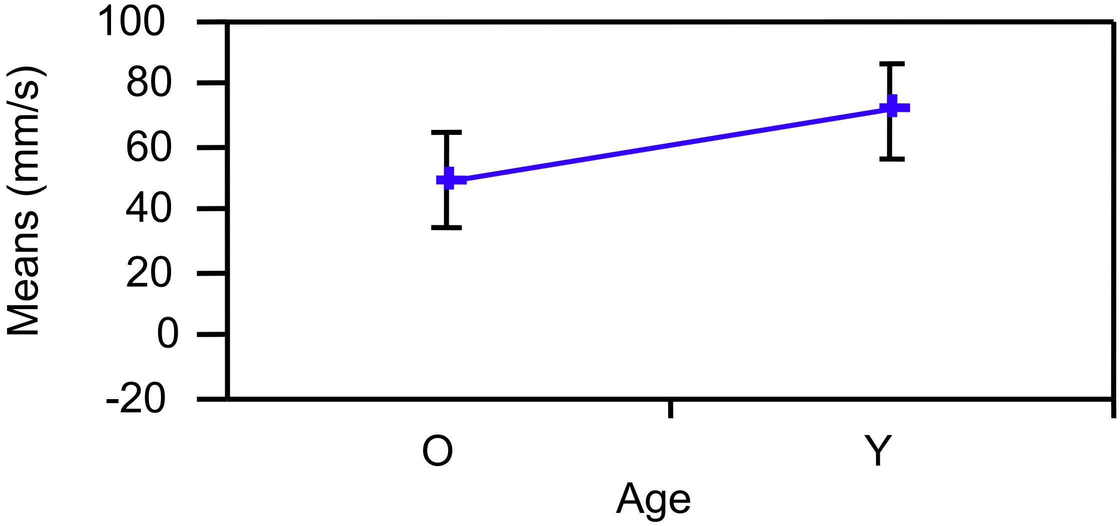


Figure 4.25 Age effect on COM_{Diff}

4.3.5.2 Gender Comparisons

The results indicated no statistically significant differences ($F_{1, 24} = 1.4417$, $p = 0.2473$) between female and male participants (Table 4.28 and Figure 4.26).

Table 4.28 Descriptive summary of COM_{Diff} (mm/s) on main effect gender

Gender	Count	Mean	Std. Dev.
Male	14	67.25229091	14.72464964
Female	14	55.15312727	32.17964504

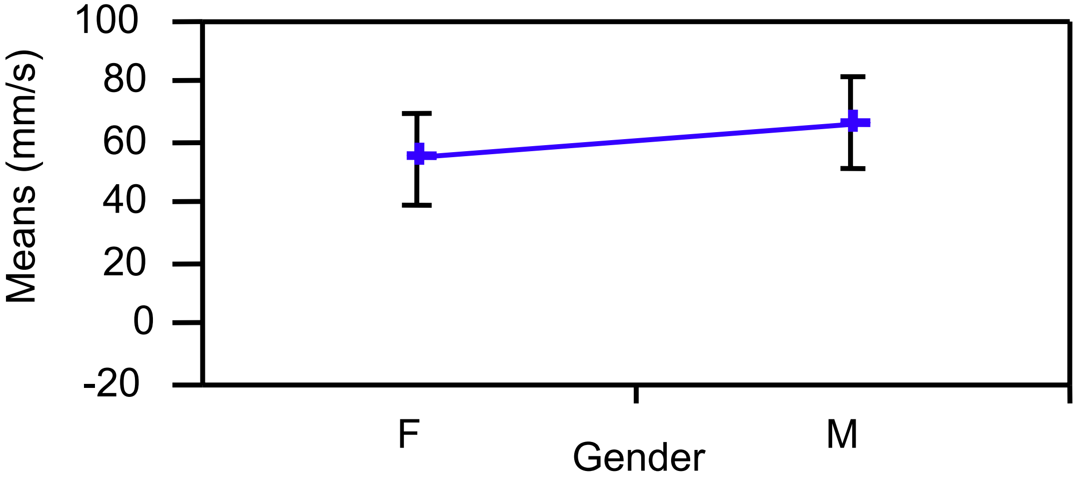


Figure 4.26 Gender effect on COM_{Diff}

4.3.5.3 Interactions

The results indicated no statistically significant age and gender interactions ($F_{1,\,24}$ = 1.4964, p = 0.2389) (Table 4.29 and Figure 4.27).

Table 4.29 Descriptive summary of COM_{Diff} (mm/s) on age and gender interactions

Interactions	Count	Mean	Std. Dev.
Old Male	7	62.48738182	11.49616895
Old Female	7	38.06189091	35.98239302
Young Male	7	72.0172	17.28906138
Young Female	7	72.24436364	17.46233058

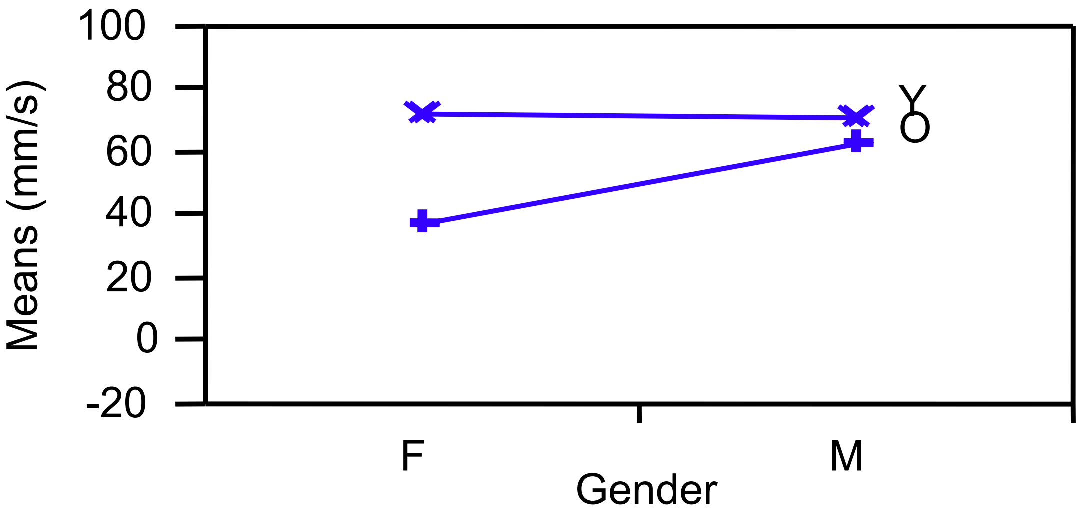


Figure 4.27 Interactions effect on COM_{Diff}

4.3.6 Friction Demand (RCOF)

4.3.6.1 Age Comparisons

The results indicated statistically significant differences ($F_{1, 24} = 10.8013$, $p = 0.0046$) between the two age groups. In general, younger individuals' RCOF was higher than their older counterparts (Table 4.30 and Figure 4.28).

Table 4.30 Descriptive summary of RCOF on main effect age

Age	Count	Mean	Std. Dev.
Old	14	0.151918698	0.022076206
Young	14	0.180054829	0.020758022

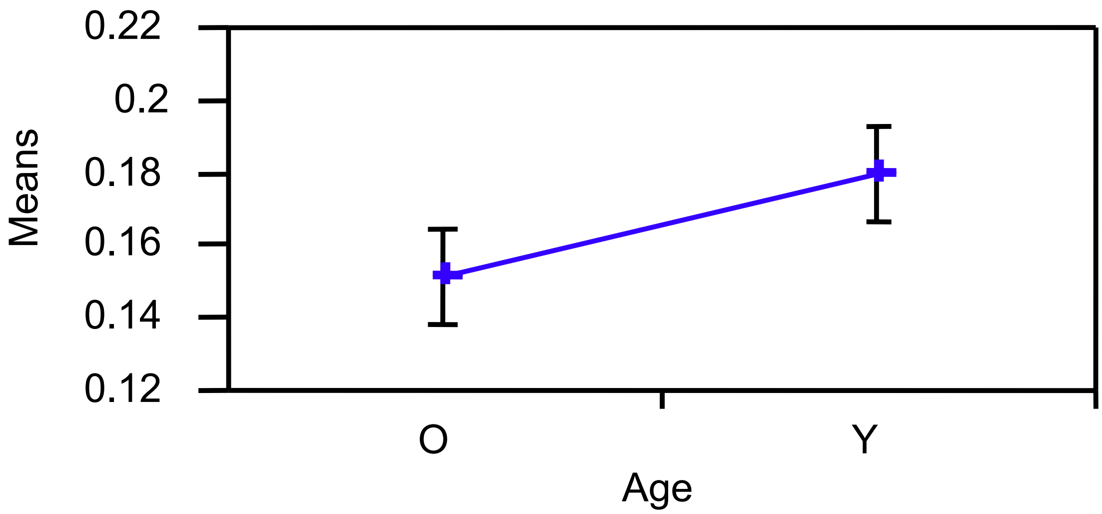


Figure 4.28 Age effect on RCOF

4.3.6.2 Gender Comparisons

The results indicated no statistically significant differences ($F_{1, 24} = 2.2989$, $p = 0.1490$) between female and male participants (Table 4.31 and Figure 4.29).

Table 4.31 Descriptive summary of RCOF on main effect gender

Gender	Count	Mean	Std. Dev.
Male	14	0.159496542	0.019632816
Female	14	0.172476985	0.029647956

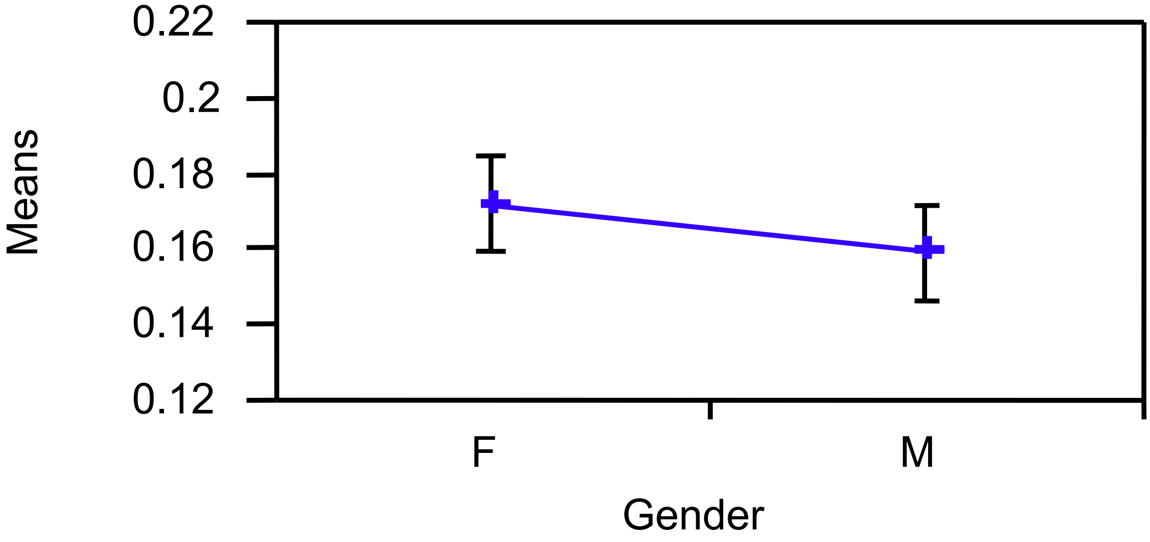


Figure 4.29 Gender effect on RCOF

4.3.6.3 Interactions

The results indicated no statistically significant age and gender interactions ($F_{1, 24}$ = 4.2529, p = 0.0558) (Table 4.32 and Figure 4.30).

Table 4.32 Descriptive summary of RCOF on age and gender interactions

Interactions	Count	Mean	Std. Dev.
Old Male	7	0.154256047	0.025846251
Old Female	7	0.14958135	0.020368378
Young Male	7	0.164737037	0.011426774
Young Female	7	0.195372621	0.015885741

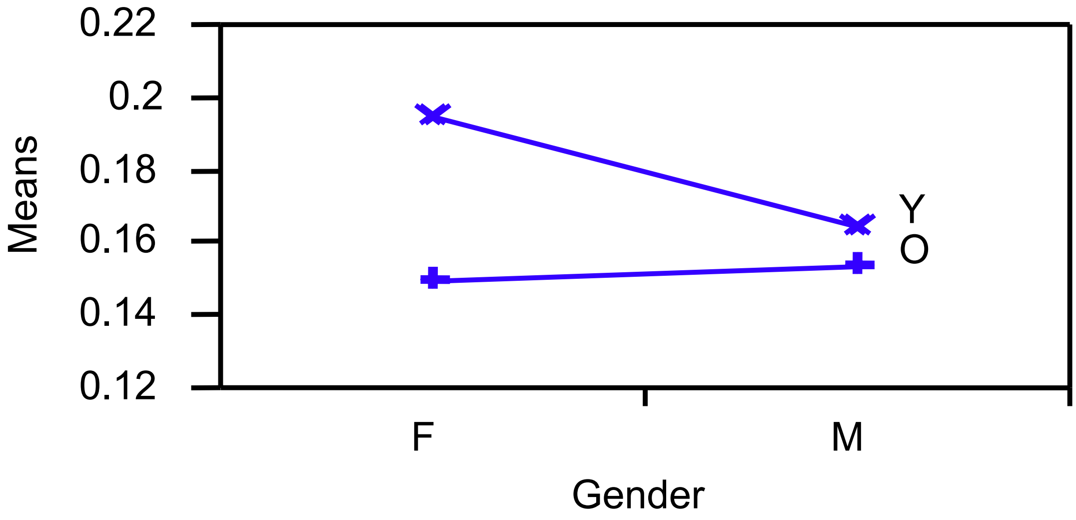


Figure 4.30 Interactions effect on RCOF

4.3.7 Slip Distance I (SDI)

4.3.7.1 Age Comparisons

The results indicated no statistically significant differences ($F_{1, 24} = 0.0226$, $p = 0.8823$) between the two age groups (Table 4.33 and Figure 4.31).

Table 4.33 Descriptive summary of SDI (mm) on main effect age

Age	Count	Mean	Std. Dev.
Old	14	26.87748676	35.57012758
Young	14	25.16649215	13.51908751

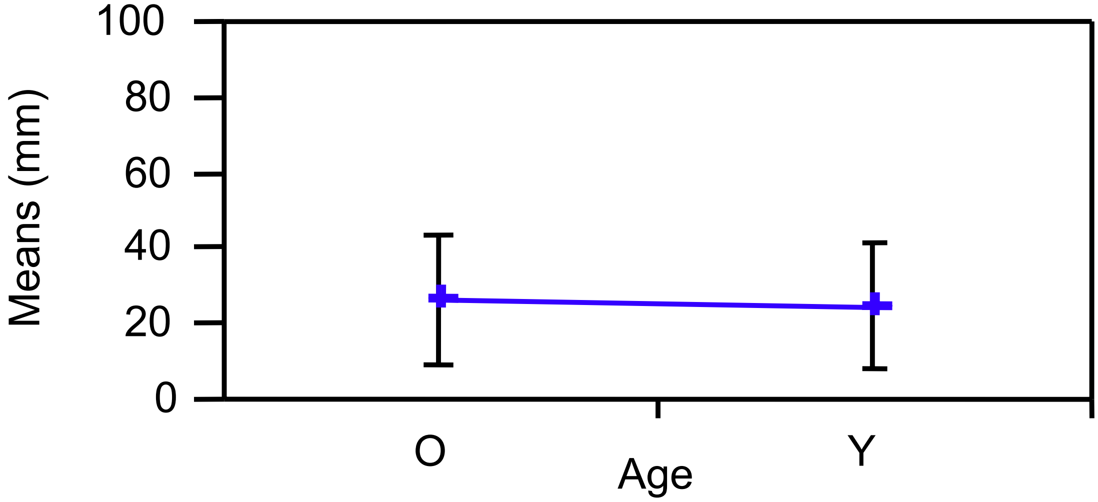


Figure 4.31 Age effect on SDI

4.3.7.2 Gender Comparisons

The results indicated no statistically significant differences ($F_{1,24} = 2.6018$, $p = 0.1263$) between female and male participants (Table 4.34 and Figure 4.32).

Table 4.34 Descriptive summary of SDI (mm) on main effect gender

Gender	Count	Mean	Std. Dev.
Male	14	16.84896179	16.11206312
Female	14	35.19501713	31.67080483

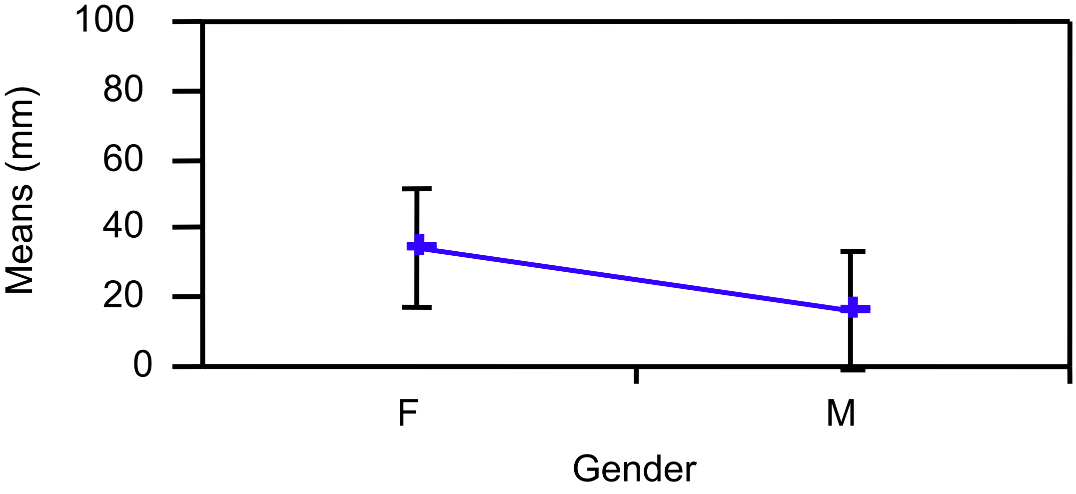


Figure 4.32 Gender effect on SDI

4.3.7.3 Interactions

The results indicated no statistically significant age and gender interactions ($F_{1, 24}$ = 1.5461, p = 0.2316) (Table 4.35 and Figure 4.33).

Table 4.35 Descriptive summary of SDI (mm) on age and gender interactions

Interactions	Count	Mean	Std. Dev.
Old Male	7	10.63323747	11.61366296
Old Female	7	43.12173606	45.30132659
Young Male	7	23.06468611	18.77848665
Young Female	7	27.26829819	6.895458904

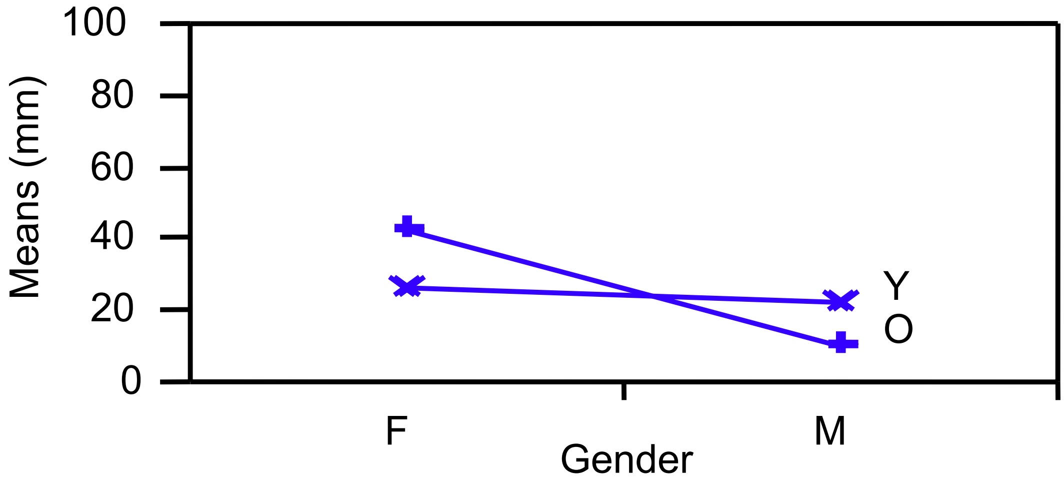


Figure 4.33 Interactions effect on SDI

4.3.8 Slip Distance II (SDII)

4.3.8.1 Age Comparisons

The results indicated no statistically significant differences ($F_{1, 24} = 0.1806$, $p = 0.6766$) between the two age groups (Table 4.36 and Figure 4.34).

Table 4.36 Descriptive summary of SDII (mm) on main effect age

Age	Count	Mean	Std. Dev.
Old	14	103.9633869	157.0498686
Young	14	83.39177131	54.40282436

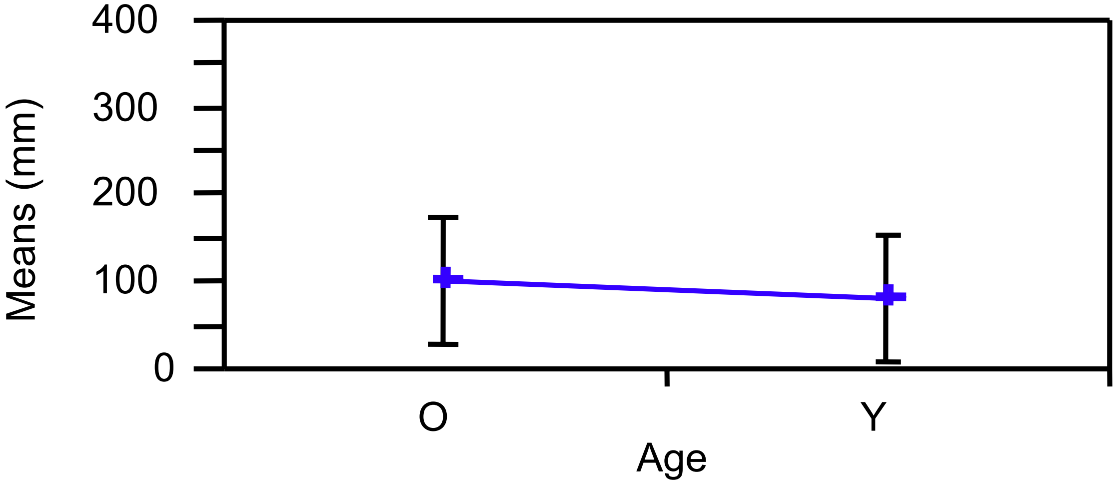


Figure 4.34 Age effect on SDII

4.3.8.2 Gender Comparisons

The results indicated statistically significant differences ($F_{1, 24} = 4.7146$, $p = 0.0453$) between female and male participants. In general, female individuals' SDII was higher than male individuals (Table 4.37 and Figure 4.35).

Table 4.37 Descriptive summary of SDII (mm) on main effect gender

Gender	Count	Mean	Std. Dev.
Male	14	41.11711176	37.23903898
Female	14	146.2380465	142.5958332

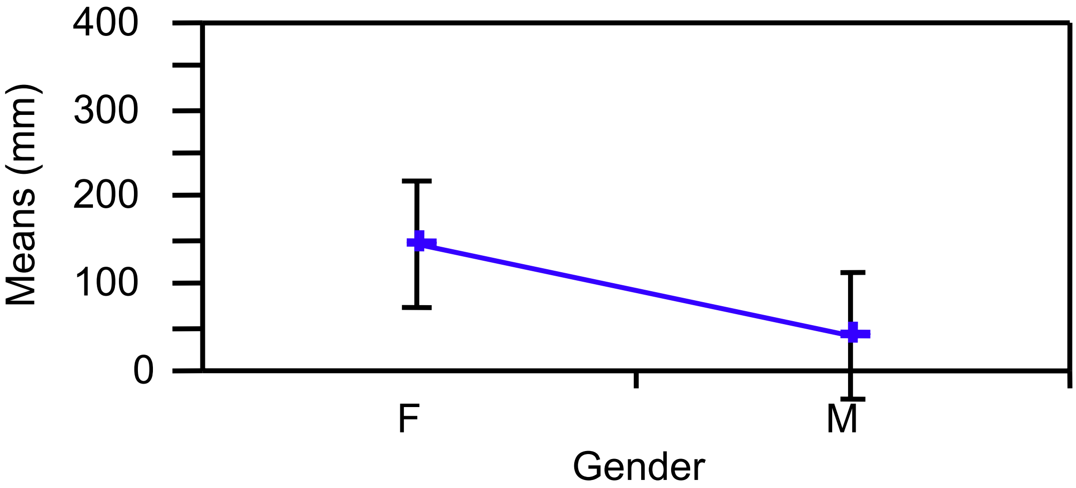


Figure 4.35 Gender effect on SDII

4.3.8.3 Interactions

The results indicated no statistically significant age and gender interactions ($F_{1,\ 24} = 0.4997$, $p = 0.4898$) (Table 4.38 and Figure 4.36).

Table 4.38 Descriptive summary of SDII (mm) on age and gender interactions

Interactions	Count	Mean	Std. Dev.
Old Male	7	34.29199488	43.58946327
Old Female	7	173.634779	203.6177528
Young Male	7	47.94222864	33.22170519
Young Female	7	118.841314	49.13140072

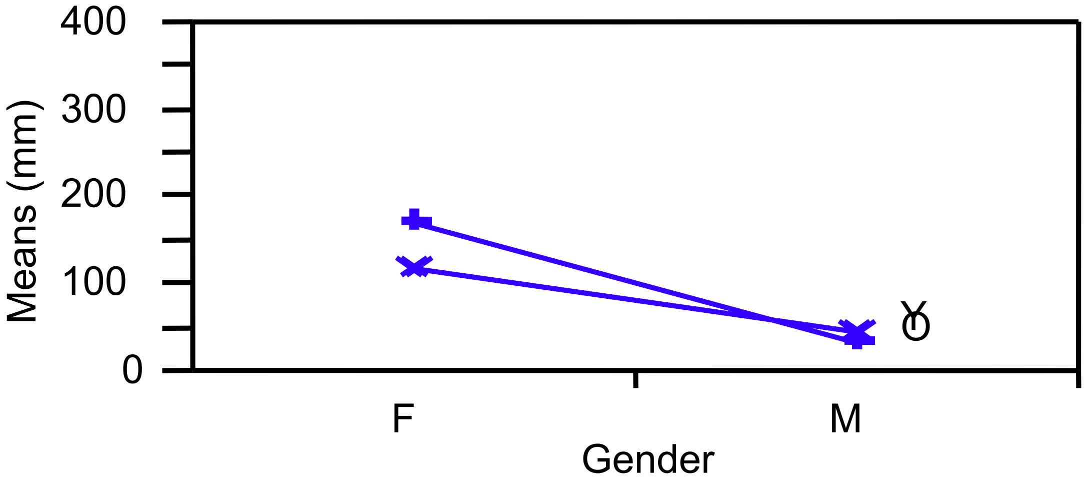


Figure 4.36 Interactions effect on SDII

4.3.9 Total Slip Distance (Total SD)

4.3.9.1 Age Comparisons

The results indicated no statistically significant differences ($F_{1, 24} = 0.1426$, $p = 0.7170$) between the two age groups (Table 4.39 and Figure 4.37).

Table 4.39 Descriptive summary of total SD (mm) on main effect age

Age	Count	Mean	Std. Dev.
Old	14	130.8408737	192.4684825
Young	14	108.5582635	60.60693882

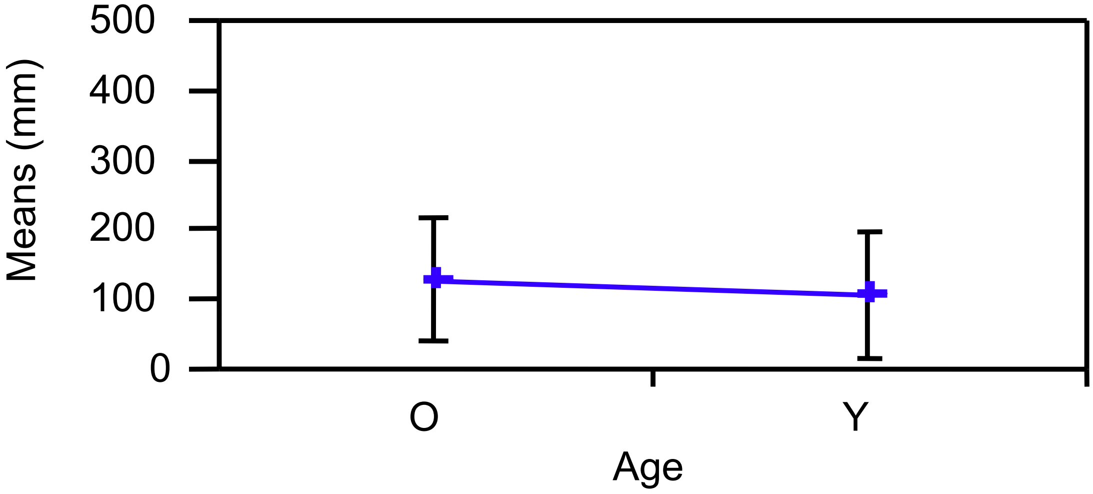


Figure 4.37 Age effect on total SD

4.3.9.2 Gender Comparisons

The results indicated statistically significant differences ($F_{1, 24} = 4.3983$, $p = 0.0502$) between female and male participants. In general, female individuals' total SD was higher than male individuals (Table 4.40 and Figure 4.38).

Table 4.40 Descriptive summary of total SD (mm) on main effect gender

Gender	Count	Mean	Std. Dev.
Male	14	57.96607355	49.37286419
Female	14	181.4330636	173.45471

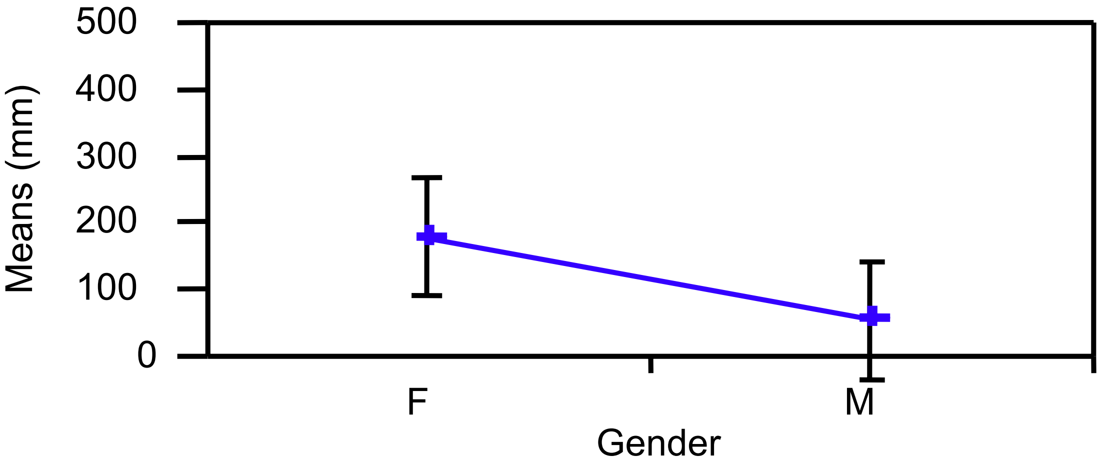


Figure 4.38 Gender effect on total SD

4.3.9.3 Interactions

The results indicated no statistically significant age and gender interactions ($F_{1, 24}$ = 0.6718, p = 0.4245) (Table 4.41 and Figure 4.39).

Table 4.41 Descriptive summary of total SD (mm) on age and gender interactions

Interactions	Count	Mean	Std. Dev.
Old Male	7	44.92523235	55.19269434
Old Female	7	216.7565151	248.695166
Young Male	7	71.00691475	44.87078124
Young Female	7	146.1096122	52.21164467

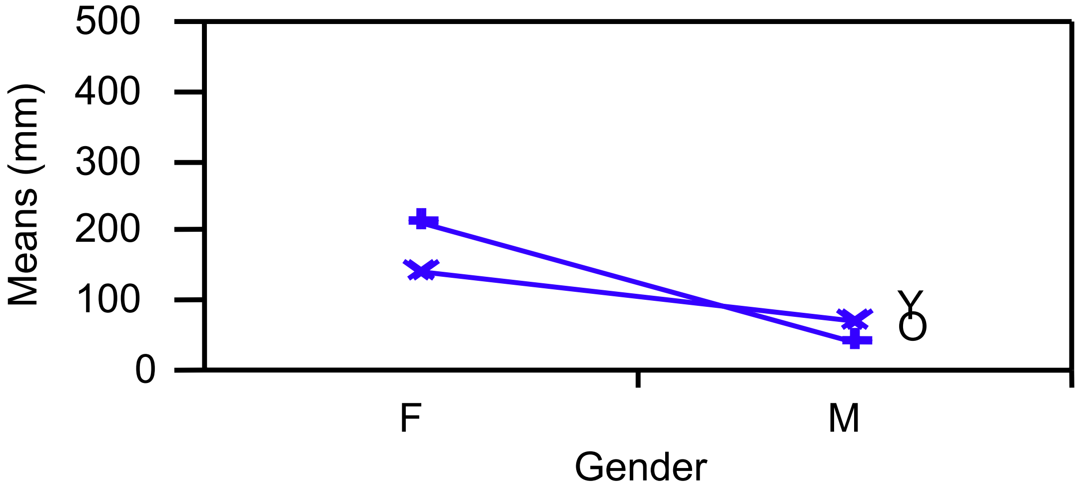


Figure 4.39 Interactions effect on total SD

4.3.10 Sliding Heel Velocity (SHV)

4.3.10.1 Age Comparisons

The results indicated no statistically significant differences ($F_{1, 24} = 0.3682$, $p = 0.5525$) between the two age groups (Table 4.42 and Figure 4.40).

Table 4.42 Descriptive summary of total SHV (mm/s) on main effect age

Age	Count	Mean	Std. Dev.
Old	14	576.9182364	522.8876389
Young	14	681.4744348	314.5507237

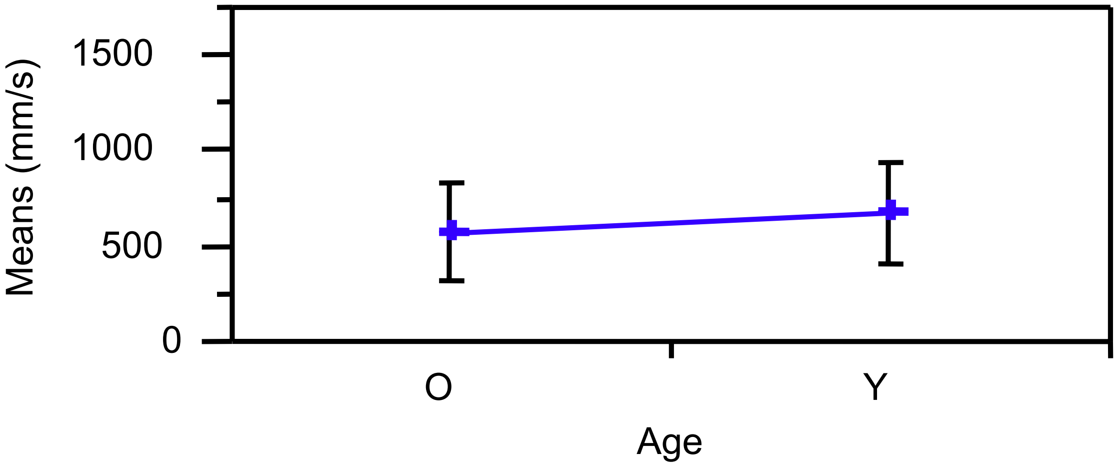


Figure 4.40 Age effect on SHV

4.3.10.2 Gender Comparisons

The results indicated statistically significant differences ($F_{1,24} = 6.5636$, $p = 0.0209$) between female and male participants. In general, female individuals' SHV was higher than male individuals (Table 4.43 and Figure 4.41).

Table 4.43 Descriptive summary of SHV (mm/s) on main effect gender

Gender	Count	Mean	Std. Dev.
Male	14	408.4795321	244.5201187
Female	14	849.9131391	458.6712471

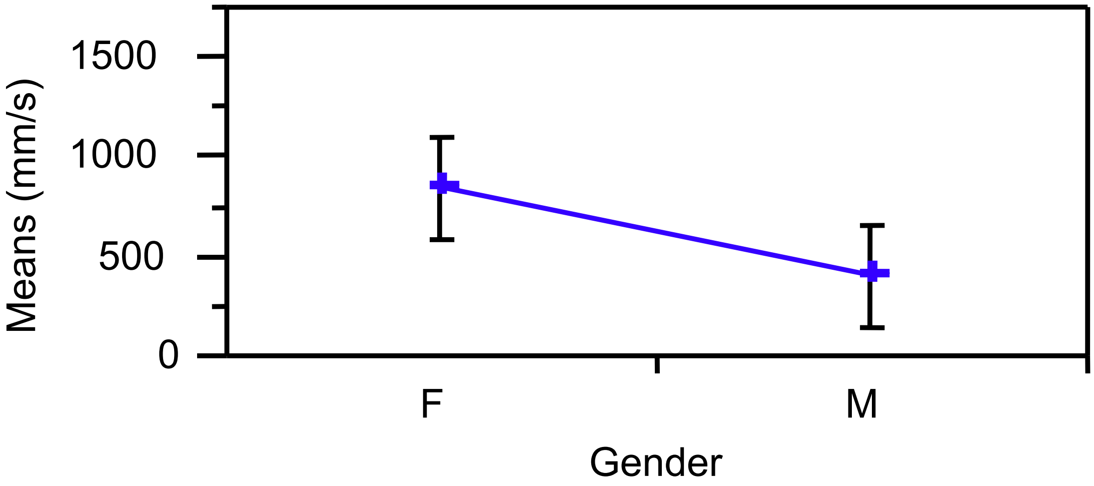


Figure 4.41 Gender effect on SHV

4.3.10.3 Interactions

The results indicated no statistically significant age and gender interactions ($F_{1, 24}$ = 0.0119, p = 0.9143) (Table 4.44 and Figure 4.42).

Table 4.44 Descriptive summary of SHV (mm/s) on age and gender interactions

Interactions	Count	Mean	Std. Dev.
Old Male	7	346.7866406	281.2990296
Old Female	7	807.0498323	635.3308696
Young Male	7	470.1724235	214.2043948
Young Female	7	892.776446	255.1763751

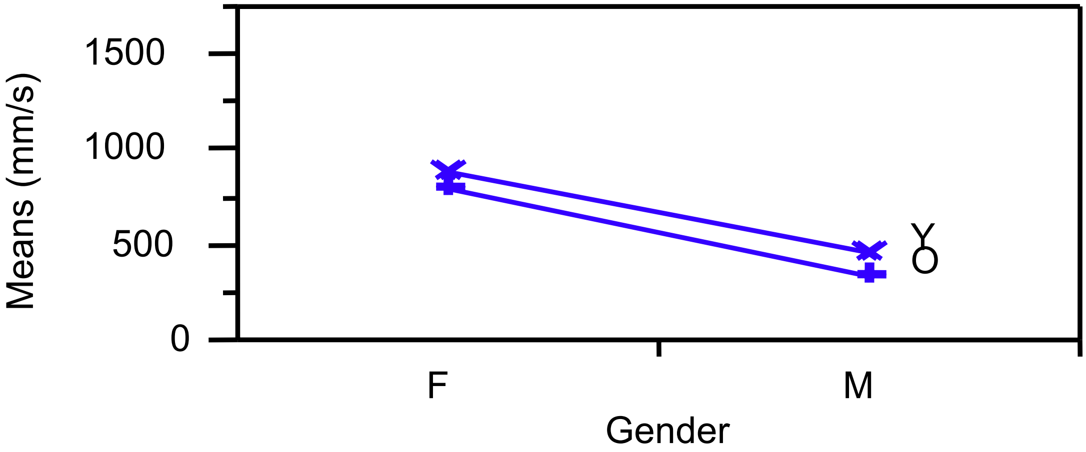


Figure 4.42 Interactions effect on SHV

4.3.11 Horizontal Velocity of the Whole Body COM During Slip (COM_{Slip})

4.3.11.1 Age Comparisons

The results indicated statistically significant differences ($F_{1, 24} = 8.2292$, $p = 0.0111$) between the two age groups. In general, younger individuals' COM_{Slip} was higher than their older counterparts (Table 4.45 and Figure 4.43).

Table 4.45 Descriptive summary of COM_{Slip} (mm/s) on main effect age

Age	Count	Mean	Std. Dev.
Old	14	1259.993501	199.5811611
Young	14	1460.561822	126.7698967

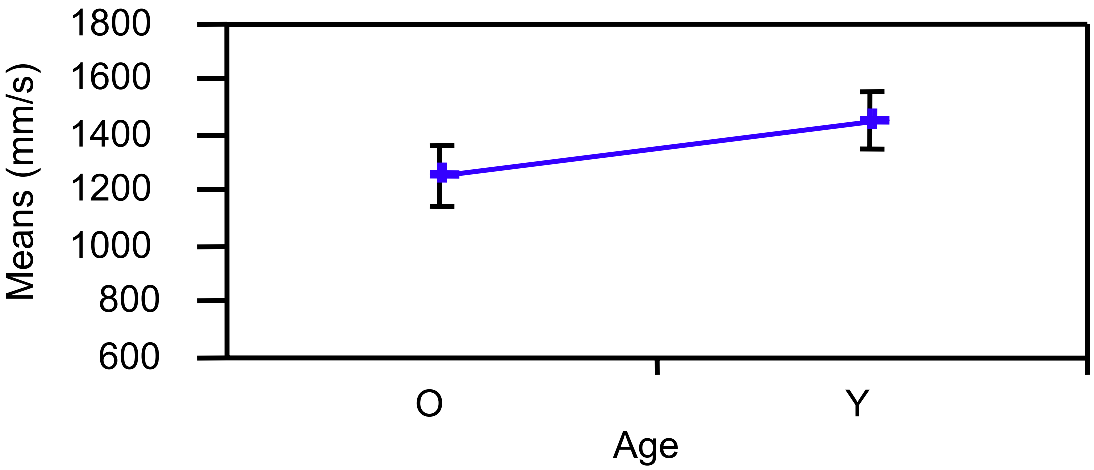


Figure 4.43 Age effect on COM_{Slip}

4.3.11.2 Gender Comparisons

The results indicated statistically significant differences ($F_{1,24} = 4.5475$, $p = 0.0504$) between female and male participants. In general, female individuals' COM_{Slip} was higher than male individuals (Table 4.46 and Figure 4.44).

Table 4.46 Descriptive summary of COM_{Slip} (mm/s) on main effect gender

Gender	Count	Mean	Std. Dev.
Male	14	1287.387094	212.8611917
Female	14	1433.168229	145.379884

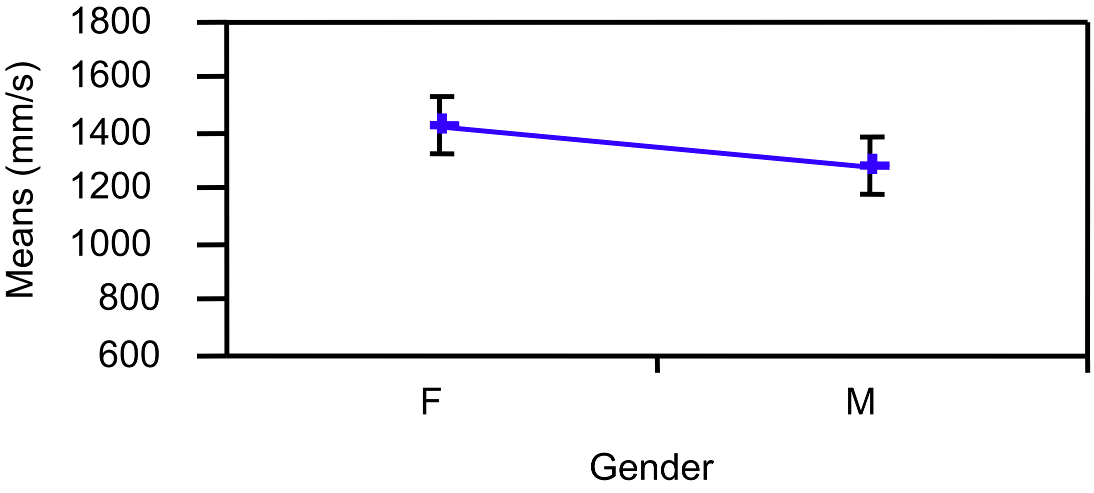


Figure 4.44 Gender effect on COM_{Slip}

4.3.11.3 Interactions

The results indicated no statistically significant age and gender interactions ($F_{1, 24}$ = 0.2372, p = 0.6328) (Table 4.47 and Figure 4.45).

Table 4.47 Descriptive summary of COM_{Slip} (mm/s) on age and gender interactions

Interactions	Count	Mean	Std. Dev.
Old Male	7	1170.076529	218.7323261
Old Female	7	1349.910474	146.8569187
Young Male	7	1404.697659	140.3531033
Young Female	7	1516.425985	93.0476206

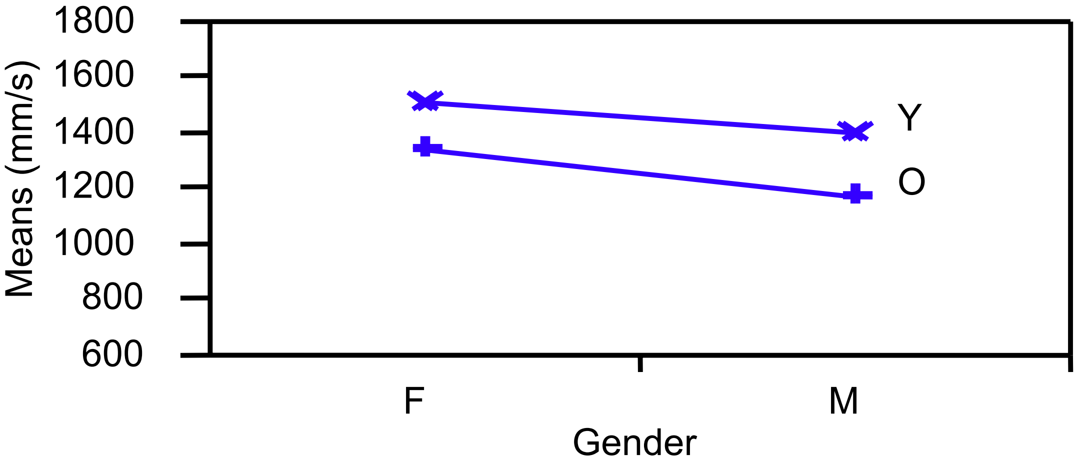


Figure 4.45 Interactions effect on COM_{Slip}

4.4 Correlation Analysis

Bivariate correlation analyses were used to determine the relationships among all dependent variables; ankle strength, ankle joint torque, ankle joint power, the transitional velocity of the whole body COM, friction demand, slip distance, and sliding heel velocity. Summary of correlation analysis results are listed on Table 4.48.

Table 4.48 Summary of Correlation Analysis

Relationships	r^2
*ISOK$_{right}$ -30°/s and Ankle Joint Torque	$r^2 = 0.39$*
*ISOK$_{right}$ -60°/s and Ankle Joint Torque	$r^2 = 0.37$*
*ISOK$_{right}$ -120°/s and Ankle Joint Torque	$r^2 = 0.47$*
ISOK$_{left}$ -30°/s and Ankle Joint Torque	$r^2 = 0.12$
ISOK$_{left}$ -60°/s and Ankle Joint Torque	$r^2 = 0.12$
ISOK$_{left}$ -120°/s and Ankle Joint Torque	$r^2 = 0.03$
ISOM$_{right}$ -0° and Ankle Joint Torque	$r^2 = 0.23$
ISOM$_{right}$ -15° and Ankle Joint Torque	$r^2 = 0.10$
*ISOM$_{right}$ -30° and Ankle Joint Torque	$r^2 = 0.38$*
ISOM$_{left}$ -0° and Ankle Joint Torque	$r^2 = 0.13$
ISOM$_{left}$ -15° and Ankle Joint Torque	$r^2 = 0.08$
ISOM$_{left}$ -30° and Ankle Joint Torque	$r^2 = 0.06$
ISOK$_{right}$ -30°/s and Ankle Joint Power	$r^2 = 0.02$
ISOK$_{right}$ -60°/s and Ankle Joint Power	$r^2 = 0.02$
ISOK$_{right}$ -120°/s and Ankle Joint Power	$r^2 = 0.004$
ISOK$_{left}$ -30°/s and Ankle Joint Power	$r^2 = 0.01$
ISOK$_{left}$ -60°/s and Ankle Joint Power	$r^2 = 0.007$
ISOK$_{left}$ -120°/s and Ankle Joint Power	$r^2 < 0.001$
ISOM$_{right}$ -0°/s and Ankle Joint Power	$r^2 = 0.009$
ISOM$_{right}$ -15°/s and Ankle Joint Power	$r^2 = 0.14$
ISOM$_{right}$ -30°/s and Ankle Joint Power	$r^2 = 0.09$
ISOM$_{left}$ -0° and Ankle Joint Power	$r^2 = 0.02$
ISOM$_{left}$ -15° and Ankle Joint Power	$r^2 < 0.001$
ISOM$_{left}$ -30° and Ankle Joint Power	$r^2 = 0.003$
*Ankle Joint Power and COM$_{Before}$	$r^2 = 0.21$*
*Ankle Joint Power and COM$_{After}$	$r^2 = 0.18$*
Ankle Joint Power and COM$_{Diff}$	$r^2 = 0.01$
*RCOF and COM$_{Before}$	$r^2 = 0.30$*
*RCOF and COM$_{After}$	$r^2 = 0.40$*
*RCOF and COM$_{Diff}$	$r^2 = 0.41$*
RCOF and SDI	$r^2 = 0.02$
RCOF and SDII	$r^2 = 0.04$
RCOF and Total SD	$r^2 = 0.04$
RCOF and SHV	$r^2 = 0.13$
*SHV and SDI	$r^2 = 0.73$*
*SHV and SDII	$r^2 = 0.85$*
*SHV and Total SD	$r^2 = 0.85$*

* significant relationship between variables

4.4.1 ISOK$_{right}$-30 and Ankle Joint Torque

The results indicated statistically significant relationship ($F_{1, 26}$ = 7.7460, p = 0.0166) between ISOK$_{right}$-30 and ankle torque with r^2 = 0.39. In other words, the significant positive relationship indicated that ankle joint torque was higher related to the higher isokinetic ankle strength at 30°/s.

4.4.2 ISOK$_{right}$-60 and Ankle Joint Torque

The results indicated statistically significant relationship ($F_{1, 26}$ = 7.0174, p = 0.0212) between ISOK$_{right}$-60 and ankle torque with r^2 = 0.37. In other words, the significant positive relationship indicated that ankle joint torque was higher related to the higher isokinetic ankle strength at 60°/s.

4.4.3 ISOK$_{right}$-120 and Ankle Joint Torque

The results indicated statistically significant relationship ($F_{1, 26}$ = 9.6262, p = 0.0101) between ISOK$_{right}$-120 and ankle torque with r^2 = 0.47. In other words, the significant positive relationship indicated that ankle joint torque was higher related to the higher isokinetic ankle strength at 120°/s.

4.4.4 ISOK$_{left}$-30 and Ankle Joint Torque

The results indicated no statistically significant relationship ($F_{1, 26}$ = 1.6498, p = 0.2232) between ISOK$_{left}$-30 and ankle torque with r^2 = 0.12

4.4.5 ISOK$_{left}$-60 and Ankle Joint Torque

The results indicated no statistically significant relationship ($F_{1, 26}$ = 1.5738, p = 0.2357) between ISOK$_{left}$-60 and ankle torque with r^2 = 0.12.

4.4.6 ISOK$_{left}$-120 and Ankle Joint Torque

The results indicated no statistically significant relationship ($F_{1, 26}$ = 0.3812, p = 0.5476) between ISOK$_{left}$-120 and ankle torque with r^2 = 0.03.

4.4.7 $\text{ISOM}_{\text{right}}$-0 and Ankle Joint Torque

The results indicated no statistically significant relationship ($F_{1, 26} = 3.2447$, $p = 0.0991$) between $\text{ISOM}_{\text{right}}$-0 and ankle torque with $r^2 = 0.23$.

4.4.8 $\text{ISOM}_{\text{right}}$-15 and Ankle Joint Torque

The results indicated no statistically significant relationship ($F_{1, 26} = 1.3226$, $p = 0.2725$) between $\text{ISOM}_{\text{right}}$-15 and ankle torque with $r^2 = 0.10$.

4.4.9 $\text{ISOM}_{\text{right}}$-30 and Ankle Joint Torque

The results indicated statistically significant relationship ($F_{1, 26} = 6.6199$, $p = 0.0259$) between $\text{ISOM}_{\text{right}}$-30 and ankle torque with $r^2 = 0.38$. In other words, the significant positive relationship indicated that ankle joint torque was higher related to the higher isometric ankle strength at 30°.

4.4.10 $\text{ISOM}_{\text{left}}$-0 and Ankle Joint Torque

The results indicated no statistically significant relationship ($F_{1, 26} = 1.8796$, $p = 0.1955$) between $\text{ISOM}_{\text{left}}$-0 and ankle torque with $r^2 = 0.13$.

4.4.11 $\text{ISOM}_{\text{left}}$-15 and Ankle Joint Torque

The results indicated no statistically significant relationship ($F_{1, 26} = 1.1002$, $p = 0.3149$) between $\text{ISOM}_{\text{left}}$-15 and ankle torque with $r^2 = 0.08$.

4.4.12 $\text{ISOM}_{\text{left}}$-30 and Ankle Joint Torque

The results indicated no statistically significant relationship ($F_{1, 26} = 0.7208$, $p = 0.4140$) between $\text{ISOM}_{\text{left}}$-30 and ankle torque with $r^2 = 0.06$.

4.4.13 $\text{ISOK}_{\text{right}}$-30 and Ankle Joint Power

The results indicated no statistically significant relationship ($F_{1, 26} = 0.2570$, $p = 0.6201$) between $\text{ISOK}_{\text{right}}$-30 and ankle power with $r^2 = 0.02$.

4.4.14 ISOK$_{right}$-60 and Ankle Joint Power

The results indicated no statistically significant relationship ($F_{1, 26} = 0.2847$, $p = 0.6034$) between ISOK$_{right}$-60 and ankle power with $r^2 = 0.02$.

4.4.15 ISOK$_{right}$-120 and Ankle Joint Power

The results indicated no statistically significant relationship ($F_{1, 26} = 0.0437$, $p = 0.8380$) between ISOK$_{right}$-120 and ankle power with $r^2 = 0.004$.

4.4.16 ISOK$_{left}$-30 and Ankle Joint Power

The results indicated no statistically significant relationship ($F_{1, 26} = 0.1154$, $p = 0.7405$) between ISOK$_{left}$-30 and ankle power with $r^2 = 0.01$.

4.4.17 ISOK$_{left}$-60 and Ankle Joint Power

The results indicated no statistically significant relationship ($F_{1, 26} = 0.0893$, $p = 0.7702$) between ISOK$_{left}$-60 and ankle power with $r^2 = 0.007$.

4.4.18 ISOK$_{left}$-120 and Ankle Joint Power

The results indicated no statistically significant relationship ($F_{1, 26} = 0.0008$, $p = 0.9775$) between ISOK$_{left}$-120 and ankle power with $r^2 < 0.001$.

4.4.19 ISOM$_{right}$-0 and Ankle Joint Power

The results indicated no statistically significant relationship ($F_{1, 26} = 0.1133$, $p = 0.7422$) between ISOM$_{right}$-0 and ankle power with $r^2 = 0.009$.

4.4.20 ISOM$_{right}$-15 and Ankle Joint Power

The results indicated no statistically significant relationship ($F_{1, 26} = 2.0897$, $p = 0.1724$) between ISOM$_{right}$-15 and ankle power with $r^2 = 0.14$.

4.4.21 ISOM$_{right}$-30 and Ankle Joint Power

The results indicated no statistically significant relationship ($F_{1, 26} = 1.2221$, $p = 0.2906$) between ISOM$_{right}$-30 and ankle power with $r^2 = 0.09$.

4.4.22 ISOM$_{left}$-0 and Ankle Joint Power

The results indicated no statistically significant relationship ($F_{1, 26} = 0.2337$, $p = 0.6368$) between ISOM$_{left}$-0 and ankle power with $r^2 = 0.02$.

4.4.23 ISOM$_{left}$-15 and Ankle Joint Power

The results indicated no statistically significant relationship ($F_{1, 26} = 0.0086$, $p = 0.9274$) between ISOM$_{left}$-15 and ankle power with $r^2 < 0.001$.

4.4.24 ISOM$_{left}$-30 and Ankle Joint Power

The results indicated no statistically significant relationship ($F_{1, 26} = 0.0320$, $p = 0.8611$) between ISOM$_{left}$-30 and ankle power with $r^2 = 0.003$.

4.4.25 Ankle Joint Power and COM$_{Before}$

The results indicated statistically significant relationship ($F_{1, 26} = 7.1174$, $p = 0.0130$) between ankle power and COM$_{Before}$ with $r^2 = 0.21$. In other words, the significant positive relationship indicated that the whole body COM velocity before the heel contact was faster related to the higher ankle joint power.

4.4.26 Ankle Joint Power and COM$_{After}$

The results indicated statistically significant relationship ($F_{1, 26} = 5.7915$, $p = 0.0235$) between ankle power and COM$_{After}$ with $r^2 = 0.18$. In other words, the significant positive relationship indicated that the whole body COM velocity after the heel contact was faster related to the higher ankle joint power.

4.4.27 Ankle Joint Power and COM$_{Diff}$

The results indicated no statistically significant relationship ($F_{1, 26} = 0.1607$, $p = 0.6942$) between ankle power and COM$_{Diff}$ with $r^2 = 0.01$.

4.4.28 RCOF and COM$_{Before}$

The results indicated statistically significant relationship ($F_{1, 26} = 5.7049$, $p = 0.0328$) between RCOF and COM$_{Before}$ with $r^2 = 0.30$. In other words, the significant positive relationship indicated that RCOF was higher related to the faster the whole body COM velocity before the heel contact.

4.4.29 RCOF and COM_{After}

The results indicated statistically significant relationship ($F_{1,26} = 8.7322$, p = 0.0112) between RCOF and COM_{After} with $r^2 = 0.40$. In other words, the significant positive relationship indicated that RCOF was higher related to the faster the whole body COM velocity after the heel contact.

4.4.30 RCOF and COM_{Diff}

The results indicated statistically significant relationship ($F_{1,26} = 9.1697$, p = 0.0097) between RCOF and COM_{Diff} with $r^2 = 0.41$. In other words, the significant positive relationship indicated that RCOF was higher related to the faster horizontal transitional velocity of the whole body COM.

4.4.31 RCOF and SDI

The results indicated no statistically significant relationship ($F_{1,26} = 0.2861$, p = 0.6025) between RCOF and SDI with $r^2 = 0.02$.

4.4.32 RCOF and SDII

The results indicated no statistically significant relationship ($F_{1,26} = 0.5194$, p = 0.4849) between RCOF and SDI with $r^2 = 0.04$.

4.4.33 RCOF and Total SD

The results indicated no statistically significant relationship ($F_{1,26} = 0.4781$, p = 0.5024) between RCOF and total SD with $r^2 = 0.04$.

4.4.34 RCOF and SHV

The results indicated no statistically significant relationship ($F_{1,26} = 1.8546$, p = 0.1983) between RCOF and SHV with $r^2 = 0.13$.

4.4.35 SHV and SDI

The results indicated statistically significant relationship ($F_{1, 26} = 49.9129$, $p < 0.0001$) between SHV and SDI with $r^2 = 0.73$. In other words, the significant positive relationship indicated that SDI was faster related to the faster sliding heel velocity during slipping.

4.4.36 SHV and SDII

The results indicated statistically significant relationship ($F_{1, 26} = 99.0837$, $p < 0.0001$) between SHV and SDII with $r^2 = 0.85$. In other words, the significant positive relationship indicated that SDII was faster related to the faster sliding heel velocity during slipping.

4.4.37 SHV and Total SD

The results indicated statistically significant relationship ($F_{1, 26} = 98.6118$, $p < 0.0001$) between SHV and total SD with $r^2 = 0.85$. In other words, the significant positive relationship indicated that Total SD was faster related to the faster sliding heel velocity during slipping.

4.5 Frequency of Falling

A fall was defined as it occurred when the total slip distance (slip-start point to slip-stop point) exceeds 10 centimeters and when the sliding heel velocity exceeds the whole body center-of-mass velocity during slipping (Lockhart et al., 2001). The results indicated that all participants slipped on the slippery surface, however, only three old female participants fell in the experiment. None of the individuals in the other three groups (i.e., old male, young male, and young female) fell after they slipped.

CHAPTER 5
DISCUSSION AND CONCLUSIONS

5.1 Hypotheses and Experimental Findings

5.1.1 Hypothesis #1

"Ankle strength in older individuals will be less than their younger counterparts due to musculoskeletal degradation."

Hettinger (1960) studied the effects of age and gender on muscle strength and suggested that on average, women were only about two-thirds as powerful as men. He also found that older individuals (50-60 years of age) produced less muscular strength than younger individuals (25-35 years of age). The reduced muscular strength at the ankle joint among the older individuals in the current study was in agreement with previous studies of this population. The results indicated statistically significant ankle strength (isokinetic) difference between two age groups. In general, older individuals' strength was significantly less than their younger counterparts. Male individuals' strength was significantly higher than female individuals in this population (e.g., $ISOK_{right}$, $ISOK_{left}$, and $ISOM_{right}$). In summary, young male individuals'strength was the highest at all levels of the strength tests. Old male individuals'strength was higher than young female individuals at all levels except for ISOM at 15° and 30°. This reduction in isometric strength may be due to the decreased strength generation capability at this range. The previous studies indicated that older individuals have less range of motion at the ankle joint compared with younger individuals (Finley et al., 1969; Nigg et al., 1994). Old female individuals' strength was the least in this study. In conclusion, ankle strength in older individuals was less than their younger counterparts perhaps due to musculoskeletal degradation as suggested by the literature review.

5.1.2 Hypothesis #2

"Ankle joint power of the push-off foot at the heel contact phase of the gait cycle in older individuals will be less than their younger counterparts. It is expected that this reduction is due to the decreased ankle strength in older individuals."

The results indicated that young individuals' ankle joint torque and ankle joint power were significantly higher than their older counterparts. The results also indicated that male individuals' ankle joint torque was significantly higher than female individuals, but there was no gender effect on the ankle joint power. A significant relationship between ankle strength and ankle joint torque was found in this study [e.g., $ISOK_{right}$ ($r^2 = 0.47$)]. However, there was no significant relationship between ankle strength and ankle joint power. Since the ankle joint power was the product of ankle joint torque and ankle angular velocity, the ankle angular velocity might affect directly to the ankle joint power. Many investigators have found that ankle joint power is directly related to walking velocity (Chen et al., 1997; Winter, 1983; 1991). In addition, there was a significant relationship ($r^2 = 0.21$) between ankle power and walking velocity (as measured by the velocity of the whole body COM before the heel contact). It can be assumed that ankle angular velocity is also related to the walking velocity. This might be due to the fact that young individuals who walked faster had significantly higher ankle joint power than older individuals. Figure 5.1, 5.2, and 5.3 illustrate the examples of ankle joint torque, ankle joint power, and ankle angle respectively from the heel contact phase (0%) of the gait cycle to the toe-off phase (100%) of the gait cycle. These results showed the similar patterns of ankle joint torque, ankle joint power, and ankle angular position during the gait cycle to the previous study (Devita et al., 2000; Redfern et al., 2001). In conclusion, ankle joint power of the push-off foot at the heel contact phase of the gait cycle in older individuals was less than their younger counterparts. This reduction might be due to the decreased ankle strength in older individuals. Further studies are needed to investigate the cause of decreased ankle joint power in older individuals.

5.1.3 Hypothesis #3

"Older individuals' transitional velocity of the whole body COM will be slower than younger individuals. It is expected that this reduction is due to the decrease of ankle joint power of the push-off foot in older individuals."

The results indicated that younger individuals' horizontal transitional velocity of the whole body COM (COM_{Diff}) was significantly faster than their older counterparts. Even though there was no significant relationship between the transitional velocity of the whole body COM

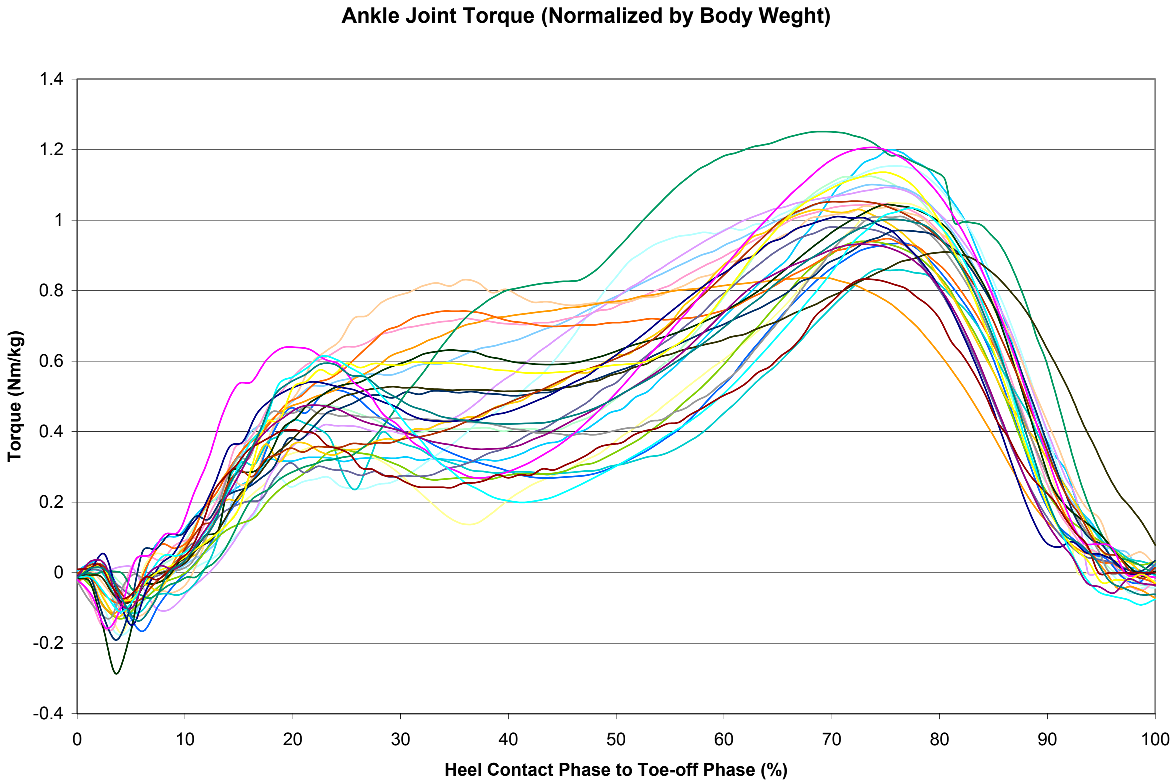


Figure 5.1 Summary of Ankle Joint Torque

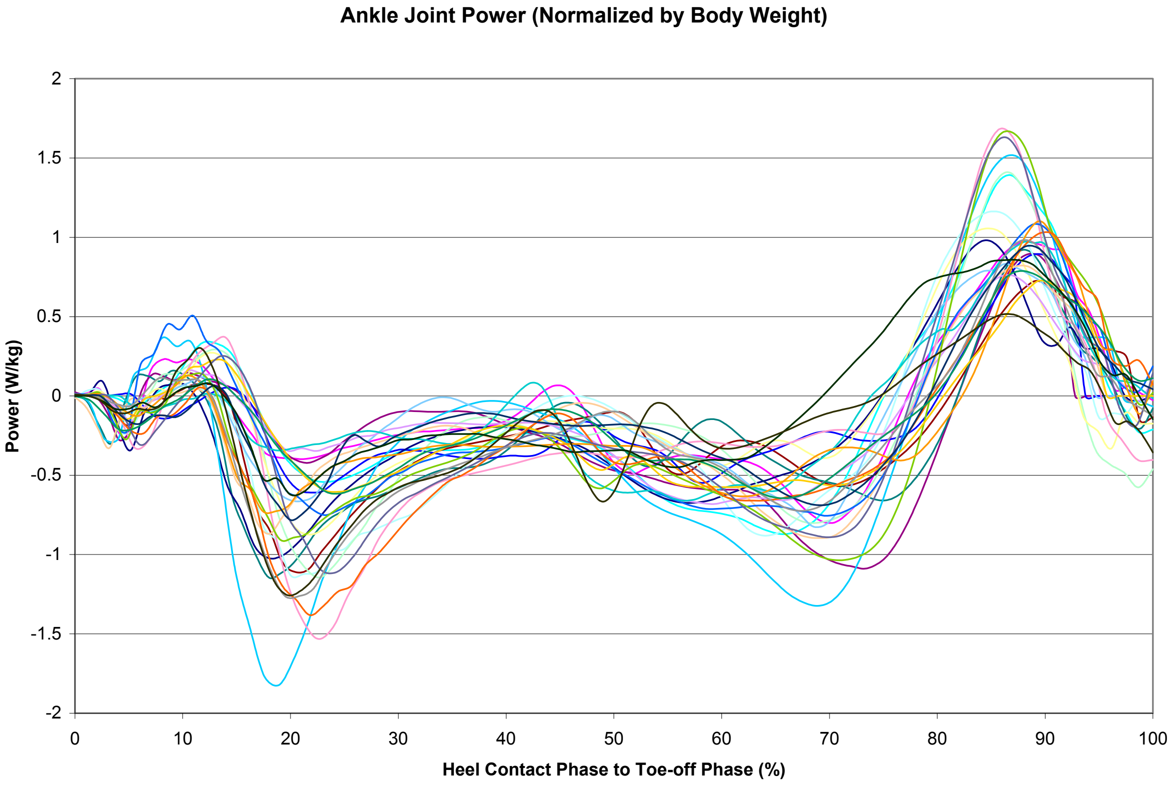


Figure 5.2 Summary of Ankle Joint Power

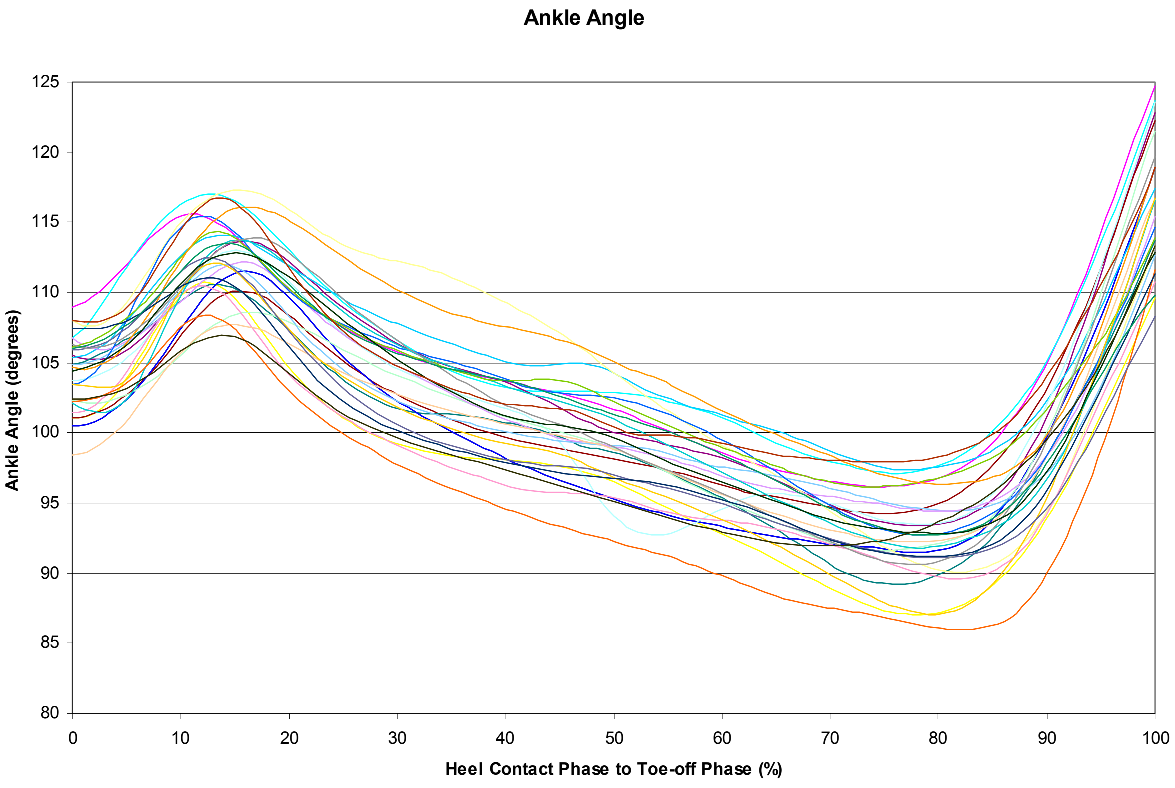


Figure 5.3 Summary of Ankle Angle

and the ankle joint power, the significant relationships between ankle joint power and the velocity of the whole body COM before the heel contact (COM_{Before}) and the velocity of the whole body COM after the heel contact (COM_{After}) were found in this study. The significant relationship may have resulted due to the walking velocity and ankle joint angular velocity profile (e.g., faster walking velocity resulted in faster ankle joint angular velocity which may have resulted in faster horizontal transitional velocity of the whole body COM). In conclusion, older individuals' horizontal transitional velocity of the whole body COM was slower than younger individuals. It may not be due to the decrease of ankle joint power of the push-off foot in older individuals, but it may be due to the decrease in walking velocity. Further studies are needed to investigate this factor as well.

5.1.4 Hypothesis #4

"Friction demand characteristic (RCOF) in older individuals will be higher than younger counterparts. It is expected that the increase of friction demand is due to the slower transitional velocity of the whole body COM."

Previous finding suggested that RCOF is a function of transfer of the whole body center-of-mass (Lockhart et al., 2001a). In other words, quicker transition of the whole body COM may reduce RCOF by increasing horizontal force. However, the results from this study indicated that RCOF in older individuals was significantly lower than their younger counterparts. The results also indicated a significant positive relationship ($r^2 = 0.41$) between RCOF and the transitional velocity of the whole body COM (i.e., faster the transitional velocity of the whole body COM higher the RCOF). This may have resulted when walking velocity in horizontal direction affected horizontal ground reaction force, ultimately influencing RCOF.

Since RCOF is the ratio of horizontal ground reaction force to vertical ground reaction force, the vertical transitional velocity of the whole body COM may play an important role in RCOF measurement. That is, the slower horizontal transitional velocity of the whole body COM in all older individuals and the faster vertical transitional velocity of the whole body COM may have reduced RCOF among older individuals. In conclusion, friction demand characteristic (RCOF) in older individuals was less then younger counterparts. The decrease of friction demand was not due to the slower horizontal transitional velocity of the whole body

COM, but it may be due to the faster vertical transitional velocity of the whole body COM instead. Further studies are needed to investigate this factor as well.

5.1.5 Hypothesis #5

"The slip distance (SD) in older individuals will be longer than younger counterparts."

On average, older individuals' slip distance (i.e., SDI, SDII, and Total SD) was longer than younger individual. However, the results indicated that slip distance was not significantly different between age groups. The slip distance was significantly different between males and females, and in general, female individuals slipped longer than male individuals. The significant faster walking velocity in female individuals (as measured by $\mathrm{COM}_{\mathrm{Before}}$) may have resulted the longer slip distance. Moreover, there was no statistically significant relationship between RCOF and slip distance (e.g., SDI, SDII, and Total SD) in this study. These results indicated that friction demand characteristics may not explain the severity of initiation of slips (as measure by SDI) and the slip behavior after the initiation of slips (as measured by SDII). There may be other variable(s) affecting slip distance. Furthermore, as suggested by Hanson et al. (1999), RCOF may not be a totally deterministic factor influencing the slip and fall events. In conclusion, the slip distance (SD) in older individuals was not significantly longer than younger counterparts. The relationship between RCOF and SD was not statistically significant.

5.1.6 Hypothesis #6

"The sliding heel velocity (SHV) in older individuals will be faster than younger counterparts."

The results indicated that sliding heel velocity was not significantly different between age groups. However, the sliding heel velocity was significantly different between males and females. In general, female individuals slipped faster than male individuals. The results also indicated a significant relationship ($r^2 = 0.85$) between sliding heel velocity and slip distance (e.g., SDI, SDII, and Total SD). Additionally, the velocity of the whole body COM during slip ($\mathrm{COM}_{\mathrm{Slip}}$) was significantly different for both age and gender groups. On average, younger individuals' $\mathrm{COM}_{\mathrm{Slip}}$ was significantly faster than their older counterparts. This might due to the fact that young individuals reacted and moved faster after slipping. Lockhart et al. (2000b) indicated that the muscle latency time (reaction time) was longer for older individuals than the younger counterparts. Therefore, the events of falls may be due to not only the initiation of slips, but also the recovery phase of slips. In conclusion, the sliding heel velocity in older individuals was not statistically significant faster than younger counterparts. The relationship between friction demand and sliding heel velocity was not statistically significant in this study as well.

5.1.7 Hypothesis #7

"Frequency of falling in older individuals will be higher than their younger counterparts."

Three older female individuals fell in this study. None of all other individuals (including older male individuals) fell. It may be concluded that not all older individuals are prone to the slip and fall accidents (i.e., all of the older male individuals and most of the older female individuals did not fall in this study). It may be due to the fact that all participants were healthy as they exercised everyday. The fitness of the individuals participated in the experiments especially older individuals may have resulted that they did not fall after slipping. In conclusion, frequency of falling in older individuals was higher than their younger counterparts. Further studies should study on various populations (i.e., not only the populations in Blacksburg, Virginia) and should have larger sample size for better normal distributions.

5.2 Conclusions and Recommendations

It can be summarized from this study that younger and older individuals were both susceptible to slips [as measured by the initial slip distance (SDI)], however, the outcome of slips (i.e., falls) occurred more often in older individuals than their younger counterparts. Physiological and biomechanical changes were hypothesized as factors of the initiation of slips and falls in this study. Ankle strength, a physiological factor, was significantly related to the ankle joint torque, a biomechanical factor, during walking. However, the relationship between ankle strength and ankle joint power was not significant. The ankle joint power in older individuals was significant less than their younger counterparts and older individuals had significantly slower horizontal transitional velocity of the whole body COM. Moreover, the results indicated the significant lower friction demand (RCOF) in older individuals than their younger counterparts.

The assumption from this finding was that the horizontal transitional velocity of the whole body COM affected the horizontal force at the time of the heel contact. Therefore, it may be assumed that the vertical transitional velocity of the whole body COM may directly affect the vertical force at the heel contact. If this assumption holds, then the lower in vertical transitional velocity of the whole body COM may be due to reduced ankle power in older individuals by increasing the vertical force at heel contact. Consequently, older individuals will have lower RCOF than their younger counterparts. Furthermore, as indicated by fall frequency results, older individuals fell more often than younger individuals. This result suggests that although factors influencing friction demand characteristics are important in assessing slip severity, RCOF may not be a deterministic factor influencing in the frequency of falls.

In summary, there was a relationship between age-related ankle strength and effects of slip and fall accidents. The older individuals fell more often than younger individuals in this population. It was suggested by many researchers that it may be due to the musculoskeletal degradation with advancing age. However, the results from this study indicated that not all older individuals fell after slipping. It may be due to the fact that all participants were active and healthy. Older individuals in this study reported that they exercised everyday such as walking, jogging, or water aerobic. Those activities may strengthen their muscles especially in lower extremities and also may help their joints have more flexibility. Also, most of older individuals who did not fall from the experiments walked slowly. It was assumed that those individuals had more cautious when they walked normally. The results from this study indicated that the faster walking velocity in older female individuals than older male individuals may play an important role in slip and fall accidents. In other words, the older female individuals in this study who walked faster would slip faster and had tendency to fall more than older male individuals. Thus, to suggest the older individuals to prevent slip and fall accidents, they should walk slowly as normal and be aware of the slippery floor surface.

From this study, the initiation phase of slips and falls was investigated. However, the cause of the increase in slip-induced fall accidents in older individuals was not thoroughly explored. The future research should consider the factors involving in recovery part of the slips and falls such as the reaction time of the lower extremities (e.g., ankle, knee, and hip) and the strength of other muscle groups (e.g., quadriceps or hamstring). It can be concluded that exercising or muscle strengthening play an important role in older individuals in terms of preventing the slip and fall accidents.

5.3 Final Remarks

5.3.1 Limitations of the Study

The following limitations apply to the study:

1. The laboratory environment including the harness system may affect the natural cadence of participants during walking in the experiments. Moreover, since the experimental shoes were provided to all participants, they may adjust their natural cadences by changing shoes (e.g., the shoes were not fit to their feel, so they slowed down).

2. Errors in identifying anatomical landmarks. Since participants wore the loose-fitted clothing, the clothing movement during walking may have resulted an error of the anatomical locations.

3. Limitations associated with the set up position in ankle strength test were recognized. The recumbent position for ankle strength was assumed to obtain the least upper body movement.

4. All participants were recruited from the local community (Blacksburg, Virginia). This population may not be a representative for all older individuals and all younger individuals.

5.3.2 Assumptions

The following assumptions were made in the study:

1. All participants responded naturally and were not aware of the unexpected slippery surface.

2. Instrumentation performed reliably and obtained sufficient information about the characteristics of gait.

3. The whole body center-of-mass calculations provided adequate estimates of the actual center of mass during walking. Body mass density was assumed to be the same between older and younger individuals.

4. The participants' ankle strength collected in this experiment was assumed to be their maximum exertions.

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APPENDIX A

Personal Data and Medical History
Grado Department of Industrial and Systems Engineering
Virginia Polytechnic Institute and State University

Effects of Aging on the Biomechanics of Slips and Falls Date______________

Personal Data

Name____ Age _______________
Sex ___________ Height (cm) ___________________ Weight (kg) ____________________
In case of emergency contact: Name _________________________ Phone _______________

Medical History

1. Please check if susceptible to
   _____ Shortness of breath _____ Fatigue _____ Headaches
   _____ Dizziness _____ Pain in arm, shoulder or chest
   If you checked any of the items above, please explain:
   ____

2. Please answer these questions (Yes or No)
   2.1 Have you ever had a heart attack? __________ If so, please explain
   ____
   2.2 Are you currently taking any type of medication? _________ If so, please explain
   ____
   2.3 Have you had or do you now have any problems with your blood pressure? _________
   If so, please explain ____
   ____
   2.4 In the last 6 month, have you had any back pain? __________ If so, please explain
   ____
   2.5 Have you had or do you now have a hernia? __________ If so, please explain
   ____
   2.6 Have you had or do you now have any problems with ankle, knee, or hip (surgery, injuries, replacements)? ______ If so, please explain _____________________________
   ____
   2.7 Have you currently had osteoporosis or treated with osteoporosis? _________
   If so, please explain ____
   ____
   2.8 Have you had or do you now have any inner ear or balance problems? __________
   If so, please explain ____
   ____
   2.9 Have you experienced slips and falls? ________ If so, how long ago? ________
   Please explain ____
   ____
   2.10 Have you had visual problems? ____________ If so, please explain
   ____

APPENDIX B

Informed Consent for Participants of Investigative Projects
Grado Department of Industrial and Systems Engineering
Virginia Polytechnic Institute and State University

TITLE: Effects of Aging on the Biomechanics of Slips and Falls

PRINCIPAL INVESTIGATOR: Thurmon E. Lockhart Ph.D.

PURPOSE

This is an experiment to investigate the changes in biomechanical parameters and ground reaction forces due to increase in age. The objective of this experiment is to measure the aging effect on different conditions with or without contaminant.

PROCEDURE

This study will last two days consisting of a familiarization session and body composition measurements, and a 20 minute walking experiment. Prior to this experiment, you will be given an opportunity to walk around the laboratory wearing a harness to familiarize yourself with the equipment (fall arresting harness), and floor surfaces. Next, you will be asked to walk across the slippery or non-slippery floor surface for 20 minutes. While you are walking along the path, please keep your eyes looking straight ahead and try to maintain the speed that you practiced.

After the familiarization session, an initial saliva sample will be collected and three other samples will be collected during the walking experiment. The saliva samples will be sent to NorthWestern University to be analyzed. Next, you will be asked to walk on specially prepared floor surfaces. The floor surface which you will walk across may or may not be slippery. As you experienced in the familiarization session, the harness system will protect you if device and allow you to “fall or slip” only 3 or 4 inches.

You will also be asked to stand on the platform and place your feet in the required position on the platform. No movement of feet on the platform is required. For your safety and confidence you will be asked to wear a safety harness. These testing procedures are not designed to make you lose your balance. One of the procedures requires you to close your eyes.

Additionally, strength test will be performed using a dynamometer. To test the leg strength, you will be asked to sit on Biodex chair with backrest. The vertical height of the chair will be adjusted to accommodate your popliteal height. The speed selector will be set at 30, 60, and 120 degrees per second. The tests will be performed for the range of 0 to 90° of flexion. The leg would begin in the neutral, 0° position corresponding to a straight, extended leg, and proceed to trace out a bending motion until the upper and lower portions of the leg formed a 90° angle. You will be asked to apply two to three maximal torques at each velocity as suggested by the Biodex Dynamometer Exercise Manual.

RISKS OF PARTICIPATION

Minor muscle sprain might occur if you lose your balance while walking on the floors. Additionally, muscle sprain might also occur after the strength test.

BENEFITS AND COMPENSATION

The benefits to you are a better understanding of floor surface slipperiness which could lead to preventing slips and falls in the elderly. Additionally, monetary compensation will be provided ($10.00 per hour).

ANONYMITY AND CONFIDENTIALITY

The data from this study will be kept strictly confidential. No data will be released to anyone but the principal investigator and graduate students involved in the project without written consent of the subject. Data will be identified by subject number.

FREEDOM TO WITHDRAW

You are free to withdraw at any time from the study for any reason. Circumstances may come up that the researcher will determine that you should not continue as a subject in the study. For example, an illness could be a reason to have the researchers stop your participation in the study.

APPROVAL OF RESEARCH

This research has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Tech, and by the Grado Department of Industrial and Systems Engineering. You will receive a copy of this from to take with you.

SUBJECT PERMISSION

I have read the informed consent and fully understand the procedures and conditions of the project. I have had all my questions answered, and I hereby give my voluntary consent to be a participant in this research study. I agree to abide by the rules of the project. I understand that I may withdraw from the study at any time.

If I have questions, I will contact:

Principal Investigator: Thurmon E. Lockhart, Assistant Professor, Grado Department of Industrial and Systems Engineering, 231-9088.

Chairman, Institutional Review Board for Research Involving Human Subjects: David Moore, 231-4991.

Signature of Subject ____Date________________

Signature of Project Director or his Authorized Representative:
____Date________________

Signature of Witness to Oral Presentation:
____ Date_______________

VITA

Tanavadee Khuvasanont was born on December 9, 1975 in Bangkok, Thailand. She got her bachelor degree in Industrial Engineering from Kasetsart University, Bangkok, Thailand in 1997. Since then, she had worked at Sanyo Universal Electric Public Company Limited. Her position was an industrial engineer in department of quality management. Her responsibility was to assure the quality system of all departments in the company to reach the international standards (i.e. ISO9000 series and ISO14000 series). In August 2000, she got a Thai government scholarship to earn a master's degree in Human Factors Engineering from Grado Department of Industrial and Systems Engineering at Virginia Polytechnic Institute and State University and graduated in July 2002. She specialized in general safety, industrial ergonomics, and biomechanics. She then has worked as a safety engineer in Minister of Labor and Social Welfare in Bangkok, Thailand.