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Is the Walking Pattern Similar Between Slope Walking and Obstacle Negotiation?

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IS THE WALKING PATTERN SIMILAR BETWEEN SLOPE WALKING AND OBSTACLE NEGOTIATION?

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IS THE WALKING PATTERN SIMILAR BETWEEN SLOPE WALKING AND OBSTACLE NEGOTIATION?

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University of Nebraska Medical Center, 2021

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Studying biomechanical characteristics of human motion sheds light on the motor control strategies in the central nervous system. Slope walking and obstacle negotiation appear to have some similarities in control strategies based on subjective observation, but these two motions have never been compared objectively in biomechanics literature. This study aimed to investigate the similarities between obstacle negotiation and slope walking in kinematics and muscle activity. The similarities were determined by the correlation of the maximum heel elevation and muscle co-activation index between obstacle negotiation and inclined treadmill walking. The strength of correlation was compared in four different pairs of conditions: 1) no-obstacle and level treadmill; 2) 3.9cm-obstacle and 5% inclined treadmill; 3) 7.8cm-obstacle and 10% inclined treadmill; 4) 11.5cm-obstacle and 15% inclined treadmill. The correlations of maximum heel elevation between obstacle negotiation and inclined treadmill walking varied from weak to very strong ($r = 0.24 - 0.81$) across all four pairs of conditions. The muscle co-activation index was strongly to very strongly correlated ($r = 0.68 - 0.83$) between two motions across all four conditions. In conclusion, there was a certain level of similarity in kinematics and muscle activities between obstacle negotiation and inclined treadmill walking, especially between obstacle negotiation with a 3.9cm-high obstacle and 5% inclined treadmill walking and between obstacle negotiation with an 11.5cm-high obstacle and 15% inclined treadmill walking.

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LIST of ABBREVIATIONS

EMG	electromyography/ electromyographic
GRF	ground reaction force
H-OB	high obstacle
H-TM	high inclination treadmill
IntEMG	Integrated EMG
LV-TM	level treadmill
L-OB	low obstacle
L-TM	low inclination treadmill
M-OB	middle obstacle
M-TM	middle inclination treadmill
NO-OB	no obstacle
PWS	preferred walking speed

CHAPTER 1: INTRODUCTION

Kinematics, kinetics, and electromyographic (EMG) activity of motions provide insight into the locomotor control strategies used by the nervous system.[1] Different motor control programs for different tasks were found based on the changes in the kinematics, kinetics, and EMG. Lay et al.[2] found significant changes in the kinematics, ground reaction force (GRF), and joint moment during upslope and downslope walking compared to level walking, indicating specific motor control strategies for upslope and downslope walking. Riener et al.[3] suggested a unique motor control strategy used by stair negotiation based on the significant differences in kinematics and kinetics between level walking and stair negotiation.

It has been shown that some different motions have some similarities in locomotor characteristics, indicating they are governed by a common motor control strategy rather than several different strategies. Similarities in peak GRF and EMG latencies and durations were found during gait initiation and initiating movement by stepping over an obstacle.[4] Crenna and Frigo[5] investigated the EMG pattern of leg muscles during different motor tasks: execution of single step forward, initiation of walking, rising on tip-toes, fast bending trunk forward and recovery of the initial vertical position, tossing and catching a basketball with two hands, and standing up from a seated position. The same EMG activation sequence, soleus inhibition-tibialis anterior burst, was presented during all motor tasks except bending forward and recovery of the initial vertical position.

Transfer of learning is one of the critical components that need to be considered when developing a motor training program. Identical element theory[6] posits that the amount of transfer of learning between two skills increases as the level of similarity between the elements of two skills increases. In other words, if two different motions share a certain level of similarity of motor control strategy in the central nervous system, the performance of one motion could be improved by the training of the other motion. Therefore, understanding the similarities and differences of fundamental motor control strategies between two motions is essential for developing a novel training protocol.

Poor motor performance in obstacle negotiation is associated with increased fall risk.[7,8] Hence, improving the performance of obstacle negotiation could be an effective approach to prevent falls. Many studies have explored the effects of different training protocols on obstacle negotiation performance; however, there is a lack of consensus on the best protocol for enhancing obstacle negotiation.[9] Further exploration of novel training protocols could provide clinicians more options to choose based on patients' physical conditions and equipment availability in the clinic.

Slope walking has been observed as using similar mechanics as obstacle negotiation — the leading limb and trailing limb are lifted higher to avoid tripping during those two motions. However, those two motions have never been compared objectively using biomechanics measures (e.g. kinematics and muscle activity). Based on the identical element theory[6], if similarities in kinematics and muscle activity are found between these two motions, slope walking might have a positive transfer of learning effect to improve obstacle negotiation performance and decrease fall risk. Therefore, this study aimed to investigate the similarities of motor control strategy between slope walking and obstacle negotiation in healthy young adults.

1. Motor Control of Obstacle Negotiation in Healthy Young Adults

1.1. Obstacle Negotiation vs. Level Walking

Compared with level walking, young adults increased step length, stride time, and foot clearance and decrease stride velocity during obstacle negotiation.[8,10–13] Such changes in gait happened even when the young adults were stepping over a 25mm-wide tape on the ground ("zero height" obstacle).[8]

Patla et al.[14] investigated the trajectories of hip, knee, heel, and toe of the leading limb during level walking and obstacle negotiation. During the stance phase, these four trajectories were similar between level walking and obstacle negotiation.[14] However, the four trajectories of obstacle negotiation deviated from those of level walking during the swing phase.[14] The maximum vertical displacement of hip, knee, heel, and toe of the leading limb significantly increased during obstacle negotiation.[14]

Stepping over an obstacle changed the maximum external joint moments of the trailing limb when the leading limb was crossing the obstacle.[10] At the hip joint, extension moment during late stance decreased, and adduction moment and external rotation during early stance increased.[10] At the knee joint, flexion moment during early stance, adduction moment during early and late stance, external rotation moment during early stance, and internal rotation moment during stance increased.[10] At the ankle joint, plantarflexion moment during early stance, dorsiflexion moment during late stance, and adduction moment during late stance increased.[10] In addition, the GRF of the trailing limb increased in the anterior-posterior component and vertical component during early and late stance when the leading limb was stepping over the obstacle.[10]

In general, the muscle activities of both leading and trailing limbs increased during obstacle negotiation.[14,15] The soleus, tibialis anterior, biceps femoris, and rectus femoris of the leading limb exhibited higher muscle activity during obstacle negotiation.[14] Stepping over an obstacle also increased the relative muscle activation of gluteus medius and vastus lateralis during double support phase and gastrocnemius during single support phase in both leading and trailing limbs.[15]

1.2 The Effects of Obstacle Height on Obstacle Negotiation

Conflicting results about the effects of obstacle height on foot clearance during obstacle negotiation have been reported.[8,11,15,16] Some studies found the obstacle height did not affect the leading and trailing foot clearance,[11,16] whereas other studies found the leading foot clearance[8] and trailing foot clearance[15] increased as the obstacle height increased. The obstacle height did not affect the leading heel-obstacle distance and trailing toe-obstacle distance.[10,16] The crossing stride length and stride time linearly increased with obstacle height.[15,17] The increased obstacle height decreased crossing speed but did not affect the approaching speed.[10,16]

The increase in obstacle height increased the maximal angular displacement of knee flexion, knee extension, and hip flexion of the leading limb.[13,18] In addition, the maximal angular velocity of ankle dorsiflexion, ankle plantarflexion, knee extension, knee flexion, and hip flexion gradually increased with the obstacle height.[18] The crossing angle was defined as the angle for a joint of the stance or swing limb when the toe of the swing limb was directly above the obstacle. Obstacle height had linear relationships with crossing angles of the hip, knee, and ankle.[16] For the crossing angles of both leading and trailing swing limbs, the hip flexion, knee flexion, and ankle dorsiflexion increased as the obstacle height increased.[16] The obstacle height increased the knee flexion crossing angle of trailing stance limb but decreased the knee flexion crossing angle of leading stance limb.[16]

Linear relationships were also found between obstacle height and peak joint moments during the stance phase.[10,17,19] For the leading limb during early stance, hip abductor moment, hip extensor moment, hip internal rotator moment, and knee extensor moment linearly decreased with the increasing obstacle height.[19] For the leading limb during late stance, knee abductor moment, knee flexor moment, knee external rotator moment, ankle plantar flexor moment, and ankle external rotator moment linearly increased with the increasing obstacle height.[19] For the trailing limb, increased obstacle height resulted in decreased hip flexor moment during late stance, increased knee extensor moment during early stance, increased knee abductor moment during late stance, and increased ankle plantar flexor moment during late stance. [10,17,19] Chen et al.[19] also found that increased obstacle height resulted in increased hip abductor moment during early stance, increased ankle external rotator moment during late stance, and decreased hip external rotator moment during late stance. In contrast, Chou et al.[10] found no obstacle height effect on these joint moments. The different results of these two studies might be due to the different experimental protocols of these two studies. One used fixed obstacle heights[10] while the other adjusted the obstacle heights to the leg lengths of participants[19].

The increased height also increased muscular challenge during obstacle negotiation.[14] The relative activation of muscles (gluteus medius and vastus lateralis during double support phase and gastrocnemius during single support phase) of both leading and trailing limbs increased as the obstacle height increased.[14]

2. Motor Control of Slope Walking in Healthy Young Adults

2.1 Spatiotemporal Characteristics

There was no consensus about the effect of inclination on the spatiotemporal parameters during slope walking in young adults. Khandoker et al.[20] reported that there was no significant difference in toe clearance between inclined treadmill walking and level treadmill walking in young adults. In contrast, Thies et al.[21] found that toe clearance increased during inclined overground walking compared with level overground walking. The different findings of these two studies may result from the different experimental protocols of these two studies.

During overground walking at the preferred speed, the sloped surface decreased cadence in young adults.[22,23] Conflicting results were found in the walking speed and stride length. Kawamura et al.[22] found that sloped surface decreased stride length and walking speed. In contrast, McIntosh et al.[23] found stride length and walking speed increased as the inclination increased. When the walking speed was constant, the inclination had no effects on stride time, stance time, and normalized stride length during overground walking.[2] When walking on a treadmill at a constant speed, young adults increased stride time and stride length as the inclination increased.[24]

2.2 Kinematics

Hip flexion, knee flexion, and ankle dorsiflexion increased at initial contact as the inclination of the surface increased.[2,23–25] Greater joint excursion of the hip, knee, and ankle joints throughout the stance phase were observed in higher inclination conditions.[2,23–25] The inclination of the surface also induced larger hip flexion and ankle dorsiflexion during mid-swing.[2,23–25]

2.3 Kinetics

There were significant inclination effects on the anterior-posterior and vertical components of GRF.[2] During upslope walking, the braking force decreased significantly while the propulsive force increased significantly.[2] The shape of vertical GRF for upslope walking was similar to that of level walking. The magnitudes of the two peaks of vertical GRF increased during upslope walking.[2] Upslope walking decreased the resultant force of GRF in the sagittal plane during mid-stance.[2]

The joint moment patterns during the swing phase were similar between upslope walking and level walking.[2] However, the joint moments during the stance phase changed significantly with the inclination of the surface.[2] The peak magnitudes of the ankle plantar flexor moment during late stance, knee extensor moment during early stance, knee flexor moment during late stance, and hip extensor moment in early stance progressively increased as the inclination increased.[2] The ankle and hip joints performed more positive work as the inclination increased.[26] Absolute work of ankle, knee, and hip joints increased during upslope walking.[26] The increase in joint work was greater when the inclination increased from 0° to 6° and from 6° to a 12° than when the inclination increased from 12° to 18°.[26]

The roles of lower limb muscles in kinetics were different between level walking and upslope walking.[27–29] During upslope walking, the plantar flexors generated more power to push the body forward, and the hip extensors absorbed more power from the trunk and generated more power to both legs.[27,30] Besides, the muscle forces decreased in gluteus minimus, iliopsoas, and tibialis anterior.[28] The muscle forces increased in gluteus maximus, quadriceps, hamstrings, gastrocnemius, and soleus.[28] The compression forces of hip, tibiofemoral, patellofemoral, and ankle increased with the increasing inclination.[29] The contributing muscles for joint compression forces were: gluteus medius for hip joint, quadriceps and gastrocnemius for tibiofemoral joint, quadriceps for patellofemoral joint, and triceps surae for ankle joint.[28]

2.4 Muscle Activity

Upslope walking increased the mean activity and burst duration of most muscles in the stance phase, including gluteus maximus, biceps femoris, rectus femoris, vastus medialis, and vastus lateralis.[25,30–32] For soleus and medial gastrocnemius, the mean activity increased during the stance phase in upslope walking while the burst duration remained the same.[25,30,31] Lay et al.[30] reported that the semimembranosus exhibited increased mean activity and burst duration in the stance phase in upslope overground walking compared with level overground walking. However, Lange et al.[32] found that the mean and peak activity of medial hamstring during the whole gait cycle did not change with the inclination of the treadmill.

Saito et al.[33] found the lower limb muscle synergies were similar between level and upslope treadmill walking. In addition, the co-activation index of shank muscles decreased by an average of 17% during upslope walking compared with level walking.[34] In contrast, no significant differences in the co-activation index of thigh muscles were found between level and upslope walking.[34]

3. Aims of Study

Further understanding of the similarities and differences of motor control strategies between two motions (slope walking and obstacle negotiation) may better inform the development of using slope walking as a novel training protocol. Slope walking and obstacle negotiation demonstrate similar lower limb trajectories based on subjective observation.

However, it is unknown if a certain motor control strategy is shared by slope walking and obstacle negotiation based on objective measurements. Therefore, this study aimed to determine the similarities in motor control strategies between slope walking and obstacle negotiation in healthy young adults by investigating kinematics and EMG during inclined treadmill walking and overground obstacle negotiation. Maximum heel elevation is a parameter for foot trajectory, which results from combined effects of the movement of bilateral hip, knee, and ankle joints.[35] Muscle co-activation index is a parameter reflecting muscle synergy, which is a combined effect of agonist and antagonist muscles in a limb.[36] Therefore, we used maximum heel elevation and muscle co-activation index to investigate kinematics and muscle activity, respectively. We hypothesized that there would be some similar characteristics shared by slope walking and obstacle negotiation in kinematics (maximum heel elevation) and muscle activity (muscle co-activation index) (hypothesis 1), and the higher obstacle height and larger inclination would increase the level of similarities between slope walking and obstacle negotiation (hypothesis 2).

CHAPTER 2: METHODS

1. Participants

Eighteen healthy young adults participated in this study. This study was approved by the Institutional Review Board in the University of Nebraska Medical Center (IRB # 006-18-FB). All participants signed the informed consent before the experiment started.

The Participants were adults aged 20 to 40, with a body mass index of less than 30. The participants were excluded if they had 1) neurological or musculoskeletal problems, 2) a recent history of lower extremity injuries, 3) a history of visual or vestibular deficits.

2. Experiment Protocol

The height, weight, and leg lengths of participants were measured at the beginning of the experiment. Leg length was defined as the distance between greater trochanter to lateral malleolus. Then, all participants were asked to perform two tasks – inclined treadmill walking and obstacle negotiation. Rest breaks were provided between trials if the participants felt tired.

2.1 Inclined Treadmill Walking

There were four conditions of treadmill inclination: level treadmill (LV-TM) 0% of grade, low inclination treadmill (L-TM) 5% of grade, middle inclination treadmill (M-TM) 10% of grade, and high inclination treadmill (H-TM) 15% of grade. All participants were asked to walk on a motorized treadmill (Biodex RTM 600, Shirley NY, USA) within the instructed walking area at their preferred walking speed (PWS) for two minutes during each condition. The instructed walking area was the middle half of the treadmill (Figure 1). The length of the instructed walking area was

78 cm. The sequence of the four different conditions was randomized. Prior to the data collection, all participants were asked to walk on the level treadmill for at least one minute to be familiarized with the marked instructed walking area and find their PWS by adjusting the treadmill speed by an increment of 0.1m/s.

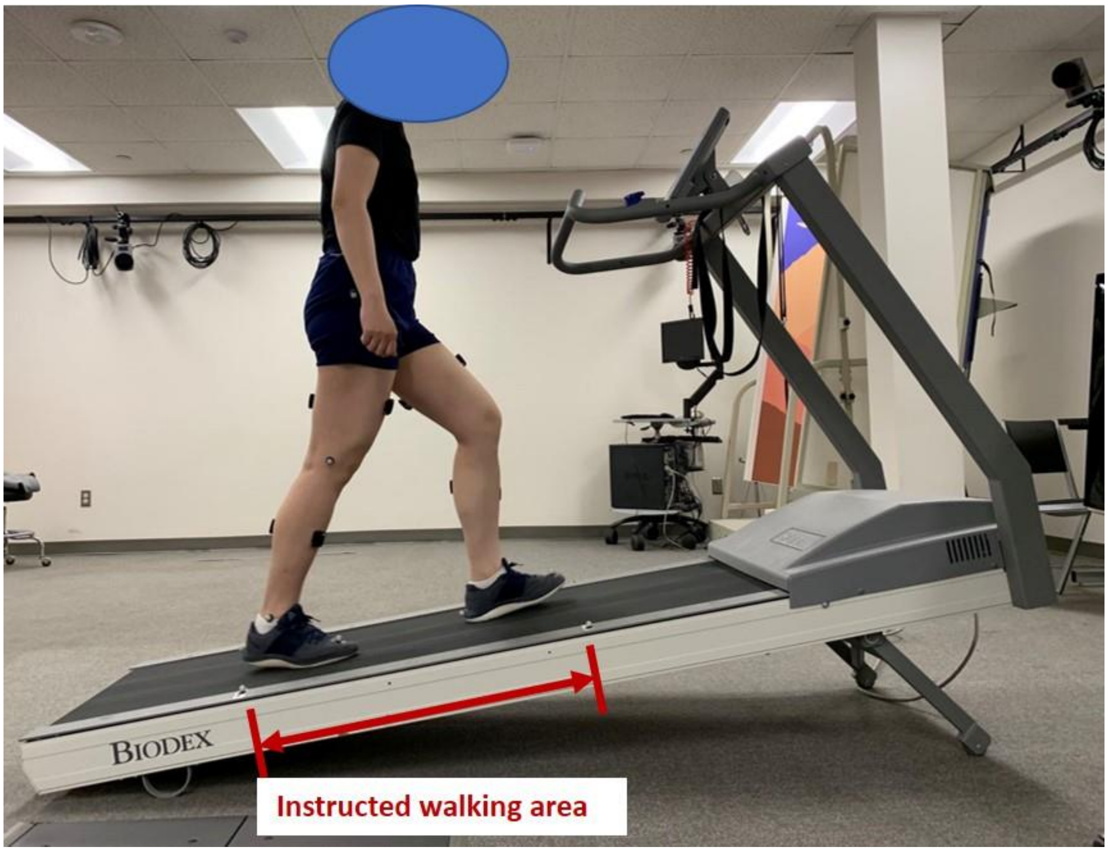

Figure 1. Illustration of instructed walking area. The treadmill is at 15% of grade in this figure.

2.2 Obstacle Negotiation

All participants were asked to cross a single obstacle on the ground at their PWS. The starting walking point and the ending walking point were five meters away from the obstacle. There were four conditions of obstacle heights: no obstacle (NO-OB), low obstacle (L-OB), middle obstacle(M-OB), and high obstacle (H-OB). The height was set as the vertical distance from the lowest point to the highest point of the instructed walking area of the treadmill (Figure 2). The obstacle heights corresponding to treadmill inclinations in different conditions are shown in Table 1. Five trials were completed for each condition (20 trials in total). The sequence of 20 trials was randomized for each participant. All participants were instructed to step over the highest obstacle two-three times to determine the preferred leading leg before the data collection.

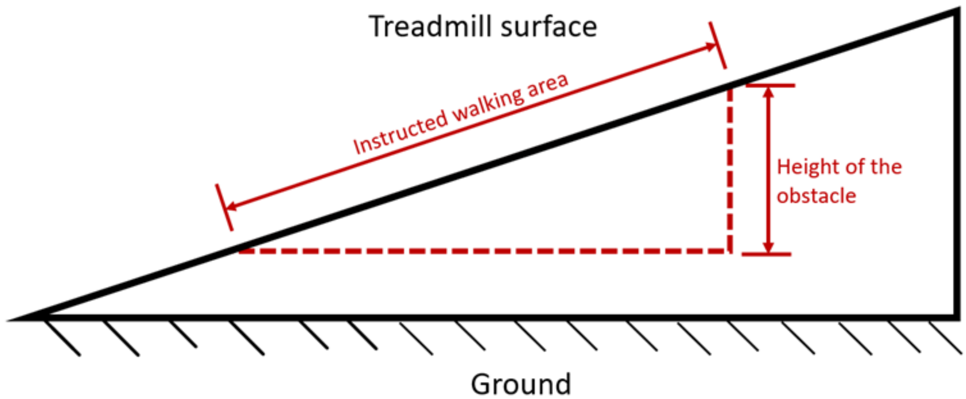

Figure 2. Illustration of the obstacle height with respect to the grade of the inclined treadmill.

Table 1. Inclinations of the treadmill surface and the corresponding heights of obstacle in different conditions

Treadmill conditions	Treadmill inclination (grade)	Obstacle conditions	Obstacle height (cm)
Level treadmill (LV-TM)	0%	No obstacle (NO-OB)	--
Low inclination treadmill (L-TM)	5%	Low obstacle (L-OB)	3.9
Middle inclination treadmill (M-TM)	10%	Middle obstacle (M-OB)	7.8
High inclination treadmill (H-TM)	15%	High obstacle (H-OB)	11.5

2.3 Data Collection

Three-dimensional kinematical data were captured at 100 Hz by an eight-camera Qualisys motion capture system (Qualisys AB, Gothenburg, Sweden) using Qualisys Tracker Manager software. Eleven retro-reflective markers were placed on each participant: five on each leg (greater trochanter of femur, lateral epicondyle of the femur, lateral malleolus, second metatarsophalangeal joint, and heel), and one on the sacrum.

Muscle activity data were captured at 2000 Hz by wireless surface EMG sensors (Trigno, Delsys Inc., Boston, MA). The surface EMG sensors were placed on lateral gastrocnemius, tibialis anterior, rectus femoris, and biceps femoris of both legs.

3. Data Processing

During inclined treadmill walking, the motor control system has information of the inclination from visual input for every step. However, during obstacle negotiation, the motor control system has information of the obstacle height from visual input for the leading leg step but not for the trailing leg step. Therefore, we only compared and contrasted the steps during inclined treadmill walking with the leading leg step during obstacle negotiation. In order to avoid potential discrepancy between right and left legs, only the same leg of the leading leg during the inclined treadmill was analyzed. Namely, if the right leg was the leading leg during obstacle negotiation trials, only the right leg data during the inclined treadmill walking trial would be analyzed.

The kinematic and EMG data were calculated using customized MATLAB (MathWorks, Inc., Natick, MA). The step length was defined as the distance between the heel contract of one foot and the heel contact of the other foot. The step time was defined as the duration between the heel contract of one foot and the heel contact of the other foot. The step speed was calculated by dividing step length by step time. Maximal heel elevation was defined as the maximal vertical displacement of the heel trajectory. Maximal heel elevation was then normalized by leg length. All EMG data were first full-wave rectified and filtered at 10 – 500 Hz using a 6th order Butterworth bandpass. The integrated EMG was then calculated for each muscle during the swing phase. Muscle co-activation index was calculated using the equation: $muscle\ co-activation\ index = \frac{2\times(IntEMG_{Rectus\ Femoris}+IntEMG_{Tibialis\ Anterior})}{IntEMG_{Rectus\ Femoris}+IntEMG_{Tibialis\ Anterior}+IntEMG_{Biceps\ Femoris}+IntEMG_{Gastrocnemius}}$, where IntEMG stands for integrated EMG.[37] During EMG data analysis, two participants were found missing EMG data from one muscle. Therefore, muscle co-activation index could not be calculated for these two participants. Muscle co-activation index of 16 participants was analyzed in the following statistical analysis.

4. Statistical Analysis

The normality of each parameter in each condition was examined before further statistical analysis. The values for skewness and kurtosis between -2 and +2 are considered as normal univariate distribution.[38] One-way repeated measure analysis of variance was used to analyze the effect of obstacle height or treadmill inclination on the maximum heel elevation, muscle co-activation index, and step speed. Greenhouse-Geisser correction was used if a violation of the assumption of sphericity presented. Bonferroni's correction was used for post-hoc pairwise comparison. The significant level was set at 0.05. Pearson's correlation and linear regression were used to analyze the relationship between obstacle negotiation and inclined treadmill walking in terms of maximum heel elevation, muscle co-activation index, and step speed. The relationship was analyzed in four pairs: LV-TM and NO-OB, L-TM and L-OB, M-TM and M-OB, and H-TM and H-OB. The strength of the relationship was determined by the absolute values of r (Table 2).[39] The standard deviation of the residuals was used to determine the spread of the data points around the regression line. The residual is the vertical distance of the data point from the fit line. The equation of standard deviation of the residuals is $Standard\ deviation\ of\ residuals = \sqrt{\frac{\sum(residual)^2}{n-1}}$, where n is the number of data points. All statistical analyses were performed using IBM SPSS version 22 statistical software (IBM Corp., Armonk, NY). Data were plotted using GraphPad Prism 7 (GraphPad Software Inc., San Diego, CA).

Table 2. The absolute values of r and strength of the correlation

Absolute values of r	Strength of the correlation
0 - 0.2	Very weak
0.2 - 0.4	Weak
0.4 - 0.6	Moderate
0.6 – 0.8	Strong
0.8 – 1.0	Very strong

CHAPTER 3: RESULTS

1. Characteristics of Participants

A total number of 18 participants (7 males, 11 females) participated in this study. Table 3 described the characteristics of participants.

Table 3. Characteristics of participants

Characteristics of participants	
Gender	7 Males, 11 Females
Age, yrs., mean (SD)	24.27 (2.67)
Height, cm, mean (SD)	172.44 (10.85)
Weight, kg, mean (SD)	70.51 (14.25)
Crossing leg	5 Left, 13 Right
Crossing leg length, cm, mean (SD)	82.41 (5.93)
Preferred walking speed, m/s, mean (SD)	2.23 (0.48)

2. Maximum Heel Elevation during Obstacle Negotiation and Inclined Treadmill Walking

There were significant height effects on maximum heel elevation during obstacle negotiation ($F_{1.23,\ 20.86} = 93.82$, $P<0.01$). The maximum heel elevation increased as the obstacle height increased. Post hoc analysis showed a significant difference between every pairwise comparison (Figure 3).

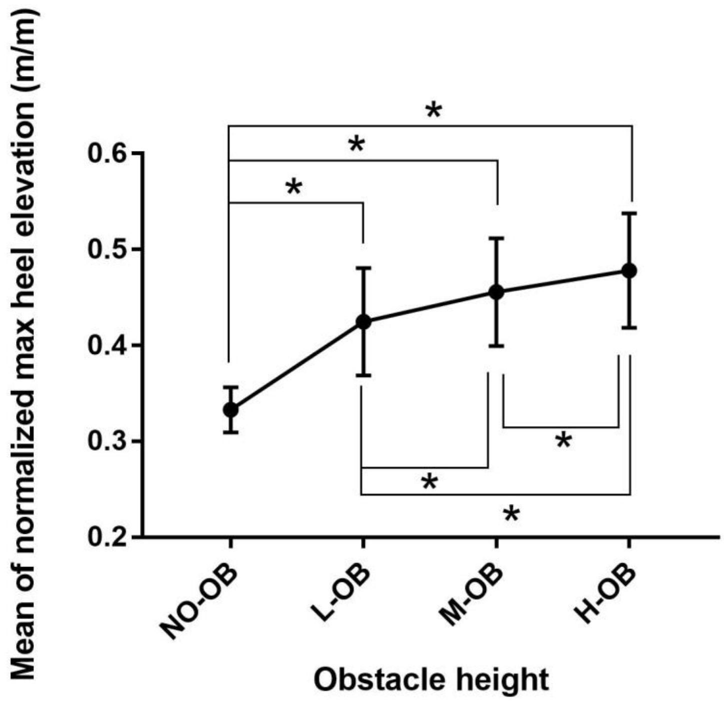

Figure 3. The effects of obstacle heights on normalized maximum heel elevation. *: significant difference based on post hoc analysis.

Significant inclination effect on maximum heel elevation during inclined treadmill walking was also noted ($F_{1.62,\ 27.59} = 41.92$, $P<0.01$). The maximum heel elevation increased as the inclination increased. Post hoc analysis showed that all pairwise comparisons were significant except for M-TM vs. H-TM (P = 0.54) (Figure 4).

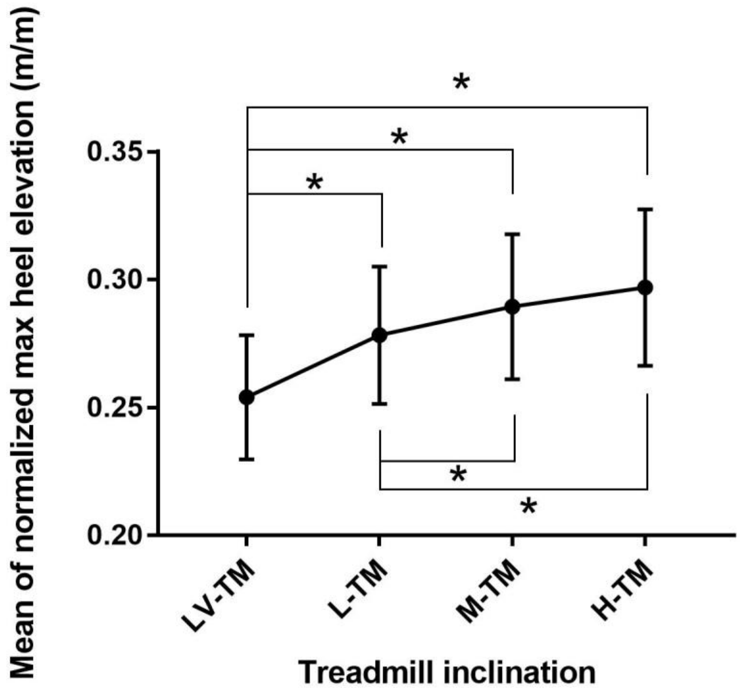

Figure 4. The effects of treadmill inclinations on normalized maximum heel elevation. *: significant difference based on post hoc analysis.

On average, maximum heel elevation during inclined treadmill walking trials was 33.83% lower than that during obstacle negotiation.

3. Correlations of Maximum Heel Elevation between Obstacle Negotiation and Inclined Treadmill Walking

Weak to very strong correlations of maximum heel elevation between obstacle negotiation and inclined treadmill walking were observed in different conditions (Figure 5 and Table 4).

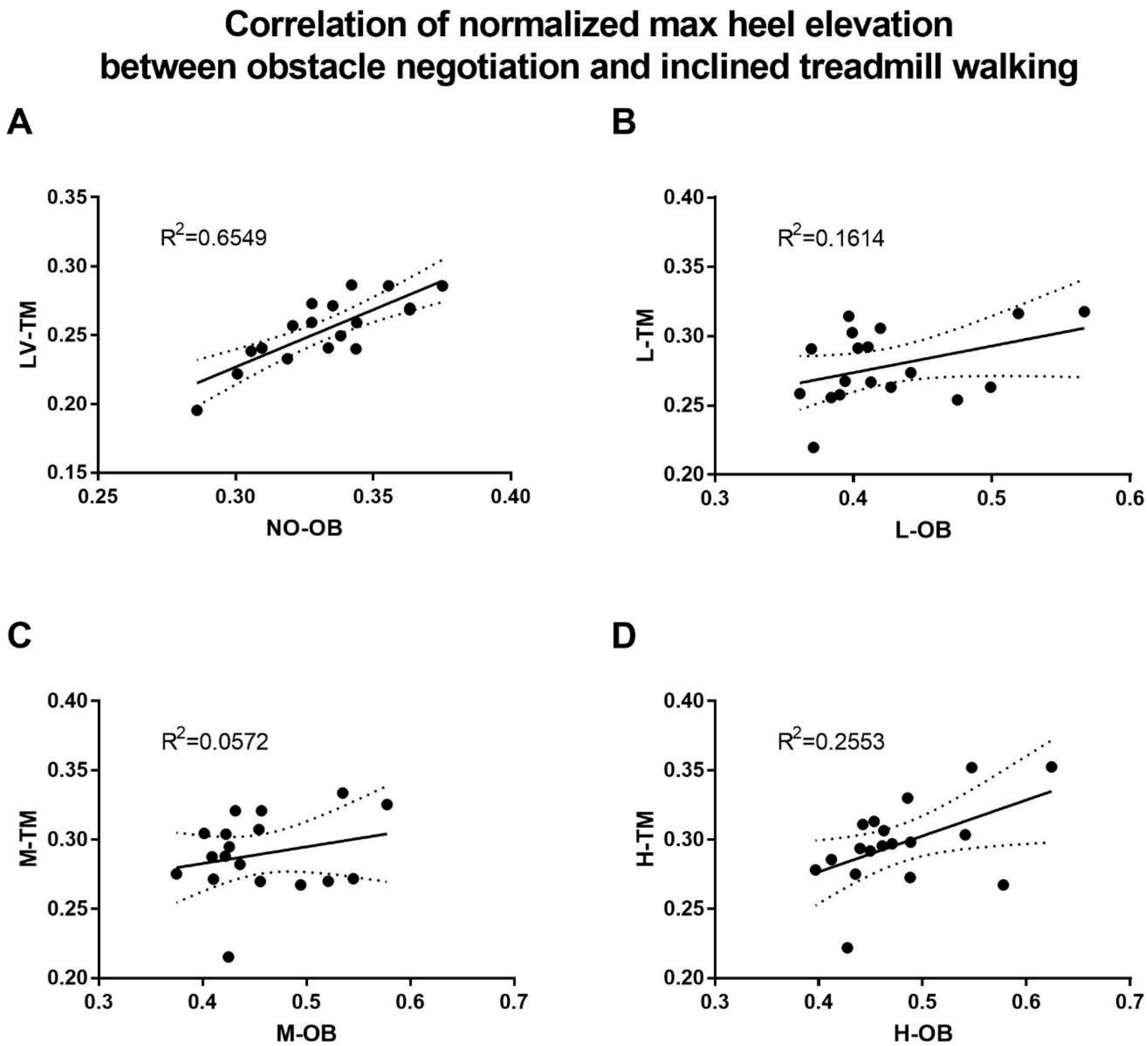

Figure 5. The correlations of normalized maximum heel elevation between obstacle negotiation and inclined treadmill walking in different conditions: NO-OB & LV-TM (A), L-OB & L-TM (B), M-OB & M-TM (C), H-OB & H-TM (D). X-axis and Y-axis: normalized maximum heel elevation (m/m). Solid line: regression line. Dotted line: 95% confidence interval of the regression line. R^2 of each regression line was illustrated in each sub-figure.

Table 4. The absolute r values, P values, the strength of correlation, and standard deviation of the residuals of maximum heel elevation between obstacle negotiation and inclined treadmill walking in different conditions.

Conditions	Absolute r values	P values	Strength of correlation	Standard deviation of the residuals
NO-OB & LV-TM	0.81	<0.01	Very strong	0.0147
L-OB & L-TM	0.40	0.10	moderate	0.0253
M-OB & M-TM	0.24	0.34	weak	0.0283
H-OB & H-TM	0.51	<0.05	moderate	0.0272

4. Muscle Co-activation Index during Obstacle Negotiation and Inclined Treadmill Walking

There were no effects of obstacle heights ($F_{1.65, 24.73}$ = 0.89, P=0.40) or treadmill inclination ($F_{3, 45}$ =0.12, P=0.95) on the muscle co-activation index (Figure 6 and 7). Overall, the muscle co-activation index during treadmill walking trials was 9.40% lower than that during overground obstacle trials.

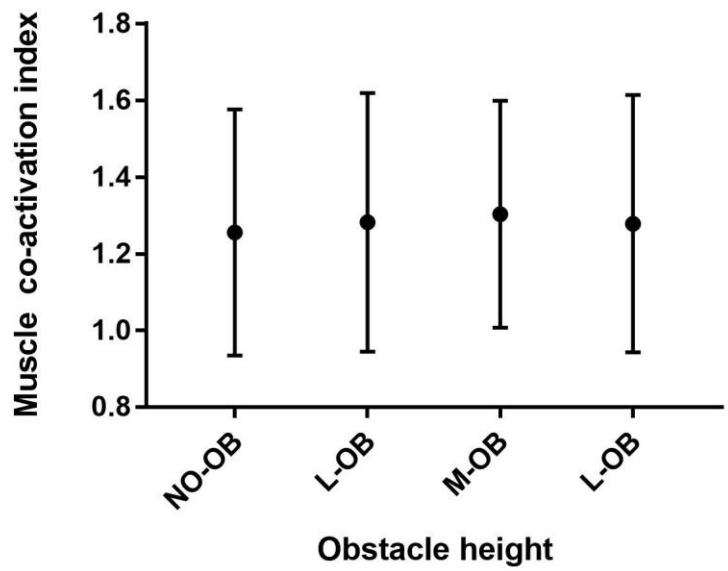

Figure 6. The effects of obstacle heights on muscle co-activation index.

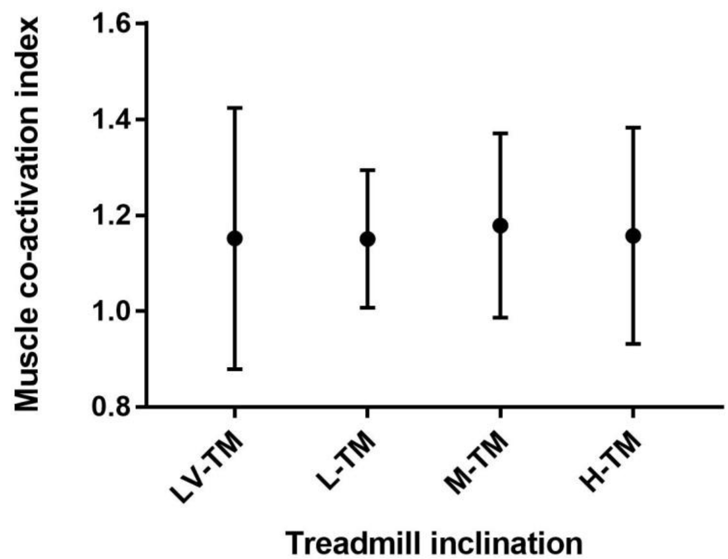

Figure 7. The effects of treadmill inclinations on muscle co-activation index.

5. Correlations of Muscle Co-Activation Index between Obstacle Negotiation and Inclined Treadmill Walking

There were strong to very strong correlations of muscle co-activation index between obstacle negotiation and inclined treadmill walking. (Figure 8 and Table 5)

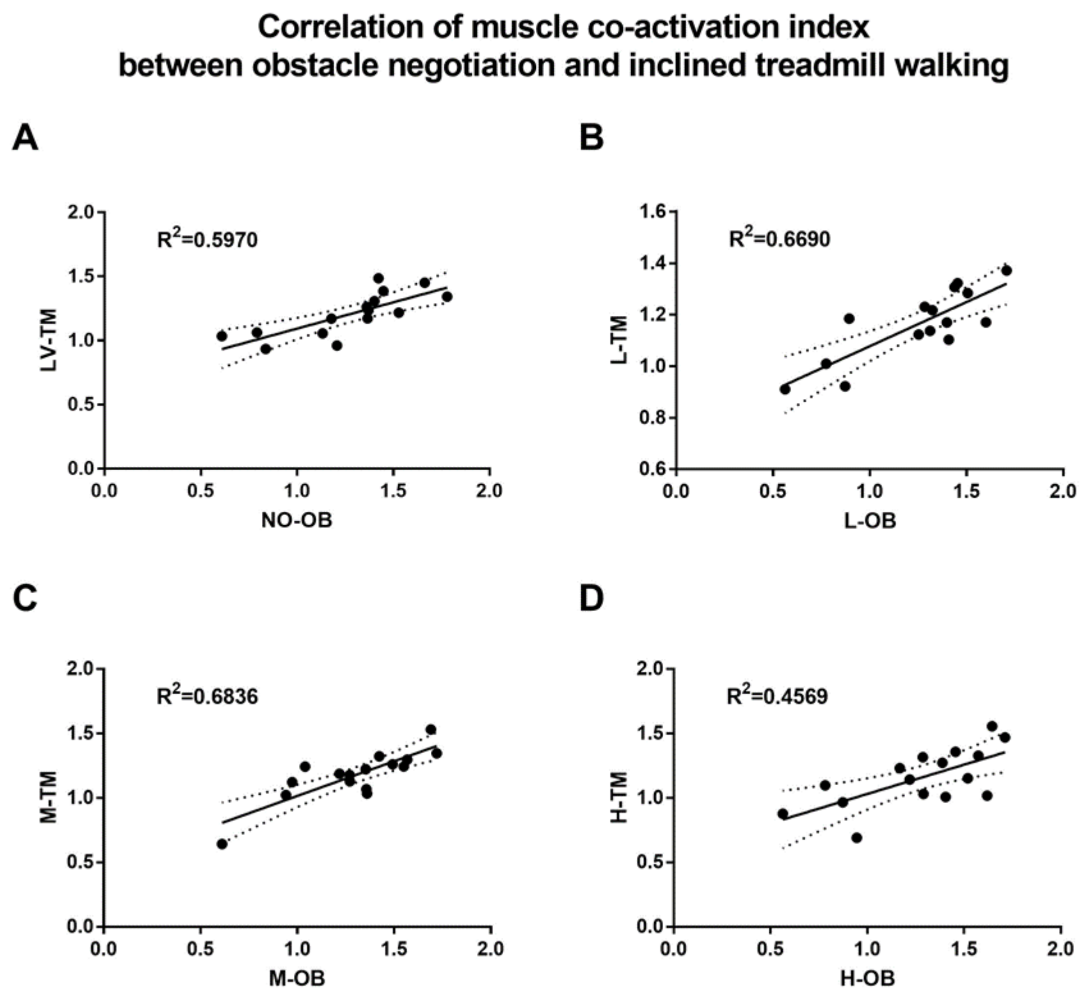

Figure 8. The correlations of muscle co-activation index between obstacle negotiation and inclined treadmill walking in different conditions: **NO-OB & LV-TM (A), L-OB & L-TM (B), M-OB**

& M-TM (C), H-OB & H-TM (D). X-axis and Y-axis: muscle co-activation index. Solid line: regression line. Dotted line: 95% confidence interval of the regression line. R^2 of each regression line was illustrated in each sub-figure.

Table 5. The absolute r values, P values, the strength of correlation, and standard deviation of the residuals of muscle co-activation index between obstacle negotiation and inclined treadmill walking in different conditions.

Conditions	Absolute r values	P values	Strength of correlation	Standard deviation of the residuals
NO-OB & LV-TM	0.77	<0.01	Strong	0.1131
L-OB & L-TM	0.82	<0.01	Very strong	0.0819
M-OB & M-TM	0.83	<0.01	Very strong	0.1119
H-OB & H-TM	0.68	<0.01	Strong	0.1721

6. Crossing Step Speed during Obstacle Negotiation and Inclined Treadmill Walking

Obstacle heights had significant effects on the crossing step speed ($F_{1.37,\ 23.36}$ =6.56, P<0.05). No significant pairwise comparisons were found in the post hoc analysis (Figure 9).

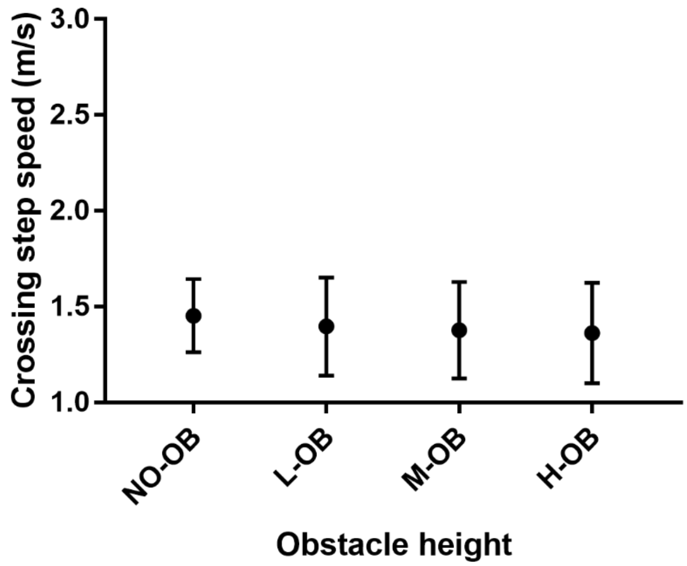

Figure 9. Crossing step speed during obstacle negotiation

There were significant treadmill inclination effects on the step speed during treadmill walking ($F_{3, 51}$ =3.65, P<0.05). Post hoc analysis showed no significant pairwise comparison (Figure 10).

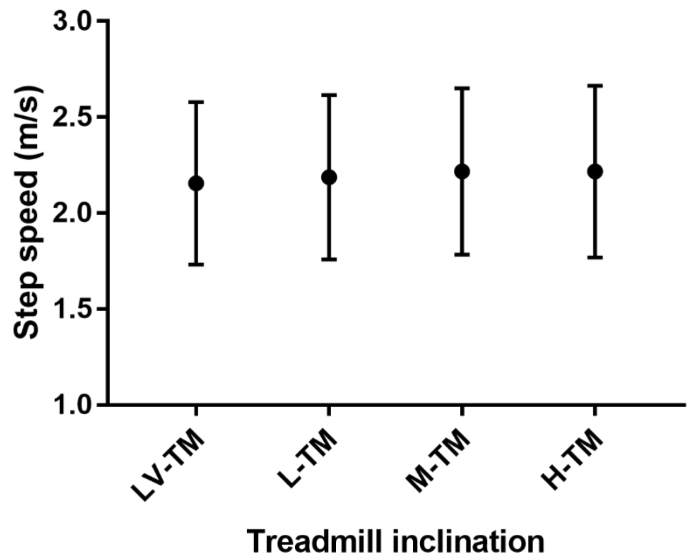

Figure 10. Step speed during inclined treadmill walking.

Overall, the step speed during inclined treadmill walking was 57.03% faster than crossing step speed during obstacle negotiation.

7. Correlations of Step Speed between Obstacle Negotiation and Inclined Treadmill Walking

There were moderate correlations of step speed between obstacle negotiation and inclined treadmill walking (Figure 11 and Table 6).

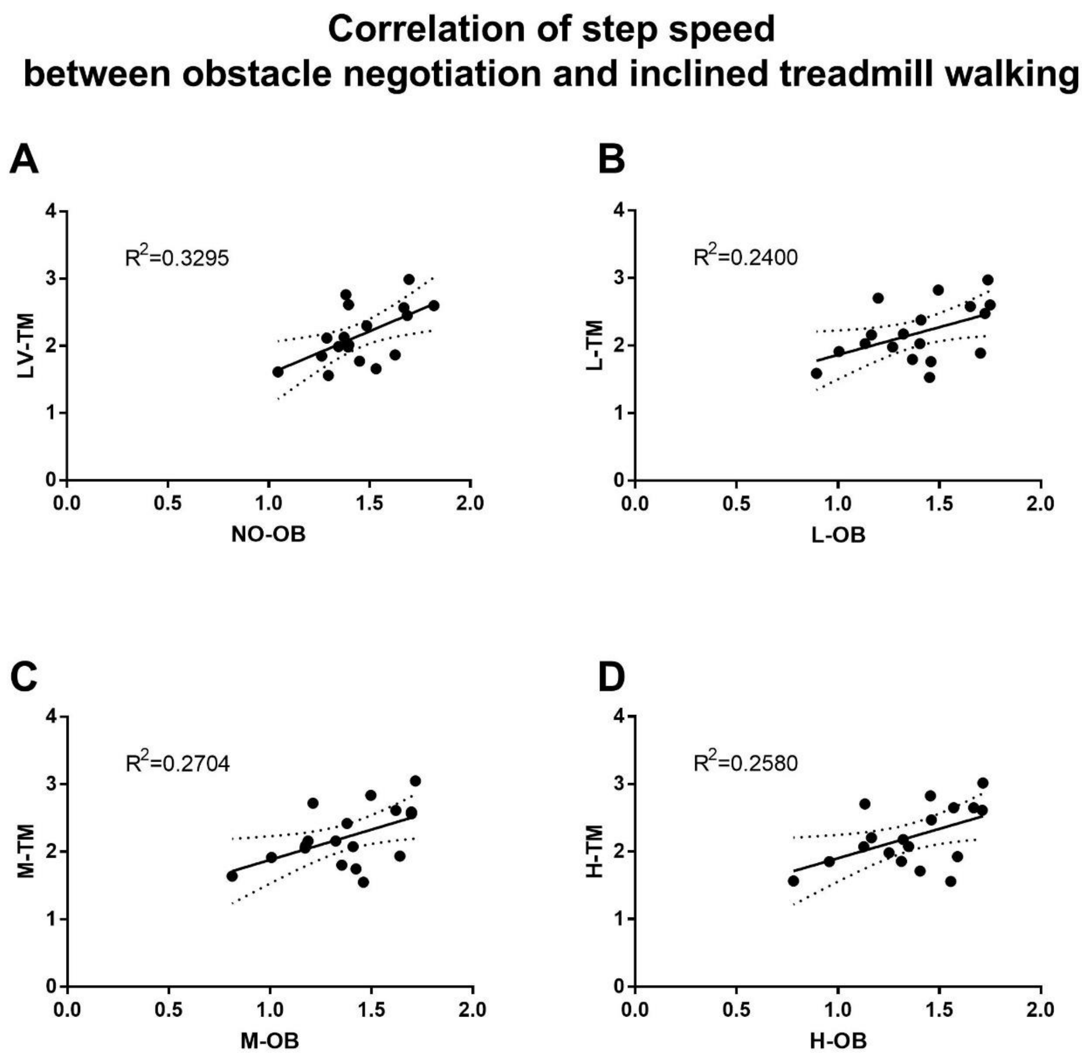

Figure 11. The correlations of step speed between obstacle negotiation and inclined treadmill walking in different conditions: NO-OB & LV-TM (A), L-OB & L-TM (B), M-OB & M-TM (C), H-OB & H-TM (D). X-axis and Y-axis: step speed (m/s). Solid line: regression line. Dotted line: 95% confidence interval of the regression line. R^2 of each regression line was illustrated in each sub-figure.

Table 6. The absolute r values, P values, the strength of correlation, and standard deviation of the residuals of step speed between obstacle negotiation and inclined treadmill walking in different conditions.

Conditions	Absolute r values	P values	Strength of correlation	Standard deviation of the residuals
NO-OB & LV-TM	0.57	<0.05	moderate	0.3575
L-OB & L-TM	0.49	<0.05	moderate	0.3851
M-OB & M-TM	0.52	<0.05	moderate	0.3817
H-OB & H-TM	0.51	<0.05	moderate	0.3972

CHAPTER 4: DISCUSSION

In this study, we explored the similarities between slope walking and obstacle negotiation in kinematics and muscle activities. There were two hypotheses in this study. The first hypothesis was supported by our results that there were similarities between slope walking and obstacle negotiation in kinematics (maximum heel elevation) and muscle activities (muscle co-activation index). However, the second hypothesis was rejected. The higher treadmill inclination and larger obstacle height did not increase the level of similarities between these two motions. In our results, the level of similarity of maximum heel elevation decreased as obstacle height/treadmill inclination increased from 3.9cm/5% to 7.8cm/10%. When the obstacle height/treadmill inclination increased from 7.8cm/10% to 11.5cm/15%, the level of similarity of maximum heel elevation increased. The changes in obstacle height and treadmill inclination did not impact the level of similarity of muscle co-activation index.

1. Similarities between Obstacle Negotiation and Inclined Treadmill Walking on Maximum Heel Elevation and Muscle Co-activation Index

Our results showed that maximum heel elevation of the leading leg increased as the obstacle height increased (Figure 3). The effects of obstacle heights on maximum heel elevation have not been directly reported in previous literature. However, similar results were indirectly reported by presenting moving trajectories of the heel in the sagittal plane during obstacle negotiation with different obstacle heights.[14]

A similar trend was observed during inclined treadmill walking that inclination increased the maximum heel elevation (Figure 4), which has not been previously reported. Minimal toe clearance is the only foot trajectory parameter during inclined treadmill walking that has been reported in the literature where it remained the same between 3° (5.24%) inclined and level treadmill walking.[20] It is speculated that higher maximum heel elevation is needed to maintain minimal toe clearance and avoid tripping during inclined treadmill walking.

A very strong correlation (r = 0.81) of maximal heel elevation was shown between non-obstacle overground walking and level treadmill walking. In these two conditions, level overground walking and level treadmill walking were investigated. An r value of 0.81 indicated level overground walking and level treadmill walking are highly similar but not the same. Similar conclusion has been found in previous studies where no significant differences between level overground walking and level treadmill walking were found in all kinematic parameters except stride time, stride length, and knee range of motion.[40,41]

Weak to moderate correlations (r = 0.24 – 0.51) of maximum heel elevation between obstacle negotiation and inclined treadmill walking were observed in three different pairs of conditions (Figure 5 and Table 4), indicating some similarities of the kinematic properties (i.e., maximum heel elevation) were shared by obstacle negotiation and inclined treadmill walking. Both obstacle heights and treadmill inclination affected the level of similarity in maximal heel elevation. The correlations were moderate between L-OB and L-TM (r = 0.40) and between H-OB and H-TM (r = 0.51), while the correlation was weak between M-OB and M-TM (r = 0.24).

Dynamic system theory proposes that the motor control system goes through an unstable transition phase from one stable attractor to another stable attractor.[42,43] The walk to run transition is a classic example of dynamic system theory. Around the transition speed, the stride duration variability increased.[44,45] The decreased gait pattern stability triggered the transition from walk to run.[44,45] Based on the standard deviation of residuals and observation of Figure 5, a higher deviation of the data points from the fit regression line was shown in the pair of M-OB and M-TM compared with the other two pairs. Therefore, it is speculated that the motor control strategy of heel elevation moved from one stable state (L-OB & L-TM) to an unstable state (M-OB & M-TM) and finally to another stable state (H-OB & H-TM) as the control parameters (height and inclination) increased.

Muscle co-activation index is an indicator of muscle synergy.[46] Muscle co-activation index during inclined treadmill walking was not affected by inclination angle (Figure 7), indicating the inclination had no effect on the synergy of lower limb superficial muscles. Saito et al.[33] compared the muscle synergies involving the deeper muscles of the lower limb and found the muscle synergies were similar between level and 10% inclined treadmill walking. The trend of muscle co-activation index during obstacle negotiation with different obstacle heights was similar to that during inclined treadmill walking with different inclinations (Figure 6 and 7). In addition, strong to very strong correlations (r = 0.68 – 0.83) were found in four pairs of conditions (Figure 8 and Table 5), indicating there is a certain level of similarity in muscle activation strategy between these two motions.

Obstacle heights and treadmill inclinations had different effects on the correlation of maximum heel elevation compared to muscle-co-activation. The strength of correlation of maximum heel elevation changed as the heights and inclinations changed, while the strength of correlation of muscle co-activation index remained constant in different heights and inclinations. Crenna and Frigo proposed a theory that the motor control of movements has two levels of modulation.[5] The first level is global control, which increases or decreases two parameters in parallel.[5] The second level is uncoupling, which results in qualitatively different effects on two parameters, i.e., one parameter increases while the other parameter decreases or remains constant.[5] The uncoupling modulation could explain the different trends of correlation strengths in maximum heel elevation and muscle co-activation index.

Considering the strengths of correlation of both maximum heel elevation and muscle co-activation index in the various conditions, the higher level of similarity presented in pairs of L-OB & L-TM and H-OB & H-TM compared to M-OB & M-TM.

2. Differences between Obstacle Negotiation and Inclined Treadmill Walking on Maximum Heel Elevation and Muscle Co-activation Index

Differences between obstacle negotiation and inclined treadmill walking on maximum heel elevation and muscle co-activation index were also revealed. This is expected because obstacle negotiation and inclined treadmill walking are two distinct motions. Besides, there are three factors also contributing to the differences in this study. First, the different environments (overground and treadmill) have different impacts on gait. Level treadmill walking and level overground walking have been shown to have differences in kinematics and muscle activities.[41] Such phenomenon was also found in our results. The amount of heel elevation and muscle co-activation index during non-obstacle level overground walking (NO-OB) was higher than during level treadmill walking (LV-TM). Compared to level treadmill walking, larger knee angular displacement was shown during level overground walking,[41] which might contribute to higher maximum heel elevation during level overground walking. In addition, level overground walking had higher activation of tibialis anterior and lower activation of gastrocnemius, hamstring, and rectus femoris during swing phase,[41] which might result in a higher muscle co-activation index that calculated by the equation of

$$\frac{2\times(IntEMG_{Rectus\ Femoris}+IntEMG_{Tibialis\ Anterior})}{IntEMG_{Rectus\ Femoris}+IntEMG_{Tibialis\ Anterior}+IntEMG_{Biceps\ Femoris}+IntEMG_{Gastrocnemius}}$$ [37].

Second, the height of obstacle was set as the vertical difference between the highest point and the lowest point of the instructed walking area on the treadmill (Figure 2). Therefore, the participants needed to lift feet higher during obstacle negotiation trials than the inclined treadmill walking trial to clear their foot and avoid tripping. Maximum heel elevation during obstacle negotiation was higher than that during inclined treadmill walking. During the swing phase, the anterior lower limb muscles contribute to foot elevation by flexing hip and dorsiflexing ankle.[36] Compared to inclined treadmill walking, higher foot clearance was needed during obstacle negotiation, resulting in the higher activation of rectus femoris and tibialis anterior and higher muscle co-activation index.

Third, the participants were instructed to walk at their PWS during overground and treadmill trials in this study, which indicated overground walking speed did not necessarily set to match the treadmill walking speed. The results showed that the step speed during treadmill trials was 57% higher than overground trials, which could contribute to the differences between obstacle negotiation and inclined treadmill walking on maximum heel elevation and muscle co-activation index.

3. Limitations and Future Studies

There were several limitations in this study. First, the setup of corresponding obstacle heights to different treadmill inclinations contributed to the higher maximum heel elevation during obstacle negotiation than inclined treadmill walking. However, because obstacle negotiation and inclined treadmill walking are two distinct motions, it is unrealistic to find a perfect match of the obstacle height and treadmill inclination that could result in the same amount of heel elevation in these two motions. Second, the overground walking speed and treadmill walking speed were not matched, which could have confounding effects on the similarities and differences between obstacle negotiation and inclined treadmill walking in the kinematics and muscle activity. However, the overground trials and treadmill trials were performed at PWS, at which the gait has the highest stability.[47] Higher gait variability presents when gait speed is either higher or lower than PWS.[47] Our results showed that PWS during overground trials was different from PWS during treadmill trials. If the overground walking speed was set to match the PWS during treadmill walking, higher gait variability during overground trials could be expected. In such circumstance, increased gait variability might confound the results. Therefore, using matched speed in overground trials and treadmill trials might not be a better experiment design than the one used in this study. Third, the muscle co-activation index was not sensitive enough to detect the changes in muscle activities across different conditions. Muscle co-activation index represents the combined effect of several muscles in a limb,[36] which provides a gross view of multiple muscle activities without examining the changes in each individual muscle activity. Further study of the similarities and differences in individual muscle activity between inclined treadmill walking and obstacle negotiation is needed. Finally, the study population was healthy young adults, limiting the generalizability of the results to other populations such as older adults and individuals with pathologies. Future studies on these populations are warranted.

4. Clinical Implications of the Study

Improving obstacle negotiation performance through training could be an effective fall prevention approach because those who have poor obstacle negotiation performance are at high fall risk.[7,8] According to the principle of task-specificity of neuroplasticity,[48] practicing obstacle negotiation would be the best way to improve its performance. Individuals with post-stroke hemiplegia achieved a 10% improvement in obstacle clearance after completing six sessions of overground obstacle crossing training.[49] However, improving the performance of one motion by repetitively practicing the same motion may not be feasible due to safety concerns and lack of equipment and space. In such circumstances, developing an alternative training protocol consisted of another motion is needed.

Treadmill walking training can improve gait in individuals with neurological pathologies.[50,51] Adding treadmill inclination to the training protocol enhanced the effects of the partial body weight-support treadmill gait training in individuals with hemiparesis.[52] In our study, we found similarities in kinematics and muscle activities between obstacle negotiation and inclined treadmill walking. As the learning effect could be transferred between similar motor tasks,[6,53] it is speculated that inclined treadmill walking could improve the performance of obstacle negotiation. Compared with overgound obstacle training, inclined treadmill training can achieve a larger volume of repetitions in a short period of time. In addition, inclined treadmill training only requires a small area and could use an overhead body weight-support system to keep patients safe during training.

It is known that the more similar the two motions are, the greater the transfer of learning will be yielded.[6] We found a high level of similarity presented between 3.9 cm height obstacle negotiation and 5% inclined treadmill walking and between 11.5 cm height obstacle negotiation and 15% inclined treadmill walking. We speculated that 5% inclined and 15% inclined treadmill walking could be used to improve the 3.9 cm height and 11.5 cm height obstacle negotiation, respectively. However, such speculation needed to be verified by further studies.

5. Conclusions

With this study, it is confirmed that there are certain similarities between obstacle negotiation and inclined treadmill walking in kinematics and muscle activities. In different conditions of obstacle heights and treadmill inclinations, the level of similarity of maximum heel elevation is different but the level of similarity of muscle co-activation index is similar. Taking both maximum heel elevation and muscle co-activation index into account, the higher level of similarity presents between obstacle negotiation with a 3.9cm-high obstacle and 5% inclined treadmill walking and between obstacle negotiation with an 11.5cm-high obstacle and 15% inclined treadmill walking. Further understanding of the similarities and differences of motor control strategies between obstacle negotiation and inclined treadmill walking may better inform the development of using slope walking as a novel training protocol.

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