THE VARIATION IN STRENGTH DECREMENT OF LOWER EXTREMITY MUSCLE GROUPS AND BIOMECHANICAL PLASTICITY IN OLDER ADULTS

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Age-associated biomechanical plasticity (BP) has been established as the distal to proximal shift of joint mechanical output in old adults while walking. The cause of BP is still unknown, but changes in muscle strength of the lower extremities due to age are thought to be one of the underlying causes of BP. Old adults who had overall weaker lower extremities have been shown to have increased BP while walking on level and incline surfaces, however individual muscle groups have not yet been evaluated. We hypothesize that one causal factor of BP with age is that hip extensor muscles are more similar in strength in young and old adults than are ankle plantarflexor muscles, thus enabling old adults to walk with larger mechanical contributions from hip muscles as compensation for reduced contributions from ankle muscles. The purposes of the study were 1) compare muscle strengths of hip extensors and ankle plantarflexors between young and old adults, 2) verify BP in old adults by comparing hip and ankle joint torques and powers between age groups in level and incline walking & 3) examine the relationship between the relative strength in hip vs ankle muscles and the magnitude of BP in old adults during these gaits. 14 young (20yrs) and 22 old (76yrs) adults performed maximal isometric and isokinetic standing hip extension (20° of hip flexion) and seated ankle plantarflexion (15° of dorsiflexion). Age-based comparisons of muscle strength were made with 2X3 factor repeated measures ANOVAs, $p<0.05$. The same participants performed incline and level walking while ground reaction forces and 3D kinematics were obtained data. Walking joint torques and powers were calculated with inverse dynamics and were assessed using peak hip-to-ankle ratios with larger ratios indicating a larger shift of mechanical output to the hip. 2X2 factor repeated measures ANOVAs ($p<0.05$) for level and incline conditions were used to compare the torque and power ratios between age groups, with significant differences indicating BP. Pearson's correlations ($p<0.05$) were used to examine the relationship between walking power/torque ratios and the ratio of hip to ankle muscle strength in old adults. Old adults' hip extensor and ankle plantarflexor muscles were significantly weaker than young by 20% and 39%, ($p<0.05$). Old adults displayed a significant increase in hip/ankle ratios for both torque and power during level and incline conditions, indicating that the old adults exhibited BP ($p<0.05$). However, the correlations between ratios of hip and ankle isometric strength and hip/ankle peak torque and power were not significant for either level or incline walking. These findings suggest that there is a variation in strength decrement of individual lower extremities muscle groups due to age which may partially cause BP with age. However, we were unable to identify a relationship between the hip/ankle muscle strength ratio and BP, indicating the possibility of multiple factors contributing to BP.

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Chapter I: Introduction

Introduction

As humans age into older adults, there is a notable decline in physical capacity and the ability to perform regular activates of daily living. Because walking is an important part of retaining independence, walking gait characteristics have been used to categorize the older population into various health categories. For example, gait speed can be used as an indicator of current health and a predictor of length of hospitalization [69]. Other spatial parameters, such as stride length, can also be used to distinguish the frailty level of an older adult [78]. When compared to the gait of younger adults, older adults have a 4% lower cadence, and a 4% shorter stride length [23]. The combination of these reduced kinematics produces a slower walking velocity and thus a reduction in physical activities and capabilities. There are also stereotypical differences in the distribution of lower extremity joint torques and joint powers which drive the locomotion task. These differences lead to altered work production in various muscles of older compared to younger adults. Notably, there is a shift from distal to proximal joints and muscle groups in older adults [16,23,45,47,51]. While walking at the same speed, the contributions of the ankle to the total work decreases from 73% to 51%, while the hip increases its contributions from 16% to 44% of the total work in old compared to young adults [23]. A similar redistribution pattern can be seen in older adults while running as well[51]. This same shifting of joint torques notably increases in magnitude when older adults walk up an inclined surface, with an increase in hip extensor torque but no increase in ankle plantarflexor torque[31]. This redistribution of joint contributions in the lower extremities from distal joints to proximal joints while walking and running, called Biomechanical Plasticity, is the underlying cause of the reduced kinematics in older adults. However, the degree of Biomechanical Plasticity can vary depending on an individual’s characteristics. For instance, an older adult with more physical capacity demonstrates a greater shift of joint torques, power and work than an older adult with less physical capacity[49].

These gait adaptations in older adults are due to a variety of underlying physiological, neurological, and biomechanical factors, one of which is the decline of muscle quality and thus a loss in the ability to function properly [47]. Muscle functional capabilities can be evaluated by muscle strength or power, which have both been shown to decline in older adults. Concentric and isometric muscle strength can decline by 31N and 32N, respectively, per decade [46]. It was demonstrated by Thom et al. 2007 [84], that the normalized peak power of older men was 72% lower than young adults. These observations in decline in muscle strength and power, and others[12,46,58,85], have led to the exploration of this age-related decline in muscle quality and function. Three elements associated with aging and muscle decline are the change in fiber characteristics of the muscle, the decrease in fast twitch motor units, and the changes in mitochondrial properties.

Muscle fibers can change in length, size, and type with age [37,75,81]. Older adults have a smaller fascicle length [81] and cross-sectional area [37,81] when compared to younger adults. Although the muscle volume decreases as a whole, the different fiber types have been shown to diminish at varying rates. The size of fast fibers is reduced by 33% with age, while slow fibers remain a constant size [64]. The explanation for this could lie in the fact that slow fibers have greater frequency of expression of protein complexes that control both synthesis and degradation, which are useful in maintaining the turnover rate of sarcomeres throughout the lifespan [64]. This suggests the possibility of muscles declining at varying rates depending on the proportion of fast and slow fibers that comprise the muscle.

Rowan et al. 2012 [75] poses that the main contributor to muscle atrophy is the denervation of motor units. 25% of spinal motor neurons are lost with age, which leads to the reduction in muscle fiber number and size [1]. This motor unit loss may even occur at different rates for different muscles, the tibialis anterior loses motor units at an earlier age than the soleus [21]. Some of the decrease in motor unit function can be attributed to the axons associated with the motor units. A decrease in myelinated fibers, intermodal length, as well as dropouts of large axonal fibers, can reduce axonal conduction speed with age [26,59], which could disrupt the overall motor unit function, and cause, at least partially, the reduction in muscle force production.

Sarcomere mitochondria have also been shown to decline with an increase in age, which can also affect muscle quality and function. Mitochondrial abundance has been shown to be age dependent, with younger adults having 32% more mitochondria and 26% higher mitochondrial density in the subsarcolemma compared to older adults [17]. This decline in mitochondrial numbers with age could potentially be due to the increase in deletion mutation found in mitochondrial DNA, which increase from 0.1% to 0.225% from ages 83-93 [9]. Mitochondrial fission and mitophagy also increases with age [38,64]. These would all cause a decline in mitochondrial function, and thus the inability to properly supply the muscles with ATP needed to produce a contraction properly.

Strength loss can be seen across all muscles; however, the proportion of strength loss varies between muscle groups [45]. Aging has a greater effect on lower extremities, and usually a decline in function is demonstrated at an earlier age than in upper extremities [12,58], which is one reason why gait parameters are used to determine health in older adults. The elbow extensors of older adults showed the least amount of decline in cross sectional area in comparison to knee flexors, knee extensors, and ankle plantar flexors[12], suggesting that lower extremities experience a greater amount of atrophy. McDonagh et al. 1984 [55] demonstrated that the elbow flexors lost 20% of their maximum voluntary contractile force when comparing old to young, while the Triceps Surae lost 41%. This observation raises the notion of individual muscle groups deteriorating at varying rates as well, not just between regions. Evidence for differential rates of decline across muscles is minimal and should be explored further in order to determine the best way to prevent and restore muscle loss for specific muscle groups.

The comparisons between loss of muscle strength in upper and lower extremities indicate that it is possible for different muscle groups' strength to decline at varying rates. The shifting of torque and work contributions away from the ankle plantarflexors and toward the hip extensors while walking [23], suggests that the ankle plantar flexor strength and power decline at a greater rate than that of the hip extensors. Anderson & Madigan, 2014 [2] contradicted this theory when they demonstrated older adult's maximum isometric strength declined by 32% in the hip extensors, and a 20% strength decline in the plantar flexors, when compared to younger adults. However, Harbo et al., 2012 demonstrated old women had a of 41% strength decrement at the ankle plantarflexors and 33% strength decrement at the hip extensors when compared to young women. The decline in strength in the ankle plantar flexors vary across other studies from 20-40% between young to old adults [7,20,51,88]. The contribution of knee extensors and flexors to joint torque and work contributions remain fairly constant during walking [23,45], and as expected, decline in strength similarly (~2%/year) when compared to each other [36]. Because total leg strength has been associated with the amount of Biomechanical Plasticity [45], we postulate that the individual muscles groups' decreasing strength in older adults may be related to the proportion of proximal to distal shift in joint contributions while walking in older adults. To date, no study has linked the amount of decline in muscle strength in the lower extremity muscle groups primarily responsible for powering walking to the amount age-associated Biomechanical Plasticity.

Hypotheses

This study will center on two hypotheses:

1) Older adults will show a greater decrement in muscle strength of the ankle plantar flexors when compared to hip extensor muscles, and
2) While walking, older adults' lower extremity joint torques and powers will shift from the muscle groups that show a greater decrement in muscle strength and toward muscle groups that have less decrement in muscle strength compared to young adults.

Purpose

The purposes of this thesis were to 1. Examine the age-related changes in muscle strength of the various muscle strength groups of the lower extremities, 2. Verify age-associated biomechanical plasticity in the old adults of this study, and 3. Determine as well as the relationship between the variation in muscle strength decrement and the magnitude of biomechanical plasticity on level and incline walking in old adults.

Delimitations

1. Young adults will be between the ages of 18-25 years, and the older adults will be between the ages of 65-85 years.
2. Subjects will be healthy and have no history of musculoskeletal or neuromuscular disorders.

3. Subjects will have a Body Mass Index below 30kg/m^2
4. Subjects will be able to perform activities of daily living without assistance
5. Strength measurements will be taken from only the hip and knee extensor muscles and ankle plantarflexor muscles.

Operational Definitions

Age-associated Biomechanical Plasticity- The redistribution of joint kinetics during walking from distal joints to proximal joints in older adults.

Biomechanical Plasticity Ratio- Hip walking mechanical output divided by ankle walking mechanical output. A difference in ratio is used to determine the magnitude of biomechanical plasticity exhibited between groups.

Chapter II: Review of Literature

Introduction

The purpose of this study is twofold. The first is to determine and examine the amount of muscle strength between muscle groups of the lower extremities in young and older adults. The second is to determine the relationships between strength losses with age in various lower extremity muscle groups and the amount of Biomechanical Plasticity observed during level and incline walking. This review of literature will explore the following concepts: neuromuscular properties and aging, decrease in strength and power, various rates in decline of strength and power, changes in walking mechanics due to age, speed, and incline, biomechanical plasticity, and a summary.

Neuromuscular Properties and Aging

Muscle size and length have been shown to change as a muscle ages. A decline in muscle mass can result in a decline in muscular strength and power [89]. A significant loss of muscle mass, due to age, has been observed in both upper and lower extremity muscles [12,36,65,84], and is suggested to be one underlying factor of the loss in muscle strength. The loss of muscle mass due to aging has been coined Sarcopenia [18,87] and affects up to 13% of adults over 60, and up to 50% of adults aged 80 or older [61]. Compared to younger adults, older adults have half the contractile volume in their dorsiflexors and only 25% of the contractile volume in their plantarflexors [43]. With this decline in contractile volume of muscles, older adults would be unable to produce the same amount of force as younger adults. This would affect the forces produced during daily activities, such as walking. Fascicle length has also been shown to decline in the medial gastrocnemius of older adults compared to younger [81,84]. Shorter fibers would reduce the maximal force produced due to the force-length relationship of muscle. As people age, their muscles lose the ability to produce the same amount of contractile force, due to the decrease in muscle mass as well as the shortening of fibers.

Changes in fiber characteristics due to age can also be dependent on the type of fiber. Type 1 fibers have been shown to remain a constant size throughout the life span, which would indicate that it does not change due to the effects of aging. Type 2 fibers however can decrease in size by 33% in older adults. It is postulated that Type 1 fibers are able to maintain sarcomere turnover rates more effectively than Type 2 fibers, due to an increase in protein complexes that control synthesis and degradation in Type 1 fibers [64]. Murgia et al., 2017[64] also discovered that older fast fibers have a sharp decline in glycolytic enzymes, while slow fibers actually increased the expression of glycolytic enzymes. The abundance of proteins involved in glycogen storage and metabolism follows this same pattern of reduction in fast fibers and rise in slow fibers with age. These two findings would effectively diminish the amount of force produced by Type 2 fibers due to the decreased ability to produce glycogen from non-aerobic sources, a process that fast twitch fibers rely on heavily. Muscles which incorporate more fast twitch fibers would be greatly affected, which brings about the topic of varying magnitudes of muscle strength decline due to age in different muscle groups.

The denervation of motor units also plays a role in age dependent decline of muscle function, and is thought to be the main contributor of muscle atrophy [75]. Motor unit denervation and reinnervation can change the fiber-type composition [68], this remodeling of motor units typically involves the denervation of fast twitch fibers. These fast twitch fibers are then reinnervated by motor units that have split off from slow twitch fibers [52]. This would cause a slow change in fiber type, and lead to an increase of slow twitch fibers in a particular muscle, and alter the function of that muscle. The sprouting capacity of motor neurons to reinnervate muscles seems to also be dependent on location, as the motor neurons of an injured distal muscles have been shown to have less sprouting capacity than motor neurons of an injured hip muscle [67]. The denervation of motor units in injured muscles can be analogous to what occurs in aged muscles, which would indicate that older distal muscles could have less sprouting capacity compared to a muscle at a more proximal joint with a shorter motor neuron. A muscle with fewer motor units would reduce the physical abilities of that muscle, which suggests the plausibility that while all muscles degrade, they may degrade at a varying rates. Denervation of motor units is not the only neuromuscular change that affects muscle function. Demyelination of axons of motor units is also affected by aging [5]. The decrease in Schwann cells of motor unit axons, leads to the increase in length of the axonal Nodes of Ranvier [22], which would ultimately decrease the conduction velocity of axons. This reduces the ability of neurons to effectively and efficiently transmit motor commands [74,88], and thus potentially decreases the functional ability of muscles.

Muscle force production is also dependent on the amount of Adenosine Tri Phosphate (ATP) available for energy usage to complete a contraction according to the sliding filament theory[44]. Mitochondria aid in the production of ATP through aerobic cellular respiration. Because of its importance in the production of ATP, changes in mitochondrial abundance can severely impair a muscle’s capability to produce a contraction. Younger adults have 132% more muscle mitochondria than older adults, which leads to the conclusion that the abundance of mitochondria is at least partially age dependent[17]. This can be attributed to a deletion sequence mutation found on mitochondrial DNA that has been shown to increase in prevalence with age [9]. Older adults have also been shown to have an increase in mitochondrial fission and mitophagy that parallels mitochondrial decline [17,38]. Mitochondrial DNA is more susceptible to damage and mutation due to the fact that it lacks histones and is exposed to damage caused by free radicals, as well as the fact that it contains fewer repair mechanisms [73]. As the mitochondria DNA accumulates damage over time, it declines in function and its ability to produce ATP [8]. With a decrease in the number of functioning mitochondria, the muscles of older adults have less ATP available in order to contract muscles needed for movement. This could potentially affect muscles comprised of slower twitch fibers than fast twitch, due to the mitochondria's importance in oxidative phosphorylation, which is the primary source of ATP in Type 1 fibers.

From these conclusions, it is clear that aging has various effects on muscle characteristics, and thus, functional ability. These functional changes would negatively affect the ability of a muscle to produce forces needed to compete everyday tasks important to independent living. These changes seem to also affect one fiber type over another, and as such introduces the idea that the rate of muscle decline could vary depending on fiber type composition. The limited sprouting capacity of distal motor neurons seems to also suggest that a muscle can degrade at a different rate due to proximity.

Various Rates in Decline of Strength and Power

As discussed, aging changes muscle characteristics, which results in a decline of muscular function. Aging can affect muscular properties such as fiber length, type, and cross-sectional area, it can also affect the amount of ATP available for muscle contraction. These changes reduce the amount of contractile force produced by a muscle, and hinder the ability to perform daily activities of living. Decline in muscular strength and power can be seen in muscles in various rates between both upper and lower extremities, and possibly between muscle groups of lower extremities.

It has been shown that upper extremity muscles reduce in both muscular strength and power [12], however they are not affected by aging as much as lower extremity muscles[58]. In both extremity regions, muscle strength starts to decline by the age of 60 years, however, lower extremities have a faster rate of decline [7,12,14,58]. The decline in muscle strength of leg muscles has been shown to have a higher negative correlation to changes in age, body mass, and height than muscles of the arm [42]. This suggests that lower extremity muscles are more susceptible to the changes that were previously discussed that occur because of aging. When comparing between upper and lower extremities, lower extremity torques and power had a greater magnitude of decline due to aging than the elbow extensor and flexors [12]. Elbow extensors had a 20% decline in isometric force production from young to older adults, while the triceps surae decline by 40% [86]. Ankle plantar flexors of older adults showed the greatest decline in muscle isometric force between 6 muscle groups of the upper and lower extremities [14]. This suggests that muscle strength and power can also decline between muscle groups of the same region.

Lower extremity muscle groups that produce locomotive movements, such as walking, have been examined to determine the amount of strength and power decline due to aging. Hortobagyi et al., 2016 used knee flexor strength during a leg press to represent overall lower extremity muscle strength, which declined due to age by 43%. However Hortobagyi et al., 2016 does not compare the rates of decline of individual muscle groups. Reports on the decline in older adult ankle plantar flexor strength can vary from 20-40% [2,42,43,86], this variation can make it hard to directly compare ankle muscles with the decline in other lower extremity muscle strength. Hip extensor and flexor muscles have shown a 33% and 34% decline in strength between young and older adults, respectively [2], while knee extensor muscles decline similarly to the knee flexor muscle group (~2%/year) [36]. The powers of these muscles have been shown to follow a similar pattern of decline at a greater magnitude [20,51,70,84]. Buddahev & Martin, 2016 and Anderson & Madigan, 2014, demonstrated that more proximal hip extensor muscles had a larger decrement (33% and 45%, respectively) than the distal ankle plantarflexor muscles (27% and 20%). However, those results are not supported by Harbo et al., 2012, who demonstrate that men have no variation in muscles strength decrement due to age between ankle plantarflexors (35%) and hip extensors (35%), while women have a strength decrement of 42% at the ankle plantarflexors and 33% strength decrement at the hip extensors when compared to young women. This area of research should be explored more in order to get a full understanding of the rates in decrement for each muscle group.

The exploration into preventing muscle strength loss has increased due to the importance of maintaining strength to combat the loss of physical capacity. In general, strength training programs cause hypertrophy as well as an increase in maximal force production in healthy individuals. With that in mind, the implementation of similar strength training programs should help maintain and even restore some muscle strength lost with age.

Elderly people are, in fact, able to partially recover strength and power of muscles that are critical to locomotion [28,29,62]. After an 8-week training program, older adult subjects gained strength in both their right (174%) and left (180%) legs [29]. Elderly individuals have been shown to increase their plantar flexor power by 33.1% [28], torque by 20% and activation by 9.2% with strength training [63]. Function isn't the only component that can be affected by strength training, the cross-sectional area of the quadriceps and hamstrings have also been shown to increase without a significant increase in intramuscular or subcutaneous fat [29]. This impies the capability of muscle hypertrophy in older populations. However, these changes in muscle properties are not permanent, and muscle strength can once again decline if training is not continued [29]. The effects of strength training on older adults further verifies that muscles can decline at varying rates, and that perhaps the implementation of strength training in not only older adults who have lost strength, but in all adults, would prevent and limit the amount of strength lost due to age.

Changes in Walking Mechanics due to Age, Speed, and Incline

According to the 2014 US Census, adults over the age of 65 years were 13% of the US population and will increase to 20% by the year 2030. More people are living longer, and this trend can be observed across other developed countries as well. As such, it is important to understand the effects aging has on the human body. With an increase in age, there is a decrease in physical function and cognitive abilities [15]. 15.3% of adults 65 years and older are considered frail. This increases to ~27% for adults over the age of 80 [3]. Frail adults are considered to be in a state of high vulnerability for adverse health outcomes, such as falls, the need for long-term care, and even death [3,13,35]. Muscle weakness, low endurance, and weight loss are key descriptors of frailty [35] that negatively impact older adults in their ability to perform activities of daily living, such as walking. Walking is one of the fundamental movements in locomotion that able bodied individuals use regularly, and as such, is an important component for both living independently and quality of life. Impairments in this locomotive ability can lead to an increase in risk of falls, injuries, hospitalizations, and in extreme cases, death [83,87]. This has led to the exploration into walking and its ability to assess physical capacity and frailty. Gait speed has been established as a determining factor in categorizing non-frail, pre-frail, and frail adults [13,69,78]. Gait speed is comprised of stride cadence and stride length kinematic components. Stride length decreases when transitioning from pre-frail to frail [78]. Healthy older adults have been shown to have a slower gait speed, with a shorter stride length, but a faster cadence compared to young adults [23,47]. With the increase in older adult population, it is important to investigate the potential underlying causes of decreased gait speed in healthy older adults in order to maintain their independence and quality of life.

Changing speed while walking is an important capability for maintaining independence. Most individuals walk at their self-selected speed that is most efficient for them, however some instances require a change in speed, like trying to cross the street before the light changes. While walking at an increased speed, there are no changes in the joint angle patterns[91]. The joint torque and power patterns during the stance phase are also similar at increasing speeds, however the amplitude of the ‘power burst’ at these joints increase with an increase in speed. This suggests that the increase in stride length and cadence of walking is a result of a power increase, not an increase in relative timing, indicating that a similar motor program is being used at various speeds[91].

The capability of walking on an inclined surface can also be pertinent to everyday life, like walking up a ramped walk-way into a building. Walking stride length and frequency remain the same with an increase in incline[48]. However, the knee and hip have an increase in flexion upon initial contact. There is also an increase in hip extensor movement with a delayed transition into flexion in late stance phase. As the incline increases, the ankle position is more dorsiflexed throughout the stance phase, but has the same peak plantarflexion position as level walking. This leads to an increase in peak plantarflexor moment as the angle of incline increases[53]. There is a greater support torque during inclined walking as opposed to level walking due to the increase in both hip and ankle moments. Inclined ascent requires more work from the lower extremity muscles than level walking in order to raise the center of mass with each step[25]. This is also supported by the EMG muscle activation increasing in the hip and knee extensors as well as the ankle plantarflexors as the incline grade increases[33]. However, these increases in joint torques and muscle activations are not all equal. The hip extensors increase more than the knee extensors or the ankle plantarflexors in both joint torque and muscle activity, demonstrating its pivotal role in inclined walking.

Biomechanical Plasticity

Walking is a locomotive activity that most able-bodied people participate in every single day to get from one point to another. Maintaining healthy walking mechanics is important, especially for older populations who are at risk for falls and injuries. The mechanics of healthy walking in both young and older adults have been investigated to help shed light on the changes in walking due to age. This section will explore the causes to the previously mentioned gait changes in older adults.

The stance and swing phases make up 60% and 40% of a healthy adult walking gait cycle, respectively. The changes seen in healthy older adults, such as decreased stride length, happen mostly in the stance phase of a gait cycle, in which the foot being observed makes contact with the ground, accepts weight, and then actively propels the body forward. The summation of the hip extension, knee extension, and ankle plantarflexion torques is known as the support torque[92]. Although there are variations in the amount of support torque contribution from the hip, knee, and ankle, the support torque summation remains relatively similar. This suggests that if there is a decrement in one joint toque, the other joints compensate to keep the total support torque consistent[92]. As such, this section will identify the kinetic changes that are occurring during the stance cycle to help illuminate the adaptations occurring in the gait of older adults.

When comparing the kinetic variables of the stance phase in healthy older adults to that of their younger counterparts, adaptations in the hip and ankle joints are clearly present. During the beginning portion of the stance phase, hip extensor torque and power has been found to be greater in older adults [23,45,47,60]. The effects of aging on knee kinetics during walking have been disputed [16,23,47,51,93]. Ankle plantar flexor torques and powers have been shown to decrease between young and older adults during the late portion of the stance phase [16,23,47,51,60]. Ankle plantar flexors are important for pushing off the ground and initiating the swing phase of the gait cycle. The combination of the decrease in ankle plantar flexor kinetics and an increase in hip extensor kinetics has led to the interpretation that older adults use their hip extensors to ‘pull’ themselves through the stance phase of the gait cycle, instead of using ankle plantar flexors to ‘push’ themselves into the swing phase [93].

The joint work contribution of each lower extremity joint during the stance phase, when walking at the same speed, has been quantified [23]. The contributions of the hip to the total joint work increases from 16% to 44% when comparing young and older adults, respectively. The knee decreases joint work contributions from 11% in young adults to 5% in older adults. The proportion of joint work that is produced by the ankle joint decreases between young and older adults, from 73% to 51%, respectively. These data demonstrate that the contributions of each joint to the total joint work produced during the stance phase of a gait cycle are redistributed due to aging. There is a decrease in the amount of work produced by the ankle joint, and an increase in the amount of joint work produced by the hip. This redistribution can also be seen in older adults as they walk at faster speeds as well [80].

In older adults the amount of walking torque redistribution is also dependent on the incline of the surface. As described previously, during ramp ascent there is an increase in positive joint torques from the hip and knee extensors and ankle plantarflexors[25]. The hip extensors have a greater increase in both torque and muscle activation, indicating that uphill walking requires more hip extensor contribution than other muscle groups[33,54]. However, in older adults, the hip joint torque increases, but the ankle torque does not[32]. This demonstrates that older adults exhibit a greater torque shift when walking uphill when compared to level walking because of the greater demand from the hip extensors, and less demand from the already impaired ankle plantarflexors. A more difficult task like walking at an incline requires more torque from the lower extremities, however if a joint is not producing enough torque, the other joints must compensate.

This shifting of joint work and torques from distal to proximal joints is termed Biomechanical Plasticity, and is the underlying cause in the changes in gait speed seen in older adults. The amount of Biomechanical Plasticity has been suggested to vary depending on strength between older adults [45], with stronger adults having less joint work redistribution. Physical capacity has also been shown to have a positive relationship with the magnitude of biomechanical plasticity[50]. As discussed, the strength and power of individual muscle groups can decline at various rates, and even regain some strength with training. These findings highlight the possibility that not all older adults have the same magnitude of Biomechanical Plasticity. The joint work shifting due to a decrement in muscle strength from distal to proximal joints, seems to indicate that the muscles of the distal ankle joint have more muscle strength decrement due to aging than the muscles of the proximal hip joint.

Summary

Decreases in gait speed, due to stride length, can be detrimental to older adults and lead to the increase risk of injury, falls, hospitalization and sometimes death. This makes examining the underlying kinetics that contribute to these gait adaptations important in figuring out the cause of these changes.

This review of literature highlighted the fact that older adults increase the amount of hip torque and power during the initial stance phase of the gait cycle, and decrease the ankle torque and power during the last stages of the stance phase. These changes also mirror the inverse relationship found between the contributions of the total joint work of the hip and ankle, in which in the proportion of hip joint work increases while the ankle joint work decreases in older adults. This shifting of joint work and torque from distal joints to proximal joints, identified as

Biomechanical Plasticity, and can be associated with a decline in strength and power of the joint musculature.

Muscle strength is known to depend on changes in muscle fiber length and type, neuromuscular architecture, and mitochondrial abundance that are attributed to aging. It has been shown that older adults have a decrease in muscle mass and muscle strength with an increase in age. Muscle cross-sectional area and contractile volume have been shown to decrease with age. Fiber length has also been shown to be shorter in older adults compared to young. Fiber type changes due to aging can also play a role in the size and function of a muscle, with Type 2 fibers having a decrement in both length and cross-sectional area as well as glycolytic proteins. An increase in age is also associated with the remodeling of motor units and the decrease in myelination of motor neuron axons. The last change in muscle due to aging that was discussed in this review of literature was the decrease of mitochondrial concentration in the muscles of older adults. The neuromuscular changes due to aging can have an adverse effect on the amount of force a muscle is able to produce.

The rate of decline in muscle strength can be attributed, in part, to aging. However, it has been also discussed that different muscles can decline at various rates. Some individual muscle groups of the lower extremities have shown various degrees of decline between studies, however the rate in decline between all lower extremity muscle groups has yet to be examined in its entirety.

The decline in ankle joint work contribution to the total work produced during the stance phase of the gait cycle has been shown to decrease from young to old adults, while the proportion of hip joint work increases. This Biomechanical Plasticity can be attributed to the changes of musculature due to aging, which decreases functional capabilities. This leads to the notion that perhaps ankle plantar flexors, which produce less torque and power during walking gait of older adults, decline at a greater rate than that of the more proximal lower extremity muscles. The focus of this study will be to not only determine the different rates of decline in muscle function due to age, but how those rates also relate to the magnitude of Biomechanical Plasticity in older adults while walking.

Chapter III: Methods

Introduction

It has been hypothesized that the distal ankle muscle groups will have more strength and power decrement than the other lower extremity muscle groups. It was also hypothesized that the rate of muscle strength and power decrement will be related to the magnitude of Biomechanical Plasticity seen in older adults while walking. In order to test these hypotheses, we recruited both healthy young adult and healthy older adult participants. In order to test the first hypothesis, each participant's muscle strength was tested at the hip, knee, and ankle joints. For the second hypothesis, each participant performed walking trials in which their kinematic and kinetic gait characteristics were collected and analyzed. The muscle strength was compared between young adults and older adults as well as between muscle groups in order to determine the amount of muscle strength decrement. The walking torque and power of each joint will be correlated and regressed to determine the relationship between the amount of joint torque and power and the joint muscular strength and power. This section will provide a detailed description of the proposed methods, including the participant criteria, the equipment, the measurement protocol, the data processing, and the statistical analysis, needed to test these hypotheses.

Participants & inclusion/exclusion criteria/ IRB approval

This study includes 14 young adults and 22 old adults, all of whom were recruited from Greenville, NC, and surrounding area. Participants were recruited through flyers, ads, and in person recruitment. Participants were screened for eligibility prior to data collection via a phone interview (Appendix A). On the first day of data collection, the participant provided a written informed consent (Appendix B) that is approved by the Institutional Review Board of East Carolina University (Appendix C). The participant was also required to fill out a short form health survey (SF-36) (Appendix D) to determine physical capacity[90]. The exclusion and inclusion criteria for both the young and older adults is provided below.

Inclusion Criteria for Young Adult Participants:

1. Young adult participants are between the ages of 18 and 30 years at time of data collection.
2. Participants have a Body Mass Index of less than 28kg/m^{2}to prevent obesity effects on gait
3. Participants are healthy with no previous musculoskeletal injuries or neuromuscular disorders that may affect gait.
4. Participants provide written informed consent.

Exclusion Criteria for Young Adult Participants:

1. If the participant has any cardiovascular or neuromuscular pathologies
2. If the participant has had a neuromuscular injury within the past 6 months
3. If the participant has a history of lower limb or back surgery

Inclusion Criteria for Older Adult Participants:

1. Participants are between the ages of 65 and 80 years at the time of data collection
2. Participants have a Body Mass Index of less than 28kg/m^2, to prevent obesity effects on gait.

3. Participants are healthy and have no previous musculoskeletal injuries or neuromuscular disorders that may affect gait
4. Participants are able to walk on level surface without any assistance.
5. Participants provide written informed consent.

Exclusion Criteria for Older Adult Participants

1. If the participant has any cardiovascular or neuromuscular pathologies
2. If the participant has had a neuromuscular injury within the past 6 months
3. If the participant has a history of lower limb or back surgery, or joint replacement
4. If the participant has a terminal illness.

Instrumentation

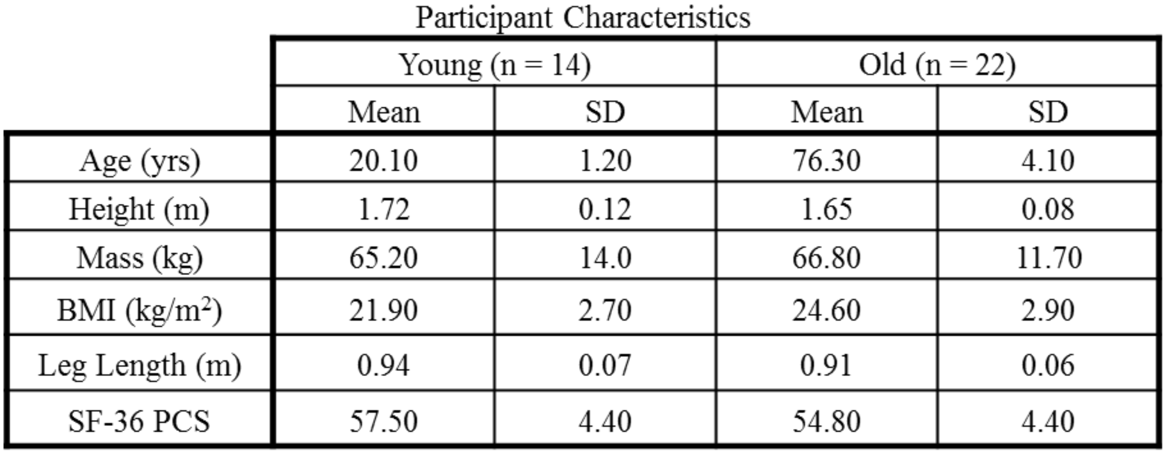
A health questionnaire (Appendix A) was used to determine the eligibility of the participant. A Short-Form Health Survey (SF-36) (Appendix D) was used to determine the health and physical capacity of the participants[90]. Muscle isokinetic and isometric data was collected using a HUMAC NORM Dynamometer (CSMI, model 502140, Stoughton, MA). Walking kinematic data was collected along a level walkway using a 12-camera motion capture system (Qualisys, Göteburg, Sweden). The frequency of each camera was set to 120Hz. The ground reaction force data for each trial was collected at the same time using a force platform (AMTI Model BP6001200 Newton, MA), that was set at a frequency of 960Hz and a gain of 4000 with six analog channels. Inside the motion capture area, an infrared timing system (TracTronix Wireless Timing Systems, Lenexa, KS) was used to measure the gait speeds of the participants, with two timing gates placed 3-meters apart. Data was collected using Qualisys Track Manager

Software (Qualisys AB, Göteborg, Sweden). The data was then analyzed using Visual 3D (C Motion, Germantown, MD), as well as QuickBasic.

Measurement Protocol

All testing was performed in the East Carolina University Biomechanics Laboratory (Ward Sports Medicine Building, 332) in Greenville, NC. The data collection protocol was separated into three days that were scheduled within a 10 day period.

Upon arrival on the first day, the participant read and signed an informed consent form (Appendix B) approved by the Institutional Review Board of East Carolina University (Appendix A). The participant's anthropometric data were then be measured and recorded (Table 1). The participant then filled out a Short Form Health Survey (SF-36) in order to determine physical capacity (Appendix C). The participant also performed a shortened version of the data collection protocol, without the recording of data, in order to be familiar with the equipment and the movements required. The participants were then sent home and be instructed to return on their scheduled data collection days. This is done in order for the participants to become comfortable with the procedures and the data collection team before data is collected.



Participant Characteristics

	Young (n = 14)		Old (n = 22)	
	Mean	SD	Mean	SD
Age (yrs)	20.10	1.20	76.30	4.10
Height (m)	1.72	0.12	1.65	0.08
Mass (kg)	65.20	14.0	66.80	11.70
BMI (kg/m^2)	21.90	2.70	24.60	2.90
Leg Length (m)	0.94	0.07	0.91	0.06
SF-36 PCS	57.50	4.40	54.80	4.40

Table 1: Participant characteristics including average age, height, mass, BMI, leg length, and PCS scores for both young and old adults.

On the second day, the participant was re-informed of the data collection procedures. The participants then performed either the muscle strength testing protocol or the walking protocol, in a randomized order.

For muscle isokinetic and isometric strength testing, the participants performed movements at the hip, knee and ankle, of their right leg. For all joints, the muscle strength was tested at three speeds in a randomized order, 0^0/s (isometric), 90^0/s, and 180^0/s, with three trials each. Prior to each joint being tested, the limb was weighed for gravity correction through the software. For hip testing, participants stood with their right thigh at anatomical zero, their right greater trochanter aligned to the axis of rotation of the dynamometer arm, and their right knee flexed at approximately 90°. The arm of the dynamometer was secured to the right thigh 2 inches above the patella. For testing isometric hip extension, the dynamometer arm was set at 20^0 of hip flexion, and for isometric hip flexion, the dynamometer arm was set at 20^0 of hip extension. The participant performed three trials for the isometric condition. Isokinetic testing involved concentric testing of both flexor and extensor muscles in three consecutive trials for both speeds. For knee testing, the participants were seated with their hips flexed at 90^0 and their lateral distal femoral epicondyle of their right leg aligned to the axis of rotation of the dynamometer arm. The right shank was secured to the dynamometer arm two inches above the ankle. For testing isometric knee extension and flexion, the dynamometer arm was set at 60^0 of knee flexion. The participant performed three trials for the isometric condition. Isokinetic testing involved concentric testing of both flexor and extensor muscles in three consecutive trials for both speeds. For the ankle, the participant was seated with their hips flexed at 90^0 and their lateral malleolus of their right ankle aligned to the axis of rotation of the dynamometer arm. The right foot was secured into the ankle attachment of the dynamometer arm, with straps placed securely over the metatarsals. For testing isometric ankle plantar flexion, the dynamometer arm was set at 15^0 of dorsiflexion. For testing isometric dorsiflexion, the dynamometer arm was set at 20^0 of plantar flexion. The participant performed three trials for the isometric condition. Isokinetic testing involved concentric testing of both plantarflexor and dorsiflexor muscles in three consecutive trials for both speeds. The angles tested for isometric muscle strength for each joint were to mimic similar joint positions at moments of peak torque produced during the stance phase of walking.

For the walking test protocol, the participants performing both level and incline (at 10°) walking trials in order to gather kinematic data. In order to define the pelvis and right lower limb segments, spherical reflective markers were placed on the participant's body. The right and left iliac crests and greater trochanters were used to define the pelvis. The right and left grater trochanters as well as the right leg medial and lateral femoral epicondyles were marked to define the right thigh. The right shank was defined by the right leg medial and lateral femoral epicondyles as well as the right medial and lateral malleoli. The right medial and lateral malleoli in combination with the right foot 1st and 5th metatarsals heads were used to define the right foot. Rigid plastic shells were placed on the lateral aspect of the right thigh and shank and the top of the right foot in order to capture the segment motion during walking trials. The shells of the thigh and shank will have four markers while the foot shell will have three markers. The right and left anterior and posterior superior iliac spines were also marked during the walking trials in order to capture segment motions. Markers used only to define joint centers were removed after a 5 second static calibration trial.

During the walking protocol, the participants performed 5 trials at a standard walking speed (1.3m/s for level and 1.2m/s for incline) and 5 trials at faster walking speed (1.8m/s for level and 1.6m/s for incline) for both level and incline walking conditions. A trial was considered successful if the full right foot made contact with the force platform. If the trial did not meet this criterion, it was discarded and the participant was asked to continue until 5 successful trials were completed. In order to avoid ‘targeting’ the force plate, participants were instructed to walk as naturally as possible while looking forward and their starting position was monitored and altered accordingly to get a successful trial.

Data Processing

The isokinetic peak torque, work, and power for each joint (hip, knee, and ankle) at each speed (60^0/s, 120^0/s, and 180^0/s) was recorded by the HUMAC program. The isometric peak torque for each joint (hip, knee, and ankle) for flexion and extension was recorded by the HUMAC program. All data from the HUMAC program was then exported to an excel worksheet. MatLab was used to separate isokinetic flexion and extension trials using joint position and joint velocity curves, as well as identify and average the peak torque for each joint and strength testing condition.

For the walking kinematics, data was collected using the Qualysis Track Manager Software. Visual 3D was then be used to process the walking data. Using the static calibration recording, a subject-specific linked rigid-segment model of the pelvis and right lower limb was created in Visual 3D. The calibration recording was also be used in order to determine the location of the individual reflective markers within a global coordinate system, as well as defining a local coordinate system. The data collected from the static calibration was used in order to locate the virtual joint centers, and each segment’s center of mass. For the ankle and knee, the joint centers were calculated as 50% of the distance between the medial and lateral malleoli calibration markers and medial and lateral femoral epicondyle calibration markers, respectively. The hip joint center was determined by calculating 25% of the distance between the right and left greater trochanters calibration markers. These data were then used to define the segment’s longitudinal axis by creating a line from the distal to proximal virtual joint centers of each segment. The position of each segment’s center of mass was determined by anthropometric calculations.

In order to calculate joint reaction forces and joint torques, Visual 3D utilizes linear and angular Newtonian equations of motion. For these calculations, the ground reaction forces, center of pressure, segmental anthropometrics, and kinematic position and acceleration data are needed. This inverse dynamics approach began with the segment where the known ground reaction forces come from, in this case, that segment will be the foot. This process then moved proximally to the shank and then the thigh, using the previous segment to calculate the next segment. Visual 3D always used the right hand rule to determine the direction of the calculated torque. The mechanical outputs identified as the dependent variables were peak hip torque (Figure 1, HT), peak ankle platarflexor torque (Figure 1, AT), peak hip power (Figure 2, HP) and peak ankle positive power (Figure 2, AP). The angular impulse and work were calculated as the area under the torque and power curves, respectively.

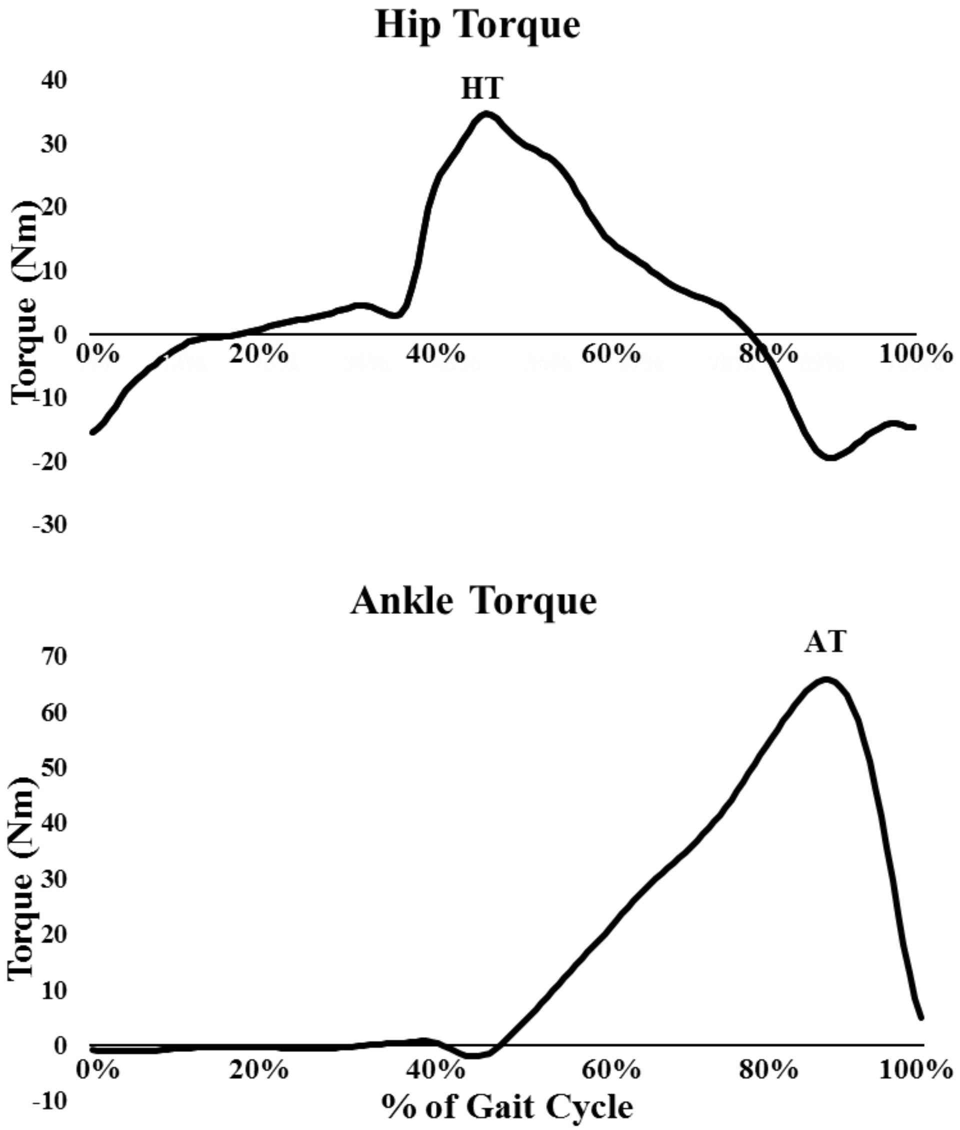


Figure 1: An example of the walking hip (top) and ankle (bottom) torques for the stance phase of level walking at a standard speed. Positive indicates and extensor or plantarflexor torque, negative indicates a flexor or dorsiflexor torque. **HT** represents the peak hip extensor torque location. **AT** represents the peak ankle plantarflexor torque location. ~40% marks the end of swing phase and the beginning of stance phase (heel strike).

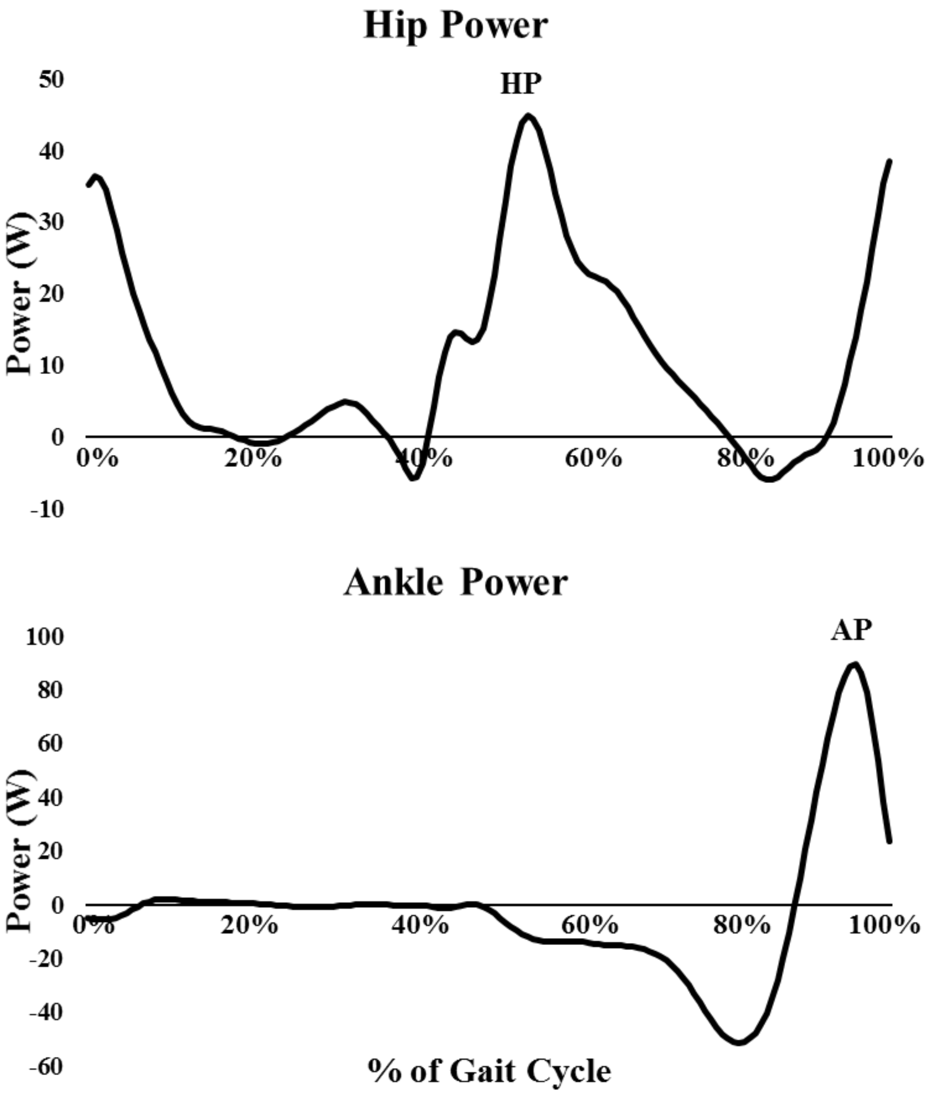
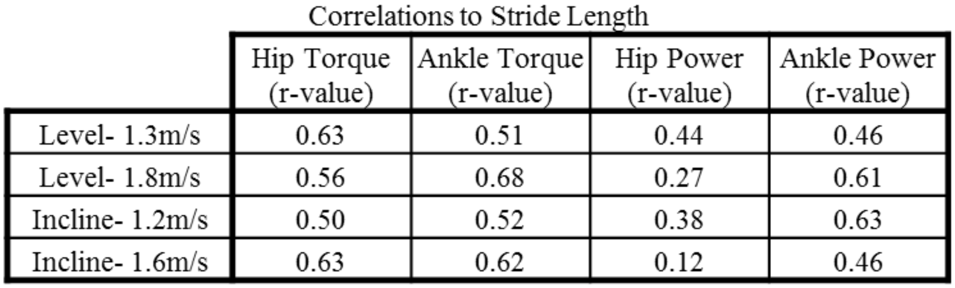


Figure 2: An example of the walking hip (top) and ankle (bottom) power for the stance phase of level walking at a standard speed. Positive indicates a concentric contraction, negative indicates an eccentric contraction. **HP** represents the peak hip positive power location. **AT** represents the peak ankle positive power location. ~40% marks the end of swing phase and the beginning of stance phase (heel strike).

The identified joint mechanical outputs were then normalized to mass as well as stride length. Stride length has a significant relationship to joint power and joint torque at all four conditions (Table 2). Due to this relationship, the walking dependent variables in this study were normalized to stride length.



Correlations to Stride Length

	Hip Torque (r-value)	Ankle Torque (r-value)	Hip Power (r-value)	Ankle Power (r-value)
Level- 1.3m/s	0.63	0.51	0.44	0.46
Level- 1.8m/s	0.56	0.68	0.27	0.61
Incline- 1.2m/s	0.50	0.52	0.38	0.63
Incline- 1.6m/s	0.63	0.62	0.12	0.46

Table 2: The r-values of old adults stride length and peak hip torque, ankle torque, hip power, and ankle power outputs during the four walking conditions.

The peak hip and ankle mechanical outputs were then used to create a biomechanical plasticity ratio. The peak hip output was divided by the peak ankle output (i.e. peak hip torque/ peak ankle torque). As hip output increases and ankle output decreases, the ratio increases, indicating a greater magnitude of biomechanical plasticity. If both joint outputs change at the same rate, or no change occurs, the ratio will not significantly change, indicating no biomechanical plasticity was exhibited. This ratio will be used to compare young and old adults in order to determine the magnitude of biomechanical plasticity exhibited by the old adults.

Statistical Analysis

To test the first hypothesis, separate two (group: Young vs Older adults) by two (joint: hip and ankle) factor ANOVAs ($p < 0.05$), with repeated measures on joint, was conducted for extensor muscle strength isometric and isokinetic testing with alpha set to $p < 0.05$.

Level and inclined gait biomechanics were compared between young and old adults to ensure the presence of age-related biomechanical plasticity within our sample. Separate two factor (age by speed) ANOVAs were used to identify age related differences in walking kinematics and kinetics for level and incline gait. Both analyses used alpha at $p < 0.05$.

The second hypothesis was tested using three sets of regression analyses ($p < 0.05$) within the older adult group in order to determine the relationships between the amount of muscle strength and the magnitude of biomechanical plasticity. These analyses were used to regress hip strength on hip/ankle peak torque, peak power, angular impulse, and joint work ratios. The second set of analyses were used to regress ankle strength on hip/ankle peak torque, peak power, angular impulse, and joint work ratios. The third set of analyses were used to regress the ratios of hip/ankle isometric extensor strength on hip/ankle peak torque, peak power, angular impulse, and joint work ratios. Each set of analyses examined both walking speeds in level and incline walking.

Chapter IV: Results

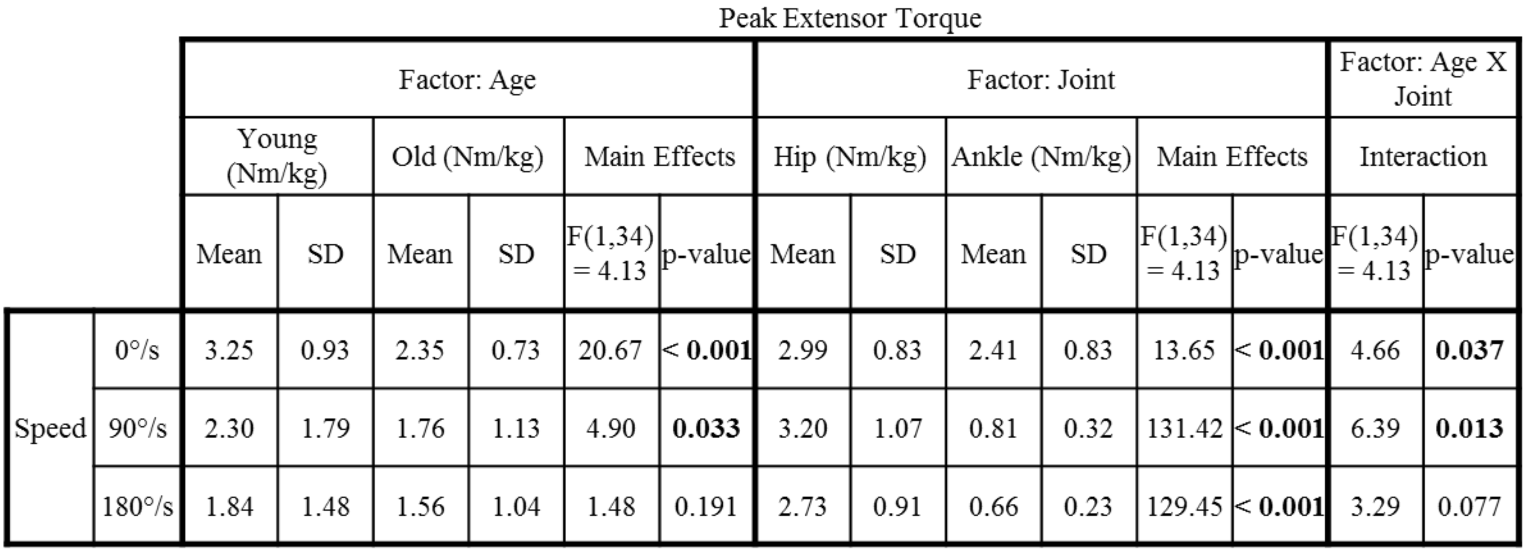
Introduction

The purposes of this study were to compare muscle strengths of hip extensors and ankle plantarflexors between young and old adults, verify BP in old adults by comparing hip and ankle joint torques and powers between age groups in level and incline walking & examine the relationship between the relative strength in hip vs ankle muscles and the magnitude of BP in old adults during these gaits. It was hypothesized that the hip extensor muscles in old adults are more similar in strength to hip extensor muscles in young adults than are ankle plantarflexor muscles, and that this similarity in hip muscle strength and significant decrement in ankle muscle strength may be one cause of the Biomechanical Plasticity in gait observed in old adults.

This chapter is partitioned into the following result sections: Old compared to young muscle strength, Old compared to young level walking, Old compared to young incline walking, Correlations between muscle strength and biomechanical plasticity, and a summary.

Old Compared to young muscle strength

Repeated Measures 2 X 2 ANOVAs with factors of age and joint were used to compare the maximal isometric (0 °/s) and isokinetic (90°/s, 180°/s) torques produced by the young and old adults at the hip and ankle extensor muscle groups (Table 3). There was a significant interaction between the Age and Joint factors ($F_{(1,34)} = 4.66$) for the isometric test (p = 0.037). Student's t-tests were used to analyze the simple main effects for age at each joint. For the isometric condition (Figure 3), old adults' hip muscles were significantly weaker than the young adults' hip muscles by 20% (p = 0.005). At the ankle joint for the isometric strength test, the old adults' ankle plantarflexors were significantly weaker than the young adults' ankle plantarflexors by 39% (p < 0.001). There was a significant interaction between the Age and Joint factors for the isokinetic 90°/s test (p = 0.013). For the 90°/s condition (Figure 4), the old adults were significantly weaker at the hip extensors than the young adults by 39% (p < 0.001), but the ankle plantarflexors were not significantly different between the age groups (p = 0.497). There was not a significant interaction between Age and Joint factors for the isokinetic 180°/s strength test (p = 0.077). For 180°/s (Figure 5), the old and young peak torques were not significantly different (p = 1.91), but the hip extensor muscle group was significantly stronger than the ankle plantarflexor muscle group (p < 0.001). Comparisons of young and old strength for all muscle groups for all testing conditions can be found in Appendix E, Table 19.



Peak Extensor Torque

		Factor: Age						Factor: Joint						Factor: Age X Joint	
		Young (Nm/kg)		Old (Nm/kg)		Main Effects		Hip (Nm/kg)		Ankle (Nm/kg)		Main Effects		Interaction	
		Mean	SD	Mean	SD	F(1,34) = 4.13	p-value	Mean	SD	Mean	SD	F(1,34) = 4.13	p-value	F(1,34) = 4.13	p-value
Speed	0°/s	3.25	0.93	2.35	0.73	20.67	**< 0.001**	2.99	0.83	2.41	0.83	13.65	**< 0.001**	4.66	**0.037**
	90°/s	2.30	1.79	1.76	1.13	4.90	**0.033**	3.20	1.07	0.81	0.32	131.42	**< 0.001**	6.39	**0.013**
	180°/s	1.84	1.48	1.56	1.04	1.48	0.191	2.73	0.91	0.66	0.23	129.45	**< 0.001**	3.29	0.077

Table 3: Mean, standard deviation (SD), main effects and interaction effects of Age (young vs old) and Joint (hip vs ankle) on the peak extensor torque for isometric (0°/s) and isokinetic (90°/s and 180°/s) strength tests. **Bolded i**ndicates a significant difference ($F_{(1,34)} = 4.66$, $p < 0.05$).

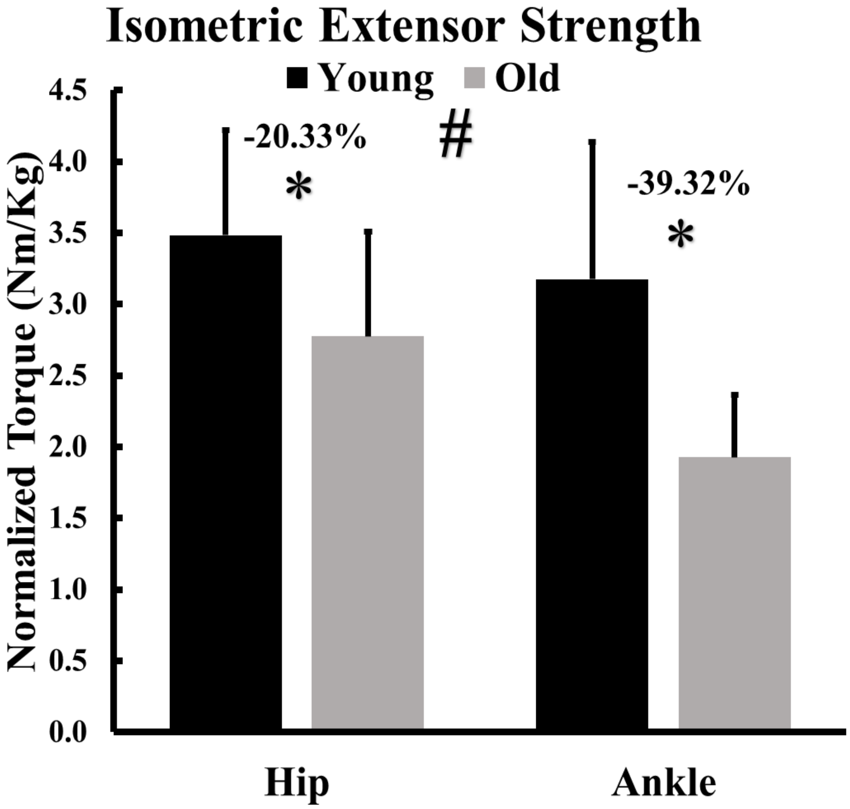


Figure 3: The peak isometric extensor torque at the Hip and Ankle joints between young (black) and old (grey) adults. * Indicates a significant difference ($p < 0.05$). # Indicates a significant interaction between Age and Joint ($p < 0.05$).

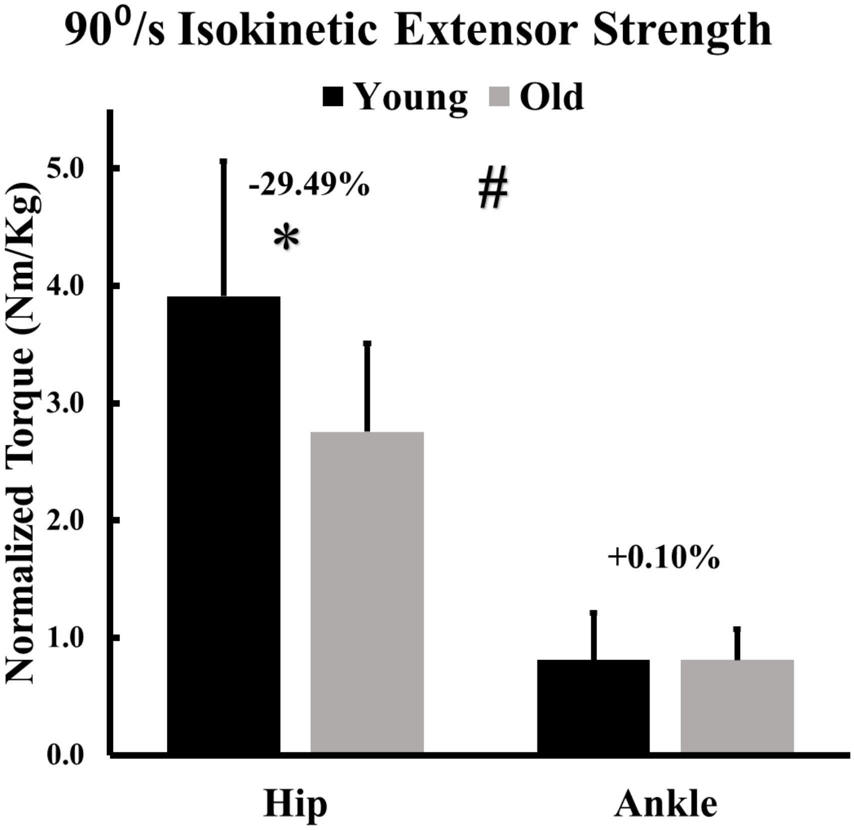


Figure 4: The peak isokinetic 90°/s extensor torque at the Hip and Ankle joints between young (black) and old (grey) adults. * Indicates a significant difference ($p < 0.05$). # Indicates a significant interaction between Age and Joint ($p < 0.05$).

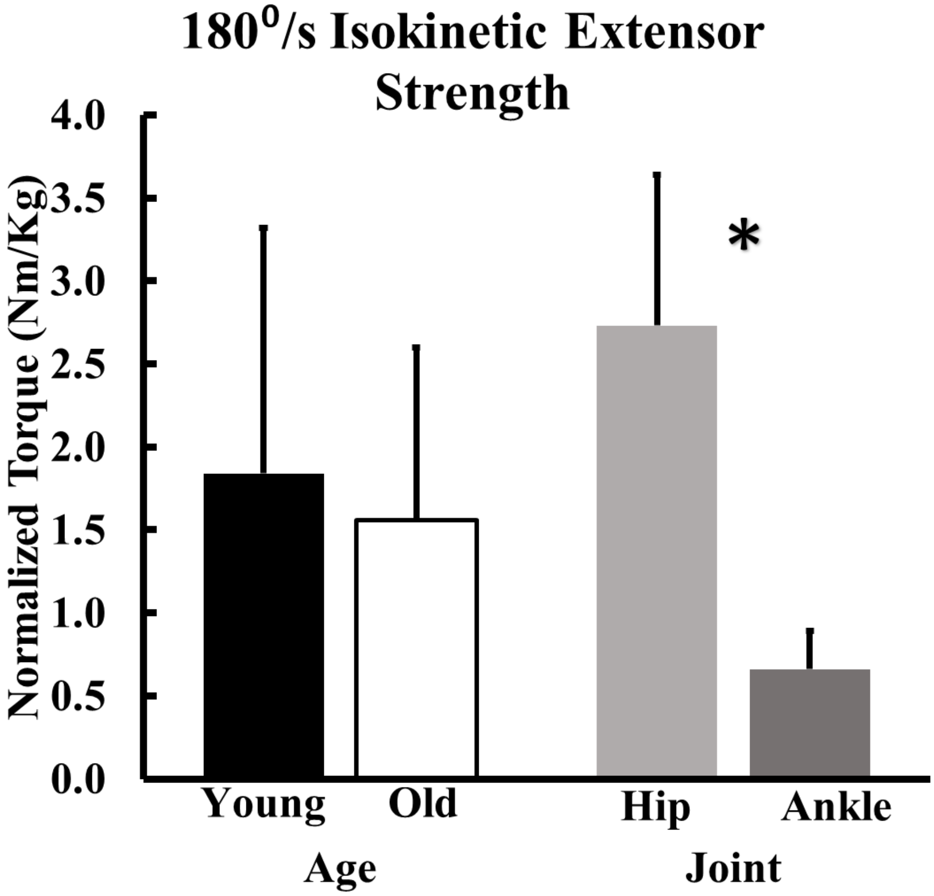


Figure 5: The main effects of Age (young (black) and old (light grey)) X Joint (hip (white) and ankle (dark grey)) on the isokinetic 180°/s peak extensor torque ratio (non-dimensional).
* Indicates a significant difference ($p < 0.05$).

Student's t-tests were also used to compare the hip/ankle peak torque ratio of the extensor muscle groups during the isometric (0°/s), and isokinetic tests at 90°/s and 180°/s (Table 4). The older adults' hip/ankle ratio for the isometric strength test (Figure 6) was significantly greater by ~29% than the young ($p < 0.05$). This indicates that the decrement in muscle strength between young and old was not constant between the hip and ankle muscles, with the ankle plantarflexors having a greater decrement between young and old than the hip extensors. The older adults' hip/ankle ratio for both isokinetic at 90°/s and 180°/s strength tests were significantly lower than the young, by ~48% and ~34% (Table 3, $p < 0.05$). This may be because the ankle plantarflexor peak torques for these tests were not significantly different between young and old (Table 1 & 2). The Hip/Ankle strength ratios for 90°/s and 180°/s are in Appendix E (Figures 4 and 5

Hip/Ankle Peak Extensor Torque Ratio

	Young		Old		%Δ	P-value
	Mean	SD	Mean	SD		
0 °/s	1.17	0.40	1.50	0.47	28.63	**0.021**
90°/s	7.03	5.17	3.66	1.16	-47.89	**0.006**
180°/s	5.75	3.48	3.78	1.13	-34.28	**0.005**

Table 4: Mean, standard deviation (SD), % change, and simple main effects of Age (young and old) on the Hip/Ankle peak extensor torque ratio for isometric (0°/s) and isokinetic (90°/s, 180°/s) strength tests. % change is defined as (old-young)/young * 100 and used to quantify the difference between the two age groups. **Bolded i**ndicates a significant difference ($p < 0.05$).

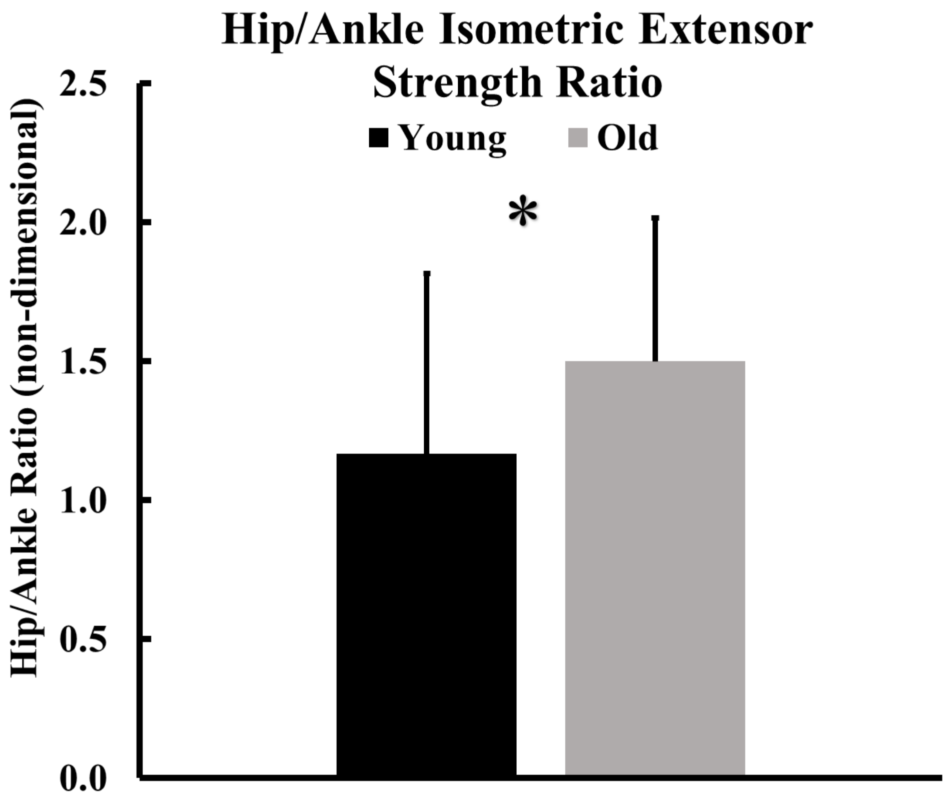
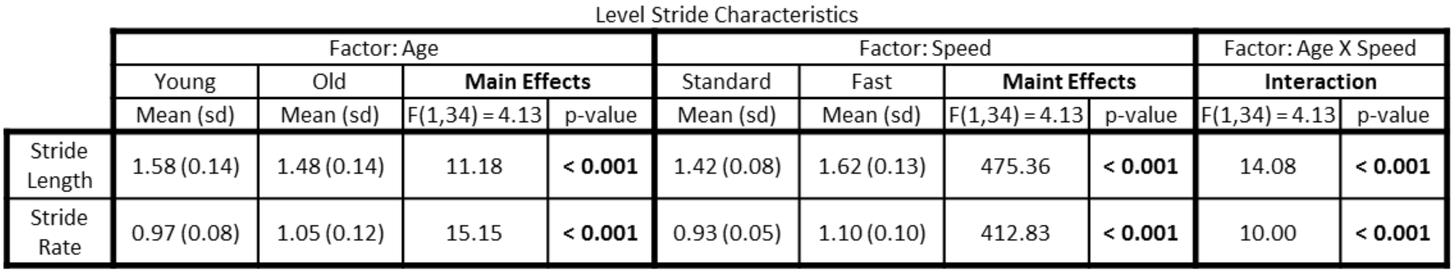


Figure 6: Isometric Hip/Ankle maximal extensor torque ratio (non-dimensional) of young (black) and old (grey) adults. * Indicates a significant difference ($p < 0.05$).

Old compared to young level walking

Biomechanical plasticity ratios were calculated as the quotient between hip biomechanical output and ankle biomechanical output (peak torque and power) to assess the magnitude of plasticity with age and mode of locomotion. Higher ratios indicated more hip and less ankle outputs. Biomechanical plasticity ratios were used to verify the presence of biomechanical plasticity in the older adults, with higher ratios indicating a higher magnitude of biomechanical plasticity. For this section and the incline walking section, we show the hip/ankle ratios of the peak torque and peak power outputs for the level condition at a standard speed of 1.3m/s and a fast speed of 1.8m/s.

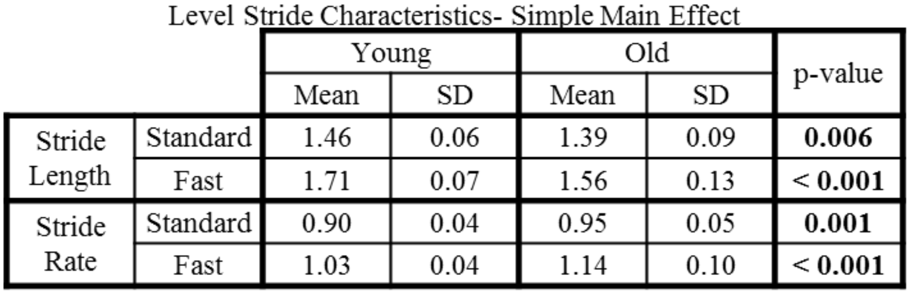
We first however determined that the biomechanical plasticity ratios were strongly affected by stride characteristics, such as stride length and stride rate. In order to compare the young and old adults' stride characteristics, two Repeated Measures 2 X 2 ANOVAs ($F_{(1,34)} = 4.66$) were used to compare the stride length and stride rate of the young and old groups at the standard and fast speeds (Table 5). In the case of a significant interaction, student's t-tests were used to compare the simple main effects of age and speed on stride length and stride rate (Table 6). For stride length, there was a significant interaction between the Age and Speed factors ($p < 0.001$). At the standard speed, the old adults had significantly shorter stride length by ~5% ($p = 0.06$), while at the fast speed, the old adults had significantly shorter strides by ~8% ($p < 0.001$). There was a significant interaction between Age and Speed factors on stride rate ($p < 0.001$). The older adults had significantly faster stride rate by ~6% at the standard speed ($p = 0.001$) and by ~10% faster at the fast speed ($p < 0.001$). Because both groups walked at the same speeds (1.3m/s and 1.8m/s) but older adults had shorter stride lengths and faster stride rates (Figure 7), the biomechanical plasticity ratios were normalized using stride length (ratio/ stride length).



Level Stride Characteristics

	Factor: Age				Factor: Speed				Factor: Age X Speed	
	Young	Old	**Main Effects**		Standard	Fast	**Maint Effects**		**Interaction**	
	Mean (sd)	Mean (sd)	F(1,34) = 4.13	p-value	Mean (sd)	Mean (sd)	F(1,34) = 4.13	p-value	F(1,34) = 4.13	p-value
Stride Length	1.58 (0.14)	1.48 (0.14)	11.18	**< 0.001**	1.42 (0.08)	1.62 (0.13)	475.36	**< 0.001**	14.08	**< 0.001**
Stride Rate	0.97 (0.08)	1.05 (0.12)	15.15	**< 0.001**	0.93 (0.05)	1.10 (0.10)	412.83	**< 0.001**	10.00	**< 0.001**

Table 5: Mean, standard deviation (SD), main effects and interaction effects of Age (young vs old) and Speed (standard vs fast) on stride length and stride rate for level walking conditions. **Bolded i**ndicates a significant difference ($F_{(1,34)} = 4.66$, $p < 0.05$).



Level Stride Characteristics- Simple Main Effect

		Young		Old		p-value
		Mean	SD	Mean	SD	
Stride Length	Standard	1.46	0.06	1.39	0.09	**0.006**
	Fast	1.71	0.07	1.56	0.13	**< 0.001**
Stride Rate	Standard	0.90	0.04	0.95	0.05	**0.001**
	Fast	1.03	0.04	1.14	0.10	**< 0.001**

Table 6: Mean, standard deviation (SD), and simple main effects of Age (young and old) on the stride length and stride rate for the level walking conditions. **Bolded i**ndicates a significant difference ($p < 0.05$).

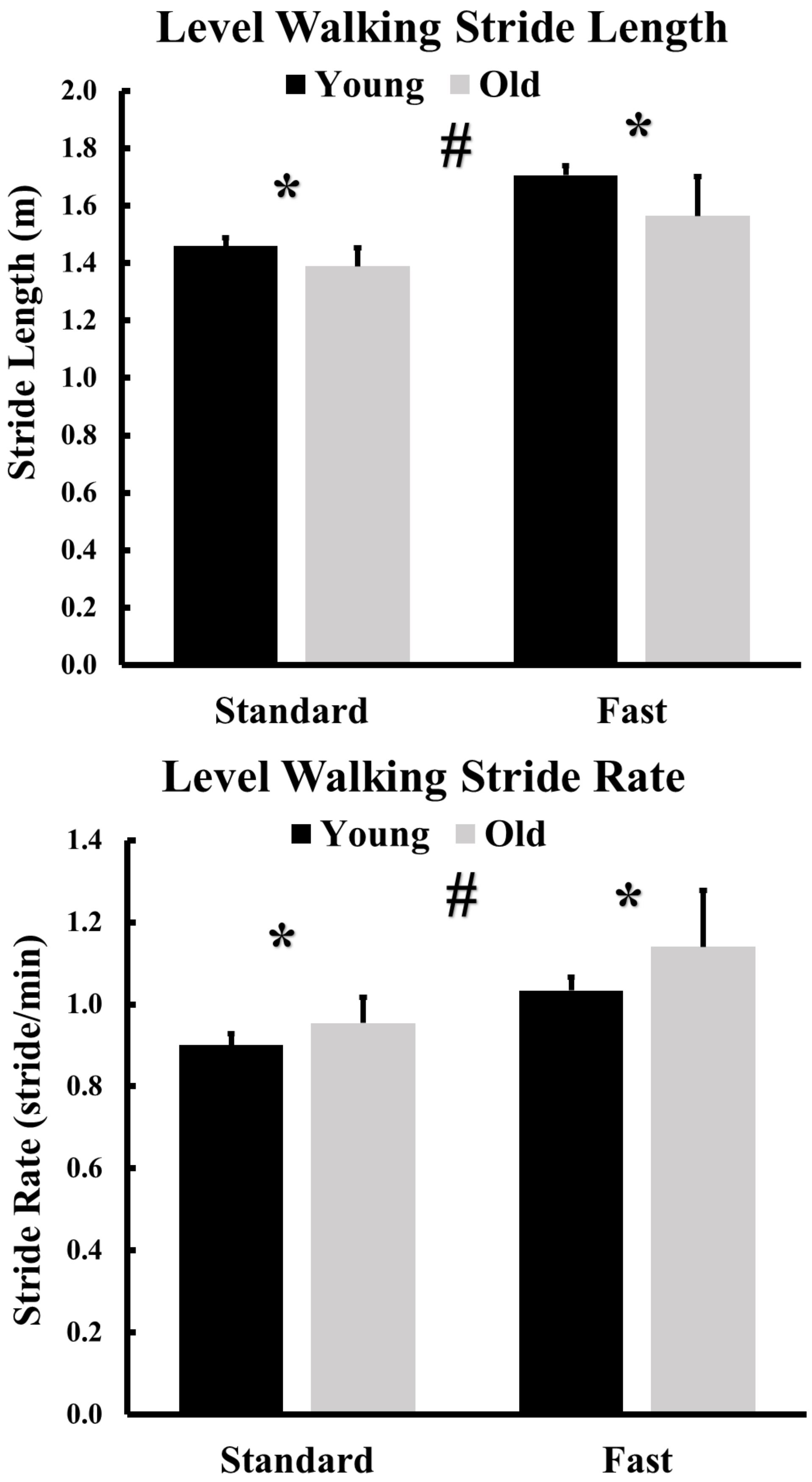


Figure 7: Level walking stride length (top) and stride rate (bottom) of young (black) and old (grey) adults at standard and fast level walking speeds. * Indicates a significant difference ($p < 0.05$). # indicates a significant interaction between Age and Joint ($p < 0.05$).

Two Repeated Measures 2 X 2 ANOVAs were used to compare the effects Age and Speed on the Hip/Ankle peak torque (Figure 8) and peak power (Figure 9) ratios for standard (1.3m/s) and fast (1.8m/s) level walking (Table 7). There was a significant interaction between Age and Speed for the Hip/Ankle peak torque ratios ($p = 0.03$). The older adults had significantly greater Hip/Ankle peak torque ratios than the young adults by ~33% at the standard ($p < 0.001$) level walking speed. The older adults also had significantly greater Hip/Ankle peak torque ratios at the fast level walking speed by ~42% ($p < 0.001$) (Table 8). There was not a significant interaction between Age and Speed for the Hip/Ankle peak power ratio ($p = 0.25$). The older adults had greater Hip/Ankle peak power ratios than young ($p < 0.001$). Both old and young adults had significantly greater Hip/Ankle peak power ratios at the faster walking speed ($p = 0.01$). The Hip/Ankle angular impulse and joint work ratios follow similar trends and can be found in Appendix E (Table 5).

Level Hip/Ankle Peak Torque and Peak Power Ratios

	Factor: Age						Factor: Speed						Factor: Age X Speed	
	Young		Old		**Main Effects**		Standard		Fast		**Main Effects**		**Interaction**	
	Mean	SD	Mean	SD	F(1,34) = 4.13	p-value	Mean	SD	Mean	SD	F(1,34) = 4.13	p-value	F(1,34) = 4.13	p-value
Hip/Ankle Peak Torque	0.40	0.09	0.55	0.14	18.22	**< 0.001**	0.43	0.11	0.55	0.16	71.21	**< 0.001**	5.36	**0.03**
Hip/Ankle Peak Power	0.28	0.10	0.40	0.15	9.17	**< 0.001**	0.33	0.13	0.38	0.16	6.88	**0.01**	10.00	0.25

Table 7: Mean, standard deviation (SD), main effects and interaction effects of Age (young vs old) and Speed (standard vs fast) on Hip/Ankle peak torque and peak power ratios for level walking conditions. **Bolded i**ndicates a significant difference ($F_{(1,34)} = 4.66$, $p < 0.05$).

Level Hip/Ankle Peak Torque Ratio- Simple Main Effect

		Young		Old		p-value
		Mean	SD	Mean	SD	
Hip/Ankle Peak Torque	Standard	0.36	0.07	0.48	0.10	**< 0.001**
	Fast	0.44	0.10	0.62	0.15	**< 0.001**

Table 8: Mean, standard deviation (SD), and simple main effects of Age (young and old) on the Hip/Ankle Peak torque ratios for the level walking conditions. **Bolded i**ndicates a significant difference ($p < 0.05$).

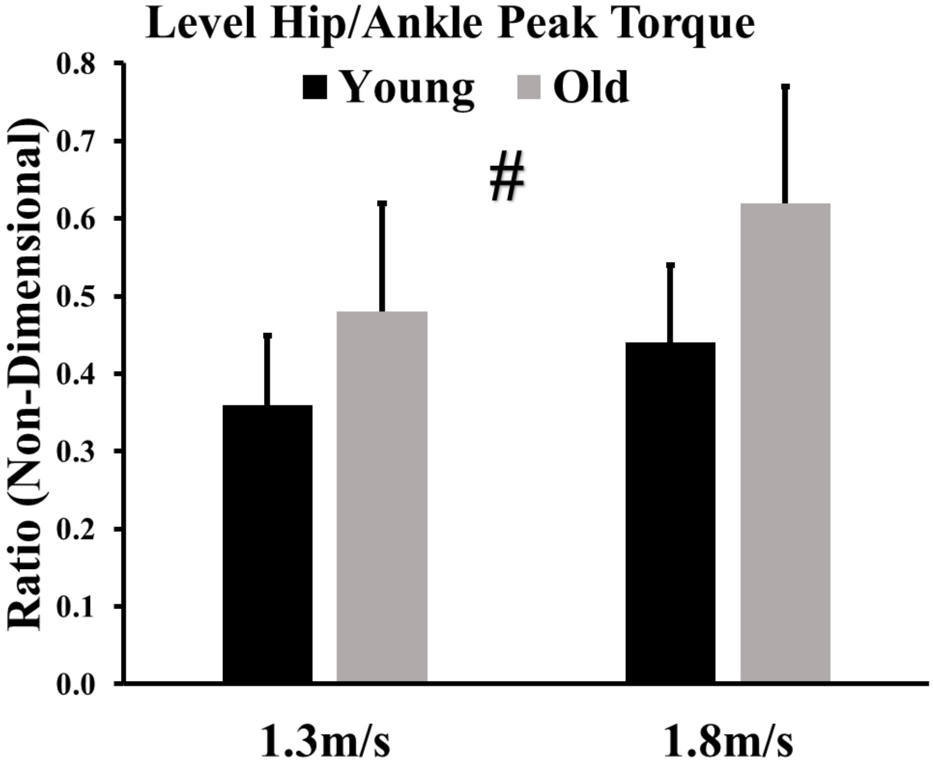


Figure 8: Level walking Hip/Ankle peak torque ratios of young (black) and old (grey) adults at standard (left) and fast (right) level walking speeds. * Indicates a significant difference ($p < 0.05$). # Indicates a significant interaction between Age and Speed ($p < 0.05$).

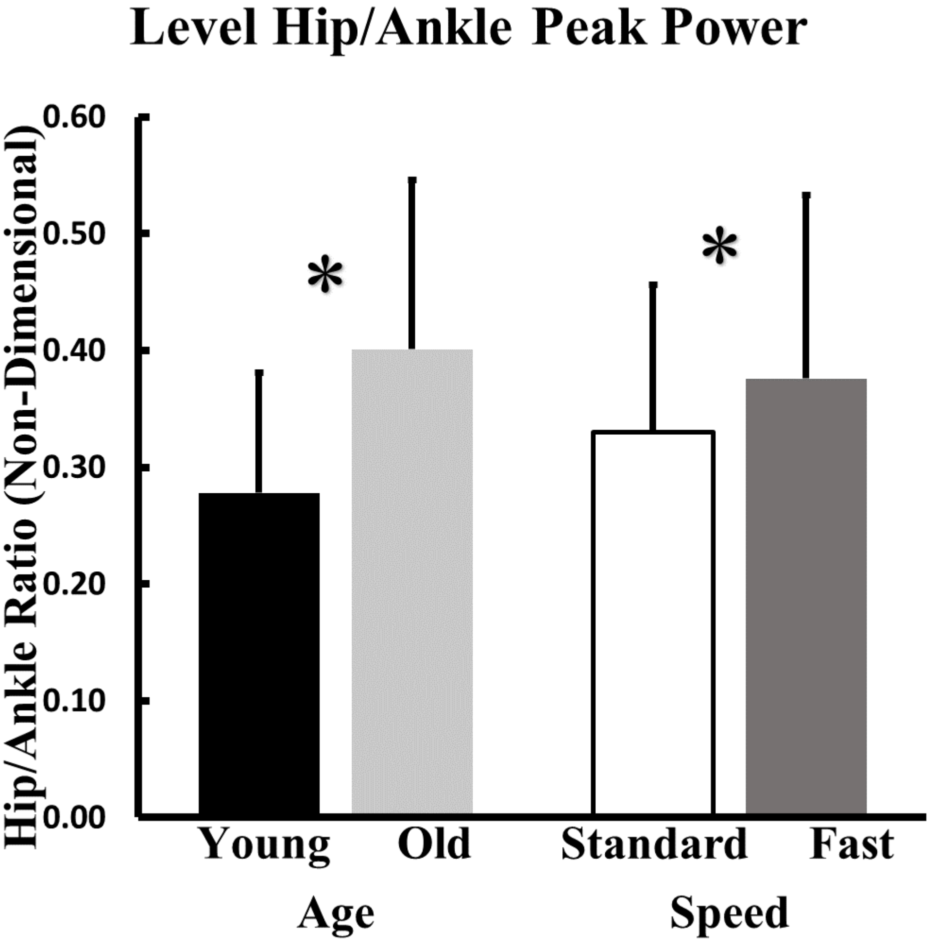


Figure 9: The main effects of Age (young (black) and old (light grey)) X Speed (standard (white) and fast(dark grey)) on the Hip/Ankle peak power ratio (non-dimensional) for level walking * Indicates a significant difference ($p < 0.05$).

Old compared to young incline walking

As stated previously, the biomechanical plasticity ratios are strongly affected by stride characteristics, such as stride length and stride rate. In order to compare the young and old adults' stride characteristics, two Repeated Measures 2X2 ANOVAs ($F_{(1,34)} = 4.66$) were used to compare the stride length and stride rate of the young and old groups at the standard (1.2m/s) and fast (1.6m/s) speeds (Table 9). There was a significant interaction between the Age and Speed factors on stride length ($p < 0.001$). Student's t-tests were used to compare the simple main effects of age and speed on stride length (Table 10). The old adults had significantly shorter stride lengths by ~9% at the standard ($p < 0.001$) and were ~16% shorter at the fast ($p < 0.001$) incline walking speeds. There was not a significant interaction between Age and Speed factors on stride rate ($p = 0.09$). The older adults had significantly faster stride rates at both incline walking speeds ($p < 0.001$). The faster walking speed had significantly faster stride rates for both age groups ($p < 0.001$). Because both groups walked at the same speeds (1.2m/s and 1.6m/s) but older adults had shorter stride lengths and faster stride rates (Figure 10), the biomechanical plasticity ratios were normalized using stride length (ratio/ stride length).

Incline Stride Characteristics

	Factor: Age						Factor: Speed						Factor: Age X Speed	
	Young		Old		**Main Effects**		Standard		Fast		**Main Effects**		**Interaction**	
	Mean	SD	Mean	SD	F(1,34) = 4.13	p-value	Mean	SD	Mean	SD	F(1,34) = 4.13	p-value	F(1,34) = 4.13	p-value
Stride Length	1.60	0.14	1.39	0.13	30.53	**< 0.001**	1.41	0.13	1.53	0.18	96.94	**< 0.001**	25.56	**< 0.001**
Stride Rate	0.91	0.07	1.04	0.07	25.13	**< 0.001**	0.91	0.07	1.07	0.13	113.42	**< 0.001**	3.08	0.09

Table 9: Mean, standard deviation (SD), main effects and interaction effects of Age (young vs old) and Speed (standard vs fast) on stride length and stride rate for incline walking conditions. **Bolded i**ndicates a significant difference ($F_{(1,34)} = 4.66$, $p < 0.05$).

Incline Stride Characteristics- Simple Main Effect

		Young		Old		p-value
		Mean	SD	Mean	SD	
Stride Length	Standard	1.50	0.10	1.35	0.12	**< 0.001**
	Fast	1.70	0.09	1.43	0.14	**< 0.001**

Table 10: Mean, standard deviation (SD), and simple main effects of Age (young and old) on the stride length for the incline walking conditions. **Bolded i**ndicates a significant difference ($p < 0.05$).

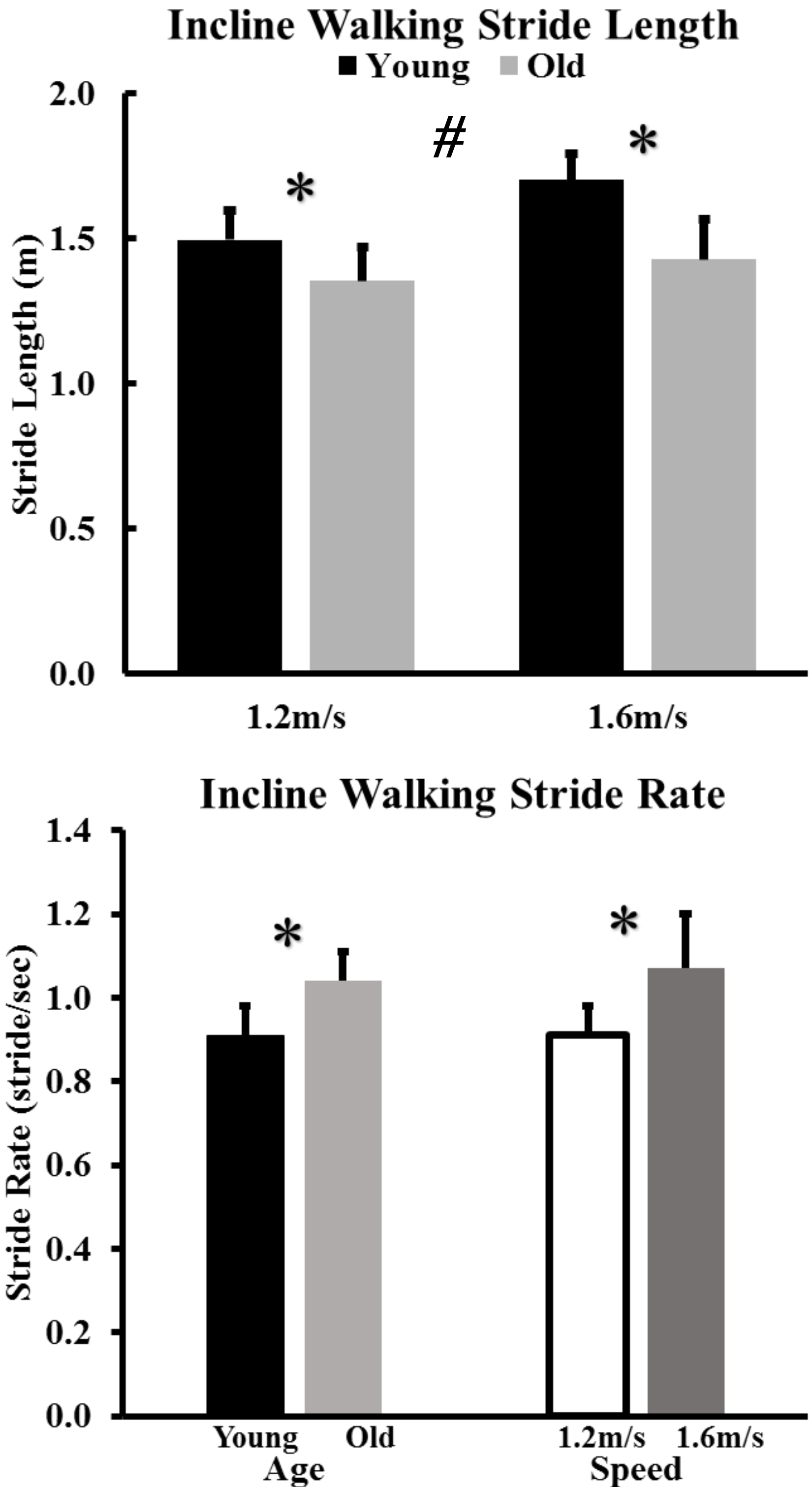


Figure 10: *Top*: Simple main effects of Age (young and old) on the stride length for the incline walking conditions. *Bottom*: The main effects of Age (young (black) and old (light grey)) X Speed (standard (white) and fast(dark grey)) on the stride rate during incline walking. * **i**ndicates a significant difference ($p < 0.05$), # indicates significant interaction.

Two 2 X 2 Repeated Measures ANOVAs were used to compare the effects of Age and Speed on the Hip/Ankle peak torque (Figure 11) and peak power (Figure 12) ratios (Table 11). There was not a significant interaction between Age and Speed for either Hip/Ankle peak torque ($p = 0.076$) and peak power ($p = 0.39$) ratios. The older adults had significantly higher Hip/Ankle peak torque ratios at both speeds ($p = 0.006$). Both young and old adults had significantly higher Hip/Ankle peak torque ratios at the faster walking speed ($p < 0.001$). The old adults had significantly higher Hip/Ankle peak power ratios for both standard and fast incline walking speeds ($p = 0.005$). Both age groups had higher Hip/Ankle peak power ratios when walking at the faster speed than the standard speed ($p < 0.001$). The Hip/Ankle angular impulse and joint work ratios followed similar trends and can be found in Appendix E.

Incline Hip/Ankle Peak Torque and Peak Power Ratios

	Factor: Age						Factor: Speed						Factor: Age X Speed	
	Young		Old		**Main Effects**		Standard		Fast		**Main Effects**		**Interaction**	
	Mean	SD	Mean	SD	F(1,34) = 4.13	p-value	Mean	SD	Mean	SD	F(1,34) = 4.13	p-value	F(1,34) = 4.13	p-value
Hip/Ankle Peak Torque	0.54	0.14	0.66	0.16	7.38	**0.006**	0.54	0.14	0.68	0.16	81.80	**< 0.001**	3.32	0.076
Hip/Ankle Peak Power	0.48	0.17	0.66	0.23	7.49	**0.005**	0.53	0.17	0.65	0.24	19.55	**< 0.001**	0.03	0.39

Table 11: Mean, standard deviation (SD), main effects and interaction effects of Age (young vs old) and Speed (standard vs fast) on Hip/Ankle peak torque and peak power ratios for incline walking conditions. **Bolded i**ndicates a significant difference ($F_{(1,34)} = 4.66$, $p < 0.05$).

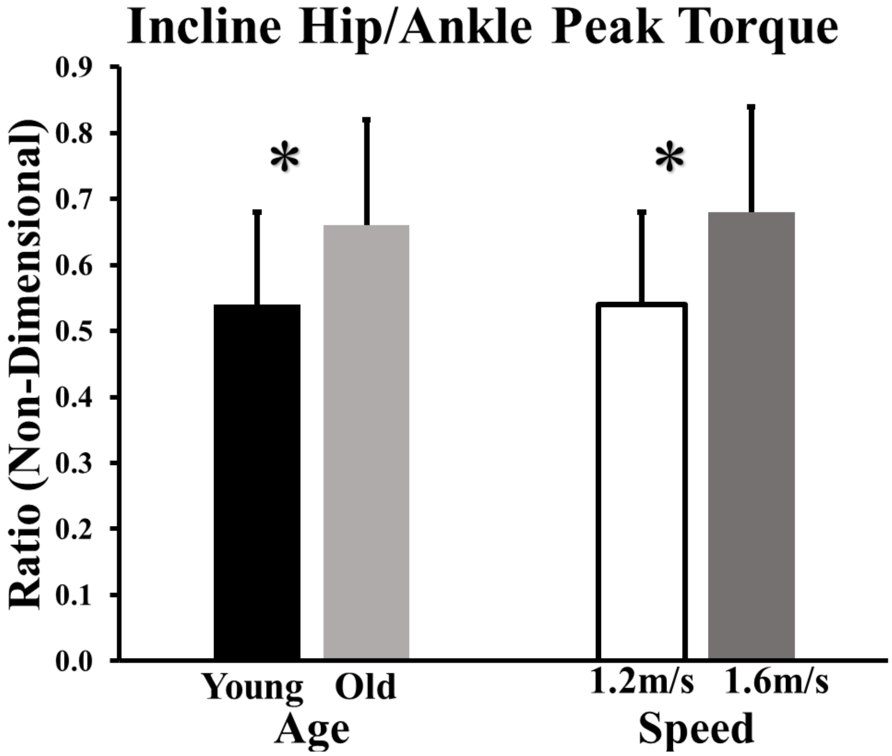


Figure 11: The main effects of Age (young (black) and old (light grey)) X Speed (standard (white) and fast(dark grey)) on the hip/ankle peak torque ratios(non-dimensional) for incline walking. *** i**ndicates a significant difference ($p < 0.05$).

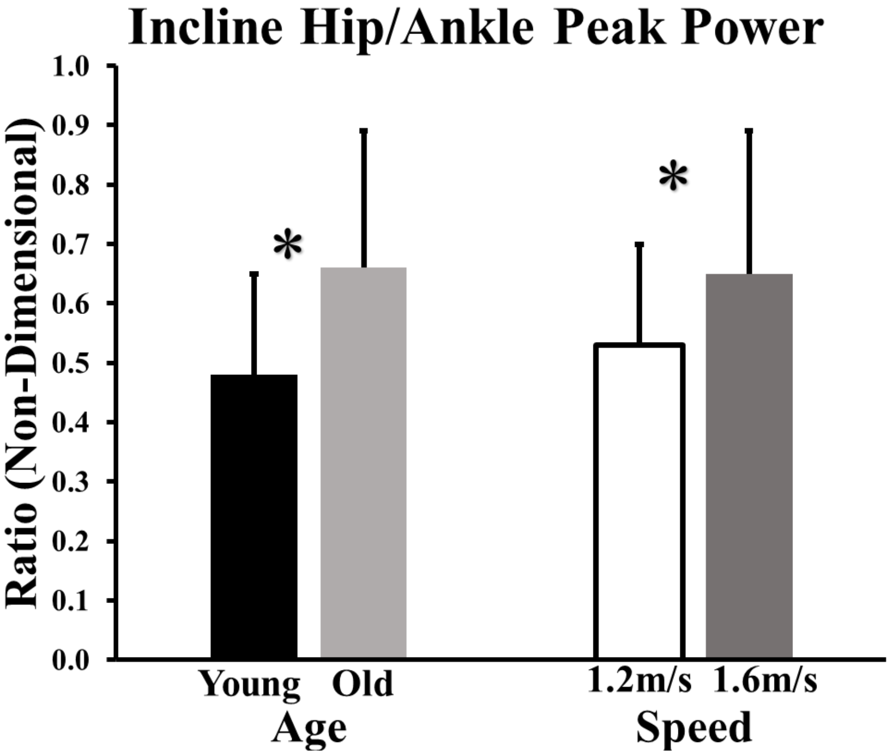


Figure 12: The main effects of Age (young (black) and old (light grey)) X Speed (standard (white) and fast(dark grey)) on the hip/ankle peak power ratios (non-dimensional) for incline walking. * Indicates a significant difference ($p < 0.05$).

Correlations between muscle strength and biomechanical plasticity

In order to determine correlations within older adults, Pearson product moment correlations were calculated at 20 degrees of freedom. These analyses were used to quantify the relationship between isometric muscle strength at the hip and ankle extensor muscle groups and the biomechanical plasticity ratios of peak torque and peak power during the four walking conditions (C1 = level 1.3m/s, C2 = level 1.8m/s, C3 = incline 1.2m/s, and C4 = incline 1.6m/s). Correlation coefficients between hip/ankle isometric strength ratios and both hip/ankle peak torque ratios and hip/ankle peak power ratios are reported in Appendix E, Table 23.

Using the Hip/Ankle muscle strength ratio as the explanatory variable yielded non-significant relationships with hip/ankle peak torque and peak power (Figure 13), as well as hip/ankle angular impulse and work ratios (Appendix E, Table 23).While using hip joint isometric strength to explain magnitude of biomechanical plasticity, there were no significant relationships with hip/ankle peak torque and hip/ankle peak power ratios (Appendix E, Table 23). While using ankle joint isometric strength as the explanatory variable in the correlational analyses, there were no significant relationships with either hip/ankle peak torque or hip/ankle peak power ratios (Appendix E, Table 23). Neither hip nor ankle muscle strength had a significant relationship with hip/ankle angular impulse ratio and hip/ankle work ratios (Appendix E, Table 23).

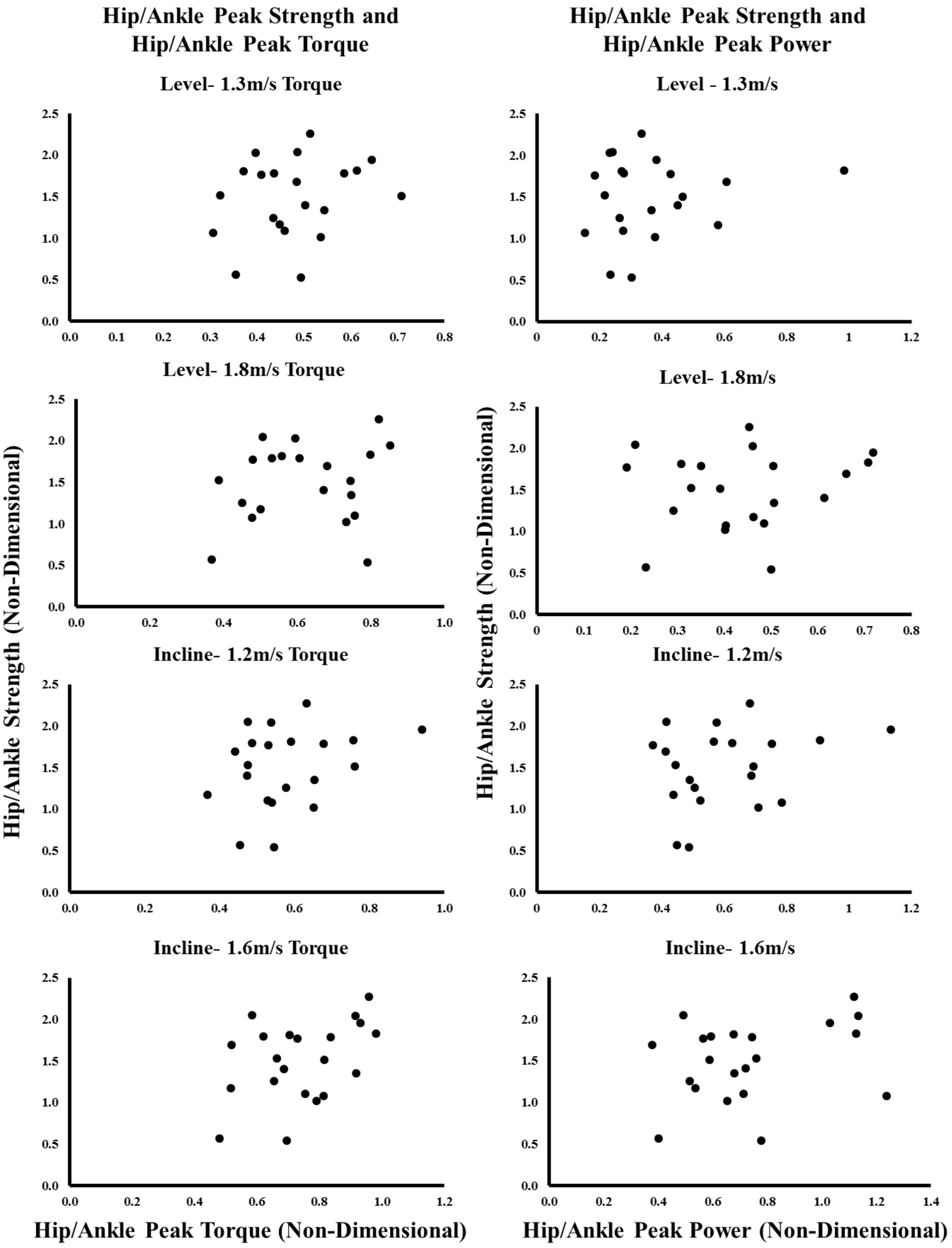


Figure 13: Scatter plots displaying the correlations between the hip/ankle isometric strength ratio (Non-dimensional) and hip/ankle peak torque ratio (left column) and hip/ankle peak power ratios (right column) for all four walking conditions.

Summary

Overall, the old adults’ hip extensors and ankle plantarflexors were significantly weaker than the young adults. For the isometric strength test, the old adults were 20% weaker at the hip extensors and 39% weaker at the ankle plantarflexors. These results suggest there is a variation in strength decrement between a proximal and distal muscle groups and is supported by the significant difference in the hip/ankle strength ratios.

We also verified that the old adults in this study exhibited biomechanical plasticity during level and incline walking at standard and fast speeds. The old adults had higher hip/ankle peak torque and peak power than the younger adults at all conditions. At faster speeds, the old adults exhibited higher magnitudes of biomechanical plasticity for both incline and level walking. These results demonstrate that these old adults produced less ankle mechanical output and compensated by producing more hip mechanical output while walking during the four conditions.

The correlational analyses did not support our second hypothesis that muscle strength decrement is significantly correlated with the magnitude of biomechanical plasticity in older adults. There were no significant correlations between the biomechanical plasticity ratios and either hip extensor or ankle plantarflexor isometric peak torque in old adults. This alludes to the conclusion that there is more than one contributing factor to the magnitude of biomechanical plasticity.

Chapter V: Discussion

Introduction

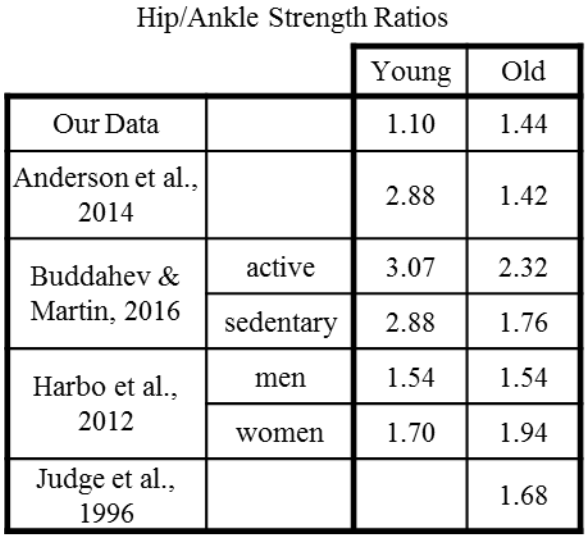
The purposes of this thesis were to 1. Examine the age-related changes in muscle strength of the various muscle strength groups of the lower extremities, 2. Verify age-associated biomechanical plasticity in the old adults of this study, and 3. Determine as well as the relationship between the variation in muscle strength decrement and the magnitude of biomechanical plasticity on level and incline walking in old adults. We hypothesized that when compared to young adults, old adults would have a larger strength decrement at the distal ankle plantarflexors than the proximal hip extensors. We also hypothesized that this variation in muscle strength is associated with age-associated biomechanical plasticity. This chapter is divided into the sections: Variation in muscle strength decrement with age, Biomechanical plasticity ratios in level and incline walking, Correlations between muscle strength and biomechanical plasticity, Delimitations, and Summary.

Variation in Muscle Strength Decrement with Age

Previous studies examining muscle strength decrement due to aging have been highly variable in results, as well as muscle groups tested. Thus far, there are a limited number of studies, that I have identified, that have examined and compared the strength decrement between the hip, knee, and ankle muscle groups in older adults. Our results determined that the old adults had a strength decrement at all three joint muscle groups, however there was a variation in the amount of decrement between the muscle groups. The old adults’ isometric hip extensors had a 20% strength decrement when compared to the young adults, while the old adults’ isometric ankle plantarflexors had a 39% strength decrement. In the literature, the most tested muscle group in old adults is the plantarflexor muscle group, which has resulted in highly variable decrement between studies, ranging from 14.5% to 44.9% and averaging 30.8% [2,7,10,21,42,55,81,88]. The average strength decrement of ankle plantarflexors in previous studies is lower than the decrement observed in our study of 39%, however our results are still within the range of values in the previous literature. The other strength decrement of interest in our study was that of the hip extensors, in which only three other studies, that I have found, have reported. In one previous study that was found, healthy old adults had a hip extensor muscle strength decrement of 34%[42]. When compared to young adults of the same sex, healthy old men had a hip extensor strength decrement of 35% while old women had a slightly lower decrement of 33%[2]. Active old adults had a hip extensor strength decrement of 44% and inactive old adults had a hip extensor strength decrement of 50%, when compared to young adults of the same activity level [10]. The old adults in this study had a smaller strength decrement than previous studies at the hip extensors, with a 20% decrement of the young adults' hip extensor strength. In our study, the older adults' stood with a flexed knee during hip strength testing. Anderson & Madigan, 2014 performed the testing with participants in a similar position, but with the knee at 0° of flexion. Harbo et al, 2012 had the participants laying in a supine position for their hip strength testing and only tested isokinetic hip extension. Buddahev & Martin 2016 active old adults were only required to exercise for 30mins twice a week, were as our participants were required to exercise 3 times a week for 30mins, suggesting their active participants were less active than our participants. A lower activity level requirement would suggest that Buddahev & Martin, 2016 old adults could have a higher loss in muscle strength due to inactivity rather than age. Anderson & Madigan, 2014 had no physical activity requirement, so it is uncertain how their adults compare to our old adults in this aspect. The methodological differences in testing, with positioning of the participants and the strength tests performed, as well as the physical activity level of the participants, could result in the differences observed between the data presented in this study and the data of previous studies.

Our study suggests that there is a variation in strength decrement, in which there is a greater loss of strength at the ankle plantar flexor muscle group when compared to the hip extensors. This pattern of variation is evident in our old adults' ankle plantarflexor strength decrement of 39% compared to the 20% decrement at the hip extensors compared to young adults. Only a few studies, that we have found, have examined more than one muscle group. Harbo et al., 2012 identified a 35% decrement at the ankle plantarflexors and a 35% decrement at the hip extensors for men, while women had decrements of 41% and 33% at the ankle plantarflexors and hip extensors, respectively. When compared to this study, the women of Harbo et al., 2012 demonstrate a similar pattern of strength decrement between the distal and proximal muscle groups. For this study, both old and young adult participant groups contained male and female participants, however the majority were female participants (79% female for young adults and 72% female for old adults). While Buddahev & Martin, 2016 support an opposing relationship with active old adults having a 27% decrement at the ankle plantarflexors and a 44% decrement at the hip extensors compared to active young adults. The same study showed that inactive old adults had a smaller strength decrement of 17% at the ankle plantarflexors but a greater hip extensor strength decrement of 50% when compared to inactive young adults[10]. Anderson & Madigan, 2014 found similar results to Buddahev & Martin, 2016, with a decrement of 20% and the ankle plantarflexors and a decrement of 33% at the hip extensors.

The old adults' hip/ankle strength ratios of previous studies were similar to our isometric hip/ankle strength ratio of 1.44[2, 10, 42] (Table 12). The young participants in this study had hip/ankle strength ratio of 1.10, indicating that our young adults had more proportional strength between hip and ankle than previously reported. Harbo et al., 2014's data demonstrate that men do not change their hip/ankle strength ratios (1.54 for <30 years and 1.54 for >70 years), while women had an increase in ratio due to age from 1.7 (< 30 years) to 1.94 (>70 years). Anderson & Madigan, 2014 and Buddahev & Martin, 2016 however, reported a decline in the ratio between young and old adults, indicating an inverse relationship as reported in this study.



Hip/Ankle Strength Ratios

		Young	Old
Our Data		1.10	1.44
Anderson et al., 2014		2.88	1.42
Buddahev & Martin, 2016	active	3.07	2.32
	sedentary	2.88	1.76
Harbo et al., 2012	men	1.54	1.54
	women	1.70	1.94
Judge et al., 1996			1.68

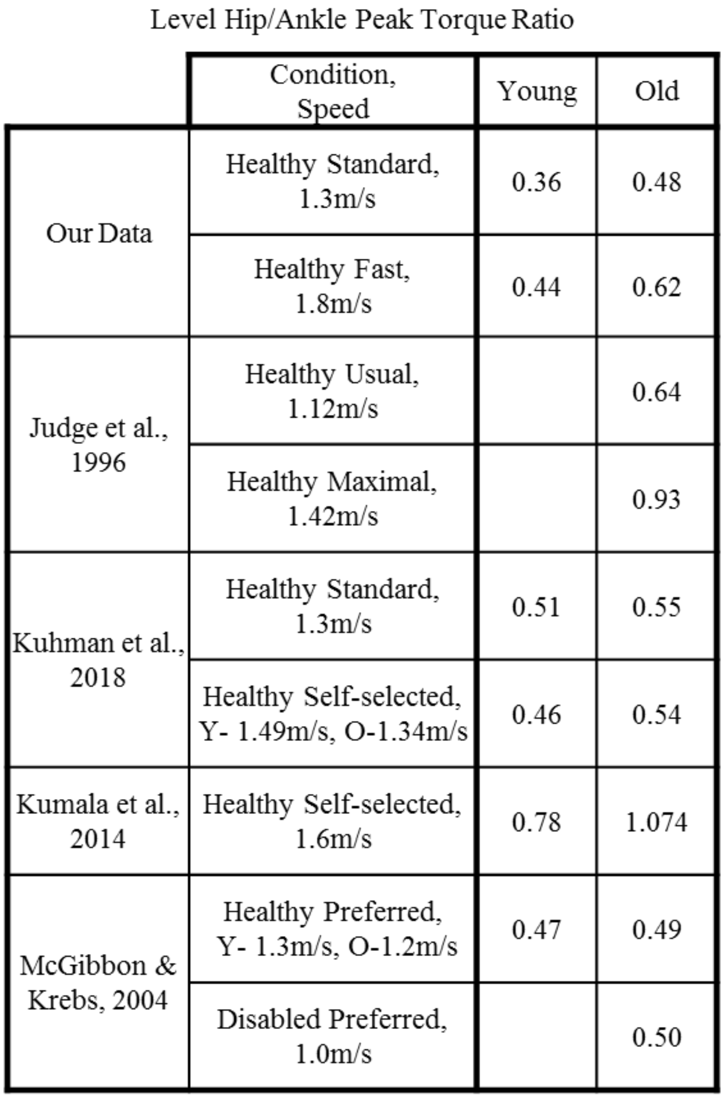
Table 12: Hip/Ankle extensor maximal torque ratios for current and previous studies' young and old adults.

A limited number of studies have examined the variation in muscle strength decrement of the lower extremities due to aging, but two out of three studies report a greater strength decrement at the hip extensors than the ankle plantarflexors. Our results, as well as the hip and ankle strength decrements of Harbo et al., 2012, indicate that while all lower extremity muscles were weaker in the old adults compared to young, the ankle plantarflexor muscle group had a significantly larger strength decrement than the hip extensors. We accept our first hypothesis, that older adults have smaller decrement in muscle strength at the proximal hip extensors and a larger strength decrement at the distal ankle plantarflexors.

Biomechanical Plasticity Ratios in Level and Incline Walking

The second purpose of this study was to verify age-associated biomechanical plasticity in the old participants of this study. Age-associate biomechanical plasticity is defined as a distal to proximal redistribution of joint mechanical contributions during the stance phase of walking. The results for this study confirmed that the old participants exhibited age-associated biomechanical plasticity by displaying higher hip/ankle peak torque, peak power, angular impulse, and joint work ratios during all four walking conditions: level standard (1.3m/s), level fast (1.8m/s), incline standard (1.2m/s), and incline fast (1.6m/s). There was also an increase in the ratios for the old adults when comparing the standard to fast speeds. An increase in the difficulty of a task requires an increase in the mechanical output at the hip, knee, and ankle joints. However, instead of increasing mechanical output at all three joints, the old adults of this study increased their hip output to a greater magnitude than their ankle output. This is displayed in the increase of the hip/ankle biomechanical plasticity ratios for all variables during the fast walking condition.

Biomechanical plasticity ratios are not prevalent in previous literature. In order to make comparisons between the data in this study and previous research, the hip and ankle joints peak torque, peak power, angular impulse, and joint work reported were converted into hip/ankle output ratios. The level walking hip/ankle peak torque ratios for this study and previous studies can be observed in Table 13. The hip/ankle peak torque ratios for level walking in this study were similar to the calculated hip/ankle peak torque ratios of Kuhman et al., 2018 and McGibbon & Krebs, 2004. When walking at the standard speed of 1.3m/s, the young adults in this study had lower peak torque ratios than Kuhman et al., 2018 at both standard (1.3m/s) and self-selected speeds (1.49m/s), indicating these young adults were using less hip and more ankle during the stance phase than the young adults of Kuhman et al., 2018. Comparing to McGibbon & Krebs, 2004, the young adults of this study at the standard speed had lower peak torque ratios. The older adults at the slow speed were also lower than both standard (1.3m/s) and self-selected (1.34m/s) speed of Kuhman et al., 2018. The old adults of this study at the standard speed had similar ratio to both McGibbon & Krebs, 2004 healthy and disabled old adults. At the fast speed of 1.8m/s, our old adults displayed lower hip/ankle peak torque ratios than old adults of previous research walking at slower fast speeds (1.42m/s and 1.6m/s)

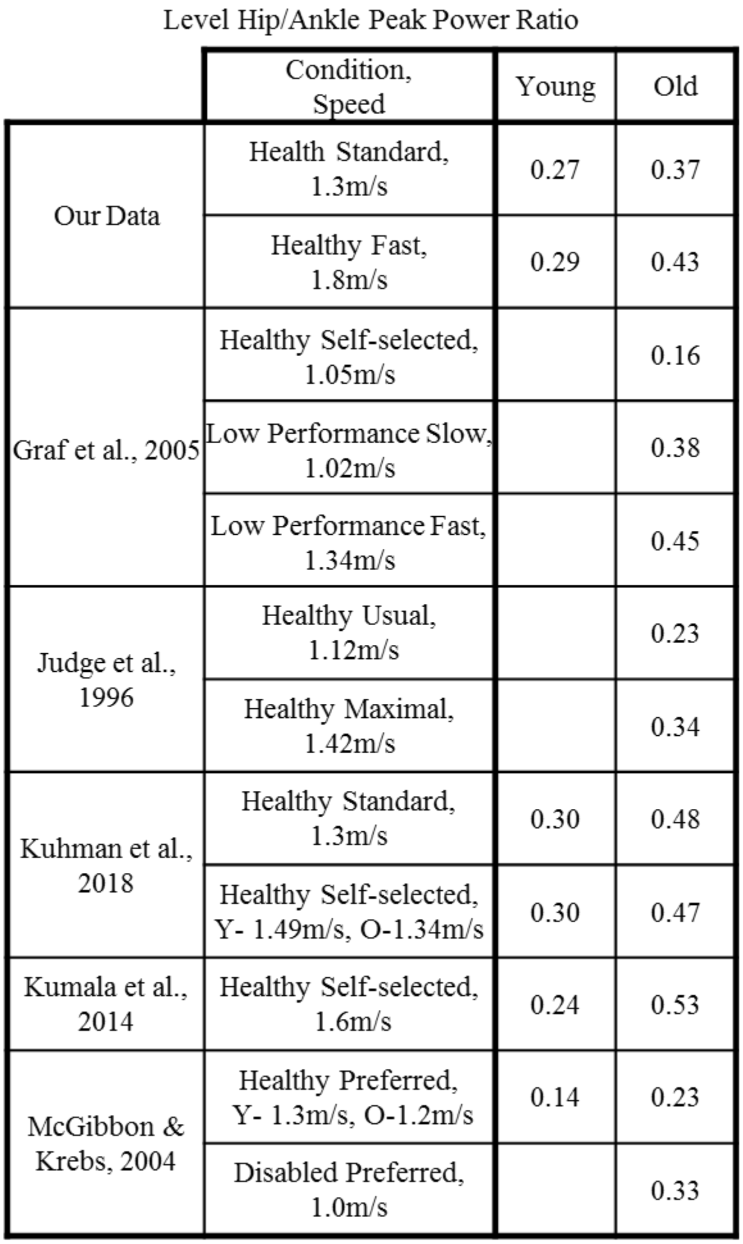


Level Hip/Ankle Peak Torque Ratio

	Condition, Speed	Young	Old
Our Data	Healthy Standard, 1.3m/s	0.36	0.48
	Healthy Fast, 1.8m/s	0.44	0.62
Judge et al., 1996	Healthy Usual, 1.12m/s		0.64
	Healthy Maximal, 1.42m/s		0.93
Kuhman et al., 2018	Healthy Standard, 1.3m/s	0.51	0.55
	Healthy Self-selected, Y- 1.49m/s, O-1.34m/s	0.46	0.54
Kumala et al., 2014	Healthy Self-selected, 1.6m/s	0.78	1.074
McGibbon & Krebs, 2004	Healthy Preferred, Y- 1.3m/s, O-1.2m/s	0.47	0.49
	Disabled Preferred, 1.0m/s		0.50

Table 13: Hip/Ankle peak torque ratios at level walking conditions for current and previous studies of young and old adults.

The average hip/ankle peak power ratios for level walking are displayed in Table 14 for this study and previous studies. At both fast (1.8m/s) and standard (1.3m/s), the young adults of this study displayed similar peak power ratios compared to Kuhman et al., 2018 young participants at standard (1.3m/s) and self-selected (1.49m/s). McGibbon & Krebs reported lower peak power ratios than this study as well as Kuhman et al., 2018, while also walking at the speed of 1.3m/s. While walking at both standard and fast speeds, the old adults of this study produced lower peak power ratios than Kuhman et al., 2018 old adults walking at self-selected (1.34m/s) and standard speeds (1.3m/s), as well as Kumala et al., 2014 old adults walking at 1.6m/s. This indicates that our older adults displayed less distal-to-proximal shift. However, other studies demonstrated lower peak power ratios than our older adults, suggesting that our old adults had higher magnitude of biomechanical plasticity [40,47,56,77]. For Graf et al., 2005, the healthy old adults walking at a comfortable speed had lower peak power ratios than the low performance old adults walking at a comfortable speed and a faster speed. The old adults of this study had more similar peak power ratios to that of the lower performance adults in Graf et al., 2005.

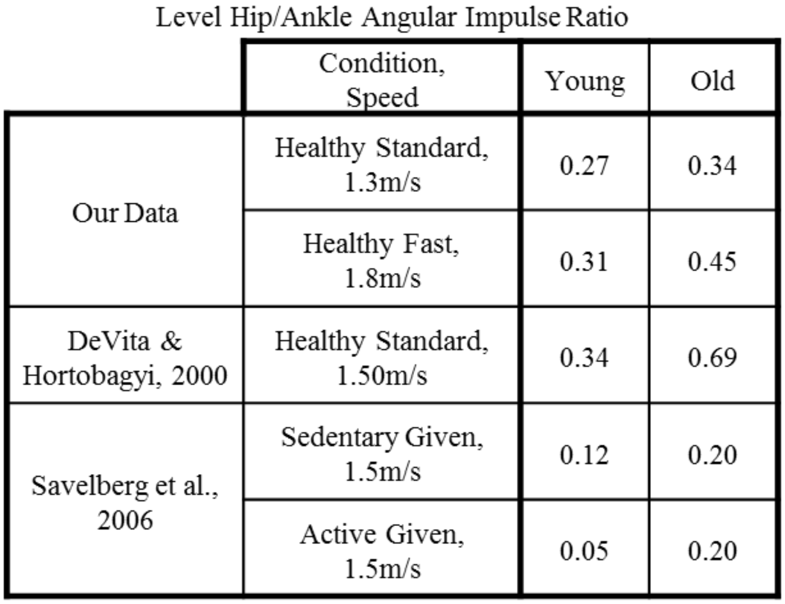


Level Hip/Ankle Peak Power Ratio

	Condition, Speed	Young	Old
Our Data	Health Standard, 1.3m/s	0.27	0.37
	Healthy Fast, 1.8m/s	0.29	0.43
Graf et al., 2005	Healthy Self-selected, 1.05m/s		0.16
	Low Performance Slow, 1.02m/s		0.38
	Low Performance Fast, 1.34m/s		0.45
Judge et al., 1996	Healthy Usual, 1.12m/s		0.23
	Healthy Maximal, 1.42m/s		0.34
Kuhman et al., 2018	Healthy Standard, 1.3m/s	0.30	0.48
	Healthy Self-selected, Y- 1.49m/s, O-1.34m/s	0.30	0.47
Kumala et al., 2014	Healthy Self-selected, 1.6m/s	0.24	0.53
McGibbon & Krebs, 2004	Healthy Preferred, Y- 1.3m/s, O-1.2m/s	0.14	0.23
	Disabled Preferred, 1.0m/s		0.33

Table 14: Hip/Ankle peak power ratios at level walking conditions for current and previous studies of young and old adults.

The angular impulse ratios for level walking in this study were lower than that of DeVita & Hortobagui, 2000, but higher than that of Savelberg et al., 2006 (Table 15). For this study, the young and old adults walked at 1.3m/s and 1.8m/s, while the two other studies had their participants walk at 1.5m/s. Both the active and sedentary young and old adults of Savelberg et al., 2006 display much lower ratios than both this study and Devita & Hortobagyi, indicating the mechanical output for the participants of Savelberg et al., 2006 was more similar when comparing between the hip and ankle joint. Between young and old participants of Savelberg et al., 2006, there is still an increase in ratio, indicating the older adults of Savelberg displayed age-associated biomechanical plasticity, just at lower magnitudes than this study and DevVita & Hortobgayi 2000. The angular impulse ratios of this study fall between the ratios calculated from previous literature.

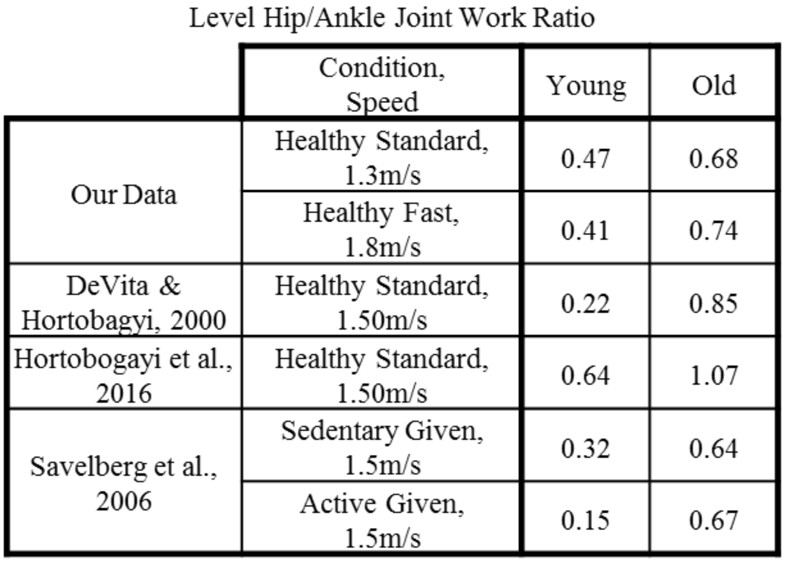


Level Hip/Ankle Angular Impulse Ratio

	Condition, Speed	Young	Old
Our Data	Healthy Standard, 1.3m/s	0.27	0.34
	Healthy Fast, 1.8m/s	0.31	0.45
DeVita & Hortobagyi, 2000	Healthy Standard, 1.50m/s	0.34	0.69
Savelberg et al., 2006	Sedentary Given, 1.5m/s	0.12	0.20
	Active Given, 1.5m/s	0.05	0.20

Table 15: Hip/Ankle angular impulse ratios at level walking conditions for current and previous studies of young and old adults.

The joint work ratios of the old adults in this study at the standard speed (1.3m/s) were most similar to the inactive and active old adults of Savelberg et al., 2007 walking at a faster speed of 1.5m/s (Table 16). DeVita & Hortobagyi, 2000 displayed lower hip/ankle joint work ratios when comparing their young adults walking at 1.5m/s and our young adults walking at both 1.3m/s and 1.8m/s. However, DeVita & Hortobagyi, 2000 reported higher joint work ratios for their older adults at 1.5m/s compared to the old adults of this study at both 1.3m/s and 1.8m/s.



Level Hip/Ankle Joint Work Ratio

	Condition, Speed	Young	Old
Our Data	Healthy Standard, 1.3m/s	0.47	0.68
	Healthy Fast, 1.8m/s	0.41	0.74
DeVita & Hortobagyi, 2000	Healthy Standard, 1.50m/s	0.22	0.85
Hortobogayi et al., 2016	Healthy Standard, 1.50m/s	0.64	1.07
Savelberg et al., 2006	Sedentary Given, 1.5m/s	0.32	0.64
	Active Given, 1.5m/s	0.15	0.67

Table 16: Hip/Ankle joint work ratios at level walking conditions for current and previous studies of young and old adults.

For incline walking, this study found similar trends, but at higher magnitudes of biomechanical plasticity than level walking (Table 17 & 18). Kuhman et al., 2018 tested participants on the same ramp, but demonstrated higher hip/ankle peak torque ratio than the participants at the standard speed in this study. The hip/ankle peak power ratios follow similar results, with Kuhman et al., 2018 demonstrating higher ratios, and thus a higher magnitude of biomechanical plasticity than those in this study. This comparison is similar to that of the level walking, suggesting that overall, the old adults in this study had lower magnitudes of biomechanical plasticity compared to Kuhman et al.,2018. Franz & Kram, 2014 demonstrated slightly higher peak torque ratios for both young and old adults at a slightly faster speed. However, the young adults of Franz & Kram, 2014 displayed smaller peak power ratios, while the old adults had higher peak power ratios when compared to our participants.

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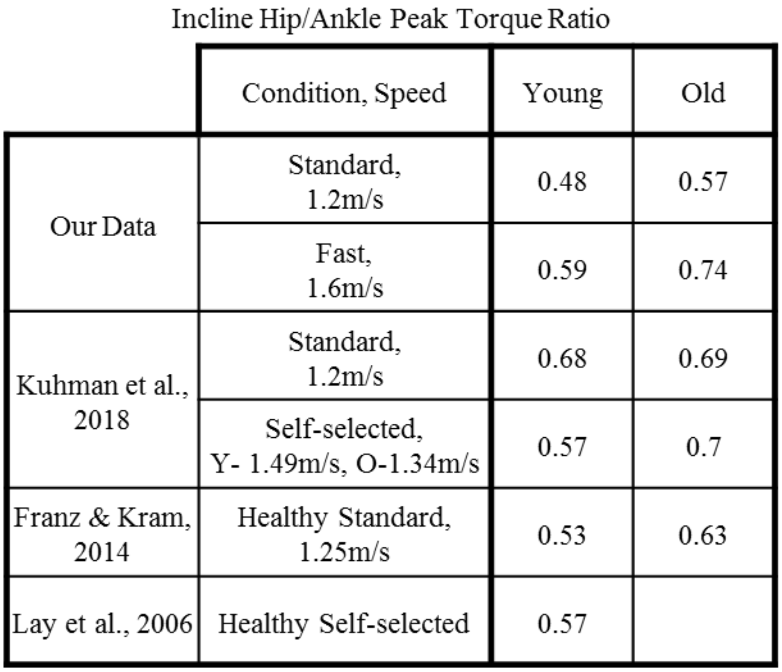
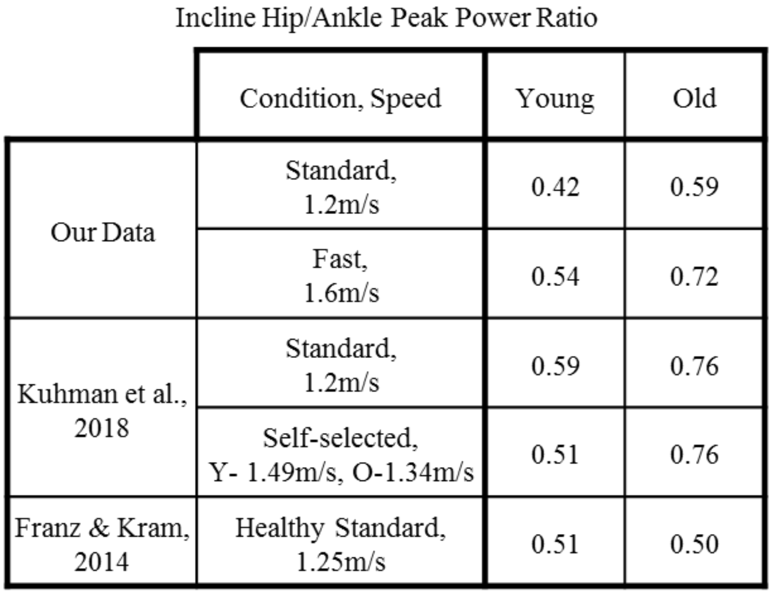


Incline Hip/Ankle Peak Torque Ratio

	Condition, Speed	Young	Old
Our Data	Standard, 1.2m/s	0.48	0.57
	Fast, 1.6m/s	0.59	0.74
Kuhman et al., 2018	Standard, 1.2m/s	0.68	0.69
	Self-selected, Y- 1.49m/s, O-1.34m/s	0.57	0.7
Franz & Kram, 2014	Healthy Standard, 1.25m/s	0.53	0.63
Lay et al., 2006	Healthy Self-selected	0.57	

Table 17: Hip/Ankle peak torque ratios for incline walking conditions for current and previous studies of young and old adults.



Incline Hip/Ankle Peak Power Ratio

	Condition, Speed	Young	Old
Our Data	Standard, 1.2m/s	0.42	0.59
	Fast, 1.6m/s	0.54	0.72
Kuhman et al., 2018	Standard, 1.2m/s	0.59	0.76
	Self-selected, Y- 1.49m/s, O-1.34m/s	0.51	0.76
Franz & Kram, 2014	Healthy Standard, 1.25m/s	0.51	0.50

Table 18: Hip/Ankle peak power ratios for incline walking conditions for current and previous studies of young and old adults.

Overall, there was a wide variation in ratios for these four variables, indicating that a high variability in magnitude of biomechanical plasticity amongst old adults, Kuhman et al., 2018 made a similar conclusion. Our results fall within reasonable ranges for level and incline walking for both young and old adults at both fast and standard speeds.

Correlation of Muscle Strength and Biomechanical Plasticity

Hortobagyi et al., 2016 concluded that stronger old adults display less biomechanical plasticity than weak old adults. This conclusion, along with the evidence that more distal muscles may decline faster than more proximal muscles, led to our second hypothesis which was that old adults have a larger strength decrement at the ankle plantarflexors, and a smaller decrement at their hip extensors, and the magnitude of this variation in strength decrement is positively related to the magnitude of biomechanical plasticity in order to maintain physical capacity and independence. Our data did not support this hypothesis. The correlations between isometric muscle strength ratios and biomechanical plasticity ratios were not statistically significant. This lack of relationship suggests that variation in muscle strength decrement may be just one of many age-related changes affecting walking biomechanics.

Kuhman et al., 2018 concluded that adults with higher physical capacity had higher magnitudes of biomechanical plasticity. This study, however, had higher SF-36 scores and overall lower walking ratios and thus lower magnitudes of biomechanical plasticity compared to Kuhman et al., 2018. Data in Graf et al., 2007, can be interpreted as low performance older adults have higher magnitudes of biomechanical plasticity. Savelberg et al., 2007, concluded active old adults have an increase in redistribution of joint mechanical output compared to sedentary old adults. Buddahev & Martin 2016, also compared physical activity to the magnitude of biomechanical plasticity, but found a statistically non-significant relationship. Hortobagyi et al., 2016, determined that weaker old adults had higher magnitude of joint work redistribution. Previous studies, as well as this study, have highly variable results between the magnitude of biomechanical plasticity and its relationship to physical activity, capacity, or muscle strength.

The old participants in this study were majority female (16 female, 6 male). This disproportionate ratio of women to men participants could potentially confound the results of this study. Previous research has grouped both men and women together when evaluating BP[24,45,49]. However, Boyer et al., 2012, determined that old adult women produce larger hip moments than men during walking at slow, normal, and fast speeds. Harbo et al., 2012's strength ratio for female participants is most similar to the one of this study, while other studies comprising of more equal male: female ratios demonstrate an alternate variation in strength decrement [2,11]. While all old adults display BP, when determining the correlation of magnitude of BP to variation in strength decrement, or other potential causes of BP, gender may be an underlying confounding variable leading to insignificant results. The comparison of magnitude of age-associated biomechanical plasticity and sex has yet to be made, but should be investigated in order to fully understand all factors that may be influencing the magnitude of BP.

Achilles tendon properties have also been shown to change with age and may affect the joint output during walking[30,81,82]. Older adults' Achilles tendons are significantly less stiff and have significantly lower young's modules when compared to young adults. However, when comparing old adults and young adults with similar maximal voluntary, there was not a significant decline in tendon stiffness[82]. Stenroth et al., 2012 conclude that the decline in the stiffness of the tendon would allow for more energy storage, and as a result maintain some joint output which may compensate for the decline in muscle strength in low-loading conditions, such as walking. For our study there was no significant relationship between the shift in joint output and muscle strength decrement, which could, in part, be attributed to the changes in Achilles tendon properties in older adults.

Healthy aging has been known to cause a decline in grey and white brain matter volume which results in a degradation of cognition in those areas, resulting in a shifting of function to another area, this is known as neural plasticity[79]. Areas such as the prefrontal cortex, supplementary motor area and medial sensorimotor cortex have been associated with the control of gait speed [41]. Significant decline in grey matter in the prefrontal cortex, supplementary motor area, and medial sensorimotor cortex[71,72] could potentially be a cause of a decline in gait speed and cadence in older adults. Age has also shown significant anterior to posterior decline in the white matter of the corpus colosseum, which regulates bilateral coordination of movement and could be attributed to inter-limb coordination in older adult continuous movement patterns[4]. Although there has been no study that have directly linked the shifting of joint torques during walking and the changes in brain function in older adults, it is plausible that neural plasticity may partially contribute to gait speed and cadence changes in older adults as well as the redistribution of joint mechanical output during walking.

An important component to any movement is the motor control pattern implemented to plan and initiate the movement. Donelan and Pearson, 2004 determined that afferent feedback is important to motor pattern generation and the decline in proprioceptive feedback is related to the age-associate atrophy of the sensorimotor cortex[39,76]. While walking, distal muscles are thought to rely on proprioceptive feedback, however more proximal muscles utilize a feed forward system[19]. This was demonstrated by Daley et al., 2007 in which a trip or fall resulted in the distal muscles responding to the change in movement, while the more proximal muscles of the hip were unable to adjust and showed no change in kinematics. The exact timing and magnitude of activity of the distal muscles are dependent on afferent feedback[27], and thus it is possible this decline in sensorimotor feedback is one reason for the age-associated change in joint output produced by the ankle during walking. The concept that the distal muscles are more reliant on afferent feedback is further supported by Franz et al., 2014 through the implementation of a real-time bio-feedback system to correct and enhance the power output of the ankle joint during walking. During this study older adults were capable of increasing their ankle joint power output as well as increasing the electrical activity of the gastrocnemius when prompted with a visual target[34]. This indicates the possibility of a decline in the sensorimotor system of the distal muscle groups, or at a higher level, the sensorimotor cortex, and results in older adults relying on a feedforward system and thus shift their output to hip muscles.

For this study, isometric joint strength was not related to magnitude of biomechanical plasticity. Strength training protocols have been shown to improve gait speed, cadence, stride length, and toe clearance [6, 66]. These gait improvements are caused by the changes in the underlying mechanics. Strength training increases hip angular impulse and joint work, but not ankle or knee, while walking[6]. This disproportionate increase of joint output would result in a greater magnitude of biomechanical plasticity in old adults. Functional training, however, results in a redistribution of joint work from hip back to ankle in adults with lower extremity impairments, while strength training increased the magnitude -of biomechanical plasticity[57]. Although biomechanical plasticity due to impairments is different than age-associated biomechanical plasticity, they share the same distal to proximal redistribution pattern, and thus functional training may also help reverse age-associate biomechanical plasticity. As previously discussed, biofeedback has been shown to increase ankle plantar flexor work while walking[34], which supports this idea that a functional training or gait re-training program may be able to reverse BP.

The aging process can affect multiple body systems that influence motor control and mechanical outputs during walking. The non-significant relationship between variation in strength decrement and BP could indicate that there is more than one factor influencing the distal to proximal redistribution of joint mechanical output. As discussed, these factors could be changes in Achilles tendon properties, neural plasticity, sensorimotor systems, as well as gender differences.

Delimitations

For this study, the participants had the inclusion criteria of a BMI less than 28 kg/m^2. This was to exclude any adults who may be considered obese or encroaching on obesity. Obese adults have been shown to display a different type of biomechanical plasticity in which there is a proximal to distal redistribution of joint mechanical outputs. The standard walking speed that was chosen to be examined in this study was 1.3m/s, which is the average speed of all adults on a level surface. The other standard speed was 1.2m/s for incline. Incline walking is a harder task, so a slower speed was used to compensate. The faster walking speed on a level surface was 1.8m/s while the incline surface was 1.6m/s, again the slower speed on the incline surface was to compensate for the harder surface task. There was no maximal walking speed, which would have increased the difficulty of the task and most likely increased the biomechanical plasticity observed. The slope of the incline used, was 10 degrees, a higher slope would have made for a more difficult task, again which would most likely increase the biomechanical plasticity observed. We are delimited to our conditions selected and our data may not be comparable to other gaits, speeds, and conditions.

Summary

Compared to our young adults, our older adults displayed a variation in strength decrement across lower extremity muscle groups. The old adults in this study had a larger strength decrement at the ankle plantarflexor muscle group and a smaller decrement at the hip extensor muscle group. This caused a higher hip/ankle strength ratio, resulting in the acceptance of our first hypothesis. Our old adults had an increase in their hip/ankle biomechanical plasticity ratios at both level and incline walking speeds compared to our younger adults. This indicates that the old adults were exhibiting biomechanical plasticity. Even though our results were within the variable range of previous biomechanical plasticity research, there was not a significant correlation between muscle strength and biomechanical plasticity. Based on these results, we reject our second hypothesis that muscle strength is associated with age-associated biomechanical plasticity. This also indicates that there are other contributors to biomechanical plasticity as discussed previously.

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Appendix A: Health Questionnaire

Relationships between lower extremity muscle group strength and biomechanical plasticity with age during level and incline walking

<u>Health survey to determine eligibility for research participants</u>

Demographic data: Date ________________________

Name ________________________ Phone number ________________________

Address ____

Birth date ________________________ Age _________ Gender M F
Height (ft/in) ________________ Height (m) ________________
Weight (lbs) ________________ Mass (kg) ________________
BMI (kg/m^2) ________________

Do you smoke? Yes____ No ____
Have you smoked in the past? Yes____ No ____
If yes, when did you stop smoking ________________________

Functional ability in daily activities:

Are you able to leave your house on a daily basis without aid? Yes _____ No _____

Can you do the following activities independently:

Dress Yes____ No ____
Walk Yes____ No ____
Climb stairs Yes____ No ____
Rise from a chair Yes____ No ____

Do you use a walker or cane when walking? Yes____ No ____

During the past year, did you fall down more than once while walking or climbing stairs?
Yes____ No ___

What physical activities do you regularly perform (e.g. run, tennis, basketball)?

How often do you do these activities (3 days/week is minimum)?

Medical:

In the past 6 months, have you suffered any musculoskeletal injuries? Yes____ No ____

Do you have a history of joint replacement surgery in the lower limb? Yes____ No ____

Do you have osteoarthritis in any of the joints in your lower-limb? Yes _____ No _____

Do you have any neurological problems such as stroke or Parkinson's disease? Yes____ No ____

Do you have any problems with your heart such as atrial fibrilliation, pace maker, coronary artery disease, or congestive heart failure? Yes____ No ____

Do you have any pulmonary diseases such as difficulty in breathing or emphysema? Yes___No ____

Do you have any peripheral artery disease? Yes____ No ____

Do you have high blood pressure (>160/90 mm Hg)? Yes____ No ____

Do you take medication to control your blood pressure? Yes____ No_____

Have you ever been diagnosed with cancer? Yes _____ No _____

Do you have any loss of vision? Yes____ No ____

If yes, do you have eye glasses or contact lenses that correct your vision? Yes____ No ____

Do you have any other medical problems we did not talk about? Yes____ No_____

If, "Yes," what is or are the conditions?

____

Please list any surgeries you have had.

____

____

Please tell us any other health illnesses you have had or currently have.

____

____

Appendix B: Approved Consent Form

East Carolina University

Informed Consent to Participate in Research

Information to consider before taking part in research that has no more than minimal risk.

Title of Research Study: The relationships between lower extremity muscle strength and biomechanical plasticity with age during level and incline walking
Principal Investigator: Paul DeVita
Institution, Department or Division: Kinesiology
Address: 332 Ward Sports Medicine Building, East Carolina University
Telephone #: 252-737-4616

Researchers at East Carolina University (ECU) study issues related to society, health problems, environmental problems, behavior problems and the human condition. To do this, we need the help of volunteers who are willing to take part in research.

Why am I being invited to take part in this research?

The purpose of this research is to examine walking gait adaptations that occur in elderly adults of differing physical capacities. You are being invited to take part in this research because you meet the inclusion criteria and appear to be free of contraindications to participating in this study. The inclusion criteria for this study are: 18-30 years old or 70-80 years old, non-smoker, and able to perform regular daily activities such as walking, climbing stairs and inclines, and rising from a chair without assistance. 18-30 year old participants should also engage in regular physical activity (minimum of 3 times per week). By doing this research, we hope to learn more about walking gait adaptations that occur in elderly adults across a range of physical capacities.

If you volunteer to take part in this research, you will be one of about 40 people to do so.

Are there reasons I should not take part in this research?

I understand that I should not partake in this research if I do not meet the inclusion criteria, have had a musculoskeletal injury in the past 6 months, history of lower limb, back, or joint replacement surgery, neurological or neuromuscular disorder such as Parkinson’s disease or stroke, cardiac disease, or any terminal illness, or use any tobacco products.

What other choices do I have if I do not take part in this research?

You can choose not to participate.

Where is the research going to take place and how long will it last?

The research will be conducted in the Biomechanics Laboratory, room 332 Ward Sports Medicine Building at East Carolina University. You will need to come to the Biomechanics Laboratory two separate times during the study. The total amount of time you will be asked to volunteer for this study is approximately 3 hours over these three visits.

What will I be asked to do?
You will be asked to do the following:

- Complete a short questionnaire that includes relevant demographic information as well as a short health history. This questionnaire is used to ensure participation eligibility.
- Complete the 36-Item-Short-Form Health Survey (SF-36). This test will be used to help determine physical capacity.
- Complete three visits within a 10 day period. The first visit will include signing informed consent, completing the SF-36 survey, and a familiarization with the data collection protocols. The second and third visit will include either the walking or strength test protocols in a randomized order.
- Undergo biomechanical gait analysis. This testing method will include walking over a level walkway and up an incline ramp (3.2-meters long; 10% incline) in the Lab. During the testing session, small spherical reflective markers will be placed on your pelvis and right leg.
- The total walking time for both Lab visits is estimated to be 1 hour and 40 minutes. You will be asked to walk approximately 30 minutes during the initial visit and 70 minutes on the second or third visit.
- Undergo Isokinetic Dynamometry. This testing method will include maximal hip flexion and extension, knee flexion and extension, and ankle plantarflexion and dorsiflexion at three speeds on the dynamometer.
- The total isokinetic dynamometry time for both Lab visits is estimated at 1 hour. You will be asked to perform testing for approximately 20 minutes during the initial visit and 40 minutes on the second or third visit.

What might I experience if I take part in the research?
We don’t know of any risks (the chance of harm) associated with this research. Any risks that may occur with this research are no more than what you would experience in everyday life. We don't know if you will benefit from taking part in this study. There may not be any personal benefit to you but the information gained by doing this research may help others in the future.

Will I be paid for taking part in this research?
We will be able to pay you $30 for the time you volunteer while being in this study. The $30 payment will be in the form of a gift card to a local store.

Will it cost me to take part in this research?
It will not cost you any money to be part of the research.

Who will know that I took part in this research and learn personal information about me?
ECU and the people and organizations listed below may know that you took part in this research and may see information about you that is normally kept private. With your permission, these people may use your private information to do this research:

- Any agency of the federal, state, or local government that regulates human research. This includes the Department of Health and Human Services (DHHS), the North Carolina Department of Health, and the Office for Human Research Protections.
- The University & Medical Center Institutional Review Board (UMCIRB) and its staff have responsibility for overseeing your welfare during this research and may need to see research records that identify you.
- Paul DeVita, the primary investigator and faculty supervisor, and Ashley Moulder, the sub-investigator.

How will you keep the information you collect about me secure? How long will you keep it?

All data files will be kept for 5 years after the study is completed. The investigators will keep your personal data in strict confidence by having your data coded. Instead of your name, you will be identified in the data records with an alphanumeric identity number. Your name and identity number will not be identified in any subsequent report or publication. The members of our research team will be the only people who know the identity number associated with your name. Any files that associate your name with your identity number will be encrypted and only members of our research team will know the password to these files. The data collected during this study will be used for research purposes.

What if I decide I don't want to continue in this research?

You can stop at any time after it has already started. There will be no consequences if you stop and you will not be criticized. You will not lose any benefits that you normally receive.

Who should I contact if I have questions?

The people conducting this study will be able to answer any questions concerning this research, now or in the future. You may contact the Principal Investigator, Paul DeVita, at 252-737-4563 (work days, between 9am and 5pm) or the student investigator, Ashley Moulder, at 252-737-4616 (work days, between 9am and 5pm).

If you have questions about your rights as someone taking part in research, you may call the Office of Research Integrity & Compliance (ORIC) at phone number 252-744-2914 (days, 8:00 am-5:00 pm). If you would like to report a complaint or concern about this research study, you may call the Director of the ORIC, at 252-744-1971.

I have decided I want to take part in this research. What should I do now?

The person obtaining informed consent will ask you to read the following and if you agree, you should sign this form:

- I have read (or had read to me) all of the above information.
- I have had an opportunity to ask questions about things in this research I did not understand and have received satisfactory answers.
- I know that I can stop taking part in this study at any time.
- By signing this informed consent form, I am not giving up any of my rights.
- I have been given a copy of this consent document, and it is mine to keep.

____

Participant's Name (PRINT) **Signature** **Date**

Person Obtaining Informed Consent: I have conducted the initial informed consent process. I have orally reviewed the contents of the consent document with the person who has signed above, and answered all of the person's questions about the research.

____

Person Obtaining Consent (PRINT) **Signature** **Date**

Date

Appendix C: Institutional Review Board Approval

EAST CAROLINA UNIVERSITY
University & Medical Center Institutional Review Board
4N-64 Brody Medical Sciences Building· Mail Stop 682
600 Moye Boulevard · Greenville, NC 27834
Office **252-744-2914** · Fax **252-744-2284** ·
www.ecu.edu/ORIC/irb

Notification of Amendment Approval

From: Biomedical IRB
To: Paul DeVita
CC:

Date: 6/1/2018
Re: Ame1_UMCIRB 18-000763
UMCIRB 18-000763
Biomechanical Plasticity & Muscle Strength - Spring 2018

Your Amendment has been reviewed and approved using expedited review for the period of 5/31/2018 to 3/31/2019. It was the determination of the UMCIRB Chairperson (or designee) that this revision does not impact the overall risk/benefit ratio of the study and is appropriate for the population and procedures proposed.

Please note that any further changes to this approved research may not be initiated without UMCIRB review except when necessary to eliminate an apparent immediate hazard to the participant. All unanticipated problems involving risks to participants and others must be promptly reported to the UMCIRB. A continuing or final review must be submitted to the UMCIRB prior to the date of study expiration.The investigator must adhere to all reporting requirements for this study.

Approved consent documents with the IRB approval date stamped on the document should be used to consent participants (consent documents with the IRB approval date stamp are found under the Documents tab in the study workspace).

The approval includes the following items:

Document	Description
Biomechanical Plasticity & Muscle Strength - informed consent 2018.docx(0.01)	Consent Forms
Biomechanical Plasticity & Muscle Strength - protocol 2018 (1).docx(0.01)	Study Protocol or Grant Application

The Chairperson (or designee) does not have a potential for conflict of interest on this study.

IRB00000705 East Carolina U IRB #1 (Biomedical) IORG0000418
IRB00003781 East Carolina U IRB #2 (Behavioral/SS) IORG0000418

Appendix D: The Short-Form Health Survey (SF-36)

Short Form Health History Form

1) In general, would you say your health is (circle one):

Excellent Very Good Good Fair Poor

2) *Compared to one year ago*, how would you rate your health in general *now* (circle one)?

Much better now than one year ago
Somewhat better now than one year ago
About the same as one year ago
Somewhat worse now than one year ago
Much worse than one year ago

3) The following items are about activities you might do during a typical day. Does *your health now limit you* in these activities? If so, how much (circle one)?

a) *Vigorous activities*, such as running, lifting heavy objects, participating in strenuous sports.

Yes, Limited a lot Yes, Limited a little No, Not limited at all

b) *Moderate activities*, such as moving a table, pushing a vacuum cleaner, bowling, or playing golf.

Yes, Limited a lot Yes, Limited a little No, Not limited at all

c) Lifting or carrying groceries

Yes, Limited a lot Yes, Limited a little No, Not limited at all

d) Climbing *several* flights of stairs

Yes, Limited a lot Yes, Limited a little No, Not limited at all

e) Climbing *one* flight of stairs

Yes, Limited a lot Yes, Limited a little No, Not limited at all

f) Bending, kneeling, or stooping

Yes, Limited a lot Yes, Limited a little No, Not limited at all

g) Walking *more than a mile*

Yes, Limited a lot Yes, Limited a little No, Not limited at all

h) Walking *several blocks*

Yes, Limited a lot Yes, Limited a little No, Not limited at all

i) Walking *one block*

Yes, Limited a lot Yes, Limited a little No, Not limited at all

j) Bathing or dressing yourself

Yes, Limited a lot Yes, Limited a little No, Not limited at all

4) During the *past 4 weeks*, have you had any of the following problems with your work or other regular daily activities *as a result of your physical health*?

a) Cut down the *amount of time* you spent on work or other activities

Yes No

b) *Accomplished less* than you would like

Yes No

c) Were limited in the *kind* of work or other activities

Yes No

d) Had *difficulty* performing the work or other activities (for example, it took extra effort)

Yes No

5) During the *past 4 weeks*, have you had any of the following problems with your work or other regular daily activities *as a result of any emotional problems* (such as feeling depressed or anxious)?

a) Cut down the *amount of time* you spent on work or other activities

Yes No

b) *Accomplished less* than you would like

Yes No

c) Didn't do work or other activities *as carefully* as usual

Yes No

6) During the *past 4 weeks*, to what extent has your physical health or emotional problems interfered with your normal social activities with family, friends, neighbors, or groups (circle one)?

Not at all Slightly Moderately Quite a bit Extremely

7) How much *bodily* pain have you had during the *past 4 weeks* (circle one)?

None Very mild Mild Moderate Severe Very Severe

8) During the *past 4 weeks*, how much did *pain* interfere with your normal work (including both work outside the home and housework) (circle one)?

Not at all Slightly Moderately Quite a bit Extremely

9) These questions are about how you feel and how things have been with you *during the past 4 weeks*. For each question, please give the one answer that comes closest to the way you have been feeling. How much of the time during the *past 4 weeks*…

a) Did you feel full of pep?

All of the time Most of the time
A good bit of the time Some of the time
A little of the time None of the time

b) Have you been a very nervous person?

All of the time Most of the time
A good bit of the time Some of the time
A little of the time None of the time

c) Have you felt so down in the dumps that nothing could cheer you up?

All of the time
Most of the time
A good bit of the time
Some of the time
A little of the time
None of the time

d) Have you felt calm and peaceful?

All of the time
Most of the time
A good bit of the time
Some of the time
A little of the time
None of the time

e) Did you have a lot of energy?

All of the time
Most of the time
A good bit of the time
Some of the time
A little of the time
None of the time

f) Have you felt downhearted and blue?

All of the time
Most of the time
A good bit of the time
Some of the time
A little of the time
None of the time

g) Did you feel worn out?

All of the time
Most of the time
A good bit of the time
Some of the time
A little of the time
None of the time

h) Have you been a happy person?

All of the time   Most of the time

A good bit of the time   Some of the time

A little of the time   None of the time

i) Did you feel tired?

All of the time   Most of the time

A good bit of the time   Some of the time

A little of the time   None of the time

10) During the *past 4 weeks*, how much of the time has your *physical health or emotional problems* interfered with your social activities (like visiting with friends, relatives, etc.) (circle one)? \

All of the time   Most of the time

A good bit of the time   Some of the time

A little of the time   None of the time

11) How TRUE or FALSE is *each* of the following statements for you (circle one)?

a) I seem to get sick a little easier than other people

Definitely true   Mostly true   Don’t know   Mostly false

Definitely false

b) I am as healthy as anybody I know

Definitely true Mostly true Don’t know Mostly false

Definitely false

c) I expect my health to get worse

Definitely true Mostly true Don’t know Mostly false

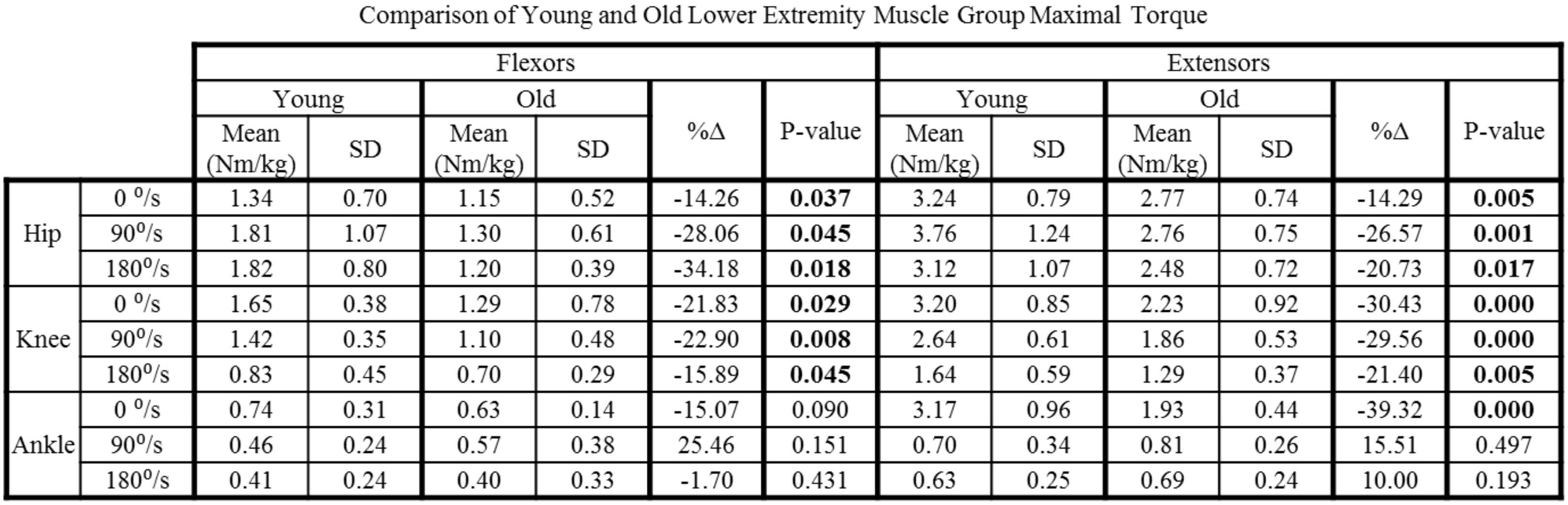
Definitely false

d) My health is excellent

Definitely true Mostly true Don’t know Mostly false

Definitely false

Appendix E: Additional Results



Comparison of Young and Old Lower Extremity Muscle Group Maximal Torque

		Flexors						Extensors					
		Young		Old		%Δ	P-value	Young		Old		%Δ	P-value
		Mean (Nm/kg)	SD	Mean (Nm/kg)	SD			Mean (Nm/kg)	SD	Mean (Nm/kg)	SD		
Hip	0 °/s	1.34	0.70	1.15	0.52	-14.26	**0.037**	3.24	0.79	2.77	0.74	-14.29	**0.005**
	90°/s	1.81	1.07	1.30	0.61	-28.06	**0.045**	3.76	1.24	2.76	0.75	-26.57	**0.001**
	180°/s	1.82	0.80	1.20	0.39	-34.18	**0.018**	3.12	1.07	2.48	0.72	-20.73	**0.017**
Knee	0 °/s	1.65	0.38	1.29	0.78	-21.83	**0.029**	3.20	0.85	2.23	0.92	-30.43	**0.000**
	90°/s	1.42	0.35	1.10	0.48	-22.90	**0.008**	2.64	0.61	1.86	0.53	-29.56	**0.000**
	180°/s	0.83	0.45	0.70	0.29	-15.89	**0.045**	1.64	0.59	1.29	0.37	-21.40	**0.005**
Ankle	0 °/s	0.74	0.31	0.63	0.14	-15.07	0.090	3.17	0.96	1.93	0.44	-39.32	**0.000**
	90°/s	0.46	0.24	0.57	0.38	25.46	0.151	0.70	0.34	0.81	0.26	15.51	0.497
	180°/s	0.41	0.24	0.40	0.33	-1.70	0.431	0.63	0.25	0.69	0.24	10.00	0.193

Table 19: Mean, standard deviation, and percent change between young and old adults maximal normalized torque (Nm/kg) of the flexor and extensor muscle groups of the hip, knee, and ankle, for isometric (0°/s) and isokinetic (90°/s and 180°/s) strength tests. % change is defined as (old-young)/young * 100 and used to quantify the difference between the two age groups. P-Values are **bolded** to indicate a statistically significant difference (p < 0.05).

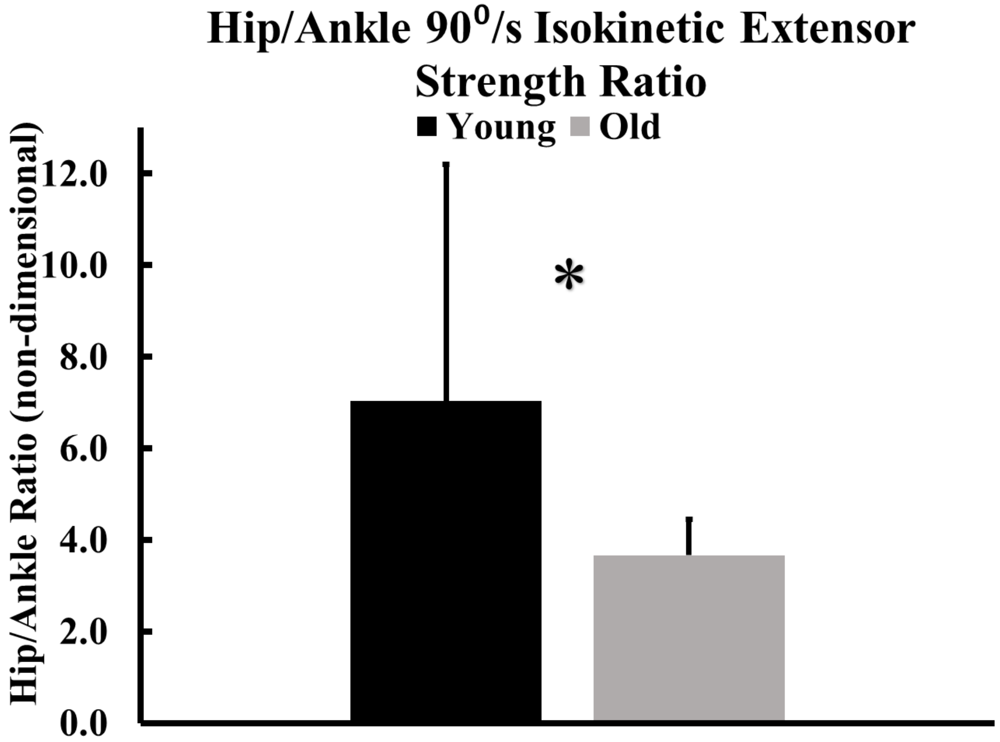


Figure 14: Isokinetic at 90 °/s Hip/Ankle maximal extensor torque ratio (non-dimensional) of young (black) and old (grey) adults. * Indicates a significant difference (p < 0.05).

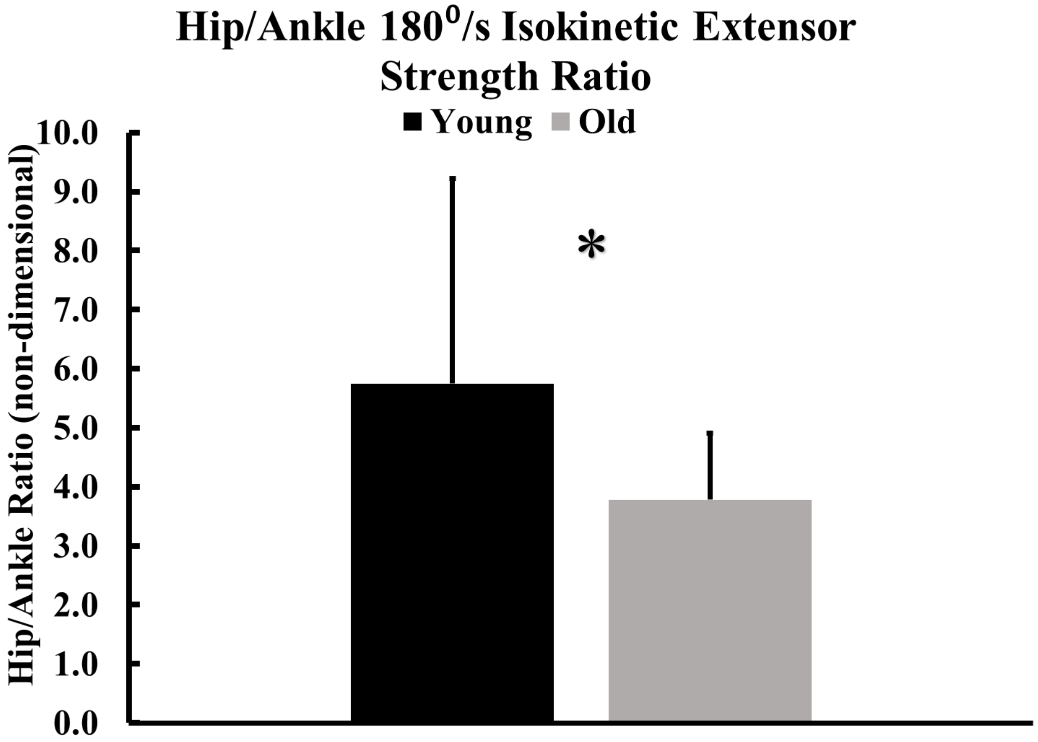
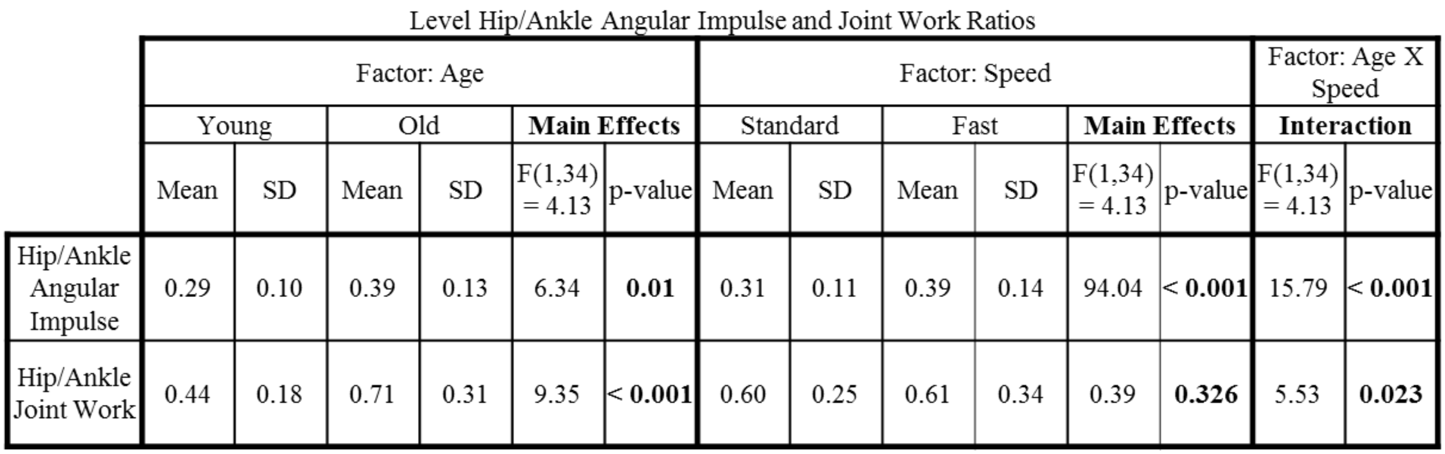
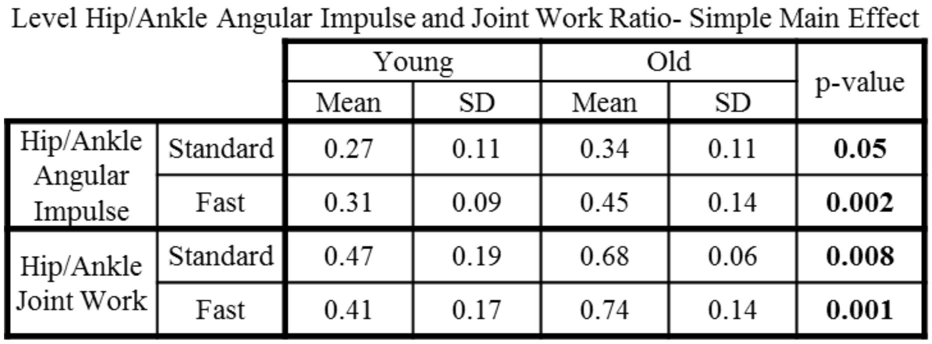


Figure 15: Isokinetic at 180 °/s Hip/Ankle maximal extensor torque ratio (non-dimensional) of young (black) and old (grey) adults. * Indicates a significant difference ($p < 0.05$).


Level Hip/Ankle Angular Impulse and Joint Work Ratios

	Factor: Age						Factor: Speed						Factor: Age X Speed	
	Young		Old		**Main Effects**		Standard		Fast		**Main Effects**		**Interaction**	
	Mean	SD	Mean	SD	F(1,34) = 4.13	p-value	Mean	SD	Mean	SD	F(1,34) = 4.13	p-value	F(1,34) = 4.13	p-value
Hip/Ankle Angular Impulse	0.29	0.10	0.39	0.13	6.34	**0.01**	0.31	0.11	0.39	0.14	94.04	**< 0.001**	15.79	**< 0.001**
Hip/Ankle Joint Work	0.44	0.18	0.71	0.31	9.35	**< 0.001**	0.60	0.25	0.61	0.34	0.39	**0.326**	5.53	**0.023**

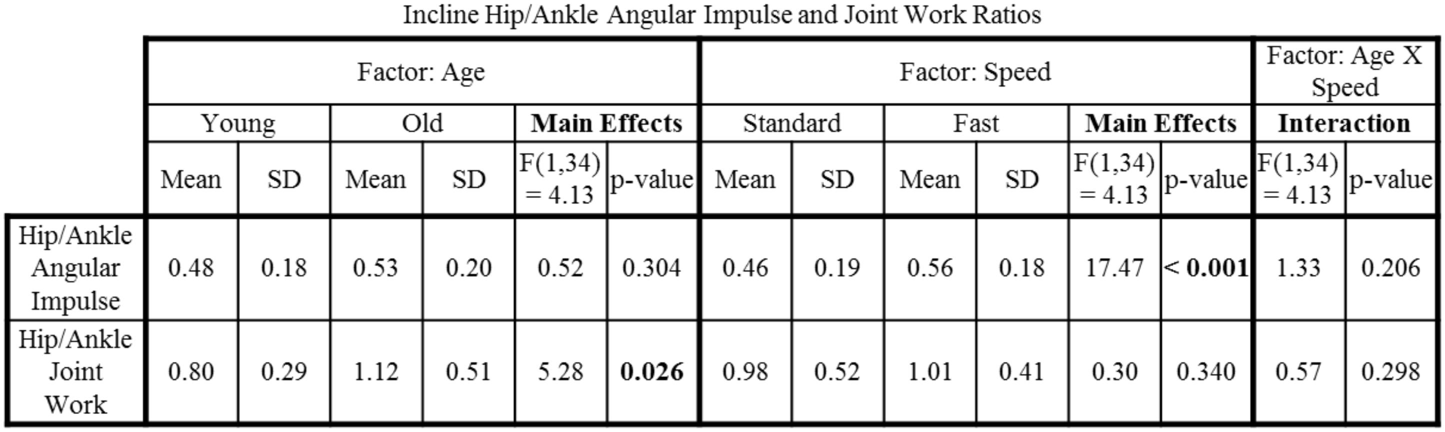
Table 20: Mean, standard deviation (SD), main effects and interaction effects of Age (young vs old) and Speed (standard vs fast) on Hip/Ankle angular impulse and joint work ratios for level walking conditions. **Bolded i**ndicates a significant difference ($F_{(1,34)} = 4.66$, $p < 0.05$).



Level Hip/Ankle Angular Impulse and Joint Work Ratio- Simple Main Effect

		Young		Old		p-value
		Mean	SD	Mean	SD	
Hip/Ankle Angular Impulse	Standard	0.27	0.11	0.34	0.11	**0.05**
	Fast	0.31	0.09	0.45	0.14	**0.002**
Hip/Ankle Joint Work	Standard	0.47	0.19	0.68	0.06	**0.008**
	Fast	0.41	0.17	0.74	0.14	**0.001**

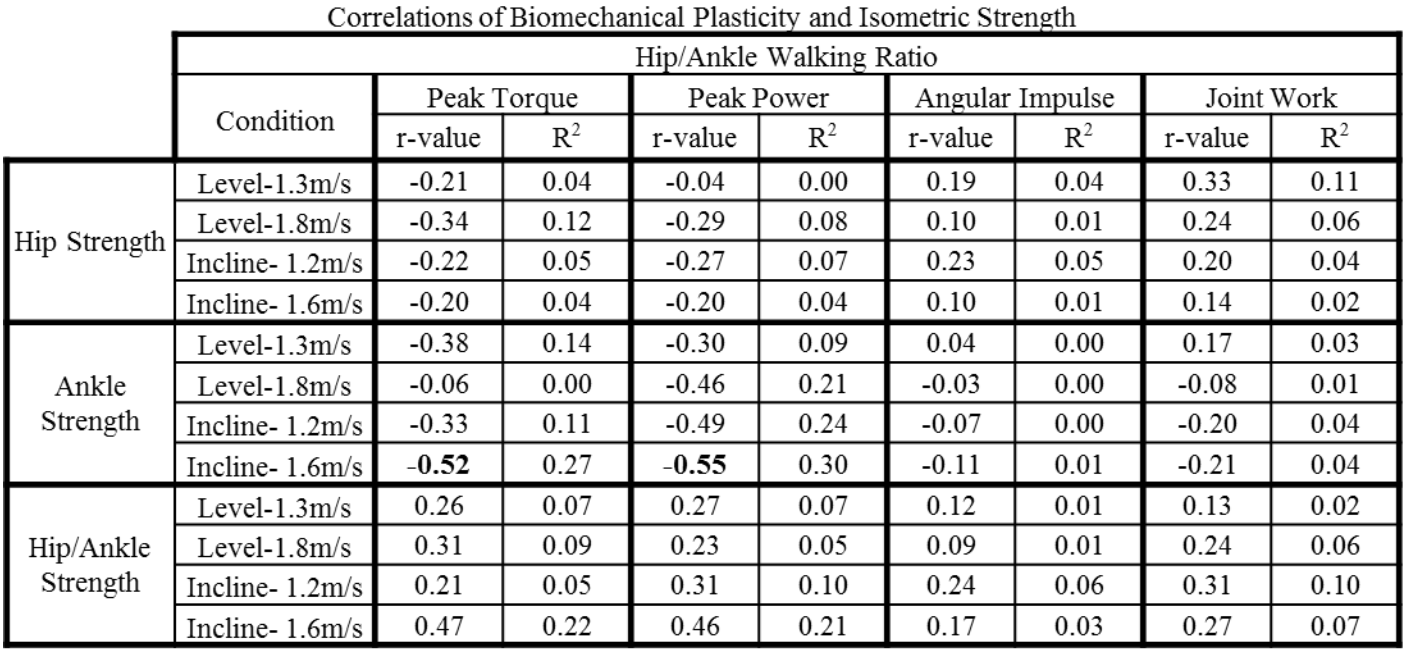
Table 21: Mean, standard deviation (SD), and simple main effects of Age (young and old) on the Hip/Ankle Peak angular impulse and joint work ratios for the level walking conditions. **Bolded i**ndicates a significant difference ($p < 0.05$).



Incline Hip/Ankle Angular Impulse and Joint Work Ratios

	Factor: Age						Factor: Speed						Factor: Age X Speed	
	Young		Old		**Main Effects**		Standard		Fast		**Main Effects**		**Interaction**	
	Mean	SD	Mean	SD	F(1,34) = 4.13	p-value	Mean	SD	Mean	SD	F(1,34) = 4.13	p-value	F(1,34) = 4.13	p-value
Hip/Ankle Angular Impulse	0.48	0.18	0.53	0.20	0.52	0.304	0.46	0.19	0.56	0.18	17.47	**< 0.001**	1.33	0.206
Hip/Ankle Joint Work	0.80	0.29	1.12	0.51	5.28	**0.026**	0.98	0.52	1.01	0.41	0.30	0.340	0.57	0.298

Table 22: Mean, standard deviation (SD), main effects and interaction effects of Age (young vs old) and Speed (standard vs fast) on Hip/Ankle angular impulse and joint work ratios for incline walking conditions. **Bolded i**ndicates a significant difference ($F_{(1,34)} = 4.66$, $p < 0.05$).



Correlations of Biomechanical Plasticity and Isometric Strength

		Hip/Ankle Walking Ratio							
	Condition	Peak Torque		Peak Power		Angular Impulse		Joint Work	
		r-value	R^2	r-value	R^2	r-value	R^2	r-value	R^2
Hip Strength	Level-1.3m/s	-0.21	0.04	-0.04	0.00	0.19	0.04	0.33	0.11
	Level-1.8m/s	-0.34	0.12	-0.29	0.08	0.10	0.01	0.24	0.06
	Incline- 1.2m/s	-0.22	0.05	-0.27	0.07	0.23	0.05	0.20	0.04
	Incline- 1.6m/s	-0.20	0.04	-0.20	0.04	0.10	0.01	0.14	0.02
Ankle Strength	Level-1.3m/s	-0.38	0.14	-0.30	0.09	0.04	0.00	0.17	0.03
	Level-1.8m/s	-0.06	0.00	-0.46	0.21	-0.03	0.00	-0.08	0.01
	Incline- 1.2m/s	-0.33	0.11	-0.49	0.24	-0.07	0.00	-0.20	0.04
	Incline- 1.6m/s	**-0.52**	0.27	**-0.55**	0.30	-0.11	0.01	-0.21	0.04
Hip/Ankle Strength	Level-1.3m/s	0.26	0.07	0.27	0.07	0.12	0.01	0.13	0.02
	Level-1.8m/s	0.31	0.09	0.23	0.05	0.09	0.01	0.24	0.06
	Incline- 1.2m/s	0.21	0.05	0.31	0.10	0.24	0.06	0.31	0.10
	Incline- 1.6m/s	0.47	0.22	0.46	0.21	0.17	0.03	0.27	0.07

Table 23: Pearson's correlation coefficients (r-value) and R^2 between hip, ankle and hip/ankle joint isometric strength and the hip/ankle peak torque, peak power, angular impulse and joint work ratios while walking in all four conditions.