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Carrying asymmetric loads while walking on an uneven surface

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ABSTRACT

Background: Individuals often carry asymmetric loads over challenging surfaces such as uneven or irregular terrain, which may require a higher demand for postural control than walking on an even surface.
Research Question: The purpose of this study was to assess postural stability in the medial-lateral (ML) direction while carrying unilateral versus bilateral loads when walking on even versus uneven surfaces.
Methods: Nineteen healthy young adults walked on even and uneven surface treadmills under three load conditions: no load, 20% body weight (BW) bilateral load, and 20% BW unilateral load. A Pedar in-shoe pressure system (Novel, Munich, Germany) was used to evaluate center of pressure (COP)-based parameters.
Results: Carrying 20% BW bilateral or unilateral loads significantly increased double support ratio. In addition, carrying a 20% BW unilateral load significantly increased coefficient of variation (CV) of double support ratio, CV of ML COP excursion, and CV of ML COP velocity. Walking on an uneven surface significantly increased double support ratio, ML COP excursion, ML COP velocity, and CV of double support ratio. When carrying a 20% BW unilateral load, unloaded limb stance had significantly increased double support ratio and ML COP velocity, although it appears that the loaded limb may be used to make step-by-step adjustments as evidenced by the higher CV of ML COP velocity.
Significance: Unilateral load carriage, walking on uneven surfaces, and unloaded leg stance are of particular concern when considering postural stability.

1. Introduction

Individuals often carry items in one hand instead of both hands during activities of daily living. Asymmetric load carriage is expected to produce a lateral shift of the center of mass and may result in a challenge to postural control during walking [1]. Previous studies have reported that asymmetric load carriage increased medial-lateral (ML) center of pressure (COP) velocities during quiet standing [2] and increased ML COP displacement during gait initiation [3]. However, a recent study reported no differences in ML COP excursion and velocity with bilateral and unilateral shopping bags during quiet standing [4]. The discrepancy in results between previous studies may be due to different load conditions or static versus dynamic conditions and indicates that further study is needed to determine how unilateral load carriage affects postural stability during walking.

Individuals may carry asymmetric loads over challenging surfaces such as uneven or irregular terrain, which may require a higher demand for postural control than an even surface. For example, walking on an irregular surface increased step width and step time variability [5], walking on a loose rock surface increased step width variability and ML center of mass (COM) velocity [6], and walking on a multi-surface terrain increased step variability and ML trunk bending variability [7]. Previous studies have also demonstrated that asymmetric load carriage resulted in significant differences in lower extremity joint moments between loaded and unloaded limbs [1,8]. These findings support the idea that the uneven surfaces are more challenging for postural control, particularly in the ML direction, and that it is of interest to investigate differences for postural control between loaded versus unloaded limb stance.

Postural stability can be evaluated using time-to-contact (TTC), which is the estimated time it takes the COP to reach the boundary of foot [9]. TTC includes both spatial and temporal (COP position, velocity and acceleration) aspects of postural control relative to the base of support [10]. TTC has been used to evaluate postural stability and provide a measure of how long an individual has to make a postural adjustment before the COP reaches a two-dimensional boundary of foot [9,10]. However, this approach has been limited to static tasks such as quiet standing. A standard TTC analysis is challenging to apply to gait since the COP must leave the boundary of one foot and shift to the other foot as the human body progresses forward. Therefore, a modified TTC

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method was proposed to evaluate postural stability during walking in the current study.

Increasing double support time is believed to be a common strategy to improve postural stability during challenging walking conditions or unstable gait. Several studies have reported that symmetric load carriage with a backpack resulted in increased double support time during walking [11,12]. In addition, increased double support time may be utilized to improve postural stability for individuals at high risk for falls [13,14]. Thus, increased double support time is indicative of an attempt to improve postural stability and to avoid loss of balance during challenging walking conditions.

Previous studies have indicated that asymmetric load carriage [2,3], walking on uneven surfaces [5–7], and unloaded limb stance [1] present postural challenges and/or loading asymmetry in the ML direction. However, we are not aware of any studies that have evaluated postural stability of unilateral load carriage while walking on an uneven surface. Therefore, the purpose of this study was to assess postural stability, particularly in the ML direction, when carrying unilateral versus bilateral loads and when walking on even versus uneven surfaces. We tested the following hypotheses:

1 ML COP velocity would be increased and ML TTC percentage would be decreased during unilateral load carriage as compared to bilateral load carriage.
2 ML COP velocity would be increased and ML TTC percentage would be decreased when walking on an uneven surface as compared to an even surface.
3 ML COP velocity would be increased and ML TTC percentage would be decreased during unloaded limb stance as compared to loaded limb stance for unilateral load carriage.

2. Methods

Nineteen healthy young adults with an age range of 18–30 (14 males and 5 females; age 25.5 ± 3.9 years; height 172.6 ± 5.0 cm; mass 69.7 ± 7.2 kg) participated in this study. Participants were free of any pathology that would affect them while walking on a treadmill or prevent them from being able to carry a 20% body weight (BW) load. Individuals were excluded if they had back, neck, leg, foot, or arm pain. Each participant read and signed an informed consent form approved by the institutional review board of Iowa State University (IRB ID: 16-058). Prior to data collection, potential participants were asked if they had any of the listed areas of body pain as part of a medical history questionnaire, and their ability to carry 20% BW load was confirmed during a warm-up session.

Three load conditions were tested: no load, 20% BW bilateral load, and 20% BW unilateral load (Fig. 1). The 20% unilateral load was carried in the participant's dominant hand, while the 20% BW bilateral load was evenly split between both sides of the body (10% BW load carried with each hand). Two hand-held bags were utilized in this study and filled with sealed bags of lead shot to match a load normalized according to each participant's body weight. These normalized loads were based on previous studies that indicated significant kinematic and/or kinetic changes when carrying loads ranging from 10% to 20% BW [1,11,12]. Two different treadmills were used for the even and uneven surface conditions (Fig. 2). Small wood strips (thickness: 1.27 cm × anterior width: 5 cm × medial-lateral length: 13.5 cm) were used to build the uneven surface treadmill with a random pattern. The participants completed six total conditions (2 surfaces × 3 loads).

The participants were instructed to walk on even and uneven surface treadmills for one minute under the three load conditions as a warm-up session to familiarize with the load carriage conditions [15]. The treadmill velocity was started at 0.22 m/s and then the speed was gradually increased or decreased until the participant signaled that the preferred walking speed had been reached. The six preferred walking speeds were recorded and then the slowest walking speed was selected as a constant walking speed for further data collection. Average walking speeds were 1.1 m/s for no load on the even surface, 0.9 m/s for 20% BW bilateral and unilateral load on the even surface, 0.8 m/s for no load on the uneven surface, and 0.7 m/s for 20% BW bilateral and unilateral load on the uneven surface. Thus, the participants were then asked to walk on the even and uneven surface treadmills (average walking speed 0.7 m/s) for 90 s under the three load conditions in a randomized order. Each participant was allowed to rest as much as necessary between conditions, with a minimum break of one minute. A Pedar in-shoe pressure system (Novel, Munich, Germany) was used to collect vertical forces and COP in each foot at 100 Hz. Each in-shoe pressure system consists of 99 sensors that allow the measurement of COP trajectory and pressure distribution (validated up to 60 N/cm^2 with a 3.9% error) [16,17].

2.1. Data processing

To minimize any carryover effect from previous conditions, we analyzed the first 10 strides during the last 30 s of each condition. During unilateral load carriage, the loaded limb was on the side of the carried load, while the unloaded limb was the opposite side. Single stance phases and double support phases were determined using the vertical forces, and double support ratio was calculated as a ratio of double support time to single stance time. Heel strike and toe-off were detected with a 5% BW threshold for vertical ground force data [18]. A rectangular base of support for each foot (Fig. 3) was defined by the dimensions of the Pedar insole sensor (8.5 cm × 26 cm or 27 cm). The origin of the insole sensor is located at the most posterior and medial point of the sensor, and thus the COP positions were recoded as anterior-posterior and ML coordinates relative to this origin. ML COP excursion and mean ML COP velocity were determined during single stance phases for each foot. ML COP velocities and accelerations were calculated with the first central difference method [19].

ML COP positions, velocities, and accelerations were used to calculate ML TTC using the equation in Fig. 3. Since the COP shifts between the boundaries of each foot during walking, the assessment of TTC commonly used during quiet stance was modified. TTC was calculated at each data point and then compared to the remaining single stance time (Fig. 4). If the TTC was less than the remaining single stance time, then the TTC value was stored for that time point, indicating a postural adjustment was required during single stance. If the TTC was greater than the remaining single stance time, then the TTC was set to the remaining single stance time, indicating double support begins before a postural adjustment was needed. TTC percentage was then calculated by normalizing TTC by mean remaining single stance. A TTC percentage of 100% indicated that no postural adjustment was required during single stance.

Variability in double support ratio, ML COP excursion, and ML COP velocity was evaluated though coefficient of variation (CV) for ten strides. Increased stride-to-stride variability can be indicative of inconsistent steps and decreased stability during walking [20]. In total, there were seven dependent variables: double support ratio, ML COP excursion, mean ML COP velocity, ML TTC percentage, CV of double support ratio, CV of ML COP excursion, and CV of ML COP velocity. COP-based parameters were calculated using a custom-made Matlab code (Mathworks Inc., Natik, MA).

2.2. Statistical analyses

The effects of the different loading conditions and the effects of different surfaces on COP parameters were analyzed using repeated measures Multivariate Analysis of Variance (3 × 2 MANOVA). To investigate these effects, the higher double support ratio, ML COP excursion, and ML COP velocity were selected between left and right limb stance during each gait cycle. The mean values were then calculated for 10 strides. The lowest ML TTC percentage was determined for 20 steps