Walking Strategies During the Transition Between Level and Hill Surfaces

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Healthy young adults transition between level and hill surfaces of various angles while walking at fluctuating speeds. These surface transitions have the potential to decrease dynamic balance in both the anterior-posterior and medial-lateral directions. Hence, the purpose of the current study was to analyze modifications in temporal-spatial parameters during hill walking transitions. We hypothesized that in comparison with level walking, the transition strides would indicate the adoption of a distinct gait strategy with a greater base of support. Thirty-four participants completed level and hill trials on a walkway with a 15-degree portable ramp apparatus. We collected data during 4 transition strides between level and ramp surfaces. In support of our hypothesis, compared with level walking, the base of support was 20% greater during 3 out of the 4 transition strides. In short, our results illustrate that healthy young adults did adopt a distinct gait strategy different from both level and hill walking during transitions strides.

Keywords: locomotion, uphill, downhill

Healthy young adults transition between level and hill surfaces in the complex, outside world while walking at fluctuating speeds. These surface transitions have the potential to influence dynamic balance in both the anterior-posterior and medial-lateral directions. Therefore, it is plausible that healthy young adults adopt a distinct gait strategy during transition strides to maintain a safe and stable walking pattern.

Past studies differentiate between gait strategies by evaluating spatial-temporal parameters such as speed, step length, stance time, and step width (Myers et al., 1996; Maki, 1997; Giladi et al., 2005; Balash et al., 2007; Delbaere et al., 2009). For instance, in an effort to improve anterior-posterior balance, older adults walk with a slower speed, shorter step length, and greater stance time (Maki, 1997; Eils et al., 2004). In addition, to enhance medial-lateral balance, both young and older adults walk with a larger step width by maintaining a greater distance between the heels or toes (Maki, 1997; Schrager et al., 2008; Menant et al., 2009). Together, changes in the mean magnitude of these parameters illustrate that individuals may modify their gait patterns in anticipation of a future decrease in balance. Moreover, changes in stride-to-stride variability of speed, step length, and stance time illustrate that individuals may modify gait patterns in response to a current perceived decrease in balance (Maki, 1997). Thus, when comparing spatial-temporal gait strategies between strides of level, hill, and transition walking, it is important to examine both mean differences as well as variability differences.

Previous investigators have examined walking spatial-temporal variables on hill surfaces but not during the transition between level and hill surfaces (Kawamura et al., 1991; Sun et al., 1996; Lay et al., 2006). Kawamura et al. (1991) measured speed, step length, stance time, and step width during walking on a 12° hill. They demonstrated that speed was significantly slower during both uphill and downhill conditions. This slower speed was reflected in a decrease in step frequency during uphill walking and a decrease in step length during downhill walking. Stance time was also greater during uphill walking. Despite these indications that hill walking differs from level walking in the anterior-posterior direction, there was no significant difference in step width, indicating no change in the medial-lateral direction. However, because Kawamura et al. (1991) only measured strides on the hill surface, it is unknown if the strides between surfaces will elicit similar hill strategies or a distinct transition strategy.

Hence, the purpose of the current study was to analyze modifications in temporal-spatial parameters during hill walking transitions. We predicted that in comparison with level walking, the transition strides would indicate the adoption of a distinct gait strategy with a greater base of support to maintain both anterior-posterior and medial-lateral balance. More specifically, we hypothesized that speed would be slower, step length would be shorter, stance time would be greater, and that the within-subject trial-to-trial variability of these measures would be greater.
than level walking. We also hypothesized that step width at the heel and toe, and base of support would be greater than level walking.

Methods

Participants

Thirty-four healthy college students, 17 men and 17 women, completed the protocol. Mean (SD) participant characteristics were as follows: age = 21.78 (1.70) years, height = 1.72 (0.09) m, and mass = 71.83 (15.58). All gave written informed consent that followed the guidelines of the Pennsylvania State University Human Research Committee.

Protocol

Each participant completed a standing trial and a series of randomly assigned walking conditions on the level and hill surfaces. All of the walking trials were completed at a self-selected velocity along a 25-m walkway. We used a custom-built portable apparatus composed of a 2.4-m ramp inclined at 15° continuous with a 4.8-m plateau (Figure 1). The minimum total walking distance was 14.2 m.

A complete data set comprised 5 level walking trials and 30 hill walking trials. Due to the limited collection volume of the motion analysis system, we shifted the apparatus to collect the appropriate stride. We collected five walking trials during the two hill-only strides, downhill ramp (DN) and uphill ramp (UP), as well as each of the following four transition strides: level plateau to downhill ramp (L-DN), downhill ramp to level floor (DN-L), level floor to uphill ramp (L-UP), and uphill ramp to level plateau (UP-L). A trial was defined as successful if a full stride of the left leg from toe-off to toe-off was captured in the collection volume. A transition stride was defined to include the left toe-off and right foot contact on the first surface and the left foot contact (Step 1) and right foot contact (Step 2) on the new surface. A stride was defined in this way to evaluate the step length and step width during the first double support after the transition. Participants were instructed to begin walking with the left or right leg at the start of each trial to adjust for changes in stride characteristics between conditions.

Kinematics

We collected kinematic data with a six-camera, passive marker 3-D photogrammetric system (Motion Analysis Corporation, Santa Rosa, CA). The calibration residual was less than 0.5 mm in a capture volume of approximately 2 m × 2 m × 2 m. Before data collection, we placed retro-reflective markers on the sacral crest as well as on the shoes of each participant superficial to the posterior calcaneus and superior hallux. We collected the marker data at 100 Hz and postprocessed the data with EVaRT software (Version 3.21, Motion Analysis Corporation). A purpose-written Matlab program (Version R2006b, Mathworks, Natick, MA) was used for subsequent data processing that included a low-pass filter for the marker trajectories at 7 Hz (fourth-order, dual-pass, Butterworth).

Dependent Variables

After data collection, we evaluated the following temporal-spatial gait parameters during each of the hill and transition strides: (1) speed—the absolute value of the difference in anterior-posterior distance of the sacral crest marker at the first left toe-off and second left toe-off divided by the stride time, (2) step length—the absolute value of the difference in anterior-posterior marker location from right heel strike to left heel strike, (3) stance time—the time from left heel strike to left toe-off, and (4) heel and toe step width—the absolute value of the

Figure 1 — Portable ramp apparatus incorporated into a 25-m walkway.
Transitioning Between Level and Hill Surfaces

In support of our hypothesis, compared with level walking, speed was slower during the L-DN and UP-L transitions. Also in agreement of our hypothesis, step length variability was greater during L-DN, L-UP, and UP-L transitions, and the base of support was 20% greater during the L-DN, L-UP, and UP-L transition strides (Table 1). The ANOVA demonstrated that there was a significant main effect for condition for all of the dependent variables. However, these summaries only begin to describe how and when walking humans modulate their gait strategy during surface transitions.

We observed multiple significant changes in the spatial-temporal parameters of speed, step length, and stance time during hill transitions compared with level walking (Table 1). Mean speed during level walking was 1.39 m/s. During both the L-DN transition (p < 0.001) and UP-L transition (p < 0.001), speed was over 7% slower. However, speed was also 6% faster during the DN-L transition, which is in agreement with our hypothesis. Step length values were significantly different for all transition strides from the average mean of 73.0 cm during level walking. Yet step length during the DN-L transition was 1.39 m/s. During both the L-DN transition (p < 0.001) and UP-L transition (p < 0.001), speed was over 7% slower. However, speed was also 6% faster during the DN-L transition. Also in agreement with our hypothesis, step length was also 6% faster during the DN-L transition. We observed multiple significant changes in the spatial-temporal parameters of speed, step length, and stance time during hill transitions compared with level walking (Table 1). The ANOVA demonstrated that there was a significant main effect for condition for all of the dependent variables. However, these summaries only begin to describe how and when walking humans modulate their gait strategy during surface transitions.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>L-DN</th>
<th>DN</th>
<th>DN-L</th>
<th>Level</th>
<th>L-UP</th>
<th>UP</th>
<th>UP-L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (m/s)</td>
<td>1.25 (0.17)</td>
<td>1.33 (0.19)</td>
<td>1.47 (0.16)</td>
<td>1.39 (0.12)</td>
<td>1.36 (0.16)</td>
<td>1.25 (0.13)</td>
<td>1.28 (0.14)</td>
</tr>
<tr>
<td>Step Length (cm)</td>
<td>66.9 (12.9)</td>
<td>65.1 (9.5)</td>
<td>81.2 (6.7)</td>
<td>73.0 (5.5)</td>
<td>79.6 (8.5)</td>
<td>70.6 (5.7)</td>
<td>76.0 (8.0)</td>
</tr>
<tr>
<td>Stance Time (ms)</td>
<td>612 (17)</td>
<td>622 (30)</td>
<td>605 (25)</td>
<td>631 (20)</td>
<td>633 (22)</td>
<td>648 (15)</td>
<td>631 (21)</td>
</tr>
<tr>
<td>Speed Variability (m/s)</td>
<td>0.10 (0.02)</td>
<td>0.04 (0.02)</td>
<td>0.04 (0.02)</td>
<td>0.04 (0.02)</td>
<td>0.03 (0.02)</td>
<td>0.04 (0.02)</td>
<td>0.04 (0.03)</td>
</tr>
<tr>
<td>Step Length Variability (cm)</td>
<td>3.2 (1.1)</td>
<td>1.9 (0.0)</td>
<td>2.1 (1.0)</td>
<td>1.8 (0.8)</td>
<td>2.5 (1.4)</td>
<td>3.1 (1.2)</td>
<td>3.5 (2.7)</td>
</tr>
<tr>
<td>Stance Time Variability (ms)</td>
<td>14 (6)</td>
<td>13 (7)</td>
<td>11 (5)</td>
<td>11 (5)</td>
<td>13 (5)</td>
<td>12 (8)</td>
<td>13 (8)</td>
</tr>
<tr>
<td>Step Width Heel (cm)</td>
<td>11.9 (2.9)</td>
<td>10.7 (2.9)</td>
<td>9.4 (3.4)</td>
<td>10.2 (2.9)</td>
<td>11.2 (3.7)</td>
<td>10.2 (3.8)</td>
<td>11.1 (3.6)</td>
</tr>
<tr>
<td>Step Width Toe (cm)</td>
<td>8.9 (5.3)</td>
<td>8.8 (5.9)</td>
<td>6.4 (4.7)</td>
<td>6.9 (4.8)</td>
<td>6.1 (4.5)</td>
<td>5.8 (4.7)</td>
<td>6.5 (5.6)</td>
</tr>
<tr>
<td>Base of Support Area (cm²)</td>
<td>416.2 (145.8)</td>
<td>384.7 (163.4)</td>
<td>312.2 (111.5)</td>
<td>364.5 (132.2)</td>
<td>427.7 (160.9)</td>
<td>421.7 (153.0)</td>
<td>430.8 (184.7)</td>
</tr>
</tbody>
</table>

Note. Top Section: speed, step length, and stance time. Middle Section: variability calculated as the between-trial variability of each participant for speed, step length, and stance time. Bottom Section: step width at the heel and at the toe, and base of support area. All data are represented as the mean raw values of each trial averaged for all 40 participants. Italicized values represent level walking. Boldface values represent a statistically significant difference as compared with level walking (p < 0.05). Shaded regions indicate the changes consistent with the direction hypothesized.

Statistical Analysis

All data were analyzed across transition conditions using a repeated-measures design (ANOVA). Where appropriate, we performed Newman–Keuls post hoc tests to analyze the differences between conditions and reported all values as mean ± SD. Significance was defined as p ≤ 0.05.
Figure 2 — Illustration of level walking stride (gray line) and transition strides (black lines) for (A) level-down, (B) down, (C) down-level, (D) level-up, (E) up, and (F) up-level. Shaded regions represent a hill surface and unshaded regions represent a level surface. The foot placement locations represent actual change in step length as well as step width at the heel and toe. Each small box is equal to a 3 cm × 3 cm square.
Next, although variability for speed and stance time was only significantly greater during a single condition, L-DN, compared with level walking, variability for step length was greater during multiple hill transition strides (Table 1). Step length variability was not significantly different from level walking during DN-L, but was significantly greater during the remaining conditions, in particular, 209% greater during UP-L ($p < .001$).

Step width at the heel and toe also exhibited differences during hill transitions compared with level walking (Table 1, Figure 2). Heel step width was slightly more consistent across conditions with a mean maximum change of 2.5 cm as compared with a change of 3.0 cm at the toe. The two significant differences for step width at the heel were during L-DN and L-UP, where step width was 18% ($p < .001$) and 10% ($p < .05$) larger, respectively. Step width at the toe during the L-DN condition was also larger by 48% ($p < .01$). However, contrary to our hypothesis, step width at the toe was smaller during both L-UP and UP-L by at least 11% ($p < .05$).

As we hypothesized, in comparison with level walking, base of support, which includes step length and step width measures, was greater during the L-DN, L-UP, and UP-L conditions by a minimum of 25% (Table 1). In contrast, due to the shorter step length, during the DN-L condition, the base of support was 13% less than level walking ($p < .01$).

Compared with level walking, hill and transition walking resulted in many significant spatial-temporal differences. But depending on the stride condition, these differences were often in different directions and of different magnitudes. During uphill walking, speed decreased while stance time, step length variability, step width at the toe, and base of support all increased. However, during both uphill transitions stance time was not significantly different from level walking and step length was significantly greater during downhill walking, speed and step length decreased while step width at the toe increased. The DN-L condition resulted in opposite changes as speed and step length increased while stance time decreased. In contrast, the L-DN condition resulted in significant differences for all variables. Similar to the DN condition, speed and step length decreased and step width at the toe increased. In addition, stance time decreased and variability for all variables increased as well as step width at the heel and base of support.

In summary, compared with level walking, speed was slower during both DN and UP conditions by 5% ($p < .05$) and 10% ($p < .001$), respectively while step length was 11% shorter ($p < .001$) during the DN condition. Step width at the toe was 52% larger than level walking during the DN condition ($p < .01$) and 23% smaller during the UP condition ($p < .05$). To add, during the UP condition, base of support was 22% greater ($p < .01$) than level walking.

### Discussion

Our results illustrate that healthy young adults adopted gait strategies different from both level and hill walking during all of the transition strides. During the L-DN transition, speed, step length, and stance time were significantly less than level walking while variability, step width, and base of support were all greater (all values $p < .05$). With the exception of stance time, these results agree with our hypothesis that during hill walking speed and step length would be less than level walking, while stance time, variability of speed, step length, stance time, step width, and base of support will all be greater. In contrast, during the DN-L transition, speed and step length were greater than level walking while stance time and base of support were less (all values $p < .05$). During both uphill transitions, L-UP and UP-L, speed was less than level walking, and step length variability and base of support were both greater, as hypothesized.

To begin, speed was significantly slower than level walking during the L-DN and UP-L transitions as hypothesized (Table 1). However, the average speed of 1.47 m/s during DN-L was 6% faster. This increase in speed, due in part to gravity, was the product of an 11% greater step length. In fact, the only transition with a significantly shorter step length was L-DN. It is possible that this stride was unique because transitioning from a level to a downhill surface does not require increased toe clearance or increased range of motion to safely cross the transition boundary. Chen et al. (1991) observed that step length increased in attempts to safely clear an obstacle during level walking. In fact, clearing an obstacle of minimal height, such as a line of tape on the floor, resulted in a 10% greater step length and this length increased more as the obstacle height increased (Chen et al., 1991). These results correspond closely to the 4–11% longer step length during the DN-L, L-UP, and UP-L conditions because of the increase in toe clearance due to the edge of the ramp.

Step length variability was also significantly greater during L-DN, L-UP, and UP-L compared with level walking (Table 1). Chen et al. (1991) reported that step length variability was greater when stepping over an obstacle and Maki (1997) concluded that this increase was an indication of increased fall risk. Therefore, it is likely that participants perceived these strides as an obstacle and they attempted various strategies to maintain anterior-posterior balance during the transition.

Step width at the heel and toe exhibited significant changes in multiple conditions (Table 1). As hypothesized, the step width at the heel was larger during L-DN as participants adopted an increased base of support to improve medial-lateral balance. It is possible that there are metabolic determinants to these step width modifications. Donelan et al. (2001) used a simple model to determine that the cost of step-to-step transitions is minimized at narrow step widths. In a subsequent study, Donelan et al. (2004) manipulated step width while measuring metabolic cost and modeled the walking mechanics. They concluded that walking humans prefer a step width that minimized metabolic cost while maintaining balance. So it appears that during L-DN, the participants in the current study altered their preferred step width to emphasize the maintenance of balance over the minimization of metabolic cost.
Similarly, toe step width was significantly larger during L-DN transition but was significantly smaller during both L-UP and UP-L (Table 1), which subsequently affects medial-lateral balance due to the reduced base of support. We did not originally anticipate the smaller toe step width during the uphill walking conditions. It is possible that this modification is a strategy used to improve propulsion. Erdemir and Piazza (2002) support this idea and stated that internal/external rotation of the foot has the potential to modify the force-generating capacity of the ankle extensors. Previous research has evaluated the effects of toe position and speed. For example, Ho et al. (2000) discovered a correlation between narrow toe position and faster walking speed in children. Furthermore, Fuchs and Staheli (1996) observed that sprint runners use a similar in-toeing strategy. In sum, it appears that the participants may have prioritized propulsion over medial-lateral balance during these L-UP and UP-L conditions as the base of support was smaller than during level walking.

Overall, our step width data, particularly at the toe, did not correspond with the ramp walking data of Kawamura et al. (1991). They found no significant difference in step width between any of the uphill or downhill conditions in comparison with level. However, our methodology differed in four critical aspects. First, they collected walking data on a ramp but did not collect data during the transitions between these conditions. It is likely that the transitions between surfaces pose a greater risk of falling than the hill independently. Second, Kawamura et al. collected data on a 12° ramp, which was less steep than our 15° apparatus. So there may be a decisive hill angle at which participants widen step width to maintain balance. Third, they measured kinematics indirectly via a force plate on the level ground below the ramp apparatus. We measured foot placement at the toe and heel using marker data. It is possible that internal and external foot rotation was a detail that was not detected from force data. Fourth, Kawamura et al. instructed their participants to complete the protocol in bare feet whereas our subjects wore recreational shoes. Thus, the cutaneous receptors stimulated during barefoot walking may have aided the participants in selecting a narrow step width due to the increased sensitivity.

Prentice et al. (2004) also conducted a thorough investigation on hill walking and more specifically the uphill transitions that provides ideal insight for the current study. They collected walking kinematic data during the approach to a ramp and during the first step on the ramp for 3°, 6°, 9°, and 12° conditions. Both limb and trunk motion was modified in a scaled fashion to navigate surface slope transitions. During the initial portion of swing, the leg trajectory was exaggerated to ensure clearance, while during the terminal portion of swing, the trajectory was specific for the present slope (Prentice et al., 2004). Our data for the transition steps show similar trends. The participants may not have been capable of optimally modifying their gait patterns until they received additional sensory feedback regarding the specific condition from contacting the new surface. For example, during the L-UP transition, heel step width was larger than during level walking, while there was no change in toe step width. As progression up the hill continued from the L-UP to the UP condition, the toe step width narrowed further.

Finally, our measure of base of support, which included step length, heel step width, and toe step width, was significantly larger for L-DN, L-UP, and UP-L transitions (Table 1). Interestingly, during the UP-L condition, toe step width was smaller for propulsion but step length was greater. These differences resulted in a greater base of support, which shows how both the need for increased propulsion and increased balance can be accounted for simultaneously during hill transitions.

The L-DN transition likely poses the highest level of fall risk as demonstrated by the adoption of a cautious gait strategy (Maki, 1997; Balash et al., 2007). During this transition, speed and step length were less than level walking while step length and stance time variability were greater as a result of anterior-posterior balance requirements. To add, step width at both the heel and the toe were significantly larger to modify medial-lateral balance. Finally, despite selecting a shorter step length, base of support area was larger to improve overall balance. It is likely that the participants modified their gait at this transition due to a greater perceived risk of falling.

In the future, we plan to quantify these spatial-temporal gait parameters during walking hill transitions in older adults. Numerous studies have concluded that balance decreases with age as evidenced by decreased step width variability and larger step width magnitude (Maki, 1997; Brach et al., 2005; Schrager et al., 2008). If these two findings correlate to hill walking, then it is possible that the transitions between level and hill surfaces could pose the highest risk for imbalance, thereby leading to falls.

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References
Brach, J.S., & Berlin, J.E., et al. (2005). Too much or too little step width variability is associated with a fall history in older persons who walk at or near normal gait speed. Journal of Neuroengineering and Rehabilitation, 2, 21.


