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

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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.

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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 et al., 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

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et al., 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 et al., 1999; Berard and Vallis, 2006; Draganich and Kuo, 2004; Lu et al., 2006; Sparrow et al., 1996). While MFC is generally between 10 and 20 mm during level walking (Mills et al., 2008), it reportedly increases for both the lead (Austin et al., 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 et al., 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 et al., 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 solider 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 et al., 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 et al., 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 (Fig. 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 m/s ± 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 et al., 2000) and held constant in order to not introduce speed as a covariate in the statistical analysis (Harman et al., 2000; LaFiandra et al., 2003). A trial was successful when a participant

Fig. 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.