JRSR 11 (2024) 25-30

Journal of Rehabilitation Sciences and Research

Journal Home Page: jrsr.sums.ac.ir

Original Article

Comparing Lower Limb Kinematics in Healthy Individuals: Walking on Real Sloped Surfaces vs. Level Walking

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ARTICLE INFO

Article History:
Received: 09/12/2022
Revised: 12/04/2023
Accepted: 31/05/2023

Keywords:
Gait analysis
Walking
Uphill
Downhill
Kinematics
Biomechanics

Please cite this article as: Masoumpour Z, Daryabor A, Rahimi A, Akbarzadeh Baghban AR. Comparing Lower Limb Kinematics in Healthy Individuals: Walking on Real Sloped Surfaces vs. Level Walking. JRSR. 2024;11(1):25-30. doi: 10.30476/JRSR.2023.97453.1338.

ABSTRACT

Background: This study aimed to investigate kinematic parameters of lower limb joints during gait on inclined surfaces compared to level ground.
Methods: In this cross-sectional study, 15 healthy individuals walked at their self-selected speed on level ground with a zero slope and on two inclined surfaces. These surfaces were constructed to mimic real environments with slopes of +8 (uphill) and -8 (downhill) along an eight-meter distance. The measured variables included the angles of the ankle, knee, and hip joints sagittal plane during different phases of gait, captured through a three-dimensional motion capture system.
Results: Significant differences were observed in uphill walking compared to level-ground walking, including an increase in ankle, hip, and knee angles at initial contact, maximum ankle dorsiflexion and plantarflexion, maximum knee flexion in the stance phase, and maximum knee extension in the swing phase. There was also a reduction in the maximum extension of the hip joint ($P<0.05$). In downhill walking compared to level ground, significant differences were observed in the increase of ankle and knee angles at initial contact, maximum ankle dorsiflexion, maximum knee flexion in both stance and swing phases, and a decrease in the maximum angle of hip extension. However, no significant difference was observed in the hip joint angle at initial contact maximum ankle plantarflexion, maximum knee extension in swing phase between level and downhill surfaces and at maximum knee flexion in swing phase between uphill and level surfaces ($P>0.05$).
Conclusion: Walking on inclined surfaces influences the flexion and extension angles of lower limb joints during different phases of gait, necessitating increased joint movement. These alterations are more pronounced during uphill walking than downhill, especially at the initial contact point.

Introduction

Alterations significantly influence the pattern of human motion in the surrounding environment. In practical scenarios, a change as simple as the slope of the surface can affect movement. Walking on inclined surfaces challenges the motor control system and can lead to musculoskeletal disorders under certain conditions. This underscores the importance of investigating and studying the impact of inclined surfaces on human gait.

Alterations in the gait pattern, encompassing muscular electrical activities, kinematics, and kinetics of lower

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limb joints on inclined surfaces, have been previously studied [1-4]. These studies have demonstrated that uphill and downhill gaits impose increased demands on the musculoskeletal and neurological systems [5, 6]. Consequently, the kinematics of the lower limb joints during walking on inclined surfaces are not exempt from changes. Specifically, uphill slopes, compared to downhill, influence gait kinematics more [7]. When walking on inclined surfaces, kinematic changes, such as increased flexion of lower limb joints at initial contact, occur to adjust the posture for repositioning the body against gravitational force [8, 9]. Findings from previous studies have suggested that walking on inclined surfaces imposes more complex biomechanical demands than level-ground walking [10, 11]. The interactions observed on inclined surfaces, compared to level surfaces, indicate that kinematic changes, as part of the strategies of gait control of the lower limb joints, differ when walking on inclined surfaces compared to level or zero-angle surfaces [12]. During uphill walking, a decrease in cadence and an increase in step length [13, 14], ground reaction forces [15], and muscle and joint forces [16] have been reported. The steepness of the slope also impacts the kinematics of the lower limb joint, most notably the knee and hip angles [17, 18].

Various settings can be employed to analyze sloped gait, including walking outdoors in a natural environment or indoors in a laboratory on a fixed surface, such as an inclined treadmill or a static ramp construction. Previous studies have attempted to reconstruct inclined surfaces and examine changes in people's gait patterns on these surfaces using a treadmill. However, the findings of these studies may not be generalizable to real-world environments due to the use of a treadmill. This is because, when using a treadmill, the motion surface is mobile, eliminating the need for the crucial propulsion stage. When walking on a treadmill compared to level-ground walking, individuals adopt cautious walking to maintain their balance and stability. This motion pattern manifests as slower walking with shorter steps, some forward bending, a decreased single-support phase, an increased double-support phase, and complete foot placement (instead of the heel) on the treadmill surface at initial contact [19-24]. However, uphill and downhill walking on a treadmill may be an unfamiliar movement skill with high coordination requirements for individuals. Consequently, the gait pattern might deviate from the habitual sloped gait, decreasing measurement validity [25]. If a real inclined surface is used instead of a treadmill, which requires individuals to generate forward movement actively and increases task validity, these results would be closer and more generalizable to walking on real ground. They could serve as fundamental information for therapists and researchers. Accordingly, in this study, efforts have been made to reconstruct inclined surfaces according to the natural environment in a motion analysis laboratory and investigate the changes in the kinematic parameters of lower limb joints.

Materials and Methods

Participants

In this cross-sectional study, all individuals were first evaluated by a physiotherapist researcher to ensure that they fulfilled the inclusion criteria. This study was performed on 15 healthy students (men: 9, women: 6) in School of Rehabilitation, Shahid Beheshti University of Medical Science, Tehran. The age range of the participants was 20-26 years with a mean of 22.93 years, height range of 160-183 cm with a mean of 174.60 cm, and weight range of 55-86 kg with a mean of 66.83 kg. The individuals had no specific musculoskeletal, neurological, or cardiopulmonary disorders, history of surgery, gait abnormalities, or pain in their lower limbs. They were not under pharmacotherapy, including antispasmodic drugs, different painkillers, or any sedative drug. The sample size of 15 individuals was determined based on a previous study conducted in 2017 [7]. Ethics committee of Shahid Beheshti University of Medical Sciences approved this study with the code of IR.SBMU.RETECH.REC.1399.222. Individuals signed the written consent form to participate in the research.

Procedure

Initially, the individuals were introduced to the biomechanics laboratory of School of Rehabilitation, Shahid Beheshti University of Medical Science, Tehran to familiarize themselves with the environment. Based on the plug-in gait model, Reflective markers were placed on the individuals' landmarks (Figure 1). Kinematic data were collected using a 3D motion capture system (Vicon 360, Oxford Metrics, UK) at a sampling frequency of 100. An inclined surface, 8 m long with an angle of 8°, was constructed using precise engineering methods by experienced biomechanics engineers (Figure 2).

Each participant first walked in the gait laboratory on level ground to conduct the test. They then traversed the uphill slope barefoot at their preferred speed (approximately 4.2 km/h). At the end of the slope was a level surface where they paused before descending the same slope. The surface of this inclined platform was covered with a rug, similar to the laboratory floor, to reduce the effects of friction and environmental errors.

This process was repeated for all walking levels until five successful repetitions were recorded. Heel and thumb markers were used to extract the gait cycle phase. The start of the gait cycle, or initial contact, was detected when the heel marker came into contact with the ground, and the beginning of the swing phase was detected when the thumb marker separated from the ground.

If all or part of the leg was not within the camera's range or the participant exhibited a targeting gait, the trial was deemed unsuccessful, and the corresponding trial was discarded. The mean of the gait parameters from at least three repeated trials was recorded for each walking level.

Data Processing

The trajectories of the reflective markers were filtered by a low-pass Butterworth digital filter with a cut-off frequency of 7 Hz and an order of 4. The link-segment model included nine body segments: the pelvis, forearms, thighs, shanks, and feet. An inverse kinematic model was

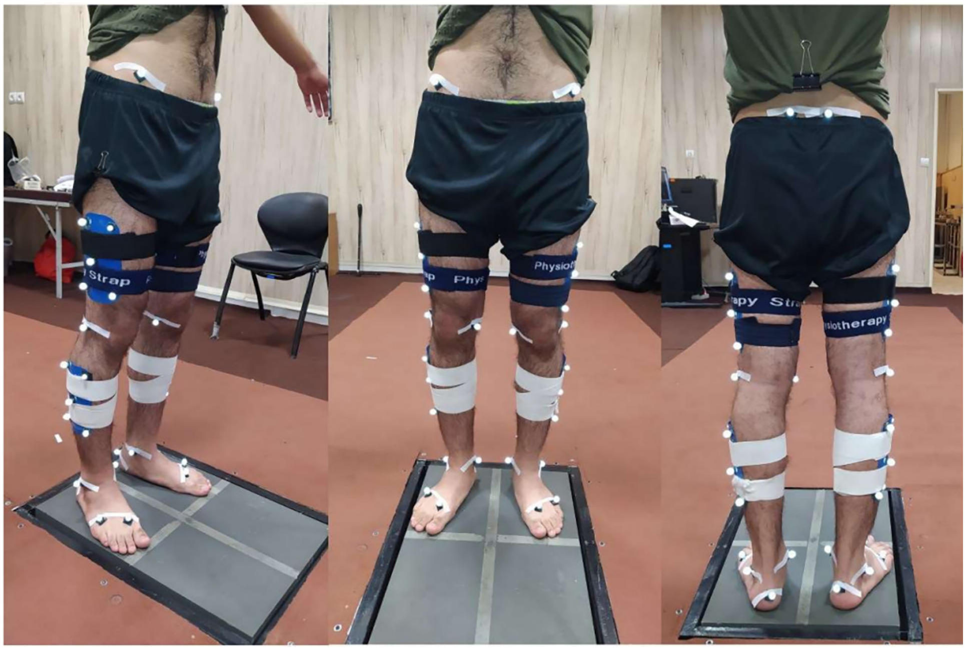

Figure 1: Marker set up based on plug-in gait model

Figure 2: Walkway constructed with the slope of 8°

employed to calculate the joint kinematics and kinetics. Joint angles of the lower limb were calculated using a 6-degree-of-freedom model performed in Visual 3D software. This recorded the kinematic data, including the sagittal joint angles in the ankle, knee, and hip, during different gait cycle phases. The gait parameters were calculated using custom code in MATLAB software (MATLAB R2021a) to examine joint angles in three planes.

Statistical Analysis

A Kolmogorov–Smirnov test was carried out to check the distribution of the data. A One-Way Repeated ANOVA (upslope *level*downslope) was performed to determine whether sloped gait significantly affects the lower-limb joint kinematics of healthy individuals. A Pair-Bonferroni test was conducted to compare the differences between level and sloped gait in the kinematic variables. All analyses were conducted using SPSS Ver. 16.0, with a significance level set at 0.05.

Results

Tables 1 and 2 present the changes in kinematic parameters on inclined surfaces compared to level walking. Significant differences were observed in most parameters of the sagittal kinematics of the ankle, knee, and hip joints when walking on inclined surfaces compared to level-ground walking with a zero angle ($P<0.05$).

For uphill walking, these differences were manifested as increased angles in the ankle, knee, and hip at initial contact, maximum ankle dorsiflexion, and plantarflexion during the stance phase, maximum knee flexion during the stance phase, maximum knee extension during the swing phase, as well as a decreased angle of the maximum hip extension.

For downhill walking, the significant differences were associated with increased angles of the ankle and knee at initial contact, maximum ankle dorsiflexion during the stance phase, maximum knee flexion during both the stance and swing phases, and a decreased angle of maximum hip extension.

However, no statistically significant difference was found in the hip joint angle at initial contact, maximum ankle plantarflexion, maximum knee extension in swing phase between downhill and level surfaces and at maximum knee flexion in swing phase between uphill and level surfaces($P>0.05$).

According to the results, the ankle angle at initial contact was about 2.7 times larger in plantarflexion during downhill walking than in level-ground walking. Ankle dorsiflexion at initial contact increased from 3° plantarflexion during level-ground walking to 5° dorsiflexion during uphill walking, a change of 8°. No significant difference was observed in maximum ankle dorsiflexion between level and downhill walking. However, it increased significantly by about 1.4 times during uphill walking, particularly in plantarflexion, suggesting that most changes occurred in uphill walking.

Table 1: The mean and standard deviation of kinematic parameters of lower limb between walking on level and inclined surfaces (n=15)

Lower limb joints	Variables (degree)	Level ground		Uphill		Downhill	
		Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Ankle	Ankle angle at initial contact	-3.03	3.8	5.15	3.26	-8.79	4.69
	Maximum ankle plantar flexion	-10.41	4.87	-15.61	6.42	-13.74	6.72
	Maximum ankle dorsiflexion	13.58	5.72	18.68	3.33	16.56	3.98
Knee	Knee angle at initial contact	8.43	7.06	20.57	5.32	12.97	4.32
	Maximum knee flexion in swing phase	53.36	3.73	50.9	3.74	57.62	2.77
	Maximum knee extension in swing phase	1.32	8.29	4.14	7.28	2.28	7.16
	Maximum knee flexion in stance phase	17.42	7.82	25.62	6.04	29.34	7.46
Hip	Hip angle at initial contact	18.23	2.81	42.09	3.07	16.91	2.83
	Maximum hip extension in stance phase	-11.78	4.52	-9.27	4.22	-8.28	4.75

Positive numbers above the baseline are angle of knee and hip flexion and ankle dorsiflexion, while negative numbers below the baseline are hyperextension and plantarflexion.

Table 2: Bonferroni paired comparisons of kinematic parameters

Variables (degree)	Surface (I)	Surface (J)	Mean difference (I-J)	SD	Significance level	Confidence interval 0.95 for the difference	
						Lower limit	**Upper limit**
Ankle angle at initial contact	Level ground	Downhill	5.786	1.109	0.000*	2.742	8.830
		Uphill	-7.907	0.660	0.000*	-9.719	-6.096
Maximum ankle plantar flexion	Level ground	Downhill	3.186	1.783	0.292	-1.712	8.083
		Uphill	5.679	0.923	0.000*	3.144	8.213
Maximum ankle dorsiflexion	Level ground	Downhill	-3.471	1.005	0.013*	-6.232	-0.711
		Uphill	-5.171	0.931	0.000*	-7.728	-2.615
Knee angle at initial contact	Level ground	Downhill	-4.907	1.376	0.010*	-8.686	-1.128
		Uphill	-12.243	1.610	0.000*	-16.663	-7.823
Maximum knee flexion in swing phase	Level ground	Downhill	-4.421	0.895	0.001*	-6.880	-1.963
		Uphill	2.079	1.305	0.406	-1.506	5.663
Maximum knee extension in swing phase	Level ground	Downhill	-1.971	0.934	0.164	-4.536	0.593
		Uphill	-2.943	0.851	0.013*	-5.281	-0.605
Maximum knee flexion in stance phase	Level ground	Downhill	-12.700	2.272	0.000*	-18.938	-6.462
		Uphill	-8.379	1.888	0.002*	-13.563	-3.194
Hip angle at initial contact	Level ground	Downhill	1.321	0.903	0.502	-1.158	3.801
		Uphill	-23.800	1.030	0.000*	-26.628	-20.972
Maximum hip extension in stance phase	Level ground	Downhill	-3.500	0.653	0.000*	-5.292	-1.708
		Uphill	-2.264	0.710	0.021*	-4.214	-0.315

*Significant at 0.05

At initial contact, the knee flexion angle increased in uphill (2.5 times) and downhill (1.5 times) walking. The maximum knee flexion during the stance phase increased in uphill and downhill walking compared to level-ground walking, with greater flexion observed in downhill walking.

In downhill walking, a reduction of about 10% was observed in hip flexion at initial contact. In contrast, hip flexion significantly increased in uphill walking. In the rest of the stance phase at both levels, the hip was slightly less extended than on level ground and never went into hyperextension (Tables 1 and 2).

Discussion

The most significant finding of this study was that the kinematic parameters of the lower limb joints on inclined surfaces differ considerably from those on level ground. Generally, the results indicated that during uphill walking, compared to level-ground walking, all three lower limb joints were more flexed at initial contact. These postural changes could be attributed to the suitable positioning of the ankle on the uphill surface, which helps prevent toe drag and positions the plantarflexion muscles optimally for propelling the body upwards [26].

In contrast, further hip flexion was unnecessary during downhill walking due to increased knee flexion and ankle plantarflexion, and a 10% reduction in hip flexion was even observed. Essentially, all joints are positioned to facilitate gait progression

The Effects of Slope Surfaces on Ankle Kinematics

The structure and function of the foot-ankle complex significantly impact the upper parts of the lower limbs when absorbing force and exerting pressure. They are the first components to reduce ground reaction force and transfer it to the proximal joint of the ankle when the feet hit the ground [26]. Therefore, investigating this part of the lower limb is of particular interest.

According to the results of this study, the ankle angle at initial contact became more plantarflexed during downhill walking compared to level-ground walking, which is logical given the downhill nature of the surface. Tulchin et al. suggested that the foot mechanism can change considerably during walking on inclined surfaces among healthy adults, with reduced plantarflexion at initial contact in slopes of 9% and 12% and increased plantarflexion in a slope of -7.5°. These changes prevent toe drag and position the plantar flexor muscles suitably for propelling the body upwards [26].

No significant difference was found between level-ground and downhill walking at maximum ankle plantarflexion, but it increased about 1.4 times in uphill walking. According to Tulchin et al.'s study, which used a treadmill as a walkway, there was a decrease in the peak plantarflexion angle during the third rocker of gait with the downhill condition. However, we found a non-significant increase in this angle with the downhill slope. These differences could be due to using barefoot ambulation on a treadmill. The data suggest that most changes occurred in uphill walking, aiding the propulsion to overcome gravitational force. Thus, the findings showed that the surface slope, particularly uphill, could affect most gait parameters [7, 27].

The Effects of Slope Surfaces on the Knee Kinematics

Investigating the kinematic characteristics of the knee joint during sloped walking is crucial for rehabilitating patients with knee diseases and understanding the biomechanical properties of this joint. Based on the results, the knee flexion angle significantly increased during uphill and downhill walking at initial contact. Strutzenberger et al. reported increased knee flexion angle during the stance phase of uphill walking. They also suggested that uphill walking could aid in rehabilitating patients suffering from knee osteoarthritis [24].

According to previous studies, the increase in the flexion angle at initial contact during downhill walking can be attributed to using the quadriceps muscle in an eccentric contraction and, during uphill walking, to using this muscle in a concentric contraction [28]. The increase in the knee flexion angle during both uphill and downhill slopes suggests that individuals with knee problems, such as knee arthritis, may experience more pain in their knee, especially in the patellofemoral joint. Therefore, level-ground walking is the preferred choice for these individuals. Moreover, as the knee bends more during downhill walking, its instability increases [24, 29].

The findings also demonstrated that the maximum knee flexion during the stance phase increased in uphill and downhill walking compared to level-ground walking, with greater flexion observed during downhill walking. These results align with previous studies [24, 30]. However, Yu Zhang et al. reported that during 1-12% of the gait cycle, individuals exhibited a smaller flexion angle during downhill walking than level walking [9]. This finding contrasts with the study by Strutzenberger et al. [24] and our results. These differences may be attributed to using a treadmill as the walking pathway [9].

The Effects of Slope Surfaces on the Hip Kinematics

According to the results, there was no need for further hip flexion due to knee hyperflexion and ankle plantarflexion at initial contact during downhill walking. A reduction of about 10% in hip flexion was observed in downhill walking. In contrast, uphill walking saw a significant increase in hip flexion, which could be attributed to the suitable positioning of the ankle on the surface and the prevention of toe drag.

Throughout the rest of the stance phase, the hip was slightly less extended on both surfaces compared to level-ground walking and did not go into hyperextension [7]. Lay et al. reported that the angles of the hip joint during level and upslope walking differed only in amplitude (initial contact, maximum hip extension) [30]. In their study, the hip flexion angle decreased during downhill walking compared to level walking in the early stance and late swing phases. However, it increased in the midstance, which agrees with our findings.

Considering the kinematic changes of the hip joint, it is not recommended for older adults to move on inclined surfaces. These individuals often face balance issues, leading to a reduction in hip joint mobility and a reliance on hip joint muscles compared to ankle extensor muscles. This could result in a higher likelihood of falls [28, 31].

This study had several limitations. It only included healthy young adults, excluding those with musculoskeletal problems. This restricts the generalizability of the results. Additionally, the narrow width of the inclined surface (one meter) could affect an individual's balance. Furthermore, the length of the inclined surface used in the test (eight meters) was insufficient to determine the effects of fatigue on kinematic parameters

Clinical Implication

Based on our results and previous studies, uphill and downhill gaits present challenging tasks requiring increased neurological and musculoskeletal demands [5]. Therefore, for patients in the early stages of injury or those with issues such as unstable joints, it is advisable to avoid walking on inclined surfaces as part of their treatment plan. It is also recommended to avoid these surfaces in outdoor environments. Consequently, the inclusion of these levels in rehabilitation should be carefully considered.

Conclusion

Walking on inclined surfaces significantly affects the flexion and extension angles of the ankle, knee, and hip joints during different phases of a gait cycle, necessitating greater joint movement. These changes are more pronounced in uphill walking than downhill, especially at initial contact. When designing and interpreting research studies on uphill and downhill gait, these differences must be considered, whether using a treadmill or ramp construction. Understanding these differences is crucial for future studies, data interpretation from existing literature, and clinical applications to ensure safety and awareness about walking on inclined surfaces or during rehabilitation. These observations are particularly significant for aging and disabled populations (e.g., amputees) who face limitations in these areas.

Acknowledgment

The authors would like to thank all the faculty members of the Physiotherapy Department of Shahid Beheshti University of Medical Sciences, Tehran, Iran.

Conflict of Interest: None declared.

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