Soldier-relevant body borne load impacts minimum foot clearance during obstacle negotiation.

Brown, T. N.^{1,2,3}, Loverro K. L.³, and Schiffman J.M.⁴

¹Boise State University, Boise, ID, USA

²U.S. Army Natick Soldier Research, Development and Engineering Center, Natick, MA, USA

³Oak Ridge Institute for Science and Education (ORISE), Belcamp, MD, USA

⁴Liberty Mutual Research Institute for Safety, Hopkinton, MA, USA

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Address for Tyler Brown, PhD.

Correspondence: Department of Kinesiology,
Boise State University
1910 University Drive, Boise, Idaho, 83725-1710
Phone: 508 233 5705

Email: tynbrown@boisestate.edu

Original Article

Abstract

Soldiers often trip and fall on duty, resulting in injury. This study examined ten male soldiers' ability to negotiate an obstacle. Participants had lead and trail foot minimum foot clearance (MFC) parameters quantified while crossing a low (305 mm) and high (457 mm) obstacle with (19.4 kg) and without (6 kg) body borne load. To minimize tripping risk, participants increased lead foot MFC ($p=0.028$) and reduced lead ($p=0.044$) and trail ($p=0.035$) foot variability when negotiating an obstacle with body borne load. While obstacle height had no effect on MFC ($p=0.273$ and $p=0.126$), placing the trail foot closer to the high obstacle when crossing with body borne load, resulted in greater lead ($R=0.640$, $b=0.241$, $p=0.046$) and trail ($R=0.636$, $b=0.287$, $p=0.048$) MFC. Soldiers, when carrying typical military loads, may be able to minimize their risk of tripping over an obstacle by creating a safety margin via greater foot clearance with reduced variability.

Key Words: Body borne load, obstacle negotiation, minimum foot clearance

1. Introduction

Falls are a major health concern, particularly for military personnel (Senier et al. 2002). Fall-related injuries are likely a serious threat to soldiers' health that can cause a significant loss of time on duty and subsequently threaten the operational readiness of the military. Jones et al. (2010) reported that falls and/or near falls (i.e., slips and trips) were the leading cause of hospitalization for military personnel, resulting in a hospital stay of approximately 6 days per injury (Senier et al. 2002). These injuries often occur when soldiers trip while negotiating obstacles, such as stairs, curbs and other heights, encountered on duty (Senier et al. 2002). When negotiating these obstacles, a trip occurs when a soldier unexpectedly contacts an external object creating a destabilizing force (e.g., rotation of the body) by impeding the forward progress of the swing foot, thereby resulting in a fall and potential injury if not properly attenuated (Barrett, Mills, and Begg 2010).

Possibly exacerbating soldiers' risk of falling and suffering a potential injury is the personal protective, fighting, and load carriage equipment (i.e., body borne load) that they typically don while on duty. Army doctrine recommends that soldiers keep their body borne loads to a minimum (32 kg or less) (Field Manual, 1990). These body borne loads have a deleterious effect on their physical capacity (Holewun and Lotens 1992), impairing both their static (Schiffman et al. 2006) and dynamic balance (Sell et al. 2013). Heavier body borne loads may require soldiers to exert greater postural control to maintain equilibrium and prevent falling (Schiffman et al. 2006). Consequently, when impaired by load, soldiers need to produce larger corrective torques to attenuate a

destabilizing force and maintain balance, resulting in a greater number of trip-related falls when on duty (Senier et al. 2002). These body borne loads also result in significant adaptation of trunk and lower limb kinematic during an obstacle negotiation (Loverro et al. 2015), potentially limiting their ability to correct a destabilizing force. As such, it is of particular importance for the military to assess soldiers' tripping risk when negotiating obstacles, especially when impaired with body borne load.

Tripping risk is directly linked to minimum foot clearance (MFC) – i.e., the minimum vertical distance between the swing foot (either lead or trail) and external obstacle (Winter 2005) – as clearance is reduced to zero when contact with an external object occurs. Peak anterior velocity of the swing foot also coincides with MFC, reaching nearly three times the velocity of walking (Mills, Barrett, and Morrison 2008), increasing the destabilizing force and making the potential of sustaining a trip-related fall greatest at MFC (Winter 1992). Subsequently, there has been extensive research examining MFC during locomotor tasks where trips commonly occur, particularly obstacle crossing (Austin, Garrett, and Bohannon 1999, Berard and Vallis 2006, Draganich and Kuo 2004, Lu, Chen, and Chen 2006, Sparrow et al. 1996). While MFC is generally between 10 – 20 mm during level walking (Mills, Barrett, and Morrison 2008), it reportedly increases for both the lead (Austin, Garrett, and Bohannon 1999) and trail (Sparrow et al. 1996) foot as obstacle height is increased. But the impact of obstacle height on MFC is not consistent across all studies (Draganich and Kuo 2004, Lu, Chen, and Chen 2006). To increase MFC, the limb crossing the obstacle reportedly relies upon greater angular motion and muscular effort of the hip, knee, and ankle, particularly as obstacle height increases

(Chou and Draganich 1998, Austin, Garrett, and Bohannon 1999). Yet, when impaired with body borne load, a soldier may not be able to generate the necessary angular motion and muscular effort of the hip, knee and ankle to increase MFC, as the lower limb is compromised. Perry et al. (2010) recently reported participants increased lead MFC and minimize tripping risk while crossing an obstacle with small (10 kg or less) hand-held loads. But, to date, it is unknown if soldiers negotiating obstacles with torso borne loads typically donned during military operations can increase MFC and reduce their potential for tripping.

When crossing an obstacle, a soldier's ability to increase MFC may depend on trail foot placement. Toe contact with an obstacle (i.e., trip) reportedly has a significant association with the placement of the trail foot immediately prior to an obstacle (Chou and Draganich 1998, Patla and Greig 2006) – particularly with small, hand carried loads (Perry et al. 2010). Therefore, the ability of the soldier, who is encumbered with larger torso borne loads, to increase MFC may depend on the placement of their trail foot during the obstacle negotiation.

While a small MFC may indicate a high risk of tripping, the central tendency (i.e., mean) of MFC may not be the best measure of tripping risk. When negotiating an obstacle, given the small margin of error, a soldier may want to minimize the variability of clearance to decrease risk of contacting an external object and suffering a trip-related fall (Begg et al. 2007, Mills, Barrett, and Morrison 2008). The combination of a small MFC with a large variability may be a worst case scenario in terms of tripping risk. Previous

research, however, has largely focused its assessment of MFC variability on age-related differences when walking over level ground (Begg et al. 2007, Mills, Barrett, and Morrison 2008) or descending stairs (Hamel et al. 2005). It is currently unknown if obstacle height or body borne load impacts MFC variability and subsequently tripping risk. Despite the fact, that the lower limb exhibits greater variability of kinematic and spatiotemporal measures during locomotion with body borne load (Qu and Yeo 2011) and requires greater muscular effort to safely navigate obstacles as height increased from 51 to 204 mm (Chou and Draganich 1998). During military duty, soldiers often encounter obstacles above 200 mm, particularly during unconstrained deployment environments where building codes may be absent or across a range of obstacles during training exercises. It may be negotiating an obstacle of increasing height above 200 mm with body borne load significantly elevates the risk of suffering an injury from a trip-related fall.

This study sought to determine if increasing body borne load or obstacle height had a significant effect on the central tendency and variability of MFC for the lead and trail foot when crossing an obstacle. We hypothesized that participants would increase mean MFC to mitigate the concomitant increase in MFC variability evident with larger body borne loads and higher obstacles for both the lead and trail foot, and MFC would exhibit a significant relation to trail foot placement immediately prior to the obstacle.

2. Methods

2.1 Participants

Ten male military personnel (age: 21.4 ± 2.6 yrs, height: 1.8 ± 0.1 m, weight 85.6 ± 10.2 kg) free of any lower extremity injury participated in this study. Research approval was obtained from the local institutional review board and all participants gave written consent prior to participation.

2.2 Load Configurations

During testing, participants wore two load configurations (unloaded and loaded) presented in a random order (Figure 1). For the unloaded configuration (~ 6 kg), participants wore a helmet and boots, and carried a mock weapon in the “ready” position. For the loaded configuration (~ 19.4 kg), participants donned body armor with ballistic plates, a configuration typically worn on duty (Field Manual, 1990).

2.3 Testing Protocol

With each load configuration, participants completed a series of two obstacle crossing tasks. For each task, participants walked at a $1.3 \text{ m/s} \pm 5\%$ across a 10-m walkway and stepped over either: a low (305 mm) or high (457 mm) obstacle placed approximately 5 m from the start of the walkway. The cross-bar of the obstacle was easily displaced if contacted inadvertently by a participant. Walking speed was monitored by timing gates (Bower Timing Systems Draper, UT, USA) placed at the beginning of the walkway and approximately 0.30 m before the obstacle. The walking speed was chosen in accordance with previous load carriage research (Harman, Han, and Frykman 2000) and held constant in order to not introduce speed as a covariate in the statistical analysis (Harman, Han, and Frykman 2000, LaFiandra et al. 2003). A trial was successful when a participant

walked at the requisite speed, stepped over the obstacle with his dominant limb and crossed the obstacle without contacting it. Participants performed five successful trials for each crossing task.

2.4 Biomechanical Collection and Analysis

To measure MFC, participants had reflective and virtual markers attached and digitized on each boot according to Loverro et al. (2013). Specifically, to track each boot, three reflective markers were attached via rigid marker cluster on the lateral aspect of the heel, while one marker was placed on the fifth metatarsal head of each boot. To define the toe, heel and sole regions of each boot, thirty seven virtual markers were digitized in the global coordinate system using a Davis Digitizing Pointer (C-Motion, Germantown, MD), as previously reported by Loverro et al. (2013). The obstacle was defined by two reflective markers, placed at each end of the cross bar, to visualize the centerline of the cross bar in the global coordinate system.

During each trial, three-dimensional (3D) marker trajectories were captured with twelve high-speed (240 fps) optical cameras (Oqus, Qualisys AB, Gothenburg, Sweden). The marker trajectories were low pass filtered with a fourth order Butterworth filter at a cut-off frequency of 6 Hz using Visual 3D (v4.96, C-Motion, Germantown, MD). Then, Visual 3D was used to create a local coordinate system for the virtual markers on each boot and reflective markers placed on the obstacle. For clearance analysis, the virtual markers were located in the global coordinate system at each frame of the trial. Then, a 3D vector between each virtual marker and the obstacle was calculated as the distance

between the marker and the centerline of the cross bar minus the radius (12.7 mm) of the cross bar. Foot clearance, defined as the minimum distance of the 3D vector for each virtual marker during the obstacle crossing, was exported for both the lead and trail limbs for further analysis.

The overall minimum was found for each limb (lead and trail MFC) using a custom Matlab (R2008b, Mathworks, Natick, MA) program. Specifically, lead and trail MFC was quantified from the heel region of the lead foot and toe region of the trail foot, as the minimum values were found to occur in these regions of the boot during a similar obstacle crossing by Loverro et al. (2013). In addition, specific spatiotemporal characteristics including percent of swing phase at the time of MFC for the both the lead and trail limbs, step length over the obstacle, and trail and lead foot placement before and after the obstacle were calculated, respectively. Step length was defined as the distance from the trail limb toe (at toe off) to lead limb heel (at heel strike) for the step over the obstacle. Trail foot placement was defined as the anterior-posterior distance of the trail limb toe when placed in front of the obstacle prior to crossing, whereas, lead foot placement was defined as the anterior-posterior distance of the lead limb heel when placed following obstacle.

2.5 Statistical Analysis

Each dependent variable was averaged across all five trials to calculate a subject-based mean for each task. Then, the subject-based mean was submitted to a 2 (*body borne load*) x 2 (*obstacle height*) repeated measures ANOVA with a Bonferroni

adjustment. The variability of MFC, i.e., within subject coefficient of variation (CV), was also calculated for each foot and submitted to 2 x 2 repeated measures ANOVA with a Bonferroni adjustment. For each foot, CV was calculated as the within subject standard deviation over the five trials was divided by the mean MFC for those respective trials and expressed as a ratio:

$$CV = \frac{\sigma}{\mu} * 100$$

Additionally, Pearson correlation coefficients were used to examine the linear relation between lead and trail MFC and trail foot placement for each body borne load and obstacle. All statistical analyses were performed using SPSS (v21.0, IBM Inc. Chicago, IL, USA). Statistical significance was set at 0.05 for analyses.

3. Results

3.1 The effect of body borne load and obstacle height on MFC parameters

No significant interaction effects between body borne load and obstacle height were observed and thus, only the main effects are presented below. Minimum foot clearance was significantly greater with the loaded as compared to the unloaded configuration for the lead foot ($p=0.028$), but similar differences between load configurations were not evident for the trail foot ($p=0.192$) (Table 1 and Figure 2). Both the lead and trail foot exhibited a significant reduction in MFC variability with the loaded as compared to the unloaded configuration ($p=0.044$ and $p=0.035$)

(Figure 2). Body borne load, however, did not exhibit a significant effect on the timing (i.e., percent of swing phase) of MFC for either the lead ($p=0.194$) or trail foot ($p=0.331$), respectively (Table 1).

Obstacle height did not exhibit a significant effect on MFC for either the lead ($p=0.273$) or trail foot ($p=0.126$) (Table 1). However, MFC occurred significantly later in the swing phase for both the lead ($p=0.010$) and trail foot ($p<0.001$) when crossing the high as compared to low obstacle (Table 1). Further, obstacle height had no significant effect on the MFC variability ($p=0.814$ and $p=0.166$) for either the lead or trail foot (Table 1).

Neither body borne load ($p=0.932$) nor obstacle height ($p=0.230$) had significant effect on step length when crossing the obstacle (Table 2). However, the participants did place their lead foot significantly closer ($p=0.012$) and trail foot significantly further away ($p=0.048$) when crossing the high as compared to low obstacle (Table 2). But similar differences were not evident for either lead ($p=0.981$) or trail foot ($p=0.980$) placement between the loaded and unloaded conditions, respectively.

3.2 Relation of step placement with MFC

Trail foot placement was found to have significant correlation with lead ($R=0.640$, $b=0.241$, $p=0.046$) and trail ($R=0.636$, $b=0.287$, $p=0.048$) MFC, but only for the loaded configuration when crossing the high obstacle (Figure 3 and Appendix). Specifically, when participants' placed the trail foot 10 cm further away from the high obstacle, lead and trail foot clearance decreased 24.1 mm and 28.7 mm while carrying the body borne load. The relationship between trail foot placement and lead or trail MFC was not significant ($p>0.05$) when crossing either obstacle (low or high) with the unloaded configuration, or when crossing the low obstacle with the loaded configuration (Appendix).

4. Discussion

In this study, participants increased MFC and reduced CV while negotiating an obstacle with body borne load – particularly for the lead foot. This strategy likely minimized the immediate risk of tripping by creating a safety margin during obstacle negotiation. To create the lead foot safety margin, the participants exhibited a substantial 25% increase in MFC (from approximately 80 mm to 100 mm) with the addition of body borne load. Foot clearance is reportedly sensitive to small kinematic changes (e.g., 1° to 2° of hip, knee and ankle flexion) of the stance and swing limbs (Austin, Garrett, and Bohannon 1999), such as those reportedly evident while stepping over a 305 mm obstacle with body borne load (Loverro et al. 2015). Loverro et al. (2015) found that participants wearing similar equipment to that used in the current study, exhibited a substantial increase in trunk extension

posture while negotiating an obstacle with the addition of body borne load. This extended trunk posture may shift the body borne load backwards creating space to allow soldiers to make the necessary adjustment in angular motion of the lead limb (i.e., greater flexion of the hip and knee) to increase MFC. Conversely, the extended trunk posture may similarly constrain the trail limb by preventing the necessary angular motion (i.e., greater hip, knee and/or ankle flexion) to increase clearance. The fact that the current participants did not exhibit a significant increase in trail limb MFC during the loaded compared to unloaded condition supports this contention. However, further research is warranted to determine whether the small, but statistically insignificant, increase in trail limb clearance (approximately 8%) is clinically significant and coincides with a reduction in tripping risk for soldiers negotiating obstacles when impaired by body borne loads.

Foot clearance during an obstacle crossing may be dependent on trail foot placement immediately prior to the obstacle crossing. During an obstacle crossing, toe contact with an obstacle (i.e., trip) was found to have a significant association with incorrect trail foot placement when approaching the obstacle (Chou and Draganich 1998, Patla and Greig 2006) – particularly with a hand carried load (Perry et al. 2010). Perry et al. (2010) reported a significant relationship between trail foot placement and lead foot clearance when crossing an obstacle with weighted boxes (2, 5, and 10 kg each) carried in the hands at the front of the torso; however, a similar relationship was not present during a no load (no weighted box)

condition. Our current experimental findings support this as we found a significant correlation between trail foot placement and both lead and trail MFC. Specifically, when the participant placed the trail foot 10 cm further away from the high obstacle, while carrying the body borne load, their lead and trail foot clearance decreased 24.1 mm and 28.7 mm, respectively. Proper trail foot placement may be necessary to afford the swing limb adequate time and space to increase angular motion and muscular effort necessary to sufficiently create a safety margin when crossing taller obstacles, particularly with body borne load. However, further research is needed to determine all the factors necessary to create a safety margin as trail foot placement currently only accounted for $\sim 40\%$ of the variance in MFC.

Contrary to our hypothesis, participants reduced variability of minimum clearance while crossing an obstacle when impaired by body borne load. Specifically, the current participants exhibited a significant reduction in CV of approximately 7.5 and 8 percent for the lead and trail foot. Despite the fact, load carriers are thought to use greater kinematic variability of the trunk and lower limb during locomotion (Qu and Yeo 2011). This increased kinematic variability may translate to larger variance in foot clearance, and given the small margin of error when crossing an obstacle, an increased risk of injury related to a trip-related fall (Begg et al. 2007, Mills, Barrett, and Morrison 2008). Yet, our results indicate that during the loaded condition, the participants exhibited tighter end-point control of clearance (i.e., smaller variability), potentially reducing the risk of tripping and suffering a related injury

when negotiating an obstacle. With tighter end-point control, participants may be compensating for the compromised balance and increased likelihood of falling from a destabilizing force when impaired by body borne load.

Obstacle height did not have a significant effect on tripping risk as the current participants did not exhibit a substantial modification in MFC or CV as height increased. Minimum clearance, for instance, had an insignificant increase of approximately 10 mm and 30 mm for the lead and trail limbs as obstacle height increased from 305 mm (low) to 457 mm (high), respectively. It was previously reported that minimum clearance increased (Austin, Garrett, and Bohannon 1999, Sparrow et al. 1996) as an obstacle height increased, but that finding is not consistent across all studies (Draganich and Kuo 2004, Lu, Chen, and Chen 2006) and contradict the current findings. To increase foot clearance, particularly as obstacles get taller, the hip, knee and ankle joints of the swing limb need to increase in flexion, so that the leg can effectively shorten. To accomplish this, participants need to maintain postural control and provide a stable core. The stable core is needed to effectively increase the muscular effort of the stance limb (Chou and Draganich 1997, 1998) and provide an adequate foundation for the swing limb to perform the necessary increases of angular motion (Chou and Draganich 1997, Patla and Prentice 1995). However, during locomotion, body borne loads elicit significantly larger muscular effort, i.e., lower limb joint moments (Brown et al. 2014), of the stance and swing limb. The body borne load may compromise both

limbs during locomotion rendering the muscles of the lower extremity unable to produce the muscular effort necessary for greater clearance and tighter end-point control that would coincide with a reduction in variability when obstacle increases in height. The current participants, however, exhibited a non-significant reduction in CV of 3 and 11 percent when crossing the taller obstacle for the lead and trail foot, respectively. Future research ought to determine whether soldiers, when donning typical military loads, can tighten the end-point control of their lead and trail limbs to reduce the risk of tripping, as obstacle height increases.

In safely crossing the high as compared to a low obstacle, participants exhibited substantial spatiotemporal changes. These spatiotemporal adaptations may reflect changes in the motor control and/or kinematic strategies to create a safety margin, reducing the risk of tripping. Obstacle height, for instance, had a significant effect on the timing of MFC (i.e., percent of swing phase of MFC), as well as the placement of both the lead and trail foot during the obstacle negotiation. Specifically, in agreement with Sparrow et al. (1996), the lead foot crossed significantly earlier in the gait cycle as obstacle height increased, which resulted in the heel of the lead foot landing significantly closer to the obstacle upon placement on the floor following the negotiated obstacle. This modification, however, may increase the likelihood of contacting the obstacle on the descent to the ground if not appropriately gauged, because the lead foot lands closer to the obstacle (Lowrey, Reed, and Vallis 2007). Yet, as suggested by Chen et al. (1991), this strategy may carry an increased risk of

causing a stumble induced by heel or midsole contact with the obstacle, rather than an increased risk of tripping from toe contact. Having the lead foot cross the obstacle earlier, while the trail limb is still supporting the center of mass, might increase the likelihood of arresting a trip that occurs from contact of the lead limb during the obstacle crossing. Conversely, the timing of the MFC for the trail foot occurred significantly later in the gait cycle and resulted in the trail foot being placed further from the high as compared to low obstacle. This strategy may potentially further decrease the risk of tripping. If obstacle contact were to occur, waiting to have the trail limb cross the obstacle until the center of mass is within or moving towards the base of support of the lead limb might increase the chance of producing an adequate corrective torque and arresting a destabilizing force, reducing the likelihood of a trip-related fall.

4.1 Limitations

The body borne loads currently adopted (i.e., approximately 6 kg and 20 kg) may be a limitation of the current study. The loads currently chosen did not elicit any significant changes in step length when negotiating an obstacle, which are commonly evident during other locomotor tasks (Birrell and Haslam 2009). Although the currently chosen body borne loads are commonly worn on duty, soldiers often carry loads greater than 20 kg, which often include an additional posterior torso borne load i.e., rucksack (Team Task Force Devil Combined Arms Assessment. 2003). These heavier posterior borne loads may elicit a different

biomechanical response than evident with the currently chosen load configurations, particularly when crossing an obstacle. As such, further research is needed to determine if these heavier, posterior borne loads result in biomechanical adaptations that subsequently increase the risk of suffering a trip-related fall when a soldier is on duty, particularly as they fatigue (Kesler et al., 2016). The current sample size may also be a limitation of the study. Increasing the sample size may have increased the power to detect a difference in trail limb clearance.

5. Conclusion

In conclusion, participants increased lead foot MFC and reduced CV in both the lead and trail MFC to create a safety margin when negotiating an obstacle with body borne load typically of military operations. These modifications likely reduce the soldier's immediate chance of tripping, and are potentially mechanisms to compensate for the compromised balance and greater likelihood of falling from a destabilizing force when impaired by body borne load. Obstacle height had no effect on foot clearance, but to safely navigate crossing the taller obstacle soldiers altered their foot placement. When negotiating the taller obstacle, participants placed their lead foot closer to and trail foot farther from the obstacle. Conversely, when impaired with body borne load, placing the trail foot closer to the obstacle may be an important compensatory mechanism to increase both lead and trail foot MFC and safely navigate crossing the obstacle.

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Figure Captions

Figure 1. Equipment for the loaded configuration (~ 19.4 kg) while crossing the high obstacle (457 mm) is presented. For the unloaded configuration (~ 6 kg), the participant only wore the helmet and boots, and carried the mock weapon.

Figure 2. The MFC and CV of MFC for the lead and trail foot with the loaded and unloaded configurations. * denotes significant differences ($p < 0.05$) between the unloaded and loaded configurations.

Figure 3. Scatter plot of trail foot placement (cm) and MFC (mm) for the lead and trail foot when negotiating the high obstacle for the loaded and unloaded configurations.

Table 1. Mean (SD) of MFC, CV and timing of MFC (% of swing) for both the lead and trail feet **within the two load and obstacle configurations.**

		Lead		Trail	
		Low	High	Low	High
MFC (mm)	Unloaded	78.1 (45.4)	85.5 (25.4)	150.6 (65.5)	182.0 (47.6)
	Loaded	94.8 (35.6)	111.2 (35.1)	161.6 (52.9)	196.8 (42.1)
Variability of MFC (%)	Unloaded	0.25 (0.08)	0.25 (0.14)	0.33 (0.28)	0.14 (0.05)
	Loaded	0.19 (0.07)	0.17 (0.09)	0.17 (0.12)	0.13 (0.04)
Timing of MFC (% of Swing)	Unloaded	60.3 (4.1)	54.5 (8.2)	37.6 (8.5)	53.4 (6.3)
	Loaded	61.0 (4.2)	55.8 (7.4)	35.7 (7.1)	53.1 (8.2)

Table 2. Mean (SD) of step length (cm) for the unloaded and loaded configurations, and lead and trail foot placement (cm) while crossing the low and high obstacles.

		Low	High
Step Length:	Unloaded	80.1 (8.0)	78.0 (10.9)
	Loaded	80.7 (8.4)	77.6 (10.3)
Foot Placement:	Lead *	28.3 (6.9)	24.8 (6.6)
	Trail *	24.2 (8.5)	26.4 (7.0)

* denotes significant difference ($p < 0.05$) between low and high obstacle

Figure 1

Figure 2

Figure 3