The effects of sloped surfaces on locomotion: Backward walking as a perturbation

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Abstract

The purpose of this study was to examine lower extremity kinetics and muscle activity during backward slope walking to clarify the relationship between joint moments and powers and muscle activity patterns observed in forward slope walking. Nine healthy volunteers walked backward on an instrumented ramp at three grades (\(-39\% \ (-21^\circ), 0\% \ (\text{level}), +39\% \ (+21^\circ))\). EMG activity was recorded from major lower extremity muscles. Joint kinetics were obtained from kinematic and force platform data. The knee joint moment and power generation increased significantly during upslope walking; hip joint moment and power absorption increased significantly during downslope walking. When compared to data from forward slope walking, these backward walking data suggest that power requirements of a task dictate the muscle activity pattern needed to accomplish that movement. During downslope walking tasks, power absorption increased and changes in muscle activity patterns were directly related to the changes in the joint moment patterns. In contrast, during upslope walking tasks, power generation increased and changes in the muscle activity were related to the changes in the joint moments only at the ‘primary’ joint; at adjacent joints the changes in muscle activity were unrelated to the joint moment pattern. The ‘paradoxical’ changes in the muscle activity at the adjacent joints are possibly related to the activation of biarticular muscles required by the increased power generation at the primary joint. In total, these data suggest that changing power requirements at a joint impact the control of muscle activity at that and adjacent joints.

Keywords: Neural control; EMG; Kinetics; Backward slope walking; Biomechanics

1. Introduction

Forward slope walking is a locomotor task that has been used to study neural control in humans (Earhart and Bastian, 2000; Lay et al., 2006b) and quadrupeds (Gregor et al., 2001; Smith and Carlson-Kuhta, 1995). Data from humans suggests that up- and downslope walking require different control strategies than level walking (Lay et al., 2006a, b). Understanding such strategies requires exploration of the association between muscle activation patterns and joint moment patterns. From forward slope walking data we hypothesize that the primary influence on muscle activation patterns is joint power requirements. One way to test this hypothesis is to perturb joint power requirements during slope walking and reevaluate the relationship between joint mechanics and muscle activity patterns. Backward slope walking was chosen for this purpose. This task has received only limited attention in the biomechanics literature (Cipriani et al., 1995; Hooper et al., 2004; Minetti and Ardigo, 2001).

The purpose of this study was to compare joint kinetics and muscle activity patterns observed in the hip and knee joints during backward slope walking to those observed during forward slope walking. We expect that forward and backward upslope walking and forward and backward downslope walking will have similar relationships between the mechanics and the muscle activation patterns because the joint power requirements are similar in these pairs of tasks. The findings presented herein will complement...
previous reports (Lay et al., 2006a, b), and provide insight into neural control of challenging locomotor tasks.

2. Methods

Nine healthy young adults (five male, four female) volunteered and gave informed consent before participating in the study, which was approved by the Institutional Review Board at the Georgia Institute of Technology. The experimental protocol and data processing are described here briefly, but have been presented in detail in previous reports (Lay et al., 2005, 2006a, b).

Electrodes were applied unilaterally on each participant’s preferred limb (8R, 1L) over the bellies of the rectus femoris (RF), vastus medialis (VM), biceps femoris (BF), and semimembranosus (SM). Retroreflective markers were placed over 15 bony landmarks (Vaughan et al., 1999). Participants were habituated to the ramped walkway and then performed at least eight walking trials at every grade (−39% (−21°), 0% (level), +39% (+21°)). Trials were discarded if foot contact with the force platform was incomplete, or if visible stride alterations were made to target the platform. Walking speed was not controlled during the experimental testing.

This report will focus on stance phase data from level and ±39% grades. Temporal stride parameters, joint moments, and joint powers were calculated from the collected kinematic and force platform data. Points of interest on the joint moment curves were identified for statistical analysis (Table 1). Burst onset, duration, and offset (as %stride) as well as mean activity (as %activity of that burst during level walking) were calculated for all EMG data. All variables were compared across grades using a repeated measures analysis of variance design (ANOVA) (α = 0.05, a priori). When a significant main effect for grade was identified for any kinetic variable, Bonferroni confidence interval adjustments were used during follow-up analysis. For the EMG variables, when a significant main effect for grade was identified dependent t-tests with an adjusted p-value (p = 0.01667) were used in follow-up analyses. Select results from these analyses are presented here. The complete data set has been reported previously (Lay, 2005).

3. Results

Although walking speed was not controlled during the trials, no grade effect was observed for either the stance or stride durations (Table 2).

During backward upslope walking there were significant increases in the knee extensor moment, but the hip moment was similar to that for backward level walking (Fig. 1, Table 3). These joint moment changes were similar to those observed during forward downslope walking. Power generation increased at the knee with increased slope (Fig. 2). During backward upslope walking the mean BF and SM activity levels were statistically the same as during level walking, but the duration of activity increased (Fig. 3). Durations of the stance RF and VM bursts did not change, but mean activity levels increased significantly from level walking (Fig. 4).

During backward downslope walking, as in forward upslope walking, the knee joint moment was similar to that...
during level walking, but the hip extensor moment increased significantly (Fig. 1, Table 3). Power absorption increased at the hip as slope increased (Fig. 2). During backward downslope walking, BF and SM burst onset was earlier, and the mean SM activity increased significantly (Fig. 3). RF and VM activity showed no statistical differences from level walking (Fig. 4).

4. Discussion

4.1. Backward upslope walking

The most noticeable change in joint moments during backward upslope walking was the increased knee extensor moment. The substantial increase in power generation at the knee during backward upslope walking is similar to that observed at the hip joint during forward upslope walking (Lay et al., 2006b), and was expected to result in similar changes in muscle activity patterns. In forward upslope walking, the RF and VM activity increased significantly in magnitude and duration, although the knee joint moment did not change significantly from level walking. These 'unexpected' changes in RF and VM activity were attributed to the need to counteract possible knee flexion by the biarticular hamstrings, which were active to contribute to the large hip extensor moment (Lay et al., 2006b). Similarly, during backward upslope walking the hip joint moment does not change, but the duration of BF and SM activity increases. As in forward upslope walking, the RF and VM activity increased significantly in magnitude and duration, although the knee joint moment did not change significantly from level walking. These 'unexpected' changes in RF and VM activity were attributed to the need to counteract possible knee flexion by the biarticular hamstrings, which were active to contribute to the large hip extensor moment (Lay et al., 2006b). Similarly, during backward upslope walking the hip joint moment does not change, but the duration of BF and SM activity increases. As in forward upslope walking, this increased activity does not appear to correspond to the joint moment pattern until the role of biarticular muscles is considered. There is a large knee extensor moment and power is generated, which requires increased RF and VM activity. However, this increased RF activity would increase the hip flexor moment if not counteracted by the increased BF and SM activity. Therefore, changes in muscle activity patterns are indeed similar to those observed during forward upslope walking, which also requires power generation; this indicates that joint power requirements may be the primary cause of changes in the muscle activity pattern.

To generalize, increased power generation at a joint requires increased biarticular muscle activity around the 'primary' joint, which is directly related to the change in the joint moment. This, in turn, requires recruitment of muscles at adjacent joint(s) to counteract activity of the biarticular muscles. Increased activity of the antagonists at adjacent joint(s) does not directly correspond to the joint moment pattern. This influence of joint power requirements seems to supersede the effect of kinetic patterns as an influence on control strategies. Data from the task of descending stairs also supports this idea (McFadyen and Winter, 1988). The knee joint moment during stair descent is similar to the knee joint moment during forward downslope walking and backward upslope walking; but power is absorbed in the first two tasks, and generated in the third. Knee extensor activity increases dramatically in

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Fig. 2. Group ensemble average joint power data, normalized to body mass. Positive is power generation, negative is absorption. Plots begin and end with toe contact, vertical line marks heel off.

The values for point HM2 are in time (normalized stride), while all other values are in Nm/kg. A repeated measures ANOVA indicated a significant grade effect for all variables except KM4 and HM1. A significant difference from 0% based on the follow-up comparisons is denoted by the symbol § (p<0.05).
all tasks. In both stair descent (McFadyen and Winter, 1988) and forward downslope walking hamstring activity is similar to that during level walking. In backward upslope walking, however, hamstring activity increases substantially from level walking. In other words, when power generation increases at a joint, changes in muscle activity at adjacent joints are unrelated to the joint moment pattern.

4.2. Backward downslope walking

The increase in the hip extensor moment was the prominent change in joint moments during backward downslope walking. The increase in power absorption at the hip joint during backward downslope walking was similar to that observed at the knee joint during forward downslope walking (Lay et al., 2006b). Again, similar changes in muscle activity patterns were expected in these tasks. During forward downslope walking, changes in muscle activity corresponded directly to changes in joint moments (Lay et al., 2006b); there were significant increases in knee extensor activity and the knee extensor moment. This was also observed here in backward downslope walking: there were increases in both hamstring muscle activity and the hip extensor moment. These changes in joint moments are similar to those observed during forward upslope walking, but increased activation of antagonists does not occur here. Instead, the lack of change in knee extensor activity resulted in muscle activity patterns that corresponded closely to the joint moment patterns, similar to forward downslope walking. From these data it seems that under similar kinetic demands, increasing power absorption reduces the need to activate antagonists to the biarticular muscles, which makes muscle activity patterns more closely related to joint moment patterns.

Fig. 3. Hamstring EMG activity. For each muscle a representative trial was chosen for each grade from a single participant’s data to demonstrate the typical activity. Each trial was normalized to its stride time and plotted in %stride, with heel strike occurring at 0%. The toe-off time for each trial was also normalized to %stride and is indicated with a vertical line (average over all 24 representative trials for all eight muscles = 62.8%). Horizontal lines representing the average burst data (mean for all subjects exhibiting the burst) are overlaid on each plot, and the values are also displayed on the plots: a = the group average mean activity (as a percentage of mean activity at 0% grade), d = the group average burst duration (in %stride). For bursts that do not start at heel strike o = the onset time (in %stride). Any significant differences from 0% based on the follow-up comparisons are denoted by the symbol (p<0.01667).
5. Conclusions

Backward slope walking was used to elucidate whether power requirements influence movement control strategies. Based on the data presented here, it appears that power requirements of tasks influence the muscle activity pattern needed to accomplish the movements. This idea was suggested previously by Grasso et al. (1998) for backward level walking, where it appeared that kinematic patterns were conserved via a reorganization of muscle activity patterns. Our data suggest this reorganization is due to changes in joint power requirements. During tasks where power absorption increased, changes in muscle activity patterns were directly related to changes in joint moment patterns. In contrast, during tasks where power generation increased, changes in muscle activity were related to changes in joint moments only at the ‘primary’ joint; at adjacent joints changes in the muscle activity were unrelated to joint moment patterns. These ‘paradoxical’ changes in muscle activity are likely related to activation of biarticular muscles required by increasing power generation. In total, these data suggest that increased power generation requirements at a joint may significantly impact control of muscle activity at adjacent joints.

6. Future directions

Although this series of investigations used forward and backward slope walking at steep inclines as a perturbation of normal locomotion to study neural control mechanisms, slope walking at smaller inclines is an important activity of daily living. With this in mind, a larger study could be proposed to address similar control issues in the elderly, where strength, power and neural control mechanisms are compromised; or in a larger population of both young and older adults to evaluate the effect of gender and age on gait performance (Kerrigan et al., 1998; Laufer, 2003).

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References


