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Falls present a large danger to the geriatric population, with one in three individuals over the age of 65 experiencing at least one fall annually. With most falls occurring while walking, the relationship between inclined walking and fall risk has not been fully explored. In this study, 16 healthy young participants (age: 26.8 ±5.4 years, height: 175.0 ±11.0 cm, weight: 68.2 ±19.9 kg) walked on a treadmill with level surface and 10 degrees incline/decline in a virtual environment laboratory. We found that gait parameters and lower extremity joint moments were affected by surface inclination. These observed changes in joint moments and gait parameters may present challenges to the older population especially with musculoskeletal disorders and thereby increase the risk of falls. This study offers new information on the effects of incline and decline surface walking compared to normal flat ground surface walking.

INTRODUCTION

Due to increases in the geriatric population, fall risk research has been of growing interest. In the United States alone, one in three individuals over the age of 65 experience at least one fall annually [1]. Falls can cause serious injuries to hip and wrist fractures [2] and lead to morbidity and mortality in the elderly. Many of these falls occur during walking, and little research has been done on walking on inclined planes. Incline walking, is associated with deviated gait patterns, including gait variability, stride time variability and alterations in mediolateral center of mass (COM) and joint angles, thus increasing fall risk. [2, 3, 4].

Individuals at risk of fall adapt often by walking slower, with shorter strides and a lower step frequency [5]. With shorter strides, an individual can keep COM above the base of support and have better balance. A declined slope places more demands on the knee and hip extensors. Normally, an individual walking on declined surface gains excessive momentum that must be counteracted; thus, hip extensors must contract eccentrically to maintain balance and not overwhelm frictional forces [6]. A certain amount of friction is needed to resist slip and is commonly termed Required coefficient of friction (RCOF) [7]. Older adults exhibit higher risks of falling due to their inability to rapidly regulate RCOF [8, 9].

In this study, we have investigated how surface inclination influences gait and joint moments during walking.

METHODS

A total of sixteen participants (8 males and 8 females) participated in this study. The anthropometric information for participants is given in table 1.

Age (years)	Height (cm)	Weight (kg)
26.8 ± 5.4	175.0 ± 11.6	68.2 ±19.9

Table 1: Mean and Standard Deviations of Participant Anthropometrics

All participants signed a written informed consent which was approved by Chapman University Institutional Review Board (IRB) prior to participation in the study. Motek Medical

GRAIL (Gait Realtime Analysis and Interactive Lab, Netherlands) system was utilized in this study. The GRAIL system consists of an instrumented dual belt treadmill, three video cameras, a motion capture system, and an Electromyography (EMG) system [10]. The GRAIL treadmill has a self-paced mode that allows individuals to initiate their gait at a self-selected pace. All the components of the GRAIL lab are integrated and synchronized from the D-flow software, making the data available in real-time for the analysis of the desired gait parameters [10]. For data analysis, the Gait Offline Analysis Tool (GOAT) was also used. This tool presents the video data, motion capture data, graphs, and ground reaction forces. GOAT makes it possible to analyze calculations such as standard deviations, gait parameters, and averages [10].
The order of each walking condition was randomized for each participant. 26 markers were placed on each subject according to Human Body Model (HBM 2) [11, 12] markers set to define and track motion. After the corresponding markers were placed, the participants were acclimated to walking conditions on the GRAIL. Each participant walked in all conditions for two minutes. Study conditions include walking on a 10 % inclined surface, 10% declined surface, or flat surface on the GRAIL treadmill (figure 1). Each trial was repeated three times. The pre-selected speed of 1m/s was selected first, and then self-selected pace was activated for all 3 walking conditions. Statistical analysis such as Multivariate Analysis of variance (MANOVA) was performed utilizing the

JMP statistical software.

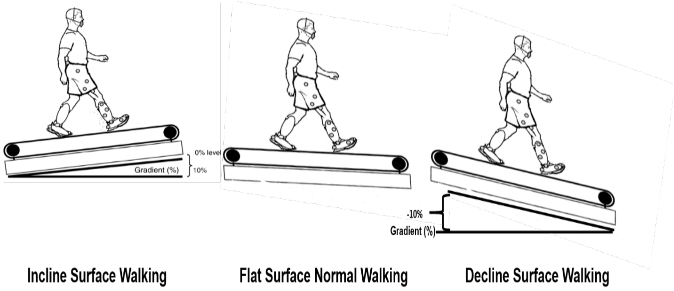

Figure1: Three walking conditions i) Incline surface walking ii) Flat surface normal walking iii) Decline surface walking

RESULTS

	Normal Walking	Decline Walking	Incline Walking
Stance to Swing ratio	66.5 ±0.4	63.9 ±0.4 ▼	66.7 ±0.4 ▲
Stance Time (s)	0.77±0.02	0.60 ±0.02 ▼	0.75±0.02 ▼
Step Length (m)	0.56 ±0.01	0.51 ±0.02 ▼	0.589 ±0.01 ▲
Step Width (m)	0.14 ±0.01	0.17 ±0.01 ▲	0.17 ±0.01 ▲
Stride Length (m)	1.15 ±0.03	1.02 ±0.03 ▼	1.18 ±0.02 ▲
Stride Time (s)	1.15 ±0.02	1.03 ± 0.02 ▼	1.18 ±0.02 ▲
Swing Time (s)	0.38 ±0.01	0.37 ±0.01 ▼	0.39 ±0.01 ▲

Table 2: Mean and Standard Deviations of Gait Parameters

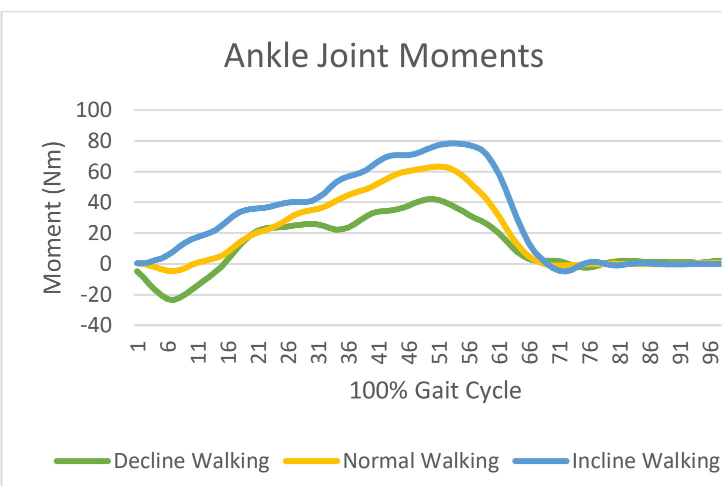

Figure 2: Average ankle joint moments for three walking conditions i) Flat surface normal walking ii) Decline surface walking, and iii) Incline surface walking

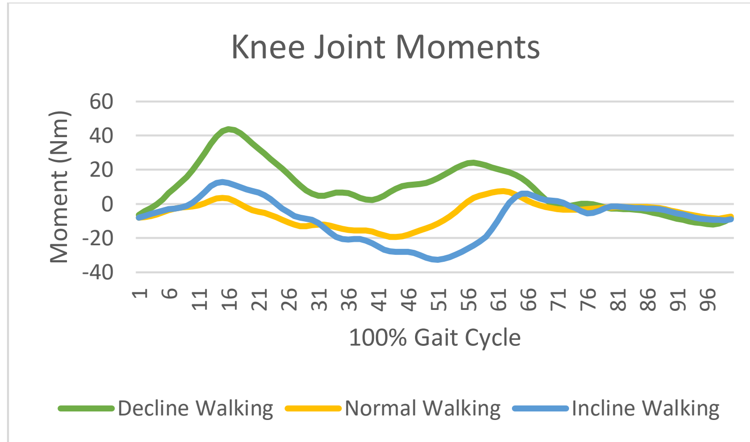

Figure 3: Average knee joint moments for three walking conditions i) Flat surface normal walking ii) Decline surface walking, and iii) Incline surface walking

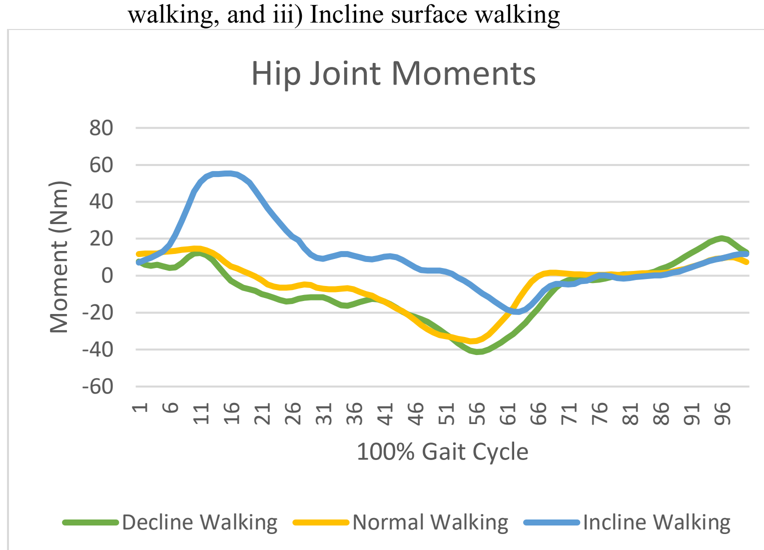

Figure 4: Average hip joint moments for three walking conditions i) Flat surface normal walking ii) Decline surface walking, and iii) Incline surface walking

MANOVA statistical test was used to determine if the gait parameters differed from one condition to another. The stance time means were 0.666 ±0.026 seconds for decline walking, 0.752 ±0.022 seconds for incline walking, and 0.773 ±0.024 seconds for normal walking. The stance time mean for normal walking was significantly different than decline walking ($p < 0.05$). The means that decline and incline walking were less than normal walking. The means for stance-to-swing ratio were 63.950 ±0.455 percent for decline walking, 66.721 ±0.404 percent for incline walking, and 66.521 ±0.426 percent for normal walking. The mean stance-to-swing ratio for incline walking and normal walking were significantly different from decline walking ($p < 0.05$). The mean step width was 0.178 ±0.009 meters for decline walking, 0.170 ±0.009 meters for incline walking, and 0.147 ±0.009 meters for normal walking. The mean step width for normal walking was significantly different and less than decline and incline walking ($p < 0.05$). The mean step length was 0.515 ±0.020 meters for decline walking, 0.589 ±0.019 meters for incline walking, and 0.564 ±0.019 meters for normal walking. The left step length means were significantly different from each other ($p < 0.05$). Incline walking was greater than normal walking which was greater than decline walking. The mean stride length was 1.027 ±0.030 meters for decline walking, 1.183 ±0.028 meters for incline walking, and 1.153 ±0.030 meters for normal walking. The mean stride length for decline walking was significantly different than incline and normal walking ($p < 0.05$) and decline walking was less than the other conditions. The mean stride time was 1.034 ± .029 seconds for decline walking, 1.182 ±0.028 seconds for incline walking, and 1.153 ±0.029 seconds for normal walking. The mean stride times for decline walking was significantly different than incline and normal walking ($p < 0.05$). The mean swing time was 0.373 ±0.011 seconds for decline walking, 0.393 ±0.010 seconds for incline walking, and 0.386 ±0.011 seconds for normal walking. The mean swing time for incline walking was significantly different and greater than decline walking ($p < 0.05$). The means and standard deviations of gait parameters are highlighted in Table 2.

Discussion

Evaluating gait deviation is an important aspect in classifying fall risks in older adults. When attempting to classify an individual as prone to high fall risk, assessing their gait parameters can help in the process. [13]. The purpose of this study is to investigate gait deviations during incline and decline walking. We found several gait parameters significantly differ with surface inclination. These gait deviations may increase fall risk during inclined walking. Gait measures have been considered potentially predictive of fall risk and may be more sensitive than clinical tests [14].

Previously, some authors found that the slope relationship between stride length did not differ between inclined and level surfaces [15]. It has also been observed that differences in incline will have an influence over the gait kinematics and kinetics, in stride length, cadence, joint moments, and degrees of joint angles [16, 17]. Specifically, for incline walking in the sagittal plane, hip, knee, and ankle exhibit greater degrees of flexion [16]. This is because as the distance between the treadmill and the body's center of mass (COM) decreases, the individual must shorten the lower extremity by flexing the joints to meet the incline surface. The shortening of the lower extremity is essential to raise the limb for toe clearance and heel strike [16]. In addition to this, in the frontal plane, the hips become progressively adducted as the incline gradient increases [16], shifting the COM more towards the ipsilateral limb and facilitating the contralateral limb to unload and prepare for toe clearance. It has also been observed that ankle dorsiflexion at heel strike increased significantly with increased uphill incline angle and remained more dorsiflexed until 50% of the gait cycle [17]. In contrast, as the downhill angle increased, there was an increase in dorsiflexion of the ankle around 50% of the gait cycle, and then a decrease in plantarflexion in the terminal stance [17]. This demonstrates that increased ankle flexibility and range of motion is required for walking on either incline or decline surfaces as compared to flat ground. The decreases in range of motion, as in the older population [4, 18], may make it so they are not able to properly adapt to the required kinematics of changing incline, thereby increasing their fall risk.

We found that stance time is significantly reduced in decline walking compared to flat surface walking. This leads to decreased stance time to swing time ratio in decline walking compared to flat surface and incline walking conditions. The decline walking condition had a 3% lower stance swing ratio, meaning swing time was larger in decline walking compared to the other two conditions. Swing duration increased significantly at the expense of stance duration. This indicates that gait speed and cadence values were significantly larger during the downhill condition [19]. We found that swing time was increased in incline walking where it was decreased in decline walking (table 2). This is attributed to the increased cadence and thus shorter steps. Coincidentally, stance time was also shown to only be significantly different from normal walking and decline walking (table 2). Swing time and stance time are found to be complementary parameters [19]. With the participant undertaking shorter swing times, this would lead to decreased stance time in the decline condition.

We also found that step width significantly increased during inclined and declined walking compared to flat surface walking. We found that step length decreased significantly during declined walking and increased significantly during inclined walking compared to flat surface walking. It is known that single legged stance time and global strength get reduced in fallers with low perceived fall risk [20]. We found stance time as lowest within the downhill walking condition (table 2). This would most likely be the more optimal strategy for an individual to walk as they would have decreased single leg stance time. It is also known that increasing step width and shortening stride lengths were strategies to maintain stability.

When walking downhill there is a tendency to shorten strides, thus leading to slower velocity. The stride length and stride time get reduced significantly during declined walking compared to flat surface and inclined walking. We also found that swing time was significantly reduced during declined walking compared to inclined walking. This change is a resultant of decreased stability and adaptation to reduce risk of falls. Moving slower is a consequence that is due to the loss of contact with the surface [15]. As portrayed in declined walking, individuals shorten stride length to counteract their stiffened joints, weak muscles and health conditions. Slower strides creates fluctuations, especially in older adults, as the individual is trying to balance stride-to-stride, which can be difficult with muscle atrophy and joint instability resulting in fatigue [21] and instability. Taking shorter but more frequent strides to increase cadence was only seen in decline condition as opposed to the other two. It is known that the steeper the slope, the shorter the step length [22]. Most research shows that walking uphill would entail a slower cadence and therefore a larger step length [22] . When it comes to step width, flat surface walking is significantly different than both decline and incline walking (table 2). The results show that an increased step width, as well as the decrease in stride length, are strategies to increase margin of stability (MoS), and thus to decrease the probability of falling [23]. Margin of stability considers both position and velocity of the center of mass and allows quantitative analysis of dynamic control of the center of mass [24].

Compared to walking on flat surface, incline and decline gait generated greater muscle recruitment of the lower extremity [16], resulting in significant joint moment differences in the ankle, knee, and hip (figures 9,10 and 11). Through observation, it has been shown that the hip and knee extensor moments increase as the treadmill gradient rises. The hip extensor moment specifically has a greater moment compared to decline gait [16], implying that the lower posterior chain muscles, such as the gluteus muscles and the hamstrings, were more active as there was an increase in elevation. Inclined walking causes the hip, knee, and ankle joints to become more flexed at heel-strike and become further extended during mid-stance, which helps move the body up the inclined treadmill [16]. Specifically, incline walking, compared to flat surface, increased the peak hip and knee extensor moments nearly four times during early stance [25]. Ankle plantarflexor and dorsiflexor moments also increase as the treadmill gradient increases [16]. The most significant increase in the peak plantarflexor moment was during push-off in terminal stance, where the gastrocnemius and soleus muscles have the greatest activation. In addition, the peak ankle plantarflexor moment during terminal stance was 19% greater than on level ground [25]. The plantarflexor and dorsiflexor muscles both play a crucial role in ankle stabilization, resulting in a greater moment with a higher surface.

However, during decline gait, the knee extensor moment had a greater moment compared to incline walking [25]. Due to their role of deceleration, the lower anterior chain muscles, such as the quadriceps muscles, exert a larger force producing a greater moment on a decline surface [25]. Ultimately, the increase in knee extensor moment clearly demonstrates a key role of eccentric contraction and lowering the body on a declined surface. At the ankle joint, all three conditions display a peak plantar flexor moment during the "Pre-swing" period of the gait cycle, with the largest moment occurring in the incline walking condition and the smallest moment occurring in the decline walking condition. The ankle joint produced the largest moment during walking. At the hip joint, an extensor moment was initiated during initial contact and loading and help decelerate the trunk and ultimately extend the hip (figure 4). During incline walking, the hip extensor moment is at its peak, and is much larger than that of the other two conditions. The hip joint moments of both decline walking and flat surface walking are almost identical at the hip joint throughout the gait cycle. They both share a fairly large flexor moment during the end of "Terminal stance" and the "Pre-swing" phase to help pull the thigh into swing. The knee joint kinetics are much different from what can be seen at both the ankle and hip joints. While the knee and hip joints share peak extensor moments up until the beginning of the "Mid-stance" period, the moment at the knee is 400% greater during decline walking than it is during incline walking (figure 3). In contrast, the results for incline walking at the knee joint show a large flexor moment through "Terminal-stance" as the plantar flexors of the ankle begin to flex the knee.

These results are consistent with existing research, as Lay et al. (2006) observed similar patterns of increased knee joint moments during decline walking as well as observed increased hip extensor moments during incline walking [26]. The findings in this study, and previous research, suggest that joint contributions differ in a comparison of decline and incline walking, showing that the ankle and hip joints are the main contributors when walking uphill, while the knee joint is responsible for decelerating and controlling knee flexion as weight is accepted when walking downhill[27]. This could potentially mean aggravated fall risk in older adults during walking on slopes or ramps. It is known that older adults produce lower joint moments than younger adults of matched weight and height [28]. This is an important finding for older adults with knee osteoarthritis, especially during downhill walking, because the amount of knee moment that is required during braking forces is very large in comparison to the other joints in the decline walking condition. Some limitations of this study were small sample size and characteristics of the population. Since the subjects examined in this study were young, healthy individuals, their alterations in gait due to differences in incline may not find external validity with older adult population.

This study offers new information on the effects of incline and decline surface walking compared to normal flat ground surface walking. To our knowledge, no previous studies have studied incline and decline walking at a self-selected pace. The findings of this study are critical in assessing fall risk on ramps in occupational environments. Fall risk increases as people age due to problems with balance, poor vision, and dementia [29]. Although fall risk is higher among older adults, the results of this study show that gait parameters change with a changing surface in younger populations as well. More caution is required, as seen through gait deviations and joint kinetics, when the ground surface is changed from flat to incline or decline. This study provides a baseline of incline/decline walking parameters for younger adults that may be useful in future comparative studies with older fall prone individuals.

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