Effect of incline on lower extremity muscle activity during sprinting

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Abstract This study aimed to investigate the effect of incline on neuromuscular mechanisms in uphill sprint running. Nine male college sprinters performed 5-sec constant speed running trials on a motorized treadmill at 7.5 m/s. Each trial was conducted under different inclined conditions (level and 5.0% grade). Surface electromyography (EMG) was recorded from 6 muscles of the lower limbs, including gluteus maximus, gluteus medius, rectus femoris, vastus lateralis, biceps femoris, and lateral gastrocnemius lateralis. We found higher muscle activity in all muscles during the stance phase in uphill sprinting except for rectus femoris and vastus lateralis. Higher muscle activation during the recovery phase was found in the rectus femoris muscle in uphill sprinting. These muscle activity adaptations in uphill sprinting were paralleled by higher step frequency and shorter step length. Our results suggest that lower limb muscle activity can meaningfully adapt to sprint-specific demand in uphill running.

Keywords: running mechanics, locomotion, uphill sprint, electromyography

Introduction

Uphill sprint training is one of the most classic resistance training protocols for improving sprint performance. This type of sprint training does not require special equipment since athletes work against gravity in an incline environment. The uphill sprint training paradigm aims at overloading lower limb muscles and optimizing running mechanics in sprinting. Therefore, understanding changes in motor control and movement patterns induced by uphill sprinting is of great value for practitioners in their pursuit of conducting meaningful training sessions and designing reasonable training plans.

During uphill running, athletes are forced to optimize their running kinematics and kinetics in order to deal with the higher energy demands due to the inclined environment. Previous studies demonstrated significantly increased step frequency, mechanical work, lower extremity joint ranges of motion, higher hip angular velocity, and significantly reduced flight times at grades from 5.2 to 30.0% uphill running. Specifically, Gottshall and Kram reported a 4.1% increment in step frequency and a 3.9% decrement of step length at 15.8% uphill running. Moreover, Padulo et al. identified that runners produced a 14.7% higher impulse during the running stance phase on a 7.0% incline. These substantial changes in running biomechanics are accompanied by alterations in the neuromuscular control of uphill versus level running.

Corresponding to higher mechanical work requirements, Yokozawa et al. demonstrated that uphill running (5.0 m/s; 9.1% grade) requires greater joint torque and higher muscle activation in hamstring, iliopsoas, hip adductor, and vastus medialis muscles. More specifically, Abe et al. also found higher muscle activation of lower limb muscles during the stance phase in uphill running (3.2 – 3.3 m/s; 5.0% grade), a +8.6% and +11.3% higher root mean square (RMS) value for the vastus lateralis during the flexion and extension phase of the knee, respectively. Furthermore, Yokozawa et al. revealed that the contribution of lower limb muscles to net joint torque differed depending on the running speed and the incline of the running surface, which could also be relevant to the altered step biomechanics. This result indicated that how each lower limb muscle contributes to bio-motor movement wouldn’t be uniform, but would change independently to satisfy the specific biomechanical function. Wall-Scheffler et al. also supported these disparities in muscle contributions at different running speeds and inclines. They reported that higher muscle activity appeared in the gluteus maximus, gluteus medius, hamstrings, rec-
tus femoris, and gastrocnemius muscles during faster (at 1.2, 1.5, 1.8, 2.7, and 3.6 m/s) and steeper uphill running (at 10.0%, 15.0%, and 20.0% grades). In brief, an inclination of the running surface lead to a significant change in running kinematics and kinetics, and the degree of this adaptation was dependent on the degree of incline and running speed.

There is clear evidence that higher running speed leads to changes in kinematics and kinetics compared to slower running speed\(^9,12,13\). Schache et al.\(^12\) found significantly increased hip extension and flexion torque above a running speed of 6.97 m/s. Furthermore, Dorn et al.\(^13\) demonstrated increased step frequency, hip joint torque, and hip muscle activation at more than 7.0 m/s running speed. These and other findings\(^14\) implicate that at running speeds above 7.0 m/s, flight time becomes substantially shorter, which requires higher torque generation and higher muscle activation of hip flexors. Nevertheless, most of the previous studies have identified characteristic features of uphill running at slow running speeds, and the differences in neuromuscular activation patterns between uphill and level running at higher speeds have not been clarified yet. Although Paradisis et al.\(^5\) (at 7.5 m/s; 5.2% grade) and Sugimoto and Maeda\(^5\) (>7.0 m/s; 1.3, 7.4, and 13.1% grades) investigated kinematic changes in uphill running at high speed, no other studies have been conducted to investigate the biomechanical characteristics of uphill sprinting. In other words, whether those neuro-mechanical changes observed in level high-speed running persist in fast uphill running is currently unknown. High speed uphill running, of over 7.0 m/s, potentially causes unique biomechanical adaptations due to specific incline requirements. Analyzing and understanding those muscle activities during an uphill sprint is a crucial component for evidence-based training prescriptions. In addition to existing knowledge on the kinematics, using electromyographic analysis could elucidate how to regulate the contribution of important muscles to adapt to an inclined environment. It could enable practitioners to better plan an evidence-based training structure and to figure out better coaching formulae.

Therefore, the purpose of the present study was to compare lower limb muscle activity between uphill and level sprint running. Firstly, we hypothesized that activation during the stance phase of uphill sprinting would be higher in accordance with previous studies indicating higher muscle activation during lower speed uphill running\(^9,11\). Additionally, based on the argument of shorter flight time and greater torque requirement for hip flexors during sprinting\(^12,14\), we also hypothesized that activation of the hip flexors during the recovery phase of uphill sprinting would be higher in order to adapt the sprint mechanics to the inclined environment.

Materials and Methods

Subjects. Nine male collegiate sprinters participated in this study (age: 20.7 ± 1.5 years; height: 1.77 ± 0.06 m; body mass: 69.9 ± 6.0 kg; 100 m personal best: 10.76 ± 0.37 sec). This study was approved by the Human Subjects Committee of the University of Tsukuba, following the Declaration of Helsinki (approval number: 30-82). Before the start of the experiment, subjects received verbal and written descriptions about the purpose of the present study and the potential risks of the experiment.

Experimental protocol. All subjects conducted two runs at 7.5 m/s on a motorized treadmill (ORK-7000; Ohtake Root Kogyo, Iwate, Japan) at both a level and 5.0% uphill slope condition. The speed of the treadmill was selected to enable runners to perform at the same speed during both level and uphill conditions. We selected a slope of 5.0% to allow for comparisons to previous research\(^3,5,10,16\). During each running trial, subjects performed 5-sec of steady speed running on the treadmill in randomized order to eliminate the potential influence of ordering effects. Subjects ran in their own running shoes. The trial that was most satisfying for the subject was selected for further analysis.

Data collection and processing. We attached 47 retro-reflective markers (14 mm in diameter) on anatomical landmarks of the whole body of each subject, as reported in previous studies\(^17,18\). The 3D marker motion was collected using 14 high-speed infrared cameras (Vicon Motion Systems, Ltd., Oxford, UK) at 250 Hz. We calculated segment endpoints from the three-dimensional coordinates of the markers according to a 15-segment body model consisting of hands, forearms, upper arms, feet, shanks, thighs, head, upper trunk, and lower trunk\(^19,20\).

The three-dimensional coordinates were smoothed by a recursive Butterworth low-pass digital filter at optimal cut-off frequencies of 5–15 Hz, which were determined using the residual method\(^21\).

Spatio-temporal variables. The instants of touch-down and take-off were identified based on peak vertical acceleration of the toe markers\(^22,23\). For the uphill condition, we calculated the component of acceleration perpendicular to the treadmill surface to identify touch-down and take-off events. The stance time (in milliseconds) and the flight time (in milliseconds) were calculated by the number of frames between touch-down and take-off while considering the sampling rate of 250 Hz. Step frequency (in Hz) is the reciprocal of the time required for one step. Step length (m) is the quotient of the treadmill belt speed divided by step frequency. These data were also averaged in each condition.

Kinematics of segments and joints. Further data analy-
sis was conducted by using MATLAB software version 2017b (MathWorks Inc., Natick, MA, USA). The global coordinate system was defined using the running lane of the treadmill in the X- (mediolateral direction), Y- (anterior-posterior direction), and Z- (vertical direction) axes. To calculate the three-dimensional lower limb joint angle, we used the joint coordinate system approach, which was defined in the same way as in Kariyama et al.20).

Electromyography. Bipolar silver/silver-chloride active bar electrodes were used to record EMG signals (sampling frequency: 1000 Hz; WEB-7000, Nihon Kohden, Tokyo, Japan). The bar electrodes were 10 mm long and 2 mm wide and were attached in longitudinal alignment with the muscle fibers at an inter-electrode distance of 20 mm. We recorded the EMG activity of the gluteus maximus (Gmax), gluteus medius (Gmed), rectus femoris (RF), vastus lateralis (VL), biceps femoris (BF), and gastrocnemius lateralis (GA) of the right leg. We shaved the participant’s hair at the site of the EMG electrode placement and subsequently cleaned the skin with alcohol before placing the electrodes. The placement of the EMG electrodes on each muscle was determined following the SENIAM protocol, which is the global standard for collecting EMG data24). The raw EMG signals were bandpass-filtered between 15 and 500 Hz. The EMG data were synchronized with the kinematics data.

Each trial consisted of a sprint running gait cycle in the right leg. We defined a stride as the time from ground contact of the right foot to the next ground contact of the same foot. To adequately describe the relationship between the joint angles and the EMG data, the gait cycle was divided into five phases according to the hip and knee kinematics of the right leg: the early stance phase, beginning at foot strike and ending at maximum knee flexion during stance; the late stance phase, beginning at maximum knee flexion during stance and ending at toe-off; the early recovery phase, beginning at toe-off and ending at maximum knee flexion during swing; the mid-recovery phase, beginning at maximum knee flexion during swing and ending at maximum hip flexion; and the late recovery phase, beginning at maximum hip flexion and ending at foot strike. Neuromuscular activation during uphill and level sprinting was represented as root mean square (RMS), which was calculated for each gait phase.

Statistical analysis. The mean, standard deviation (SD) and coefficient of variation (CV) were calculated for descriptive analyses. A paired t-test was used to compare the spatio-temporal variables of the uphill and level conditions. EMG activity during each phase was determined using repeated-measures analysis of variance (Two-way ANOVA) (condition × phase). Bonferroni’s post hoc analysis was conducted if the Two-way ANOVA showed statistically significant main or interaction effects. The Cohen’s d-value effect size was calculated as a quotient of the difference between conditions divided by standard deviation, to show practical significance and interpreted as trivial (<0.19), small (0.20 – 0.59), moderate (0.60 – 1.19), large (1.20 – 1.99), and very large (2.0 – 4.0) in accordance with Hopkins et al.25). Eta squared ($\eta^2$) for Two-way ANOVA was also calculated for pair wise comparisons. Statistical significance was set at $p < 0.05$. All statistical analyses were performed using SPSS version 22 for Windows (IBM SPSS Statistics, IBM, USA).

Results

The stance time was not affected by the incline ($p = 0.580, d = 0.13$), whereas the flight time was significantly shorter in uphill compared to level sprinting ($p = 0.004, d = 1.18$). During uphill sprinting, step frequency was significantly higher ($p = 0.011, d = 0.72$) and step length was significantly smaller ($p = 0.017, d = 0.70$). Table 1 shows the mean values and standard deviations of the spatio-temporal parameters.

Mean RMS values during each phase are shown in Fig. 1. Two-way ANOVA indicated statistically significant

### Table 1. Running kinematic data under the level and uphill conditions.

<table>
<thead>
<tr>
<th></th>
<th>Level</th>
<th>Uphill</th>
<th>Paired - T</th>
<th>Cohen's d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step length [m]</td>
<td>2.09 ± 0.10</td>
<td>2.03 ± 0.08</td>
<td>$p = 0.017$</td>
<td>0.70 ‡</td>
</tr>
<tr>
<td>Stance time [ms]</td>
<td>123.0 ± 8.1</td>
<td>124.1 ± 8.6</td>
<td>$p = 0.580$</td>
<td>0.13</td>
</tr>
<tr>
<td>Flight time [ms]</td>
<td>156.7 ± 8.7</td>
<td>146.7 ± 8.3</td>
<td>$p = 0.004$</td>
<td>1.18 ‡</td>
</tr>
<tr>
<td>Step frequency [Hz]</td>
<td>3.58 ± 0.17</td>
<td>3.70 ± 0.15</td>
<td>$p = 0.011$</td>
<td>0.72 ‡</td>
</tr>
</tbody>
</table>

‡: Moderate effect size.
interaction effects in each muscle (condition × phase, Gmax: \( p = 0.011 \), Gmed: \( p = 0.010 \), RF: \( p = 0.034 \), BF: \( p = 0.005 \), GA: \( p = 0.026 \)). Activation of the Gmax muscle in uphill was significantly greater during the early stance phase (\( p = 0.047, \eta^2 = 0.406, \text{0-5\%} = 67.9\% \)), and the late recovery phase (\( p = 0.039, \eta^2 = 0.432, \text{0-5\%} = 16.7\% \)) compared to level sprinting. In addition, the Gmed muscle was also significantly more activated in uphill compared to level sprinting in the early stance (\( p = 0.016, \eta^2 = 0.539, \text{0-5\%} = 53.3\% \)), late stance (\( p = 0.035, \eta^2 = 0.445, \text{0-5\%} = 162.4\% \)), and early recovery phases (\( p = 0.037, \eta^2 = 0.440, \text{0-5\%} = 49.4\% \)). Moreover, the RF muscle in uphill was significantly more activated during the early recovery phase (\( p = 0.014, \eta^2 = 0.550, \text{0-5\%} = 28.1\% \)) compared to level sprinting. The BF and GA muscles in uphill sprinting were significantly more activated during

![Fig. 1](image-url)
the early stance phase (BF: \( p = 0.007, \eta^2 = 0.616, 0-5\% = 59.7\% \), GA: \( p = 0.048, \eta^2 = 0.406, 0-5\% = 22.5\% \)) compared to level sprinting. There were no significant interaction effects in the VL muscle (\( p = 0.733 \)). Since this study focused on a comparison between two incline conditions, the results of the simple main effect of phase within each condition are not shown.

**Discussion**

The purpose of the present study was to compare lower limb muscle activities between uphill and level sprint running in order to provide scientific insight into the neuromuscular characteristics of uphill sprint training. We found higher muscle activity in the Gmax, Gmed, BF, and GA during the stance phase in uphill compared to level sprinting, but no statistical differences in VL between conditions. Furthermore, higher muscle activation during the early recovery phase was identified in the RF muscle in uphill sprinting, which is the unique profile for uphill sprinting in contrast to low speed uphill running. These results suggest that an inclined surface induces selective lower limb muscle recruitment during sprint running.

In the early stance phase, we found higher muscle activity in the Gmax, Gmed, BF, and GA in uphill compared to level sprinting (Fig. 1). These results support our original hypothesis that higher hip extensor muscle activity would be observed during the stance phase in uphill compared to level sprint running. This higher muscle activity might be explained as an adaptation to the higher energy requirements of incline running\(^{3,8,26} \). In uphill running, the potential energy must be increased during each step to run up the sloped surface. Therefore, uphill running requires greater mechanical work to be done during the stance phase\(^3 \). In order to fulfill this requirement, it is necessary to generate a higher power output in each joint. Thus, the Gmax and BF were more activated in uphill sprinting for increasing hip extension power. Although it was impossible to examine joint kinetic data in the current study, these muscles would dominantly contribute to explosive hip extension, which would lead to lifting and propulsion of the center of mass.

Our results also demonstrated the higher Gmed activity in uphill sprint running through the stance phase. We interpret this finding to mean that the Gmed also contributes to the increased vertical requirement in uphill sprinting. This interpretation is in line with the role of the Gmed in unilateral leg stance and frontal running mechanics for vertical velocity production\(^7 \). For instance, Kariyama et al.\(^{20} \) have found increased hip abduction torque in single-leg compared to double-leg vertical rebound jumps. Based on their argument, hip abduction contributed to enhancing the acceleration into a vertical direction in the single-leg condition. This proposed mechanism of hip abductor torque/power generation would also support our findings. Moreover, Kariyama et al.\(^{20} \) have also reported greater hip abduction torque during horizontal single-leg jumps compared to vertical single-leg jumps, even though the movement is mainly in the forward direction. This result means that these frontal plane mechanics are crucial for developing vertical and horizontal force in a short stance time during horizontal single-leg movements. In line with the findings of these studies, the higher Gmed muscle activation during uphill sprinting, in this study, might promote greater hip abduction torque. Consequently, not only sagittal plane flexion/extension mechanical changes could contribute to higher force production, but changes in frontal plane mechanics could also contribute to uphill sprint running.

While most of the lower limb muscles showed higher muscle activity during the stance phase, RF and VL activities during the stance phase did not differ between uphill and level sprint running. These results may be due to the sprint-specific running mechanics of the knee joint\(^{29-31} \). Based on geometrical reasoning, Ito et al.\(^{30} \) have demonstrated that full knee extension during the stance phase cannot lead to efficient development of horizontal running speed. For this reason, the function of these muscles might be limited in sprint running, which might partly explain the result that muscle activity in knee extensors did not differ between uphill and level sprinting conditions. Another possible reason is the intensity of the incline. Sugimoto and Maeda\(^{30} \) have investigated the effects of different incline levels on sprint kinematics. They reported a significantly shorter horizontal center of mass distance during the stance phase and greater knee extension and ankle plantarflexion motion in the moderate (7.4\%) and high (13.1\%) incline conditions compared to a low incline condition (1.3\%). These results suggest an inconsistent adaptation trend due to the intensity of the incline during sprint running. Therefore, the 5.0\% incline of this study was potentially not steep enough to increase the vertical GRF component sufficiently to require greater knee extensor activation during sprinting.

In contrast to the stance phase, higher RMS values in the recovery phase were identified in the RF muscle, which also supports our second hypothesis. Although the higher RMS values of the Gmax and Gmed were also shown during the late recovery phase and early recovery phase, respectively, these higher values are considered to simply be related to higher activation in the stance phase. On the other hand, the higher activation of RF muscle in the mid-recovery phase during uphill sprint is a stance phase independent result. Several studies have examined muscle activity at low speed uphill running, but no suggestive results at the recovery phase have been reported. Therefore, this is the first study demonstrating the meaningful change of muscle activity at the recovery phase in uphill running, and it is assumed that this trait would exclusively occur in uphill sprinting. We suggest that this notable activation could result from the spatial constraint coming from the inclined environment, the bi-articular...
muscle function of the muscle, and high speed running velocity beyond submaximal. Due to the specific spatial constraints of the inclined running surface, it is well represented that the flight times from ipsilateral take-off to contralateral touch-down are significantly reduced\(^4,32\). For preparing appropriate leg orientation at the subsequent ground contact within a shorter flight phase, the swing leg must be accelerated faster and step frequency must be higher\(^5\). In order to adapt to these mechanical requirements, the RF muscle could effectively function during uphill sprinting. The RF muscle is well known as a bi-articular muscle, which means that this muscle has two anatomical functions, knee extension and hip flexion. While this muscle mainly works as a knee extensor in running, in the early recovery phase of sprint running, it has an essential role as a hip flexor muscle\(^3,33\). Moreover, our results for sloped sprinting are also supported with findings for increased running speeds on level surfaces. Dorn et al.\(^13\) reported that the increase in the running speed from submaximal to maximal was mainly due to an increase in step frequency, and that hip flexor and extensor muscles were critical components for swinging the legs quickly. They also demonstrated greater RF muscle force production in the recovery phase during maximal running. This could be a potential explanation for the remarkable RF muscle activation shown in uphill sprinting. For these reasons, the RF muscle could be more activated in the recovery phase to more quickly accelerate the free leg forward to facilitate the increased step frequency in uphill sprint running.

As a practical application, athletes and practitioners can use the uphill sprint as a specific resisted sprint training (RST). Firstly, it is crucial for the practitioner to understand the degree of mechanical change due to a certain incline during uphill sprint training. In the present study, significant changes in step variables have been reported, -2.9% step length, -6.4% flight time, and +3.4% step frequency. Previous studies investigating the effect of the same incline (5.0%) on running mechanics demonstrated a similar degree of shift, -2.4 \(-7.6\%\) decrement in flight time, +0.7 \(+2.9\%\) increase in step frequency, -5.2% decrement in step length\(^4,32\). On the other hand, our study demonstrated a notable increase in the RMS value of EMG. During the early stance phase, +67.9% RMS value of Gmax, +53.5% RMS value of Gmed, +59.7% RMS value of BF, and +22.5% RMS value of MedG were observed in this study. These increments were relatively higher than in the previous study, which was investigating neuromuscular activity during slow uphill running. Abe et al.\(^10\) revealed that a +8.6% RMS value for the ECC phase and +11.3% RMS value for the CON phase were represented on the vastus lateralis at 5.0% inclined treadmill running. Therefore, uphill sprint running has significantly higher kinetic requirements compared to the slower uphill running, while the spatio-temporal variables change to a similar degree.

Classically, it has been believed that the primary benefit of this type of training is to be able to put a greater mechanical load on all lower-limb extensor muscles, which contribute to propelling the body forward by extension of the lower limbs. However, according to the results of the present study, an uphill sprint can not only induce higher muscle activation on the sagittal extensor/flexor muscles of the hip, knee, and ankle, but also on the frontal hip abductor muscle. This means that the uphill sprint could also be used as resisted training for the muscles functioning to control and elevate the pelvis during dynamic single-leg movement. The primary function of the gluteus medius, which is a muscle that was significantly activated in this study, is hip abduction during an open kinetic chain exercise and also pelvis control during a closed kinetic chain exercise. Typical strength training of this muscle is hip abduction on the ground with a mini rubber band and/or single stance resistance exercise like the single-leg squat\(^46\). Nevertheless, an uphill sprint could place a greater load onto this muscle with higher movement velocity and with closer mechanics to the running movement. This novel finding could possibly be evidence for the unique aspect of an uphill sprint as specific resisted training, although further kinetic analyses and longitudinal intervention studies are needed to confirm this assumption.

The present study has certain limitations. Our experiments were conducted on a treadmill using a standardized sprinting speed, so it is uncertain if these insights can be directly transferred to regular outdoor sprint training directly. Notably, the lower limb muscles might be less activated under treadmill conditions due to the motorized belt movement\(^45\). In addition, this study has not collected the ground reaction force data due to the limitation of the experimental environment. Although the kinetic data of the swing leg could be calculated independently using the inverse dynamics model (IDM), future studies will demonstrate the comprehensive kinetic feature of uphill sprinting by comparing the kinetic data of the swing leg and stance leg simultaneously.

**Conclusions**

The purpose of the present study was to compare lower limb muscle activity between uphill and level sprint running in order to provide scientific insight into the neuromuscular characteristics of uphill sprint training. In conclusion, we found higher muscle activity in the Gmax, Gmed, BF, and GA during the early stance phase in uphill sprinting, but no statistical difference in VL muscle. Notable higher muscle activation during the early recovery phase was found in the RF muscle in uphill sprinting. Understanding these selective neuromuscular changes in uphill sprint running could contribute to developing more useful practical applications of uphill sprint training.
Acknowledgments

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Conflict of Interests

The authors declare no potential conflict of interests with respect to the research.

Author Contributions

MO, SK, and ST contributed to conceiving and designing this research. MO, SK, and TY contributed to performing the experiment. MO performed most of the data analysis and wrote the paper. SW, HM, and ST contributed to drafting the article. All authors read and approved the final manuscript.

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