Gait stability characteristics in able-bodied individuals during self-paced inclined treadmill walking

Chenmiao Lu
The first affiliated hospital of Zhejiang University

Rawan Al-Juaid
Ministry of Health

Mohammad Al-Amri (✉ Al-AmriM@cardiff.ac.uk)
Cardiff University

Article

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**Abstract**

Gait on inclined surfaces requires active neuromuscular control to maintain stability. This study investigated the effects of self-paced incline treadmill walking on gait stability characteristics and the activation of key lower limb muscles. Twenty-seven healthy subjects (mean age: 25.02 ± 2.06 years) walked at their preferred walking speed on an augmented instrumented treadmill for three minutes at three inclination angles (-8°, 0°, and 8°). Changes in gait characteristics (i.e., stability, walking speed, spatial-temporal, kinematic, and muscle forces) across inclination angles were assessed using repeated measures ANOVA and Freidman tests. Results showed that inclined treadmill walking had a significant impact on overall gait characteristics, reflecting changes in gait parameters and muscle activations with respect to the inclination of the treadmill. Stability and walking speed had reduced significantly during uphill walking, suggesting that it was the most challenging walking condition. During uphill walking, there was a significant increase in the peak activation of hamstrings, gastrocnemius, vastus intermedius, and vastus lateralis muscles. In contrast, the peak activation of the antagonist muscle groups including the quadriceps, tibialis anterior, and tibialis posterior muscles significantly increased during downhill walking. Our findings demonstrate that able-bodied individuals adopted walking patterns during inclined treadmill walking to maintain a comfortable and safe walking performance. Future studies should consider inclined treadmill walking as a functional assessment tool or as a rehabilitation intervention to improve gait stability by targeting muscle training.

**Introduction**

Inclined walking is a challenging daily mobility activity that requires complex adaptation to maintain gait stability compared with level walking. Evidence suggests that inclined walking decreases gait stability even in healthy individuals, and thus poses a higher risk of falling than walking on stairs with similar inclinations. Gait stability can be estimated by means of the gait stability ratio (GSR) – a measure that is derived from a ratio of cadence / walking speed. GSR can be determined in gait studies, and it has been proven to be a good indicator of stability. The study by Ferraro et al. reported higher GSR during incline walking compared to level walking, indicating more adaptations were required in an attempt to preserve gait stability. However, the generalisability of Ferraro et al.’s findings is limited to healthy elderly (mean age 77.8 ± 4.8 years) during level and uphill walking conditions only. To date, gait stability characteristics in relation to kinematic parameters and muscular adaptations have not been established in healthy individuals. This warranted further observations to develop a comprehensive understanding of gait stability and associated adaptive strategies.

Other biomechanical literature has shown the impact of inclined walking on gait performance, including changes in postural adaptations, kinetics and kinematics parameters, joint work, and muscle activity. Nevertheless, most literature has been limited by the difficulty of obtaining enough gait measurements due to a small number of continuous strides on instrumented ramps or on fixed-speed treadmills. Furthermore, muscle activity on inclined surfaces has been commonly measured...
by using electromyography (EMG) \(^1,10^{-13}\); despite its reliability, the EMG has some limitations that cannot be ignored. Firstly, the accuracy of the acquired data can be greatly affected by the displacement of the EMG electrodes during inclined walking \(^15\). Secondly, the decision to use EMG requires determining only a number of large superficial muscles from both sides \(^16\), which does not permit the provision of an overall idea about muscular adaptation on inclined walking surfaces. Taken together, there is a need to examine gait stability alongside more meaningful gait parameters including the activity of key muscles during comfortable walking speed.

Fortunately, technological advancements in instrumented treadmills can be advantageous to overcome many limitations in previous literature. These cutting-edge treadmills are laboratory-based, designed with split belts, and equipped with two embedded force plates \(^17\). They differ from conventional treadmills as they automatically adjust the belt speed in real-time to match the participant's self-paced walking \(^18,19\). Meanwhile, they allow the data collection of hundreds of continuous strides during walking within a virtual reality (VR) environment \(^17,18,20\). Recent evidence supports that self-paced walking within a VR environment would facilitate a natural walking experience, which in turn enables the collection of valid gait parameters that resemble overground walking \(^17^{-20}\). To improve the utilisation of these instrumented treadmills, a Human Body Model (HBM) has been developed and validated to allow the estimation of kinetic and kinematic parameters in real-time \(^21\). HBM also estimates the forces of several muscles, which can be a promising alternative approach to the EMG to understand the role of key muscles in walking performance. Despite the growing use of instrumented treadmills, limited studies have conducted inclined gait analysis during self-paced treadmill walking \(^18,19,22\), and only one study has employed the HBM model but on cerebral palsy children \(^22\). The self-paced treadmill study by Kimel-Naor et al.\(^18\) proposed that speed-inclination interactions can provide a comprehensive picture of slope walking. However, to the best of our knowledge, no published study has looked at gait stability and associated muscular adaptations during self-paced treadmill walking at different inclinations.

Therefore, our study aimed to investigate the effects of inclination angle during self-paced treadmill walking on gait characteristics (i.e., gait stability, walking speed, lower limb joints kinematics, and spatiotemporal parameters) and on the peak activations of key lower limb muscles. In this study, we sought to exploit the novelty of the Gait Real-time Analysis Interactive Lab (GRAIL) treadmill to collect rich, highly accurate and reliable gait data in real-time during a self-paced inclined treadmill walking within a VR environment. We estimated gait stability via calculating the GSR, and we employed the HBM model to obtain a more comprehensive understanding of the walking patterns and muscular adaptations in healthy individuals during a self-paced inclined treadmill. This study would yield valuable knowledge on gait stability and adaptive strategies during walking at different inclinations.

## Results

### Spatial-temporal parameters
During uphill walking, all spatial-temporal gait parameters changed significantly relative to level walking. Inverse relationships were noted in-between parameters such as that GSR had significantly increased by 15.58% during uphill walking compared to level walking while walking speed had significantly reduced by 23.14%. In another observation, spatial parameters had reduced significantly during uphill walking compared to level walking by 13.53% at least. Temporal parameters, in contrast, had significantly higher values during uphill walking compared to level walking by a 5.26 –10.96% increment.

During downhill walking, almost all spatial-temporal gait parameters had reduced bilaterally during downhill walking compared to level walking, except the GSR values which had increased by 3.46%. Mean walking speed during downhill walking had no significant change relative to mean speed during level walking (Table 1).

**Joint kinematics**

During uphill walking, mean max hip flexion had increased significantly by over 25% in both sides relative to level walking (P<.001). Meanwhile, mean max hip abduction, hip rotation, and knee flexion had significantly reduced during uphill walking compared to level walking (P <.001, .024, <.036 respectively). During downhill walking, in contrast, mean max knee flexion had increased significantly from about 62° during level walking to about 68° during downhill walking (P <.001). Meanwhile, mean hip flexion and ankle dorsiflexion had significant reduced (P <.001). Results showed no significant differences between the joint angle kinematics in both sides across walking conditions (Figure 1).

**Muscle activations**

During uphill walking, the mean peak activation of most muscles had increased significantly, including the hamstrings (i.e., long and short head of BF, SM, and ST), quadriceps, and gastrocnemius (p <.001). Interestingly, however, the RF was the only muscle of the quadriceps that showed significantly less activation bilaterally during uphill walking compared to level walking (P<.001). Meanwhile, both TA and TP muscles had significantly become less activated bilaterally during uphill walking compared to level walking (P<.001).

During downhill walking, in contrast, the mean activation of the quadriceps, TA, and TP had increased significantly in both lower limbs. Particularly, RF was the muscle with the highest peak activation among all other muscles. Meanwhile, there was significantly less activation of the hamstrings, gastrocnemius, and SOL muscles during downhill walking relative to level walking. Interestingly, the peak activation of TP on the right side was significantly higher than that activation on the left side (i.e., the mean peak activation of TP during downhill walking was .86 ± .31 on the right side and was .47 ± 0.34 f/fmax on the left side) (Figure 2).

Table 1: Mean spatial-temporal gait parameters on both sides across walking conditions.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Side</th>
<th>DW</th>
<th>LW</th>
<th>UW</th>
<th>P value</th>
<th>Mean Percentage difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td></td>
<td>1-2</td>
</tr>
<tr>
<td>GSR [steps/m]</td>
<td></td>
<td>1.47 ± 0.13</td>
<td>1.42 ± 0.12</td>
<td>1.66 ± 0.20</td>
<td>&lt;.001</td>
<td>3.46</td>
</tr>
<tr>
<td>Walking speed [m/s]</td>
<td></td>
<td>1.34 ± 0.16</td>
<td>1.35 ± 0.20</td>
<td>1.07 ± 0.19</td>
<td>&lt;.001</td>
<td>0.74</td>
</tr>
<tr>
<td>Stride length [m]</td>
<td></td>
<td>1.37 ± 0.12</td>
<td>1.42 ± 0.12</td>
<td>1.23 ± 0.15</td>
<td>&lt;.001</td>
<td>3.58</td>
</tr>
<tr>
<td>(R)</td>
<td></td>
<td>1.37 ± 0.12</td>
<td>1.42 ± 0.12</td>
<td>1.23 ± 0.15</td>
<td></td>
<td>3.58</td>
</tr>
<tr>
<td>(L)</td>
<td></td>
<td>1.37 ± 0.12</td>
<td>1.42 ± 0.12</td>
<td>1.23 ± 0.15</td>
<td></td>
<td>3.58</td>
</tr>
<tr>
<td>Step length [m]</td>
<td></td>
<td>0.69 ± 0.06</td>
<td>0.71 ± 0.06</td>
<td>0.61 ± 0.08</td>
<td>&lt;.001</td>
<td>2.86</td>
</tr>
<tr>
<td>(R)</td>
<td></td>
<td>0.69 ± 0.06</td>
<td>0.71 ± 0.06</td>
<td>0.61 ± 0.08</td>
<td></td>
<td>2.86</td>
</tr>
<tr>
<td>(L)</td>
<td></td>
<td>0.68 ± 0.06</td>
<td>0.71 ± 0.06</td>
<td>0.62 ± 0.08</td>
<td></td>
<td>4.32</td>
</tr>
<tr>
<td>Stride time [s]</td>
<td></td>
<td>1.03 ± 0.08</td>
<td>1.06 ± 0.09</td>
<td>1.16 ± 0.12</td>
<td>&lt;.001</td>
<td>4.32</td>
</tr>
<tr>
<td>(R)</td>
<td></td>
<td>1.03 ± 0.08</td>
<td>1.06 ± 0.09</td>
<td>1.16 ± 0.12</td>
<td></td>
<td>4.32</td>
</tr>
<tr>
<td>(L)</td>
<td></td>
<td>1.03 ± 0.08</td>
<td>1.06 ± 0.09</td>
<td>1.16 ± 0.12</td>
<td></td>
<td>4.32</td>
</tr>
<tr>
<td>Stance time [s]</td>
<td></td>
<td>0.65 ± 0.05</td>
<td>0.69 ± 0.06</td>
<td>0.77 ± 0.10</td>
<td>&lt;.001</td>
<td>5.97*</td>
</tr>
<tr>
<td>(R)</td>
<td></td>
<td>0.65 ± 0.05</td>
<td>0.69 ± 0.06</td>
<td>0.77 ± 0.10</td>
<td></td>
<td>5.97*</td>
</tr>
<tr>
<td>(L)</td>
<td></td>
<td>0.66 ± 0.05</td>
<td>0.69 ± 0.06</td>
<td>0.77 ± 0.09</td>
<td></td>
<td>4.44*</td>
</tr>
<tr>
<td>Swing time [s]</td>
<td></td>
<td>0.38 ± 0.03</td>
<td>0.37 ± 0.02</td>
<td>0.39 ± 0.03</td>
<td>.002</td>
<td>2.67</td>
</tr>
<tr>
<td>(R)</td>
<td></td>
<td>0.38 ± 0.03</td>
<td>0.37 ± 0.02</td>
<td>0.39 ± 0.03</td>
<td></td>
<td>2.67</td>
</tr>
<tr>
<td>(L)</td>
<td></td>
<td>0.37 ± 0.03</td>
<td>0.37 ± 0.03</td>
<td>0.39 ± 0.03</td>
<td></td>
<td>0.00</td>
</tr>
</tbody>
</table>

GSR: Gait stability Ratio. Mean Percentage Difference (%): 1= Downhill, 2= Level, 3= Uphill walking. No significant differences between right and left sides. * Numbers are statistically significant (* post hoc p-value < 0.05).

**Discussion**

This study established the effects of self-paced inclined treadmill walking on gait stability characteristics and muscle activation levels during downhill, level, and uphill walking conditions. Comprehensive gait data were collected bilaterally during a self-paced treadmill walking within a naturalistic VR environment (detailed in supplementary file), which offers more insights into the adaptive neuromuscular strategies that preserve stability during walking on inclined surfaces.
Overall, inclined walking has a substantial impact on gait characteristics in healthy individuals. This is evident by the significant changes in all spatiotemporal parameters, max lower limbs joint kinematics, and the peak activation of all muscles across walking conditions. Our findings support that walking on inclined surfaces requires gait adaptation to enhance stability. During both inclined walking conditions, participants were found to walk with less stability as demonstrated by the higher GSR means compared to level walking (Table 1). Off all walking conditions, gait stability and walking speed were significantly reduced during uphill walking. The participants took significantly shorter and slower strides with significantly more time spent in the stance phase during uphill walking relative to other walking conditions. These findings suggest that uphill walking was the most challenging walking condition for our participants. Reduced walking speed is often used as a stability-enhancing strategy. In a similar study, the study by Kimel-Naor et al. assessed the walking performance of comparable participants (mean age 31.8 ± 4.3 years) during self-paced inclined treadmill walking. They also found that their participants walked slower and exhibited more kinematical changes in lower extremity joint angles during uphill walking than during downhill walking condition. However, Kimel-Naor et al.’s study did not assess gait stability or muscle activity on inclined treadmill walking. In line with our study, Ferraro et al. reported that healthy elderly adults had a significant increase in their GSR and a significant decrease in their step length, cadence, and walking speed during walking on a 10° inclined overground ramp. Whilst our findings expand on the body of literature, we have established insightful biomechanical analysis about the impact of inclined treadmill walking on gait stability characteristics in relation to joint angles and muscular adaptations demonstrated as follows.

In our study, we have observed two opposite biomechanical patterns associated with the direction of the slope when compared to level walking. During uphill walking, we found an average of 60° at both hip and knee joints and 34° dorsiexion at the ankle joint were required in an attempt to bring the body’s centre of mass (COM) forward. The greater hip and knee flexion elicited a significant concentric activation of the hamstrings (BF-LH: 109.5%, BF-SH: 53.3%, SM:98.9%, ST: 90.9%) more than those of the quadriceps (VI: 12.8% and VL: 16.7%) and the plantar flexors (MG: 40.6%, LG: 35.3%). These muscular adaptations would support the pronounced role of the hamstrings in absorbing power from the trunk and producing forward momentum in the ipsilateral leg to propel the body up the inclined surface. During downhill walking, on the contrary, we found a significant reduction in flexion at both hip and ankle joints (on average by 39° and 24° respectively), whilst knee flexion significantly increased by 8.5%. These biomechanical adjustments are apparently needed during downhill walking because the COM usually becomes in front of the sagittal plane, so it has to be pushed slightly back to counteract the effect of gravity. Consequently, these biomechanical adjustments had elicited significant eccentric contraction of the quadriceps, tibialis anterior, and tibialis posterior during downhill walking relative to level walking (RF = 97.7%, VL = 70.6%, VI = 68.7%, TA = 72%, TP = 107.1%). Our findings are generally in line with previous studies which reported similar changes in gait parameters and muscular contributions during uphill and downhill walking conditions. For example, Leroux et al. examined postural changes during treadmill walking at five inclinations (0, ± 5, and ± 10%) and they reported that uphill walking induced
flexion posture in the hip, knee and ankle joints and forward tilt of the pelvis and trunk whereas downhill walking requires less flexion posture at the three main lower extremity joints. Pickle et al. and Franz and Kram pointed out the role of the proximal muscles in power generation during uphill walking, and the role of the knee extensors in power absorption to preserve dynamic stability while lowering the body on a declined surface. Surprisingly, we found that the tibialis posterior was significantly more activated on the right side (the dominant side of our participants) than that on the left side during downhill walking. Further research should look deeper into this muscle to identify if the difference between the right and left side muscle activation always exists and the reason why this phenomenon had appeared.

In our study, we investigated the effects of self-paced inclined treadmill walking only in young able-bodied subjects. Therefore, the findings of the current study are limited to a comparable population and may not reflect the adaptation strategies in individuals with impaired gait stability (e.g., the elderly or individuals recovering from an illness or injury). Nevertheless, our findings can be used as a baseline for comparison with patient populations who are at risk of falling during inclined walking. All in all, our findings reinforce the importance of adopting inclined treadmill walking as part of the gait stability assessment. Another major clinical implication of our findings is that inclined walking should be considered in neuromuscular training for target muscle groups and fall prevention programs in rehabilitation.

Methods

Study Design. A within-subject repeated-measures study design was employed.

Participants. Twenty-eight able-bodied adults (age: 25.02 ± 2.06 years; gender: 14 males and 14 females) participated voluntarily in this study. Participants were included in this study if they did not complain of any medical, musculoskeletal, neurological, cardiovascular and vestibular impairments that may affect their gait. Participants were excluded if they declare any cognitive impairments, learning difficulties, or impaired normal vision. A written consent form was obtained from each participant prior to participation. The protocol of this study was approved by the Cardiff University School of Healthcare Sciences Research Ethics Committee. All methods were performed in accordance with the relevant guidelines and regulations.

Setting. This study used the GRAIL (Motek Medical B.V.) system at Cardiff University. The GRAIL system consists of an instrumented dual-belt treadmill with two embedded force platforms, a VR system projected onto a 180° screen, and a 10-camera motion tracking system (Vicon, Oxford Metrics, UK). The speed of the two belts was based on the self-paced mode for each participant, and it was implemented as described by Sloot et al. In addition, the speed of the visual flow was maintained by the walking speed.

Experimental Procedure. All participants attended a single session at our movement analysis laboratory. Reflective markers were placed on the participant's body according to the Motek Human Body Model 2
The calibration process began by asking the participant to stand still in a T-pose on the treadmill in order to create a skeleton file in the computer. When the operator gave the order “start”, the participant started walking while looking straight forward at the screen. After calibration, each participant was familiarised with the self-paced walking mode by asking them to accelerate and decelerate their walking speed according to the operator’s order. Following the operator’s instruction, each participant had the chance to practice the walking experiments for three minutes at least prior to recording the outcomes. The participant was then given a minute to warm up and build a comfortable walking speed. Depending on the walking condition, the slope angle would then gradually change to either up or down slopes by automatic computer control. Downhill (DW), level (LW), and uphill (UW) walking conditions had been stimulated when the platform inclination had adjusted at -8°,0°, and 8°, respectively. Once the slope angle reached 8° or -8°, the subject sustained walking for two minutes. Following slope walking conditions, the inclination angle of the treadmill would return back to horizontal level for 30 seconds to return to the baseline state.

Each participant underwent three 3-min self-paced walking trials under the three walking conditions in random order. Participants completed the three walking trials in one go without rest in between trials. No instructions were given to the participants during walking trials, and no talking was allowed in the laboratory to avoid any distractions that might affect their walking performance.

**Data Processing.** For 28 participants, gait parameters were derived from the force plates and the motion capture system. The data of one participant was eliminated for some missing information. Various gait parameters had been obtained during the three walking conditions, including GSR, walking speed, max lower limb joint kinematics, and spatiotemporal parameters. The average walking speed was measured during the three walking conditions. Furthermore, estimated muscle activation levels (F/Fmax) were obtained from the HBM2 for 11 muscles around the knee joint bilaterally. Table 2 listed all the 11 measured muscles and their abbreviations. The peak muscle activation levels of these muscles were further processed in MATLAB (Version R2017, The MathWorks Inc., USA).
Table 2
Measured muscles and their abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Muscles</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF</td>
<td>Biceps Femoris</td>
</tr>
<tr>
<td>SM</td>
<td>Semimembranosus</td>
</tr>
<tr>
<td>ST</td>
<td>Semitendinosus</td>
</tr>
<tr>
<td>RF</td>
<td>Rectus Femoris</td>
</tr>
<tr>
<td>VI</td>
<td>Vastus Intermedius</td>
</tr>
<tr>
<td>VL</td>
<td>Vastus Lateralis</td>
</tr>
<tr>
<td>MG</td>
<td>Medial Gastrocnemius</td>
</tr>
<tr>
<td>LG</td>
<td>Lateral Gastrocnemius</td>
</tr>
<tr>
<td>SOL</td>
<td>Soleus</td>
</tr>
<tr>
<td>TA</td>
<td>Tibialis Anterior</td>
</tr>
<tr>
<td>TP</td>
<td>Tibialis Posterior</td>
</tr>
</tbody>
</table>

**Statistical Analysis.** The analysis aimed to compare gait characteristics and muscle activation levels across the three walking conditions. Therefore, repeated measures ANOVA and Freidman test were used to explore the effect of inclines on lower limb muscle activity and gait parameters. The level of statistical significance was set at p < 0.05. If significant effects were obtained, post hoc analyses had been performed to contrast between the three conditions and locate the significant changes. Statistical Package for the Social Sciences (SPSS) software (Version 25.0 for Macintosh) was used to perform all statistical analysis.

**Conclusions**

This study provides evidence that inclined treadmill walking is a challenging activity that requires adaptive neuromuscular control strategies to preserve stability. Gait stability characteristics and lower limb muscular activations in able-bodied individuals had been significantly affected by the inclination angle of the treadmill. Of all walking conditions, uphill walking appears to have more influence on reducing gait stability and walking speed. Future research should investigate the effects of inclined treadmill walking on other patient populations to confirm our suggestion that incline walking can be used as a functional assessment tool and a training protocol to improve stability and strengthen specific muscle groups.

**Declarations**

**Data availability:**
The datasets for this study are available upon request from the corresponding author.

**Acknowledgments:**

Part of this study was presented on a conference in Congress of the International Society of Biomechanics 2019.

**Author Contributions:**

Conceived and designed the study: Ch.L. and M.A.-A. Performed the trials: Ch.L., and M.A.-A. Analysed the data: Ch.L. and R.A.-J and M.A.-A. Wrote the paper: R.A.-J and M.A.-A. All authors reviewed the manuscript.

**Competing Interest:** The authors declare no competing interests.

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**References**


Figures
Figure 1

Mean Joint Range of Motion Across Walking Condition
Figure 2

Mean Muscle Activation Across Walking Condition

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementaryfile.pdf