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Original Article

The effect of incline walking on lower extremity and trunk mechanics in older adults

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ABSTRACT

Older adults are at an increased risk of developing knee osteoarthritis. High internal knee abduction moment during daily activities may elevate the risk of knee osteoarthritis. Incline walking exercise has been found to decrease knee abduction moment in healthy young adults. However, it is unknown if this occurs in healthy older adults. The purpose of this study was to quantify the internal knee abduction moment at different treadmill grades to determine if incline walking could reduce the knee abduction moment in healthy older adults. Twelve healthy older adult males walked on a treadmill at five incline grades (0%, 5%, 10%, 15%, and 20%) at 1.34 m·s^{-1}. The primary outcome variable was the internal knee abduction moment. A one-way repeated measures multivariate analysis of variance was performed to determine differences in the dependent variables among incline gradients. Peak knee abduction moment significantly decreased from level walking at all gradients in 10% increments (0%–10%, $p < 0.001$; 5%–15%, $p < 0.002$; and 10%–20%, $p = 0.04$). A reduction in knee abduction moment during incline walking could result in decreased knee joint loading on the medial knee compartment. For older adults, who are looking to exercise to improve their health, incline walking may be beneficial to promote lower body strength and cardiovascular ability without inflicting further harm to the aging knee joints. However, because the frontal plane knee joint was of primary interest in this study, further research is needed to determine the effects of incline walking on other joints and in other planes of motion.

1. Introduction

Globally, knee osteoarthritis (OA) is the eleventh leading cause of chronic disability in older adults.[1] Common symptoms of knee OA are pain, joint stiffness, and muscle weakness.[2] These symptoms result in restricting activities that exacerbate symptoms and mobility limitations, which may impair quality of life.[2,3] Presently, there is no cure for knee OA, therefore, current treatment options are aimed at controlling symptoms, increasing physical function, and improving quality of life.[3] Exercise has been determined to be a safe and effective way for older adults to lose weight and advance physical performance, both of which help prevent knee OA. Specifically, resistance training and walking have both been shown to improve gait and functional capacity in older adults.[4–7]

Fitness walking is popular due to its convenience and health benefits. However, walking is a repetitive activity, and the knee is exposed to loading over numerous gait cycles which could lead to additional cartilage degeneration and potential knee OA.[8,9] However, incline treadmill walking has become a more popular form of rehabilitative exercise for the knee joint. Compared to level walking, incline walking increases lower extremity muscle activity, particularly in the quadriceps, hamstrings, and triceps surae muscles, as well as range of motion, joint moments, and metabolism.[10–14] Increased muscle activity and joint moments from walking up inclines may benefit older adults with and without knee OA by strengthening the lower limb muscles.

For individuals with total knee replacements, older adults, obese individuals, or knee OA patients, incline treadmill gradients between 10% and 15% are recommended to be used for rehabilitation and exercise protocols to minimize patellofemoral discomfort and strain on the anterior cruciate ligament.[11,15] However, there is minimal research that has described the effects of incline walking on lower extremity joint mechanics. The limited research on incline walking has focused mainly on sagittal plane biomechanics and has only compared older adults to younger adults. In addition to the increased lower extremity muscle activity,[10,11,16,17] hip and knee extensor moments during early stance and

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Abbreviations

OA	osteoarthritis
IRB	institutional review board
ACSM	American College of Sports Medicine
GRF	ground reaction force
kg	kilograms
m	meters
cm	centimeters
mph	miles per hour
$m \cdot s^{-1}$	meters per second
Nm/kg	Newton meters/kilogram
Hz	hertz
MANOVA	multivariate analysis of variance
ANOVA	analysis of variance
SPSS	Statistical Package for the Social Sciences
USA	United States of America

plantarflexor moments during terminal stance significantly increase as incline increases.[15–17] When compared to younger adults, older adults walk with smaller ankle extensor moments and greater hip extensor moments.[18,19] This is also apparent when looking at lower extremity muscle activity, where older adults exhibit small increases in medial gastrocnemius and soleus activity but produce twice the recruitment of the gluteus maximus.[20]

There is still additional information that is necessary to determine if incline walking should be recommended to older adults. Frontal plane knee mechanics are important to study because they are related to knee joint health and knee OA risk. More specifically, the internal knee abduction moment is important to evaluate because it suggests how much loading is occurring at the medial compartment of the knee and has been linked to the progression and development of knee OA.[9,21] It has been reported that incline walking decreases the internal knee abduction moment in young adults, which signifies a potential reduction in medial knee joint loading and knee OA risk.[15] However, it is unknown if this finding holds true in an older adult population. Given the differences that occur with age in the sagittal and frontal planes,[14,18,19] older adults may not show the same decreases in the internal knee abduction moment.

When compared to younger adults, older adults display greater external knee adduction moments during stair climbing,[19] which may be due to altered foot kinematics.[22] Healthy older adults have reduced foot mobility in the sagittal and frontal planes compared to younger adults.[22,23] The kinematics of the foot have also been shown to change the internal knee abduction moment in individuals with medial knee OA.[24] Increased rearfoot eversion, rearfoot internal rotation, and forefoot inversion have all been associated with reduced internal knee abduction moment during the stance phase of gait.[24] Due to the differences in foot kinematics that result from aging, we cannot be sure that incline walking will result in a reduction of the internal knee abduction moment in older adults the same way it has been seen to in younger adults. By evaluating the internal knee abduction moment during incline walking in older adults, it may be possible to determine if incline walking is a suitable form of exercise to increase fitness and activity levels while still minimizing knee joint loading and knee OA risk.

Additionally, the biomechanical mechanisms that contribute to the decreased internal knee abduction moment during incline walking have not yet been established. Kinematics such as increased lateral trunk lean, decreased foot progression angle (increased toe-in angle), and a narrower stride width have been associated with reduced internal knee abduction moment in healthy individuals and thus have been used for gait-retraining[25,26] individuals with knee OA[27–30] when walking on a level treadmill.[26–32] Therefore, examining these factors at different incline gradients may help explain how incline walking reduces the knee abduction moment.

The primary purpose of this study was to quantify the internal knee abduction moment in healthy older adults while walking on a treadmill at different incline gradients to determine if incline walking may be a suitable method for reducing the risk of knee OA while improving physical fitness. It was hypothesized that a smaller knee abduction moment would be seen at greater treadmill gradients. In addition, it was hypothesized that a dose-response relationship would exist between the internal knee abduction moment and treadmill gradient, so as the treadmill gradient increases the internal knee abduction moment would decrease. The secondary purpose of this study was to quantify lateral trunk lean, foot progression angle, and stride width while walking on different treadmill gradients to help explain any changes in the internal knee abduction moment. It was hypothesized that lateral trunk lean would increase, and the foot progression angle and stride width would decrease as the treadmill gradient increased.

2. Methods

2.1. Participants

Twelve healthy males participated in this study (age: [69 ± 6] years; mass: [78.8 ± 10.9] kilograms (kg); height: [1.79 ± 0.07] meters (m); body mass index: [24.7 ± 2.3] $kg \cdot m^{-2}$). Sample size was determined by a power analysis conducted in G*power using the internal knee abduction moment with a desired power of 80%. All participants were free from any neuromuscular or lower extremity conditions that would prevent them from walking normally on level or incline surfaces and had no previous knee surgeries or lower extremity injuries within 6 months prior to data collection.

2.2. Ethical approval

All participants signed an informed consent document approved by the Ball State University institutional review board (IRB#: 837868) in accordance with the Declaration of Helsinki.

2.3. Participant preparation

Participants came to the biomechanics laboratory for one data collection session. All participants wore a tight-fitting shirt and shorts and athletic shoes (ASICS, Ltd., Kobe, Japan). Anthropometric measurements that included height, mass, leg length, knee and ankle width, and inter-ASIS distance were taken. Reflective markers were placed on anatomical landmarks following a modified Plug-In-Gait marker set with clusters.

2.4. Data collection

Following marker placement, participants completed a 3-min warm-up on a treadmill at 1.34 meter per second ($m \cdot s^{-1}$). After the warm-up, participants walked on a force-instrumented treadmill (Advanced Mechanical Technology, Inc., Watertown, Massachusetts, United States of America [USA]) at 0%, 5%, 10%, 15%, and 20% grades in a random order. A walking speed of 1.34 $m \cdot s^{-1}$ (3 miles per hour [mph]) was selected because it was considered to be a moderate to vigorous walking pace at inclines of 0%–20%, which is suggested based on the American College of Sports Medicine (ACSM) guidelines for fitness walking[33] as well as prior research in young adult studies which will allow for more direct comparisons to be made.[15] In addition, a self-selected walking speed is less likely to build muscle strength and cardio endurance, as is the goal in fitness walking. The treadmill utilized had railings on either side and easily accessible emergency stop buttons for participant safety. Participants were also fitted with a harness attached to the ceiling as an extra safety precaution. The participants walked for approximately 1 minute (min) at each grade. After ensuring a consistent walking cadence, four, 7-second (s) trials were recorded back-to-back at the end of each minute using Vicon Nexus v.2.1 (Oxford Metrics, Oxford, United Kingdom). Marker trajectories were recorded using 14 Vicon MX cameras sampling at 100 Hz, and two force plates in the instrumented treadmill sampled at 2 000 Hz. Five-minute breaks were given between each of the five conditions.

2.5. Data processing and reduction

Vicon Nexus v.2.1 was used to reconstruct and label the motion capture trials. Visual 3D v.5 (C-motion Inc., Germantown, Maryland, USA) was used to perform data processing and link-model based calculations. The 3D motion data and ground reaction force (GRF) data were filtered using a cutoff frequency of 8 Hz and 40 Hz, respectively. The peak internal knee abduction moment in early stance (1st peak) was identified for each gait cycle and normalized to body mass. Lateral trunk lean was defined as the angle between the midpoint of the anterior superior iliac spine and the midpoint of the anterior tips of the acromion processes with respect to vertical.[27] Stride width was measured as the medio-lateral distance between the heel of the foot at heel strike to the heel of the foot at the next contralateral heel strike. Foot progression angle was defined as the angle in the transverse plane between the line connecting the second metatarsal and the ankle joint center and the anterior-posterior axis corresponding to the line of progression.[30,34]

2.6. Statistical analysis

A one-way repeated measures multivariate analysis of variance (MANOVA) was used to analyze the differences among the five treadmill gradients with a statistical significance cut-off of $p \le 0.05$. The dependent variables of interest were the peak internal knee abduction moment during stance, lateral trunk lean, foot progression angle, and stride width. A significant MANOVA was followed up with individual one-way repeated measures analysis of variance (ANOVA's). Greenhouse-Geisser corrections were used when the assumption of sphericity was violated. Pairwise comparisons with a Bonferroni correction factor were run when significant differences were found. Statistical Package for the Social Sciences v. 22 (SPSS Inc., Chicago, Illinois, USA) was used to perform statistical analyses.

3. Results

The MANOVA revealed that there were significant differences among the treadmill gradient and the four dependent variables $p < 0.001$ (Table 1). A one-way repeated measures ANOVA illustrated a significant difference between the internal knee abduction moment across treadmill gradients $p < 0.001$. When compared to a level surface (0% grade), peak internal knee abduction moment was significantly reduced at 10% ($p < 0.001$), 15% ($p < 0.001$), and 20% ($p < 0.001$) grades, but not at 5% ($p = 0.95$). A dose-response relationship between the treadmill grade and the peak internal knee abduction moment was observed to occur in 10% increments. The peak knee abduction moment was significantly reduced from 0% to 10% ($p < 0.001$), 5%–15% ($p = 0.020$), and 10%–20% ($p = 0.040$) (Fig. 1).

A one-way repeated measures ANOVA also demonstrated a significant difference between treadmill grade and lateral trunk lean, $p < 0.001$. Peak lateral trunk lean was significantly greater at 20% when compared to 0% ($p = 0.002$), 5% ($p = 0.001$), 10% ($p < 0.001$), and 15% ($p = 0.002$). Additionally, a one-way repeated measures ANOVA revealed no significant difference in treadmill gradient for foot progression angle, $p = 0.36$, or stride width, $p = 0.56$.

Table 1
Variables of interest across the five different incline conditions (Mean ± standard deviation).

Variable	Treadmill Gradient				
	0%	5%	10%	15%	20%
Knee Abduction Moment (Nm/kg)[a]	0.54 ± 0.10	0.48 ± 0.13	0.40 ± 0.10[c]	0.37 ± 0.10[c]	0.31 ± 0.12[c]
Lateral Trunk Lean (degree)	3.45 ± 3.91[dc]	3.55 ± 4.01[dc]	3.68 ± 4.09[dc]	4.38 ± 4.20[dc]	5.83 ± 4.59
Foot Progression Angle (degree)	20.10 ± 5.62	19.47 ± 5.95	19.17 ± 5.31	20.30 ± 5.93	20.31 ± 5.73
Stride Width (cm)[b]	7.90 ± 2.82	7.80 ± 2.20	7.78 ± 2.50	8.81 ± 2.21	8.43 ± 3.21

[a] Nm/kg – Newton Meters/kilogram.
[b] cm – centimeters.
[c] Indicates a significant difference from 0% grade ($p \le 0.05$).
[d] Indicates a significant difference from the 20% grade ($p \le 0.05$).

4. Discussion

Incline walking is a popular form of exercise used frequently for exercise and rehabilitative purposes due to the health benefits.[5–7,10,11,17] However, there is minimal research available that describes the effect of incline walking on lower extremity joint mechanics in older adults, and it is unclear whether it is associated with changes in joint loading in this group. Therefore, the primary goal of this study was to quantify the internal knee abduction moment in healthy older adults during incline walking at multiple gradients.

The primary hypothesis was that the internal knee abduction moment would decrease as the treadmill gradient increased, which was true. The peak internal knee abduction moment decreased from level walking to all incline gradients. This relationship was significant across all inclines with the exception of the 5% grade. It was also hypothesized that a dose-response relationship between the knee abduction moment and treadmill gradient would exist, which was partially accepted. A dose-response relationship was seen in 10% increments (0%–10%, 5%–15%, and 10%–20%). This indicates that the internal knee abduction moment significantly decreases when treadmill gradients are raised in 10% increments. This is important because the internal knee abduction moment is a key parameter for predicting medial knee joint loading and knee OA risk.[21,35,36] A similar study with 15 healthy young adult men walking at the same inclines and the same speed also reported a significant decrease in peak internal knee abduction moment at each gradient compared to 0%, with the exception of the 5% condition, as well as a dose response relationship in 10% increments,[15] which agrees with our findings in the present study.

When the internal knee abduction moment increases, the stress on the medial compartment of the knee may also increase.[37] In the present study, a decrease in the peak internal knee abduction moment indicated

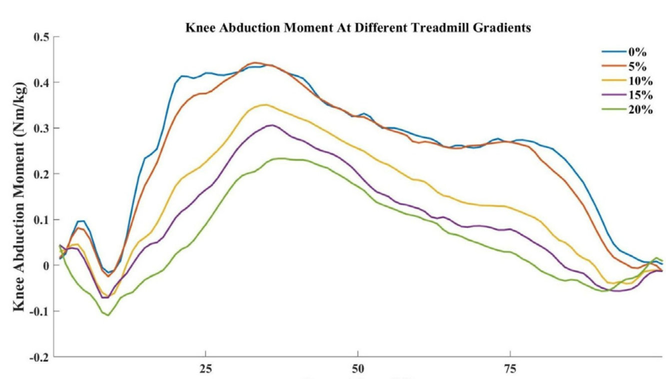

Fig. 1. Internal knee abduction moment during stance at different treadmill gradients. Positive values represent internal abduction moment and negative values represent internal adduction moment. Data represents an average of all participants.

that the loading on the medial side of the knee joint was potentially reduced. A reduction in medial knee joint loading could reduce the risk of medial knee OA, cartilage degeneration, and knee joint pain.[21,36] Since there is no cure for knee OA, effective treatments to manage pain and improve quality of life are critical. The current study provides evidence that incline walking could be a beneficial exercise for older adults who are at an increased risk of, or have developed, knee OA.

The second goal of this study was to examine the biomechanical mechanisms that contribute to a decreased internal knee abduction moment during incline walking. It was hypothesized that lateral trunk lean would increase, and foot progression angle and stride width would decrease with increasing treadmill gradients. This hypothesis was partially accepted. Results indicated that as the gradient increased, lateral trunk lean increased, but foot progression angle and stride width did not change. Previous research has shown that an increase in lateral trunk lean is associated with a reduction in the peak internal knee abduction moment during early stance.[31] Greater lateral trunk lean is thought to reduce the internal knee abduction moment because of the lateral displacement of the center of mass towards the stance limb during walking. This would result in a lateral shift in the GRF vector and, therefore, a smaller lever arm.[27,31] Foot progression angle and stride width have also been shown to reduce knee abduction moment on level terrain,[26,29,30] but did not help explain why knee abduction moment decreased with increasing treadmill gradient in the present study.

Prior research showed that when walking on an incline, adjustments are made to the lower extremity joint angles at foot strike due to the slope, including decreased ankle inversion and increased hip adduction.[15] The present study further identified that older adults make an additional accommodation at the trunk by moving the trunk segment more laterally, or increased trunk lateral lean, in an effort to perform incline walking at a given speed. Future research should focus on additional joints/segments in order to gain a complete understanding of the effect of incline walking on body mechanics.

There are a few limitations to this study. First, only healthy older adults were included and not individuals who had already developed knee OA. This was an intentional decision due to our desire to see if knee OA risk could be reduced in individuals that do not currently have knee OA. Second, only male participants were recruited to eliminate any potential gender affects, therefore, it is unknown if these results will manifest in an older adult female group. Future studies should include both females and individuals with and without present knee OA. Third, gait retraining strategies are not limited to lateral trunk lean, foot progression angle, and stride width; however, these are the most reported gait retraining strategies. Future studies need to explore additional factors that might help explain why incline walking decreases the knee abduction moment. Fourth, this study did not address the effect of fatigue on the lower extremity joint mechanics. Walking at an incline for a longer duration may elicit mechanical changes that could be important in considering when clients or patients are in the fatigue stage of their exercise regimen. Therefore, further studies are needed to assess mechanical changes in older adults after multiple weeks of incline walk training, as well as how fatigue may affect incline walking mechanics. Lastly, participants walked at a consistent pace across all grades. It is unknown how joint mechanics may change when walking at a self-selected speed in the real world. However, $1.34\ m \cdot s^{-1}$ (3 mph) is considered a moderate walking pace and was a manageable pace for the participants at all grades. Additionally, walking at a self-selected speed may not produce the same improvements in leg muscle strength and cardiovascular endurance that is desired in fitness walking due to energy efficiency.

5. Conclusion

Treadmill gradients of 10% and above significantly decreased the peak internal knee abduction moment, and a dose-response relationship between the internal knee abduction moment and the incline gradient was observed in increments of 10%. It was also shown that the decrease in knee abduction moment with increased incline gradient may have been due to the increased lateral trunk lean. Therefore, incline gradients of 10% or greater may be recommended for older adults to help reduce knee joint loading while improving physical fitness. Prior research has recommended using similar incline gradients for knee rehabilitation and exercise protocols.[11,15] These findings may be beneficial to healthy older adults, knee surgery patients, obese and healthy individuals who are involved in a rehabilitative or exercise program, and physical therapists, personal trainers, and physicians designing exercise and rehabilitation protocols for patients and clients. Additionally, these findings may help middle aged and older individuals confidently choose walking for exercise to improve health without worrying about doing harm to their knee joints.

Ethical approval statement

This study was approved by the institutional review board at Ball State University (IRB#: 837868). Informed consent was obtained from all participants prior to their participation in this study.

Authors' contributions

Seth Higgins: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **D. Clark Dickin:** Writing – review & editing, Supervision, Resources, Conceptualization. **Dorice Hankemeier:** Writing – review & editing, Conceptualization. **Meredith D. Wells:** Writing – review & editing. **He Wang:** Writing – review & editing, Writing – original draft, Supervision, Resources, Conceptualization.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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