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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.

Keywords

minimum foot clearance; obstacles; steps; stairs; tripping

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CONFLICT OF INTEREST STATEMENT

The authors have no financial or personal relationships with other people or organizations which may bias this work.

1. Introduction

Falls are the leading cause of unintentional injuries in almost every age group (NCIPC, 2007), with tripping over an object identified as the leading cause of falls in older adults (Berg, Alessio, Mills, & Tong, 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 (0.85–3.5cm) (Begg et al., 2007; Johnson et al., 2007; Mills & Barrett, 2001; Mills et al., 2007; Moosabhoy & Gard, 2006; Schulz, 2011; Winter, 1992), obstacle crossing (6.8–18cm) (Austin et al., 1999; Berard & Vallis, 2006; Berg & Blasi, 2000; Chou et al., 2003; Draganich & Kuo, 2004; Lowrey et al., 2007; Lu et al., 2006; Patla & Rietdyk, 1993; Sparrow et al., 1996), up level changes (4.7–11cm) (Begg & Sparrow, 2000; Heasley et al., 2004, 2005), down level changes (1.5–10cm) (Begg & Sparrow, 2000; McKenzie & Brown, 2004) and stair negotiation (1.7–3.6cm) (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., 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±2.9yrs) 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 (17×91×3.5cm (h × w × d)), stair ascent (AST), stair descent (DST) (7 steps with a rise/run of 17/26cm), ascending level change (ALV), descending level change (DLV) (obstacle h × w w/a 3.5m landing) and level overground (OG) walking. Participants were harnessed to an overhead track system to

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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 3m after crossing. In the stair ascent and descent conditions the participant started 2m 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, EDGE) and one on the floor surface (ground plane over which foot crossed (GR)) in the global coordinate system (Fig. 2).

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 6Hz. 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 & 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, 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 ±2mm (Hamel et al., 2005; Startzell and Cavanagh, 1999). Testing in our current laboratory found a similar level of accuracy (±1.5mm).

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. Midstair 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, 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 Figure 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).

3.2 Location of overall MFC on shoe

3.2.1 Lead limb—During overground walking and obstacle crossing, nearly all MFCs of the lead limb were located in the rear and heel portions of the shoe, typically near the most posterior or posterolateral portion of the underside of the sole (Fig 5). During ALV, the MFCs occurred throughout the shoe but were primarily located in the midfoot region (Fig. 5). During DLV, the MFC occurrences were equally split between the toe/forefoot regions and the rearfoot/heel regions (Fig. 5). For stair ascent, the MFC was typically located in the toe or forefoot region (most anterior or anteromedial tip of sole) except for the top stair (AST 7) where it shifted towards the midfoot region (Fig. 5). When descending the stairs, the MFC was located in the rearfoot and heel regions (most posterolateral aspect of heel) except for the top stair (DST 7) where it moved toward the anterior portion of the rearfoot (Fig. 5).

3.2.2 Trail Limb—During obstacle crossing, the MFC was always located in the toe region, most frequently on the most anterior point on the upper of the shoe or the upper sole (Fig. 6). For ALV, the MFC was almost always in the toe region on the anterior portion of the shoe sole (Fig. 6). When ascending stairs 1–6, the MFC was typically located at the most anterior point on the upper of the shoe, but when crossing the top stair, the MFC moved distal on the shoe to the most anterior aspect of the sole (Fig. 6).

3.3 Comparison of minimum toe clearance to overall MFC

Use of the MFC from just the toe region of the shoe (MTC) overestimated the actual MFC by 65% for lead limb obstacle crossing, 29% and 33% for ALV and DLV lead limb MFC respectively, 83–425% for stair descent, 50% for step 1 during stair ascent and 125% for overground walking (Table 1). For the lead limb MFC during stair ascent of steps 2–7 and all trail limb MFCs however, the MTC was equivalent to the overall MFC.

3.4 Differences in the gait characteristics at the point of MFC and MTC

Because the overall MFC of the lead limb for ascending level change and stairs was typically located in the toe region, there were minimal differences in the gait characteristics at the point of MFC and MTC for these tasks. There were notable differences in lead limb gait characteristics at MFC and MTC, however, for the other tasks. Overall MFC of the lead limb occurred ~20–30% later during the swing phase compared to MTC during obstacle crossing, stair descent and overground walking (Table 2). While the foot velocity in the anteroposterior direction tended to be slightly lower at MFC during these locomotor tasks than at MTC, the velocities were still substantial, ranging from 1.4 – 3.1 m/s depending on the task (Table 2). Additionally, instantaneous gait speed was nearly identical at MFC and MTC. The COM in the AP direction was closer to the front edge of the stance foot (Stance Toe-COM, Table 2) at MFC compared to MTC, however, the swing limb toe was also further in front of the COM at MFC compared to MTC.

There were no differences in MFC and MTC for the trail limb therefore only the gait characteristics at the point of MFC are presented in Table 3.

4. Discussion

The purpose of this study was determine which virtual points on the shoe come closest to the obstacle, step or stair and where on the obstacle, step or stair the MFC occurred. The results suggest that the location of MFC on the shoe changes with the locomotor task and often differs between the lead and trail limb. Additionally, overall MFC did not always occur over the front edge of the obstacle, step or stair – it varied both within and across task. The findings from this study provide future researchers with a guide for virtual marker placement on the shoe and suggest that in addition to measuring the MTC at critical points in the swing phase, the overall MFC should also be considered. The results from this study indicate that marker placements often used in the past for MFC research (e.g. great toe marker), do not provide the actual minimum foot clearance for most tasks and use of these marker placements may affect actual MFC results – especially when comparing across locomotor tasks or between lead and trail limbs within a task. In many previous studies, measurement of actual minimum clearance of the foot may not have been the goal; rather the purpose was to examine changes in swing limb kinematics following experimental perturbation. Based on the findings of this study, future research studies should identify whether the purpose in an experiment is to examine the swing limb trajectory of a single point, or whether the goal is to measure actual foot or toe clearance minimums. Although digitization of multiple edges and planes and several points on the shoe increases the complexity of the experiment, if overall MFC is required this methodology should be utilized.

The overall MFCs for all lead limb obstacle crossing conditions (7.8–9 cm) and overground walking (0.4 cm) were smaller than clearances previously reported for similar tasks (10.8–18cm and 0.9–3.5cm respectively). In this study the overall MFC for the lead limb was typically located in the rearfoot or heel of the shoe sole. The majority of previous studies on foot clearance during obstacle crossing and overground walking have used a toe marker (Begg et al., 2007; Berard & Vallis, 2006; Lowrey et al., 2007; McFadyen & Prince, 2002; Patla & Rietdyk, 1993; Sparrow et al., 1996), 5^{th} metatarsal head(Austin et al., 1999; Berg & Blasi, 2000; Chou et al. 2003; Krell & Patla, 2002; McKenzie & Brown, 2004), or the medial or lateral aspect of the calcaneus (Austin et al., 1999; Sparrow et al., 1996) to calculate clearance resulting in values that are higher than the overall MFC. Our findings are similar to those ofThies et al. (2011), who found that the use of markers on the anterior upper portion of the shoe resulted in an overestimation of MTC during ramp negotiation. An additional factor which may have played a role in smaller overall MFCs in this study is the use of the minimum 3D distance over the entire surface of the obstacle step or stair instead of the vertical distance between a single point on the shoe and a single point, line or plane on the obstacle. The 3D method used in this study would theoretically reduce sampling errors and the likelihood of “missing” the actual minimum. Additionally, the 3D vector magnitude is the actual distance between the point on the shoe and the edge or plane as opposed to just the vertical component.

The relevance of the rearfoot/heel minimum clearances in terms of fall risk is dependent upon where they occur in the swing phase and the velocity of the foot at the time of MFC. For overground walking, the overall MFC occurred at 76% of the swing phase (Table 2; Figure 1 - Supplementary Data). While the foot velocity was slightly lower than at MTC which occurred at 48% of swing, it was still ~ 3 m/s and the AP COM velocity was the same at both points. The virtual base of support was larger at MFC than MTC which would theoretically make it easier to recover from a foot contact at MFC vs MTC, especially if a lowering strategy is used to immediately place the foot on the ground (Eng et al., 1994). For a healthy young adult, contact at MFC would most likely result in a “brush” of the foot on the ground with little threat to stability. However, it is possible that at this foot velocity, contact could result in a trip if the heel of the shoe is caught thereby shortening step length, or even a slip if the coefficient of friction between the shoe and floor is low. Older adults have been shown to have higher foot velocities than young adults prior to heel contact (Lockhart et al., 2003). The implications of a heel contact in late swing in older adults or those with gait pathology have not been studied. During obstacle crossing, overall MFC for the lead limb was always over the tread or back edge of the obstacle and located on the rearfoot or heel of the shoe. Additionally, it occurred earlier in the swing phase compared to the overall MFC during level walking - shortly after the peak anterior velocity of the foot (Table 2; Figure 2 – Supplementary Data). This overall MFC likely poses a greater threat to stability than that during overground walking, particularly for taller obstacles and/or shoes with heels, where a heel contact could result in plantarflexion of the lead foot, making it difficult to use to regain balance if a lowering strategy is used (the lead foot is critical given that the COM is right at the edge of the stance foot at MFC). Older adults have been shown to decrease obstacle to heel distance and increase its variability under dual task conditions (Schrodt et al., 2004; Harley et al., 2009). Additionally, exercise training in older adults has been shown to increase vertical heel clearance (Lamoureux et al., 2003) and increase heel distance (Weerdesteyn et al., 2008) from the obstacle. These findings suggest that in addition to toe/forefoot clearances, rearfoot/heel clearances (or MFC) should also be measured.

The current study did, however, have mean clearances that were similar to previous research during trail limb obstacle crossing (virtual toe marker - Berard & Vallis, 2006), lead/trail level change ascent (virtual toe marker - McFadyen & Prince, 2002), and stair descent (minimum of ~ 300 virtual points - Hamel et al., 2005). These MFCs were similar to the current study because the marker locations chosen by previous authors were located in the region of MFC found in this study. For the lead limb ascending a level change or stairs, the overall MFC was always over the edge and typically located in the toe and forefoot regions so more standard types of clearance methodology come close to approximating the overall MFC for these tasks. For the trail limb, the overall MFC almost always came from the toe region, again matching up with more traditional measurements of foot clearance. For descending a level change and going down stairs however, the overall MFC was located in the rearfoot and heel regions of the shoe and occurred over the edge and tread regions. These rearfoot/heel clearances occur in late mid-swing (Table 2; Supplementary Data Figs. 4 and 6) and are dramatically smaller than toe clearances (Table 1) making the posterolateral border region of the shoe sole the likely region to be caught during a trip. This MFC location and small value (~1.5 cm) are of particular importance given the threat to stability that could result from a heel-catch induced plantarflexion of the lead foot, particularly near the top of a flight of stairs.

One limitation of this study that should be investigated in future research is the location of other minimum clearance points on the shoe that are within the measured accuracy (± 1.5 mm). This study only looked at the smallest value overall, however other points on the shoe may have had similar clearance values that fell within the resolution of this technique. Additional limitations included the requirement of all participants to wear the same shoes which differed from their normal footwear, the use of a harness system which may have resulted in a slower than normal gait speed and the use of a single cluster to track the movement of the shoe. Although we did not notice any toe flexion during the swing phase, it is possible that it could compromise toe clearance accuracy and the use of multiple tracking clusters should be investigated in the future.

In conclusion, MFC location is dependent upon locomotor task and can differ in location between lead and trail limb. These results suggest that when actual minimum foot clearances are required (as opposed to just the clearance of a single point), or if comparisons are being made across locomotor tasks or between lead and trail limb, the 3D surface of the shoe sole and virtual points on the toe and heel uppers should be tracked in order to ensure that the MFC is captured in addition to the MTC. Additionally, researchers should consider the regions of the obstacle, step or stair over which the clearance is calculated. Given that the location of the MFC and the gait characteristics at this point change with locomotor task and between leading and trailing limbs, it is possible that the location of the MFC and its gait characteristics may also change in response to environmental manipulation or differ between populations studied and should be examined in the future. If digitization of the entire shoe and obstacle, step or stair is not possible due to experimental constraints, future researchers can utilize these results to choose the appropriate virtual marker placement and region digitization that would likely capture the majority of the overall MFCs for each specific task. Given that tripping is the leading cause of falls in older adults, additional research is needed utilizing this methodology to examine overall MFC in older adults during these high risk locomotor tasks and to examine the relevance of rearfoot/heel contact with the obstacle, step or stair during trip-inducing experiments.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Figure 1.
Marker cluster and virtual marker locations.

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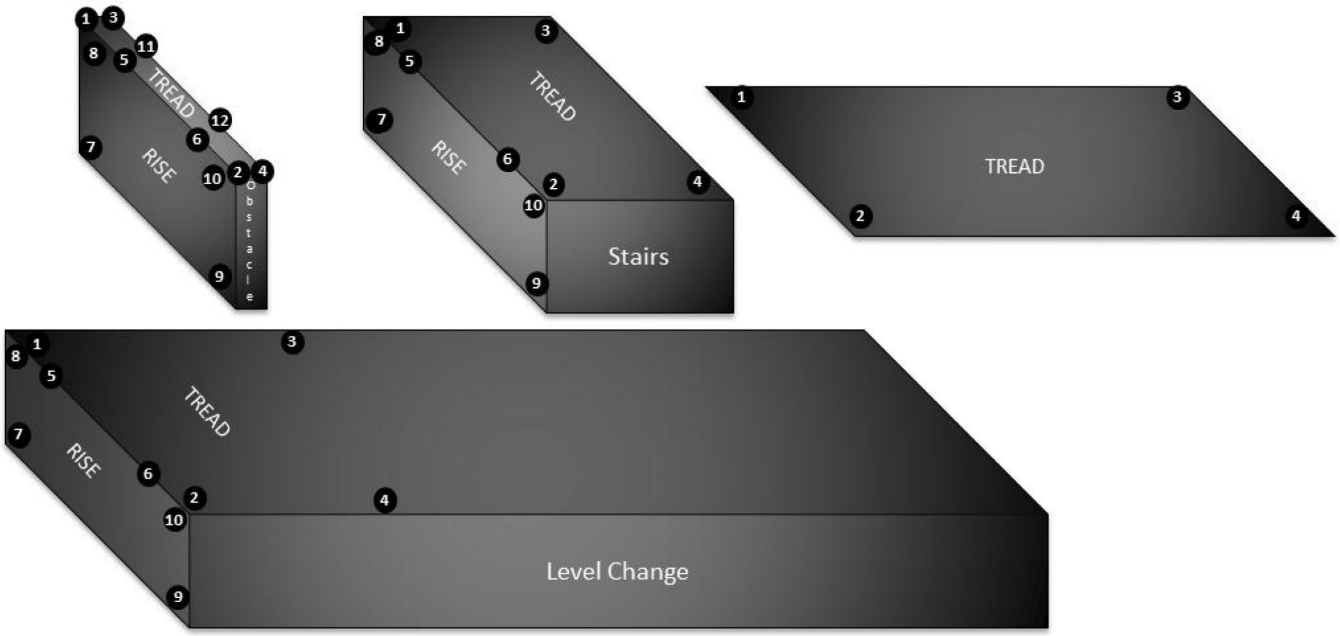
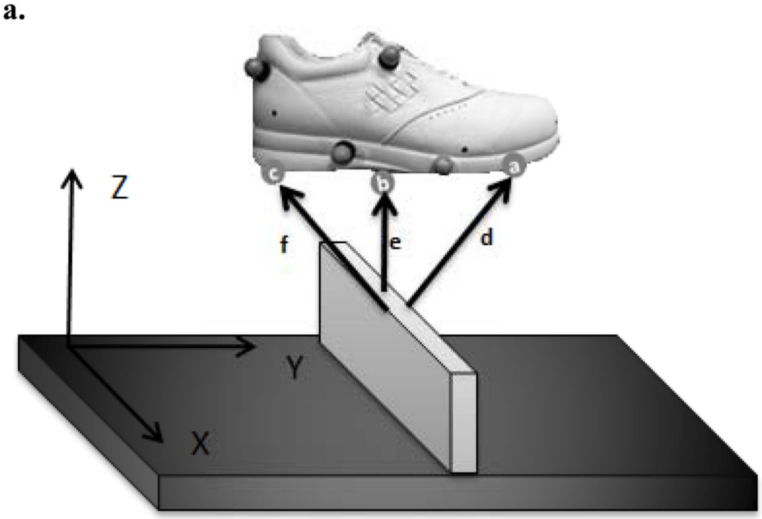


a.



b.

Figure 2.

a.) The virtual points digitized on the obstacle, level change, stairs and overground. Points 1–4 defined the tread (TR) plane or overground plane; points 5 and 6 defined the front edge (FE) of the obstacle or EDGE of the level change or stairs; points 7–10 defined the riser (RISE) of the obstacle, level change or stairs; points 11 and 12 defined the back edge (BE) of the obstacle. b.) Example of 3D distance vectors for three virtual markers. A point on the shoe (c) is projected into the front edge (line 1–2) of the obstacle, then a vector is made between the region and the point. The clearance of point c is the magnitude of this 3D vector. The clearance of point (a) is calculated in the same manner, except the back edge (line 3–4) is used. For point (b), the clearance is calculated using the top tread of the obstacle (pts 1–4).

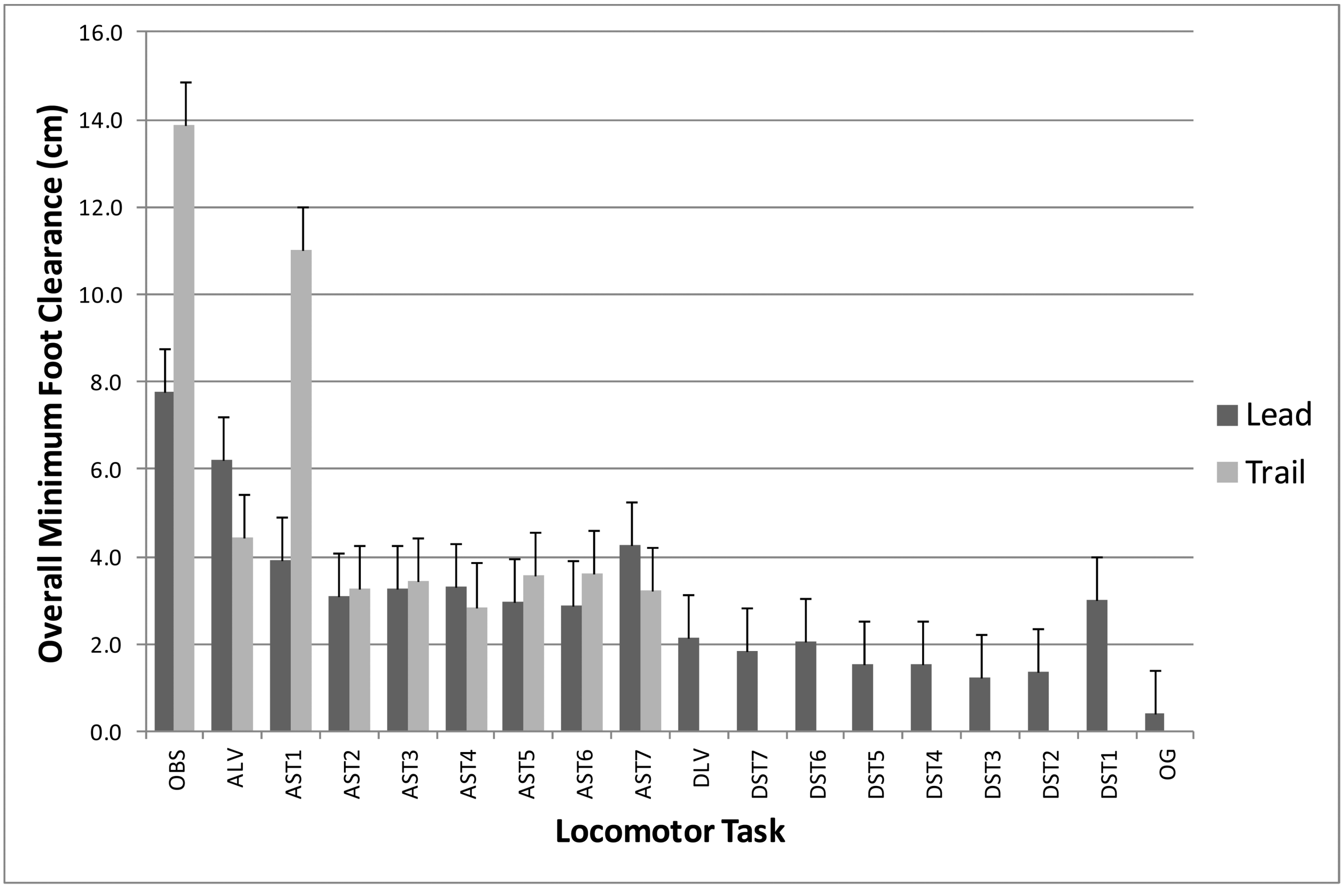


Figure 3.

Overall minimum foot clearance for each task and each limb. OBS = obstacle, ALV = ascending level change, AST = ascending stairs 1–7, DLV = descending level change, DST = descending stairs 1–7 and OG = level walking overground. There were no trail limb calculations for OG, DLV or DST (OG did not have a trail foot, while DLV and DST trail limb does not actually clear the step that it is on, but "rolls" off the tread or edge).

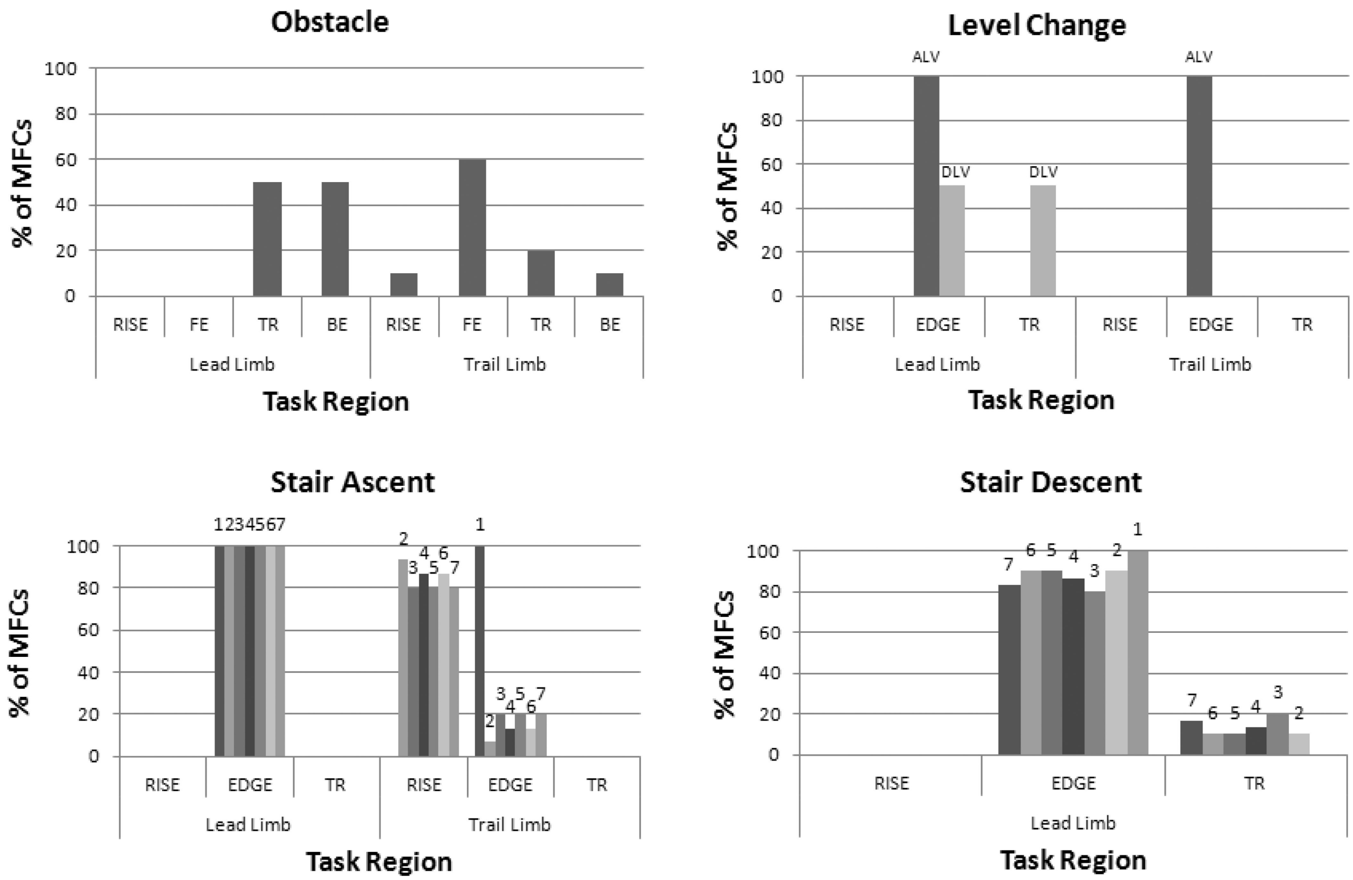


Figure 4.
Location of the overall lead and trail limb minimum foot clearances by task region (RISE – front riser, FE – front edge of obstacle, TR – tread, BE – back edge of obstacle, EDGE – edge of level change or stair). Data is displayed as the percentage of the total number of overall minimum foot clearances that occurred within each region of the obstacle, step, stair or floor. All four regions were measured for the obstacle, while RISE, EDGE and TR were measured for level change and stair negotiation. For overground walking, all MFCs occurred over the digitized plane of the floor (GR) and were not included in the figure. There were no trail limb calculations for overground, descending level change or stairs (OG did not have a trail foot, while DLV and DST trail limb does not actually clear the step that it is on, but “rolls” off the tread or edge). For stair ascent and descent, the stair number is labeled over appropriate column.

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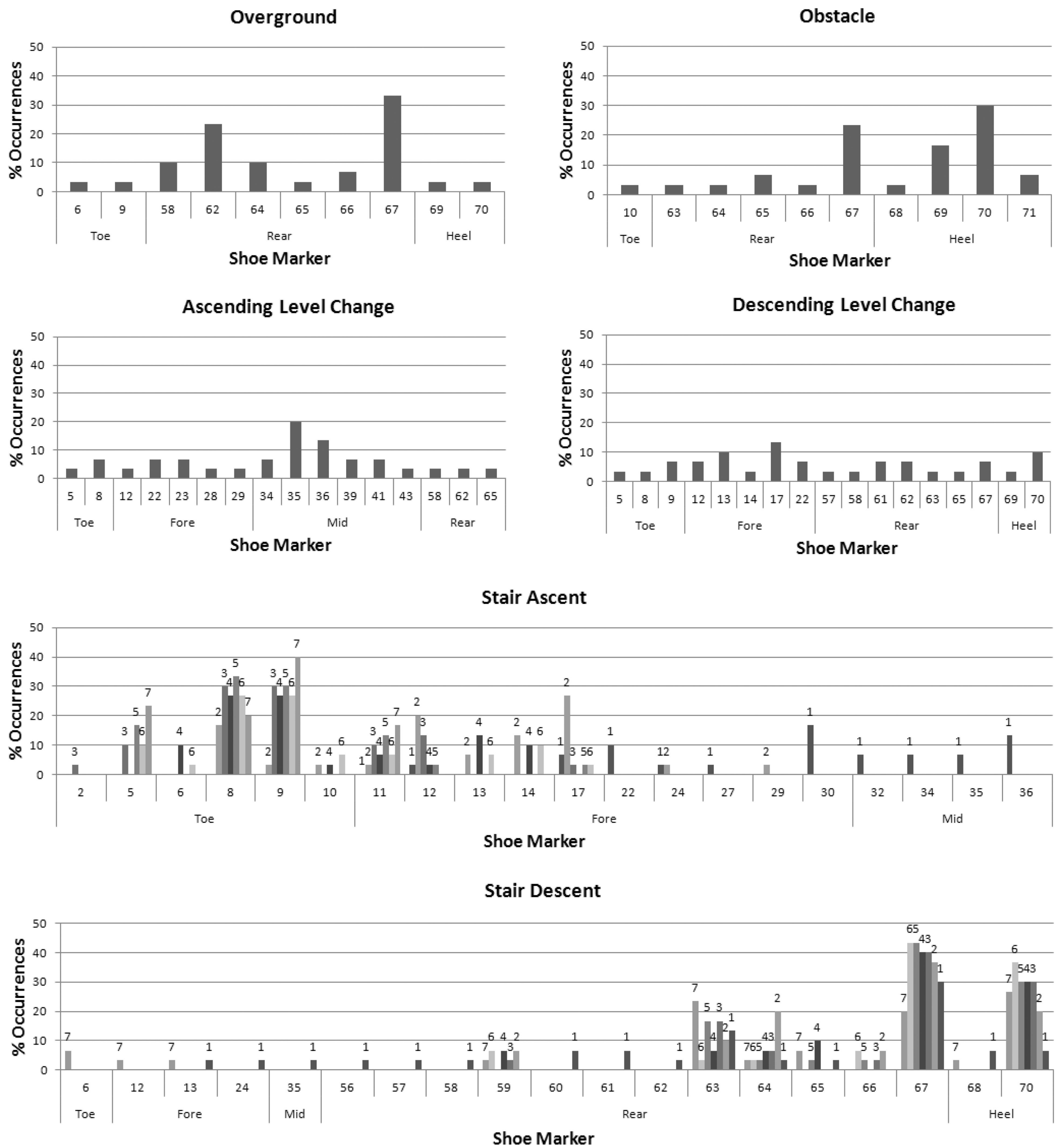

Figure 5.

Location of overall lead limb minimum foot clearances by shoe region. Data is displayed as the percentage of the total number of overall minimum foot clearances that occurred for each marker within each shoe region. Shoe regions and markers that are not shown did not experience any MFCs for that task. For stair ascent and descent, the stair number is labeled over each column.

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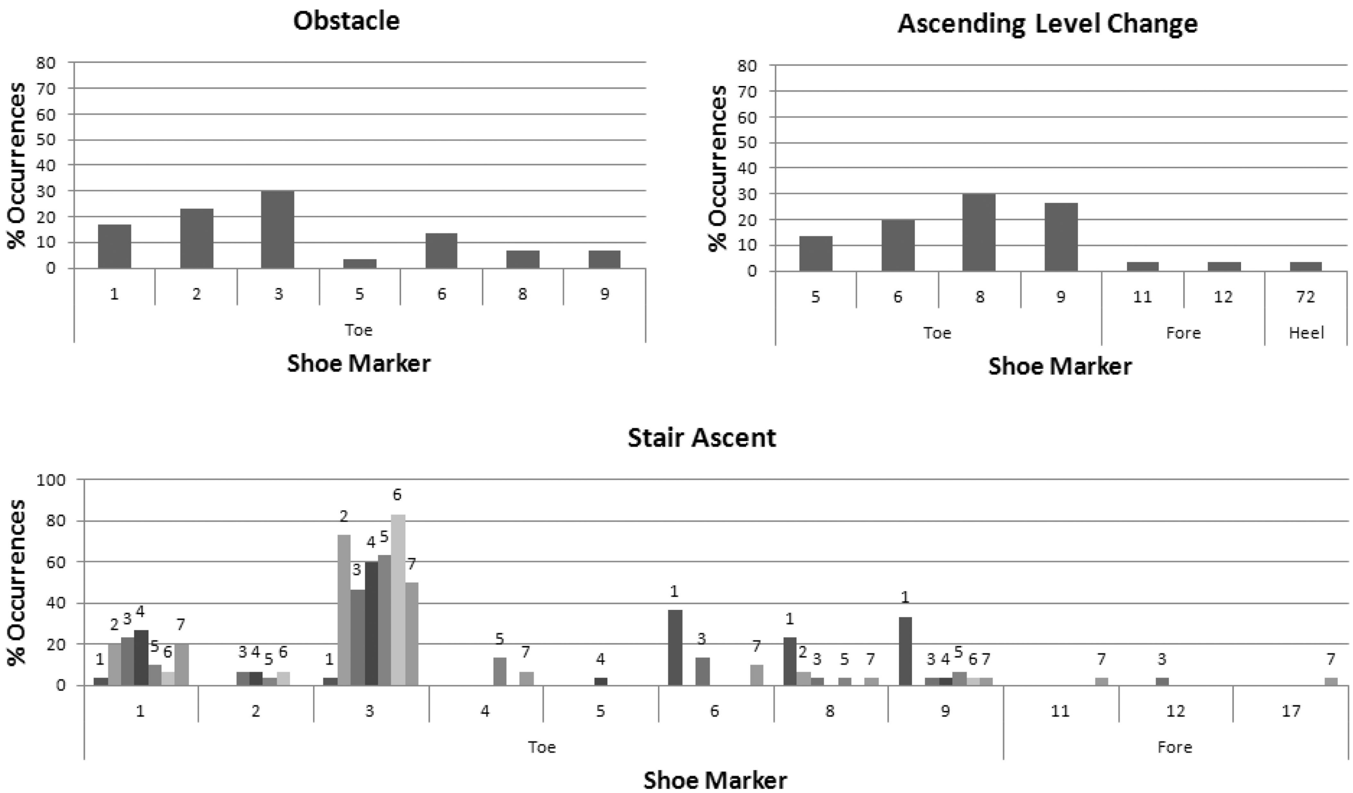

Figure 6.

Location of overall trail limb minimum foot clearances by shoe region. Data is displayed as the percentage of the total number of overall minimum foot clearances that occurred for each marker within each shoe region. Shoe regions and markers that are not shown did not experience any MFCs for that task. There were no trail limb calculations for OG, DLV or DST (OG did not have a trail foot, while DLV and DST trail limb does not actually clear the step that it is on, but “rolls” off the tread or edge). For stair ascent, the stair number is labeled over each column.

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Table 1

Comparison of the mean overall minimum foot clearance to the mean minimum clearance of the toe region for the lead and trail limbs across tasks.

	Overall MFC (cm)		Toe Clearance (cm)		% Difference	
Task	**Lead**	**Trail**	**Lead**	**Trail**	**Lead**	**Trail**
Obstacle Crossing (OBS)	7.8	13.9	12.8	13.9	65.1	0 .0
Ascending Level Change (ALV)	6.2	4.4	8	4.4	29.1	0 .0
Ascending Step 1 (AST1)	3.9	11.0	5.9	11.0	50.4	0.0
Ascending Step 2 (AST2)	3.1	3.3	3.2	3.3	3.9	0.0
Ascending Step 3 (AST3)	3.3	3.4	3.3	3.4	0.0	0.0
Ascending Step 4 (AST4)	3.3	2.9	3.3	2.9	0.0	0.0
Ascending Step 5 (AST5)	3.0	3.6	3.0	3.6	0.0	0.0
Ascending Step 6 (AST6)	2.9	3.6	2.9	3.6	0.0	0.0
Ascending Step 7 (AST7)	4.3	3.2	4.3	3.2	0.0	0.0
Descending Level Change (DLV)	2.1	N/A	2.8	N/A	33.3	N/A
Descending Step 7 (DST7)	1.8	N/A	3.3	N/A	83.3	N/A
Descending Step 6 (DST6)	2.1	N/A	7.4	N/A	252.4	N/A
Descending Step 5 (DST5)	1.5	N/A	6.8	N/A	353.3	N/A
Descending Step 4 (DST4)	1.5	N/A	5.8	N/A	286.7	N/A
Descending Step 3 (DST3)	1.2	N/A	6.3	N/A	425.0	N/A
Descending Step 2 (DST2)	1.3	N/A	5.6	N/A	330.8	N/A
Descending Step 1 (DST1)	3.0	N/A	5.7	N/A	90.0	N/A
Overground Walking (OG)	0.4	N/A	0.9	N/A	125.0	N/A

Table 2

Gait characteristics at the point of overall minimum foot clearance (MFC) and minimum toe clearance (MTC) for the lead limb

	% Swing Phase		AP COM Velocity (cm/s)		AP Foot Velocity (cm/s)		Stance Toe-COM (cm) (positive value = COM behind toe)		Swing Toe-COM (cm) (positive value = COM behind toe)		Step Length (cm)
Task	**MFC**	**MTC**	**MFC**	**MTC**	**MFC**	**MTC**	**MFC**	**MTC**	**MFC**	**MTC**	
Obstacle Crossing (OBS)	62.1±4.7	43.7±9.1	89.0±115.8	90.7±14.5	244±59.9	311.1±49.4	2.8±3.0	13.2±3.6	56.8±6.3	32.9±5.7	76.4±7.9
Ascending Level Change (ALV)	67.2±9.5	60.5±7.0	105.2±15.3	104.3±14.6	280±60.2	334.6±46.1	4.8±6.7	8.8±4.6	49.6±11.3	42.6±9.0	69.5±11.6
Ascending Step 1 (AST1)	76.5 ±7.9	67.9±7.1	81.9±12.4	81.1±12.1	178.5±38.6	255.5±27.9	5.4±4.3	9.4±4.0	49.0±7.9	42.6±6.1	54.7±7.4
Ascending Step 2 (AST2)	75.1 ±5.9	73.6±5.4	62.6±7.7	62.1±7.7	205.9±71.9	208.9±73.1	12.2±3.3	12.7±3.3	19.8±3.3	18.4±3.1	N/A
Ascending Step 3 (AST3)	68.5±4.3	68.2±4.3	49.4±4.8	49.9±4.8	217.3±19.7	217.3±19.9	8.3±3.0	8.4±3.1	14.1±2.9	13.7±2.6	N/A
Ascending Step 4 (AST4)	71.0±5.4	70.5±5.6	47.3±4.0	47.3±4.0	191.6±66.2	191.9±66.4	7.5±2.3	7.6±28	12.6±3.7	12.2±3.2	N/A
Ascending Step 5 (AST5)	69.7±4.7	69.4±4.7	45.6±3.9	45.6±3.9	209.9±17.7	209.7±17.8	7.0±2.9	7.1±2.9	12.7±2.8	12.4±2.7	N/A
Ascending Step 6 (AST6)	71.7±4.8	71.2±4.6	47.2±3.5	47.1±3.5	188.7±65.2	188.7±65.2	6.7±2.8	6.8±2.9	12.2±3.9	11.7±3.5	N/A
Ascending Step 7 (AST7)	57.1±6.7	57.0±6.5	53.7±7.1	53.7±7.1	243.9±20.5	243.6±20.7	4.8±3.5	4.9±3.5	9.3±4.1	9.2±4.0	49.5±8.1
Descending Level Change (DLV)	47.6±9.7	40.6±7.2	97.5±16.6	98.5±16.1	305.7±53.4	330.2±31.4	10.5±4.8	14.6±4.7	25.0±13.0	14.4±9.3	55.8±9.4
Descending Step 7 (DST7)	54.5±13.3	33.5±10.5	58.8±10.3	64.0±9.5	155.4±58.8	242.7±47.6	15.2±7.3	22.1±5.5	29.7±14.3	13.5±12.2	28.7±4.9
Descending Step 6 (DST6)	61.7±4.7	39.3±6.5	50.5±8.0	51.4±8.5	137.3±38.3	226.3±23.4	9.8±2.8	15.4±3.0	29.9±6.4	14.7±3.3	N/A
Descending Step 5 (DST5)	60.1±6.1	35.7±6.5	50.3±5.6	51.9±6.5	136.4±23.3	225.1±20.3	8.9±2.8	14.3±3.0	25.1±7.8	13.6±2.9	N/A
Descending Step 4 (DST4)	60.4±5.1	35.8±6.5	51.0±5.4	51.5±5.8	146.1±30.6	226.6±19.1	8.2±2.2	13.6±2.6	27.7±53.3	12.3±2.8	N/A
Descending Step 3 (DST3)	60.4±4.2	36.1±5.5	50.8±4.9	51.9±5.5	146.2±20.6	220.1±17.8	7.6±2.6	13.0±2.6	24.8±6.9	11.8±2.9	N/A
Descending Step 2 (DST2)	60.1±4.9	36.0±6.2	54.1±8.7	53.9±7.4	142.1±20.7	217.4±20.3	6.3±2.3	11.9±2.7	25.2±5.5	10.9±2.5	N/A

Task	% Swing Phase		AP COM Velocity (cm/s)		AP Foot Velocity (cm/s)		Stance Toe-COM (cm) (positive value = COM behind toe)		Swing Toe-COM (cm) (positive value = COM behind toe)		Step Length (cm)
	MFC	MTC	MFC	MTC	MFC	MTC	MFC	MTC	MFC	MTC	
Descending Step 1 (DST1)	50.1±6.5	33.0±6.3	67.0±13.2	65.0±12.0	240.5±45.3	231.0±26.6	3.1±3.8	8.3±4.1	13.8±10.2	6.1±3.8	48.8±10.0
Overground Walking (OG)	76.1±8.3	48.3±5.7	112.0±11.3	111.0±11.8	313.4±44.3	389.5±25.1	1.4±3.6	14.2±2.5	46.7±10.5	13.7±5.2	67.1±3.8

Table 3

Gait characteristics at the point of overall minimum foot clearance (MFC) for the trail limb

Task	% Swing Phase	AP COM Velocity (cm/s)	AP Foot Velocity (cm/s)	Stance Toe-COM (cm) (positive value = COM behind toe)	Swing Toe-COM (cm) (positive value = COM behind toe)
Obstacle Crossing (OBS)	31.0±21.7	100.8±14.2	212.7±77.3	27.3±7.9	−35.3±8.1
Ascending Level Change (ALV)	41.3±5.0	97.5±13.1	265.2±42.2	19.8±4.5	−14.8±6.5
Ascending Step 1 (AST1)	49.1±9.5	66.5±8.3	207.8±38.2	20.5±3.0	−5.4±3.8
Ascending Step 2 (AST2)	18.9±15.0	52.6±5.9	59.4±34.6	19.5±3.3	−3.0±9.1
Ascending Step 3 (AST3)	21.2±16.3	48.1±3.8	647±38.2	17.3±4.0	−5.2±9.6
Ascending Step 4 (AST4)	12.4±14.2	47.1±4.4	40.5±30.1	18.7±3.8	−3.2±9.5
Ascending Step 5 (AST5)	11.5±13.6	48.3±4.8	48.0±37.5	19.2±4.1	−4.2±10.2
Ascending Step 6 (AST6)	9.8±12.0	51.1±5.9	41.4±34.4	18.1±3.6	−5.5±9.7
Ascending Step 7 (AST7)	9.1±13.8	70.0±13.3	53.4±60.5	28.9±7.5	−14.5±15.3