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Location of minimum foot clearance on the shoe and with respect to the obstacle changes with locomotor task

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ABSTRACT

Minimum foot clearance (MFC) as it relates to trips and falls has been extensively studied across many locomotor tasks, but examination of this body of research yields several studies with conflicting results and a wide range of MFCs within tasks. While there are several factors that may affect the MFC variability across studies (populations studied, environmental conditions, etc.), one aspect of the discrepancies in the literature may be the result of different placements of shoe markers and/or MFC calculation methods. A marker on the toe is often used, but may only quantify one aspect of how the foot actually clears the trip hazard. The purpose of this study was to determine the location on the shoe where MFC occurs during locomotor tasks with the highest risk of tripping. Ten young adults performed three trials of locomotor tasks which included overground walking, obstacle crossing, level change and stair negotiation. Clearance was calculated for 72 points on each shoe, including those most commonly used in past research. The location of the overall MFC on the shoe sole differed both between limbs and across locomotor tasks. Additionally, the region of the obstacle, step or stair over which the MFC occurred varied both within and across task. Use of this 3D MFC methodology provided further insight into which portions of the shoe may come closest to the tripping hazard. Future research should examine whether the location and value of the MFC changes between different populations, or with environmental modifications.

1. Introduction

Falls are the leading cause of unintentional injuries in almost every age group (NCIPC Injury Report, 2007), with tripping over an object identified as the leading cause of falls in older adults (Berg et al., 1997). Over the last 20 years there has been extensive research on minimum foot clearance (MFC) in both young and older adults during overground walking, obstacle crossing, level changes, and stair negotiation—the primary locomotor tasks during which trips often occur.

The results of these studies have yielded a wide range of MFC or minimum toe clearance (MTC) both within and across locomotor tasks: walking (0.85–3.5 cm) (Begg et al., 2007; Johnson et al., 2007; Mills and Barrett, 2001; Mills et al., 2007; Moosabhoy and Gard, 2006; Schulz, 2011; Winter, 1992), obstacle crossing (6.8–18 cm) (Austin et al., 1999; Berard and Vallis, 2006; Berg and Blasi, 2000; Chou et al., 2003; Draganich and Kuo, 2004; Lowrey et al., 2007; Lu et al., 2006; Patla and Rietdyk, 1993; Sparrow et al., 1996), up level changes (4.7–11 cm) (Begg and Sparrow, 2000; Heasley et al., 2004; 2005), down level changes (1.5–10 cm) (Begg and Sparrow, 2000; McKenzie and Brown, 2004) and stair negotiation (1.7–3.6 cm) (Hamel et al., 2005). There are many factors which may have contributed to the large variability across these studies, including differences in populations studied, environmental conditions and speed of locomotion. An additional factor that may play a role is the lack of a standard MFC calculation method and/or the selection of marker placement for different tasks. Often, a single marker is placed directly on the toe or a virtual marker is digitized on the toe of the shoe. While this may be adequate for experiments investigating changes in the trajectories of that single point through experimental modification (such as changes in vision or lighting), it may not represent actual minimum foot clearance. Based on the literature it is unclear where on the foot the overall minimum clearance is located for various tasks and where during the gait cycle this overall minimum occurs. Although Startzell and Cavanagh (1999) presented a new methodology to determine the three-dimensional clearance of the entire shoe sole during the swing phase of locomotion over 10 years ago, few studies have been published which utilized this methodology (Hamel et al., 2005; Schulz et al., 2010; Schulz, 2011; Thies et al.,

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2011). While this is the only minimum foot clearance methodology that has been validated to date (Barrett et al., 2010), the complex analyses and time required to digitize the numerous points on the shoe and in the environment may have limited its use. An analysis of the location of MFC on the shoe across different locomotor tasks may help to reduce the number of virtual points which need to be tracked during a specific locomotor task thereby helping to simplify the calculation of overall MFC. Therefore, the purpose of this study was to determine which virtual marker locations on the shoe experienced the majority of MFCs for those locomotor tasks during which trip-related falls often occur and where on the obstacle, step or stair the MFC occurred (riser, front edge, tread or back edge).

2. Methods

2.1. Participants and experimental protocol

Ten healthy young adults (6 female, 24.5 ± 2.9 yrs) free from musculoskeletal or neurological impairments participated in the study. The protocol was approved by the institutional review board at San Francisco State University and all participants signed informed consent.

Participants completed three trials of nine locomotor tasks at a self-selected pace and six were chosen for further analysis: single obstacle (OBS) crossing (17 × 91 × 3.5 cm ($h \times w \times d$)), stair ascent (AST), stair descent (DST) (7 steps with a rise/run of 17/26 cm), ascending level change (ALV), descending level change (DLV) (obstacle $h \times w$ w/a 3.5 m landing) and level overground (OG) walking. Participants were harnessed to an overhead track system to prevent falls (Solo-Step, Sioux Falls, SD). No instruction was given on which foot should cross the obstacle, level change, or stair first and no practice trials were given. The participants started 3.5 m in front of the obstacle and level change and continued to walk for at least 3 m after crossing. In the stair ascent and descent conditions the participant started 2 m from either the top or bottom stair. Due to set-up and break down of the staircase, the tasks were presented in blocks: stair ascent and descent were performed first or last; level change ascent and descent, obstacle crossing and level overground walking were block randomized before or after stair negotiation.

2.2. Data collection and analysis

Each participant wore an identical model of shoes ("Canfield" P.W. Minor, Batavia, NY). Five reflective markers were attached to each shoe to create the shoe tracking clusters (Fig. 1). Sixty-two points were digitized on the bottom of each shoe (pts. 8–32 and 34–70), 6 points on the front toe of the shoe (pts. 2–7), and one point on the lower heel sole (pt. 71). The three most commonly used landmarks in clearance studies were also digitized—the tip of toe (pt. 1), the 5th metatarsal head (pt. 33), and the heel (pt. 72). All shoe points were digitized with the participant wearing the shoe to account for shoe deformation. The points were digitized in the global coordinate system using a Davis Digitizing Pointer (C-Motion, Germantown, MD) and an 8-camera VICON® MX motion capture system (Oxford Metrics, Oxford, UK). For each participant and task, key regions of the obstacle, level change, stairs or floor were digitized for use in the analysis. These digitized points allowed for the definition of four regions on the obstacle (the front riser (RISE), front edge (FE), top tread (TR) and back edge (BE)), three on the level change and stairs (RISE, TR, and EDGE) and one on the floor surface (ground plane over which the foot crossed (GR)) in the global coordinate system (Fig. 2).

Fig. 1. Marker cluster and virtual marker locations.

The 3D trajectories of all markers were collected at 120 Hz and then exported to Visual 3D® 4.75.11 (C-Motion Inc., Germantown, MD). The marker trajectories were filtered using the Visual 3D low-pass 2nd order bidirectional Butterworth filter (resulting in a 4th order filter) with a cutoff frequency of 6 Hz. Visual 3D software allowed for the obstacles, level change, stairs and floor to be visualized within each trial using the digitized points in the global coordinate system. A local coordinate system was created for each TR, RISE and GR plane. Shoe points were digitized in the global coordinate system and then tracked during trials using the local fixed coordinate system created by the shoe tracking cluster. For clearance analysis all digitized shoe points were located in the global coordinate system for every frame in each trial for all tasks. A 3D vector distance between each point on the shoe and the current region was calculated either by transforming the virtual points into the local coordinate systems of the planes (TR, GR and RISE) or by projected points on a line in the global coordinate system (FE, BE and EDGE) (Fig. 2) (Startzell and Cavanagh, 1999).

For each task, clearances were calculated in Visual 3D for each point in each region for both leading and trailing limbs except during stair descent, down level change and overground walking where only lead limb clearances were calculated. For stair ascent, each step was considered as a new obstacle so that each stair had a lead limb (LL) and a trail limb (TL). Minimums for each point within each region were then exported from Visual 3D for further analysis. The overall minimum of the whole shoe over all regions of the obstacle, steps, stairs or ground for both limbs were found using a custom Matlab (Mathworks, Natick, MA) program. For overground walking, the local minimum was found between the two maxima of the marker trajectories. Location of the overall minimum among the 72 virtual points on the shoe and the region of the task in which it occurred (RISE, FE, TR, BE, and EDGE) were recorded. In addition to the overall MFC, minimum toe clearance (MTC—the overall minimum of pts. 1–10) values were found for each task. Previous tests of accuracy utilizing this methodology for the calculation of known clearances have found the accuracy to be within ± 2 mm (Hamel et al., 2005; Startzell and Cavanagh, 1999). Testing in our current laboratory found a similar level of accuracy (± 1.5 mm).

In addition to the determination of MFC and MTC, the gait characteristics at the time of MFC and MTC were calculated. The percent of swing phase, instantaneous gait speed (velocity of the whole body center of mass in the anteroposterior direction), foot velocity in the anteroposterior direction and relationship of the stance and swing limb toes to the whole body center of mass location in the sagittal plane were calculated. The whole body center of mass was modeled using a 13-segment kinematic model in Visual 3D. Step length of the crossing step was calculated as the distance between marker 6 (anterior toe) on the trail and lead limbs. Mid-stair step lengths were not included.

2.3. Statistical analysis

The within-group mean and standard deviation of lead and trail limb overall MFC and MTC, frequency counts by marker location (pts. 1–72), and frequency counts of overall MFC within task region (RISE, FE, TR, BE, and EDGE) were calculated for each locomotor task in MINITAB (Minitab Inc, State College, PA).

3. Results

3.1. Location of overall MFC by locomotor task region

The means and standard deviations of overall lead and trail limb MFCs by locomotor task are shown in Fig. 3. For overground walking, all MFCs occurred over the digitized plane of the floor (GR). During obstacle crossing, the MFCs for the lead limb were divided with 50% occurring over the tread of the obstacle and 50% occurring over the back edge of the obstacle (Fig. 4). For the trail limb during obstacle crossing, the MFCs were dispersed throughout all 4 regions of the obstacle (Fig. 4). While going up the level change, all lead and trail limb MFCs occurred over the edge of the step (Fig. 4). During level change descent, the lead limb MFCs occurred equally over the tread and edge of the step (Fig. 4). For the lead limb during stair ascent, all MFCs occurred over the edge of each stair (Fig. 4). The trail limb MFCs during stair ascent typically occurred over the front riser or edge depending on the step (Fig. 4). During stair descent ~90% of the lead limb MFCs occurred over the edge of the step while the remaining ~10% occurred over the tread region (Fig. 4).