Effects of Load Carriage and Surface Inclination on Slip and Trip Risks

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INTRODUCTION

Slips, trips, and falls continue to be significant occupational safety concerns, and causes of occupational injuries and fatalities in the workplace and daily activities. While extensive gait research has focused mainly on level walking, less evidence is available for inclined surfaces. The latter is particularly important since walking on inclined surfaces increases the risk of instability and slips, due to the generation of higher shear forces.

Diverse work environments (e.g., construction and agriculture) require load carriage during walking on inclined surfaces. However, few studies have assessed the risks of slips or trips in such conditions. To our knowledge, this is the first study that specifically investigated different methods of load carriage without the use of packs or other assistive devices and the influence of walking on inclined surfaces. We hypothesized that surface inclination, load carriage method, and load magnitude would significantly affect biomechanical parameters related to the risks of slipping or tripping.

METHODS

Twenty participants (gender balanced), with no self-reported musculoskeletal disorders, completed the experiment after giving informed consent (procedures approved by the VT IRB). Respective means (SD) for age, stature, and body mass were 26.1 (3.3) yrs, 167.9 (7.4) cm, and 72.3 (9.0) kg. Each participant walked in 12 different loaded conditions (e.g., Fig. 1). The 12 conditions involved all combinations of: 1) three surface inclinations (SIs): level, up and down a 20° incline, 2) two types of Load Carriage (LC): on head and posterior load carriage (on upper back), and 3) two Load Magnitudes (LM): medium (7.5 kg) and heavy (15 kg) loads. Dependent variables were step length (SL), walking velocity (WV), required coefficient of friction (RCOF), heel contact velocity (HCV), and minimum toe clearance (MTC), each of which were normalized to values from additional no-load conditions.

Consistent shoes were provided to the participants, and 18 passive retro-reflective markers were placed over bony landmarks to track segmental kinematics using a 9-camera system (Vicon Motion System Inc., Los Angeles, CA, USA). Kinematic data were recorded at 120 Hz, and low-pass filtered with a cutoff frequency of 5 Hz. Ground reaction forces were sampled (960 Hz) from two force platforms (AMTI OR6-7-1000, Watertown, MA, USA), and low-pass filtered at 12 Hz.

Separate repeated-measures analyses of variance were performed to assess the effects of SI, LC, and LM on each normalized dependent measure, with post hoc comparisons done using Tukey’s HSD. Student t tests were used to compare conditions to the relevant no-load conditions. All statistical analyses were conducted using JMP Pro 11 (SAS Institute Inc., Cary, NC), and statistical significance was determined when p < 0.05.

RESULTS AND DISCUSSION

All dependent measures were significantly affected by SI (Table 1), with substantial effects in some cases (Fig. 2). Compared to the level walking, SL decreased by 5.3% going uphill, while WV and HCV respectively decreased by 2.4 and 10.4% going downhill. There were 7.4 and 6.4% decreases in RCOF during downhill and uphill walking, respectively. MTC during downhill walking was 8.9% larger than in level walking. Main effects of LC and LM were only significant on WV. Normalized WV was 1% lower when carrying the heavier loads, while it was 2% higher carrying the load on the back. During level walking, RCOF was
larger for on head versus posterior load carriage (~5%).

RCOF and HCV are the main parameters associated with friction demand during human gait [1]. A slip event can be initiated when the required friction demand exceeds the available friction. In all surface conditions, RCOF increased relative to the no-load condition, especially during level walking (~9.3%), indicating a higher risk of slip initiation. An increase in HCV has been considered to increase the likelihood of slip-induced falls [2]. Similar to previous work [1], HCV decreased with load carriage, and is likely related to adoption of slower gait (~3.8%). However, the decrease in WV was not as large as the decline of HCV, which was more pronounced in downhill walking. Specifically, WV decreased by 5.3%, while HCV decreased by 13.6%, and which might indicate adoption of safer gait to decrease slip risk during the most risky condition (walking downhill). Decreased MTC increases trip risk, and which may increase the risk of fall-related injuries [3]. While carrying a load, MTC decreased during uphill (~0.9%) and flat (~3.3%) walking, and suggests a higher trip risk.

Overall, SI was the most influential factor in this study. Except for WV, use of different LMs did not significantly affect any of the dependent variables. Similarly, the main effect of LC method (i.e., on head versus posterior load carriage) was only significant on WV. Considering RCOF, LC method was mainly influential while walking over the flat surface. In summary, interventions to decrease the risk of slips, trips, and falls while carrying a load on different surfaces may focus more on Surface Inclination, rather than the Load Magnitude or the Load Carriage method.

Table 1: Summary of ANOVA results (p values) for main and interactive effects of SI, LC, and LM.

<table>
<thead>
<tr>
<th></th>
<th>SI</th>
<th>LC</th>
<th>LM</th>
<th>SI×LC</th>
<th>SD×LM</th>
<th>LC×LM</th>
</tr>
</thead>
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<tr>
<td>SL</td>
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<td>0.48</td>
<td>0.39</td>
<td>0.65</td>
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<td>WV</td>
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<td>0.0170</td>
<td>0.08</td>
<td>0.21</td>
<td>0.94</td>
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<tr>
<td>HCV</td>
<td>0.0033</td>
<td>0.31</td>
<td>0.15</td>
<td>0.06</td>
<td>0.70</td>
<td>0.94</td>
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<tr>
<td>RCOF</td>
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<td>0.40</td>
<td>0.0053</td>
<td>0.61</td>
<td>0.50</td>
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<tr>
<td>MTC</td>
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<td>0.52</td>
<td>0.41</td>
<td>0.63</td>
<td>0.88</td>
</tr>
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REFERENCES