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Sex and stride length impact leg stiffness and ground reaction forces when running with body borne load

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ABSTRACT

This study quantified leg stiffness and vGRF measures for males and females using different stride lengths to run with four body borne loads (20, 25, 30, and 35 kg). Thirty-six participants (20 males and 16 females) ran at 4.0 m/s using either: their preferred stride length (PSL), or strides 15% longer (LSL) and shorter (SSL) than PSL. Leg stiffness and vGRF measures, including peak vGRF, impact peak and loading rate, were submitted to a RM ANOVA to test the main effect and interactions of load, stride length, and sex. Leg stiffness was greater with the 30 kg ($p = 0.016$) and 35 kg ($p < 0.001$) compared to the 20 kg load, but decreased as stride lengthened from SSL to PSL ($p < 0.001$) and PSL to LSL ($p < 0.001$). Males exhibited greater leg stiffness than females with SSL ($p = 0.029$). Yet, males decreased leg stiffness with each increase in stride length ($p < 0.001$; $p < 0.001$), while females only decreased leg stiffness between PSL and LSL ($p = 0.014$). Peak vGRF was greater with the addition of body borne load ($p < 0.001$) and increase in stride length ($p < 0.001$). Both impact peak and loading rate were greater with the 30 kg ($p = 0.034$; $p = 0.043$) and 35 kg ($p = 0.004$; $p = 0.015$) compared to the 20 kg load, and increased as stride lengthened from SSL to PSL ($p = 0.001$; $p = 0.004$) and PSL to LSL ($p < 0.001$; $p < 0.001$). Running with body borne load may elevate injury risk by increasing leg stiffness and vGRFs. Injury risk may further increase when using longer strides to run with body borne load.

1. Introduction

The incidence of musculoskeletal injury (MSI) for military personnel has increased seven-fold in the last 25 years (Bell et al., 2008), with females exhibiting twice the injury rate as their male counterparts (Bell et al., 2000). Most training-related MSIs occur in the lower limb, with approximately 25% of pain, sprain and rupture of soft-tissue and bone that constitutes an injury occurring at the knee joint (Hauret et al., 2010). These injuries commonly occur during the repetitive load-bearing activities required during military training, such as running (Hauret et al., 2010). During training, military personnel routinely run with body borne loads that weigh between 20 and 40 kg (Andersen et al., 2016). These loads reportedly produce lower limb biomechanics alterations that increase risk of MSI, particularly at the knee (Brown et al., 2014).

During running, the addition of body borne load results in a 4–13% increase in peak vertical ground reaction force (vGRF) (Teunissen et al., 2007). In response to large peak vGRFs, individuals reportedly increase leg stiffness in attempt to protect the joints and prevent collapse of the lower limb (Silder et al., 2015). The elevated leg stiffness, however, may transmit larger loads to the joint and increase injury risk in the lower limb (Dufek and Bates, 1991; Ramsay et al., 2016). Silder et al. (2015) reported individuals increase leg stiffness upwards of 25% when running with light body borne loads - i.e., <20 kg. With the stiffer leg, individuals adopted greater hip and knee flexion, and reduced the change in leg length when running with light body borne loads (Silder et al., 2015). However, similar increases in hip or knee flexion angle have not been reported and may not be attainable when running with heavy, military-relevant body borne loads (Brown et al., 2014) - potentially further increasing the leg stiffness necessary to prevent limb collapse. But, a stiffer limb may increase the rapid transmission of vGRFs to the musculoskeletal system (Zadpoor and Nikooyan, 2011), resulting in increased impact peak (the first, rapid peak of vGRF after heel strike) and loading rate (transmission speed of the vGRF following heel strike) (Williams et al., 2004), and greater injury risk (Milner et al., 2006). Large magnitudes of these vGRF measures may require greater shock attenuation by the passive structures of the lower limb (Gruber et al., 2014), increasing likelihood of injury when using the stiff limb to run with load

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(Chu et al., 1986). Although impact peak and loading rate are purported to increase with the addition of load during walking (Tilbury-Davis and Hooper, 1999) and in those with greater leg stiffness during running (Williams et al., 2004), to date, it is unknown if similar increases in leg stiffness, and impact peak and loading rate are evident when running with the heavy body borne loads commonly worn during military training (between 20 kg and 35 kg).

During military training, personnel are often required to run at a fixed-cadence, potentially contributing to the high incidence of MSI (Seay et al., 2014). Running with a fixed cadence requires all personnel to use the same stride length, causing shorter individuals to over-stride and taller individuals to under-stride. Overstriding is posited to elevate risk of MSI from a substantial increase in mechanical stress placed upon the lower limb. During unloaded running, individuals reportedly increase peak magnitude, and the impact peak and loading rate of vGRF as stride is lengthened (Farley and González, 1996; Hobara et al., 2012). When using longer strides to walk with a 20 kg load, individuals are purported to exhibit a significant increase in GRFs and knee joint moments that may coincide with elevated risk of MSI, such as stress fracture or soft-tissue injury in the lower limb; conversely, individuals may decrease GRFs and knee joint moments when under-striding (Seay et al., 2014). But, to date, there is dearth of research regarding how changing stride length impacts GRFs and leg stiffness when running with heavy body borne loads.

For female personnel, who are typically shorter and weaker than their male counterparts (Stoll et al., 2000), using a fixed-cadence to run with body borne load may present a worst-case scenario in terms of MSI risk. During running, males and females are reported to exhibit similar magnitudes of peak vGRF with (Silder et al., 2015) and without body borne load (Keller et al., 1996), and impact peak when running without load (Baltich et al., 2015). However, due their shorter stature, females may be more likely to over-stride during military training, and subsequently increase GRFs and risk of MSI, such as stress fracture, during fixed cadence running (Milner et al., 2006). Yet, it is currently unknown if males and females exhibit similar GRFs when running with heavy military body borne loads or when required to change their stride length. Therefore, this study sought to determine the changes in leg stiffness and vGRF measures that occur when using different stride lengths to run with military-relevant body borne loads, and compare whether changes differed between male and female participants. It was hypothesized that leg stiffness and vGRF measures would significantly increase with each incremental addition of body borne load and stride length; but, females would exhibit larger GRFs compared to males when required to over-stride.

2. Methods

Preliminary leg stiffness data of loaded running suggested 18 participants are needed to achieve 80% statistical power with alpha level of 0.05 between the chosen body borne loads. To ensure adequate sample size, we recruited thirty-six (20 male and 16 female) physically active participants, who self-reported ability to carry 35 kg (Table 1). Potential participants were excluded if they had: (1) a history of previous back or lower extremity surgery; (2) pain in the back or lower extremity prior to testing; (3) a recent back or lower extremity injury (previous six months); (4) and/or a neurological disorder. Prior to testing, research approval was obtained from the local IRB and each participant provided written consent.

Each participant completed four test sessions. During each test session, participants donned a different body borne load configuration (20, 25, 30, or 35 kg). For each load configuration, participants were fitted with a spandex top and shorts, and carried military equipment that included: a mock weapon (M16), standard issue military helmet (ACH), and an adjustable weighted vest (Box, WeightVest.com, Rexburg, ID) (Fig. 1). To apply the additional load required for each condition, the weight of the vest was systematically adjusted with 1 kg weights. Each configuration was weighed prior to testing and a total load ±2% of the target was accepted. Each test session was separated by at least 24 h to limit the effects of fatigue. Prior to testing, the testing order was randomized and counter-balanced using a 4 × 4 Latin Square design.

Before testing, each participant had their preferred stride length (PSL) determined. To determine PSL, participants ran at 4 m/s (±5%) through the motion capture area three times with each load configuration (20, 25, 30 and 35 kg). During each trial, stride length was calculated as the linear distance between two consecutive heel strikes of the dominant limb (Thompson et al., 2014). The PSL was calculated as average stride length exhibited with each load configuration, and then SSL and LSL were calculated as 85% and 115% of the PSL, respectively.

With each load, participants had three-dimensional (3D) lower limb joint biomechanics data recorded during an over-ground running task. During the run, a single force platform (OR6, AMTI, Watertown, MA) captured GRF data at 2400 Hz, while eight high-speed optical cameras (MXF20, Vicon, Oxford, UK) recorded lower limb motion data at 240 Hz. For the run task, participants ran approximately 10 m at 4 m/s (±5%) through the motion capture

Table 1
Mean (SD) subject demographics (age, height and weight) for both the male and female participants.

	N	Age (years)	Height (m) [a]	Weight (kg) [a]
Males	20	21.5 (2.8)	1.8 (0.1)	82.6 (11.6)
Females	16	21.2 (2.8)	1.7 (0.1)	65.0 (11.5)

[a] Denotes a significant main effect of sex.

Fig. 1. Depicts the military equipment worn for each load condition (20 kg, 25 kg, 30 kg, or 35 kg). For each condition, participants were outfitted with a helmet, weighted vest, and mock weapon. The weight of the vest was systematically adjusted to provide the load necessary for each condition.

volume using either their PSL, SSL or LSL. During each run, two sets of infrared timing gates (TF100, TracTronix, Lenexa, KS), placed 4 m apart in the motion capture volume, quantified running speed. Participants performed three successful trials with each stride length (PSL, SSL, and LSL). To minimize the number of incorrect trials, each participant's required stride length was marked on the floor with tape according to Allet et al. (2011). The order each participant performed the stride lengths was randomized using a 3 × 3 Latin Square design and assigned prior to testing. A trial was considered successful if the participant ran at the correct speed, used the correct stride length, and 'naturally' contacted the force platform with their dominant limb. During testing, participants were given water and provided adequate rest between each trial to minimize the effects of fatigue.

During each trial, lower limb biomechanics were quantified using the 3D coordinates of thirty-four retro-reflective markers using Visual 3D v6.00 (C-Motion, Rockville, MD), in accordance with our previous work (Brown et al., 2018). For each trial, synchronous 3D GRF and marker trajectory data were low pass filtered using a fourth-order Butterworth filter with a cutoff of 12 Hz. Then, a custom written MATLAB (Mathworks, Natick, MA) code calculated each dependent variable. From the filtered GRF data, peak stance phase vGRF, and impact peak and loading rate of vGRF were calculated. Because a well-defined impact peak was not present for all trials, the magnitude of vGRF at 13% stance phase was used as a proxy for impact peak (Willy et al., 2008). Loading rate was defined as the slope of the vGRF between 20% and 80% of the period between heel strike and impact peak (Milner et al., 2006). All GRF variables were normalized to subject body weight (N). Leg stiffness was calculated at the frame where leg length reached its minimum, and defined as the component of GRF directed from the center of pressure (CoP) to the hip joint center (F_e) divided by the change in leg length (L_e) (Coleman et al., 2012):

$$\text{Leg Stiffness} = \frac{F_e}{\max(\Delta L_e)}$$

Leg length was defined as the linear distance between the CoP and the hip joint center and normalized to each subject's standing leg length (Liew et al., 2017). Stance phase was defined as heel strike to toe off and defined as the moment GRF first exceeded and fell below 10 N, respectively.

Each dependent variable (leg stiffness, peak vGRF, impact peak and loading rate of vGRF, and change in leg length) was averaged across the three successful trials to create a participant-based mean. Each participant-based mean was submitted to a 3-way repeated-measures analysis of variance (ANOVA) to test the main effects of and interaction between load (*20 kg, 25 kg, 30 kg, and 35 kg*), stride length (*PSL, SSL, and LSL*), and sex (*male vs female*). Significant interactions were submitted to a simple effects analysis, and a Bonferroni correction was used for multiple comparisons. For significant pairwise comparisons, effect size was calculated using Cohen's d (1988). Independent *t-tests* were used to compare demographics between sexes. All statistical analysis was performed using SPSS v23 software (IBM, Armonk, NY) with alpha level 0.05.

3. Results

The male participants were significantly heavier ($p < 0.001$) and taller ($p < 0.001$), but not older ($p = 0.690$) than the female participants (Table 1).

3.1. Leg stiffness

The ANOVA revealed a significant stride length versus sex interaction for leg stiffness ($p = 0.001$) (Fig. 2 and Table 2). Both males and females decreased leg stiffness when using LSL compared to PSL ($p < 0.001$, $d = 0.92$; $p = 0.014$, $d = 0.50$) and SSL ($p < 0.001$, $d = 1.29$; $p = 0.049$, $d = 0.49$), but only males decreased leg stiffness using PSL compared to SSL ($p = 0.004$, $d = 0.39$). Further, males exhibited greater leg stiffness compared to females with SSL ($p = 0.029$, $d = 0.79$), but not with PSL ($p = 0.215$, $d = 0.44$) or LSL ($p = 0.999$, $d < 0.01$).

Load ($p < 0.001$) and stride length ($p < 0.001$), but not sex ($p = 0.190$) had a significant effect on leg stiffness (Fig. 2 and Table 2). Leg stiffness increased with the 30 kg ($p = 0.016$, $d = 0.49$) and 35 kg ($p < 0.001$, $d = 0.66$) compared to the 20 kg load, but no significant differences were evident between any other loads. Further, participants decreased leg stiffness with LSL compared to PSL ($p < 0.001$, $d = 0.68$) and SSL ($p < 0.001$, $d = 0.91$), but no significant difference was observed between the PSL and SSL ($p = 0.065$, $d = 0.22$) strides.

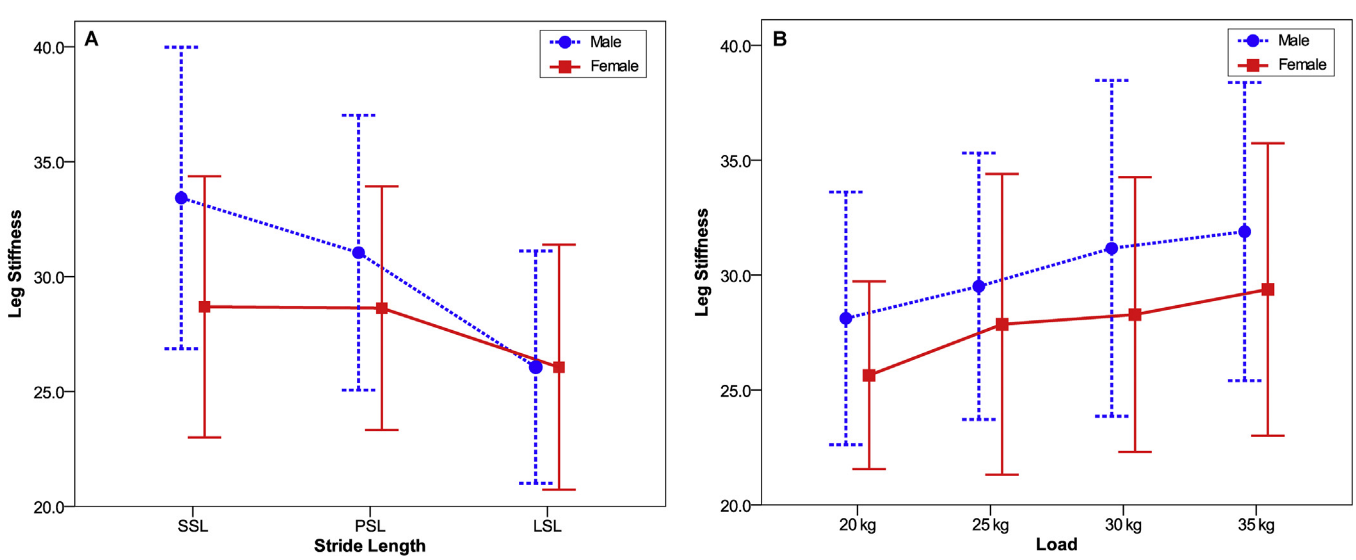

Fig. 2. Peak leg stiffness exhibited by male and female participants running with each stride length (SSL, PSL, and LSL) (**A**) and by all participants running with each body borne load (20 kg, 25 kg, 30 kg, and 35 kg) (**B**).

Table 2
Mean (SD) of each biomechanical parameter for the male and female participants running with each stride length (SSL, PSL and LSL) and body borne load (20 kg, 25 kg, 30 kg, and 35 kg).

		20 kg		25 kg		30 kg		35 kg	
		Male	Female	Male	Female	Male	Female	Male	Female
Leg Stiffness[a,b,c]	SSL	30.9 (7.5)	27.0 (6.0)	33.4 (8.1)	29.0 (7.4)	35.0 (9.6)	28.8 (5.7)	34.4 (8.0)	30.0 (6.4)
	PSL	29.1 (6.1)	26.5 (4.3)	29.5 (6.6)	29.1 (7.7)	31.7 (7.3)	28.8 (6.6)	34.0 (7.9)	30.1 (6.9)
	LSL	24.4 (5.9)	23.5 (5.2)	25.7 (5.9)	25.6 (5.9)	26.8 (7.3)	27.2 (6.8)	27.3 (6.2)	28.0 (7.1)
Peak vGRF (BW)[a,b]	SSL	2.7 (0.3)	2.6 (0.3)	2.9 (0.3)	2.7 (0.3)	2.9 (0.3)	2.7 (0.3)	3.0 (0.3)	2.8 (0.3)
	PSL	2.9 (0.4)	2.7 (0.3)	3.0 (0.3)	2.7 (0.4)	3.1 (0.4)	2.8 (0.4)	3.1 (0.4)	2.9 (0.4)
	LSL	3.0 (0.4)	2.9 (0.3)	3.1 (0.4)	3.0 (0.3)	3.1 (0.4)	3.0 (0.4)	3.2 (0.4)	3.1 (0.4)
Impact Peak (BW)[a,b]	SSL	1.4 (0.3)	1.4 (0.3)	1.4 (0.3)	1.4 (0.2)	1.5 (0.3)	1.5 (0.2)	1.5 (0.3)	1.6 (0.2)
	PSL	1.5 (0.3)	1.4 (0.3)	1.5 (0.2)	1.5 (0.2)	1.6 (0.2)	1.6 (0.3)	1.6 (0.3)	1.6 (0.2)
	LSL	1.8 (0.3)	1.7 (0.3)	1.9 (0.3)	1.8 (0.3)	1.9 (0.3)	1.9 (0.3)	1.9 (0.3)	2.0 (0.3)
Loading Rate (BW/s)[a,b]	SSL	45.0 (9.7)	46.4 (9.3)	44.7 (9.8)	48.6 (6.7)	46.7 (10.2)	49.1 (7.5)	47.3 (9.8)	51.4 (7.5)
	PSL	48.7 (10.3)	47.2 (10.8)	47.5 (9.0)	50.5 (6.5)	51.1 (7.7)	51.9 (9.9)	50.1 (11.2)	53.4 (6.4)
	LSL	55.9 (10.6)	55.3 (9.6)	55.7 (11.7)	56.9 (9.4)	56.8 (9.1)	59.5 (9.2)	58.6 (11.4)	62.0 (9.5)
Change LL (%)[b]	SSL	9.2 (2.8)	9.8 (1.5)	9.7 (4.9)	9.5 (1.9)	8.7 (2.4)	9.3 (1.4)	9.7 (5.2)	9.4 (1.4)
	PSL	10.3 (3.0)	9.9 (1.4)	10.3 (2.8)	9.6 (2.2)	9.6 (2.0)	9.9 (2.0)	9.4 (2.7)	9.6 (1.5)
	LSL	12.5 (3.7)	12.2 (3.1)	11.9 (2.9)	11.6 (3.3)	11.8 (2.7)	10.8 (2.1)	12.0 (4.4)	10.9 (2.0)

[a] Denotes a significant main effect of load.
[b] Denotes a significant main effect of stride length.
[c] Denotes a significant interaction of sex and stride length.

3.2. Peak GRF

Load ($p < 0.001$) and stride length ($p < 0.001$), but not sex ($p = 0.110$) had a significant effect on peak vGRF (Fig. 3 and Table 2). Specifically, peak vGRF was larger with 35 kg compared to 30 kg ($p = 0.001$, $d = 0.28$), 25 kg ($p < 0.001$, $d = 0.43$), and 20 kg ($p < 0.001$, $d = 0.73$) loads, and with the 30 kg ($p < 0.001$, $d = 0.44$) and 25 kg ($p < 0.001$, $d = 0.32$) loads compared to the 20 kg load. Peak vGRF was also greater with LSL compared to PSL ($p < 0.001$, $d = 0.40$) and SSL ($p < 0.001$, $d = 0.78$), and with PSL compared to SSL ($p = 0.005$, $d = 0.34$).

3.3. Impact peak

Load ($p < 0.001$) and stride length ($p < 0.001$), but not sex ($p = 0.827$) had a significant effect on impact peak (Table 2). The impact peak was larger with the 30 and 35 kg loads compared to 20 kg ($p = 0.034$, $d = 0.44$; $p < 0.001$, $d = 0.63$), and 35 compared to 25 kg ($p = 0.004$, $d = 0.48$). Impact peak also increased with LSL compared to PSL and SSL ($p < 0.001$, $d = 1.24$; $p < 0.001$, $d = 1.75$), and PSL compared to SSL ($p = 0.001$, $d = 0.52$).

3.4. Loading rate

Load ($p = 0.004$) and stride length ($p < 0.001$), but not sex ($p = 0.431$) had a significant effect on the loading rate of vGRF (Table 2). Loading rate was larger with 30 and 35 kg compared to 20 kg load ($p = 0.043$, $d = 0.31$; $p = 0.015$, $d = 0.43$), but differences were not observed between any other load. Loading rate was also greater with LSL compared to PSL and SSL ($p < 0.001$, $d = 0.95$; $p < 0.001$, $d = 1.31$), and PSL compared to SSL ($p = 0.004$, $d = 0.36$).

3.5. Change in leg length

Stride length ($p < 0.001$), but not sex ($p = 0.729$) or load ($p = 0.308$) had a significant effect on the change in leg length (Table 2). Change in leg length was larger for LSL compared to both PSL ($p < 0.001$, $d = 0.89$) and SSL ($p < 0.001$, $d = 1.07$), but there was no significant difference between PSL and SSL ($p = 0.284$, $d = 0.23$).

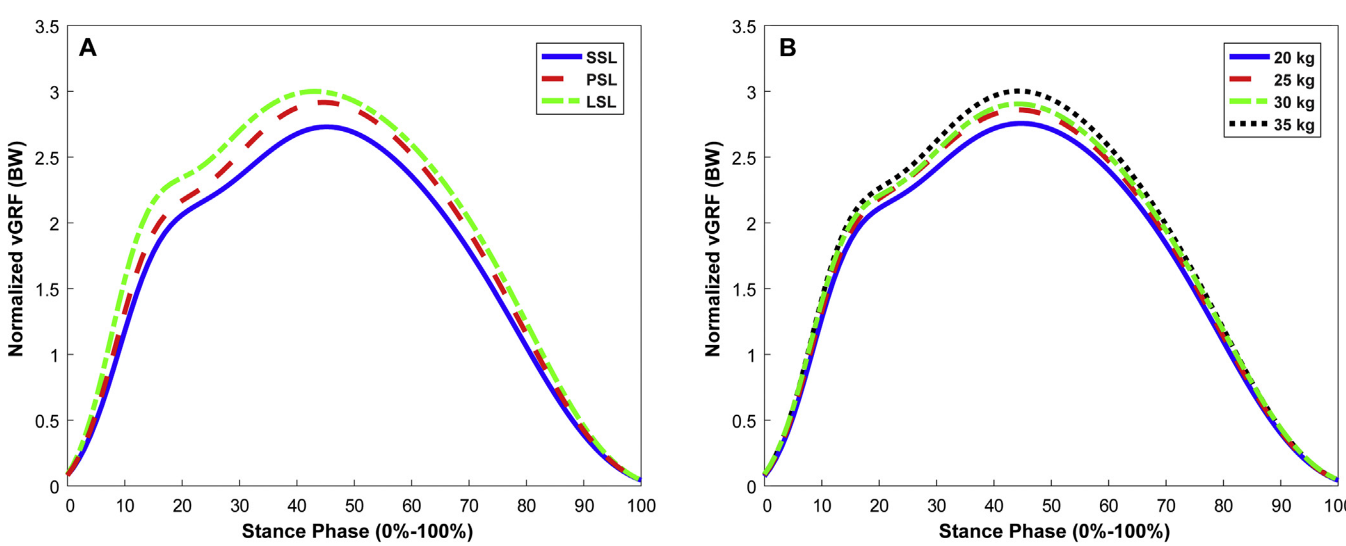

Fig. 3. Stance phase (0–100%) vGRF exhibited when running with each stride length (SSL, PSL, and LSL) (**A**) and each body borne load (20 kg, 25 kg, 30 kg, and 35 kg) (**B**).

4. Discussion

Large increases in leg stiffness when running with body borne load may contribute to the high incidence of MSI for military personnel. In agreement with previous literature (Silder et al., 2015), current participants exhibited a significant increase in leg stiffness when running with body borne load that may be attributed to larger vGRFs and no corresponding change in leg length. But, our hypothesis that each incremental addition of body borne load (from 20 to 35 kg) would produce a significant increase in leg stiffness during running was only partially supported. Participants increased leg stiffness between 7% and 14% with the addition of body borne load. Yet, a significant increase in stiffness was only observed with 30 and 35 kg compared to the 20 kg load. The stiffer leg observed with the 30 and 35 kg loads may stem from a significant 0.15 BW and 0.24 BW increase in peak vGRF that is common with the addition of load (Ramsay et al., 2016; Silder et al., 2015). During running, large vGRFs require the lower limb musculature to safely attenuate more force in order to prevent injury of the passive lower limb structures (James et al., 1978), such as a stress fracture or ligament rupture (Derrick et al., 1998). These vGRFs are primarily attenuated through eccentric quadriceps contraction as the knee flexes (Novacheck, 1998), with greater flexion related to increased energy absorption and reduced leg stiffness during weight acceptance (DeVita and Skelly, 1992; Greene and McMahon, 1979). The current participants, however, did not alter their leg length with the addition of load. In fact, the participants may stiffen their limb to prevent collapse during weight acceptance, a biomechanical adaptation that may limit active attenuation of the GRFs by the quadriceps, increasing injury risk (Derrick et al., 1998).

The larger impact peak and loading rate evident with the addition of load may further increase the risk of MSI (Milner et al., 2006). In agreement with Williams et al. (2004), the stiffer limb may lead to greater impact peak and loading rate. Specifically, the current participants exhibited a significant 7% and 10% increase in impact peak, and 5% and 8% increase in loading rate with the 30 and 35 kg load conditions. These GRF measures consist of both high and low frequency content. The low frequency content of the impact peak is actively attenuated by muscle activation and alterations in leg stiffness (Derrick et al., 1998), while the high frequency content must be attenuated through deformation of passive musculoskeletal structures such as bones, ligaments, and cartilage (Paul et al., 1978). The larger impact peak and loading rate currently observed with the addition of body borne load purportedly increase the high frequency content of impact, leading to greater attenuation by the passive musculoskeletal structures and risk of bony or soft-tissue injury (Gruber et al., 2014). Considering specific lower limb biomechanics may influence impact peak and the attenuation of impact by the musculoskeletal system (Derrick et al., 1998), future research is warranted to determine the specific hip, knee and ankle kinematics necessary to reduce impact peak and loading rate when running with load.

In contradiction to our hypothesis, running with longer strides did not further increase leg stiffness. The current participants exhibited a significant 13% decrease in leg stiffness as stride length increased from PSL to LSL, despite a concurrent 5% increase in peak vGRF. Because leg stiffness is a product of vGRF and change in leg length (Silder et al., 2015), the decrease in leg stiffness with longer strides must be attributed to a significant 19% increase in change in leg length across stance. A greater change of leg length, and subsequent reduction in leg stiffness, reportedly occurs with an increased range of flexion motion by the lower limb during stance (Farley et al., 1998). By increasing the change of leg length with longer strides, the current participants may reduce vGRFs (Hewett et al., 1996) and associated risk of MSI by increasing the active attenuation of the energy associated with heel strike with the lower limb musculature (Derrick et al., 1998). In fact, participants using greater hip and knee range of motion when landing with body borne load are purported to increase energy absorption by the knee musculature (Brown et al., 2016). Yet, running with longer strides may elevate risk of MSI by increasing both impact peak and loading rate. In support of this contention, the current participants exhibited increases of 8% and 28% in impact peak and 6% and 22% in loading rate with each incremental increase in stride length. Although, the current participants modified leg stiffness when increasing stride length, the greater peak vGRF, and impact peak and loading rate observed with the longer strides may elevate MSI risk.

The ability to modulate leg stiffness and risk of MSI across stride lengths may differ between sexes. Male participants decreased leg stiffness by 7% and 16% with each incremental increase in stride length, while the female participants only exhibited a significant 9% decrease in leg stiffness between PSL and LSL. While the reason for the current sex dimorphism is not immediately evident, the male participants exhibited greater leg stiffness when using the SSL compared to their female counterparts. Female service members, who sustain an MSI at twice the rate of their male counterparts (Bell et al., 2000), may minimize leg stiffness to aid with attenuation of the larger vGRFs of running with load, regardless of chosen stride length. However, the taller, heavier males reportedly exhibit greater hip and knee strength than females (Stoll et al., 2000). The larger male participants may possess the lower limb strength to adopt a stiffer leg and subsequently greater performance to run with shorter strides. Considering increasing leg stiffness is necessary for improved running economy (Dalleau et al., 1998), further research is warranted to determine if lower limb strength, rather than sex, impacts leg stiffness and performance during the running tasks common to military training.

The current leg stiffness calculation may be a limitation. While this is a common method for calculating leg stiffness (Coleman et al., 2012), it does not account for mediolateral GRFs or changes of leg length in the frontal plane. The exclusion of these frontal plane measures may explain why a sex dimorphism in leg stiffness or GRF measures was not observed. Previously, sex differences in mediolateral GRFs (Bazuelo-Ruiz et al., 2018), and frontal plane hip and knee biomechanics have been observed during locomotion (Ferber et al., 2003). Analyzing these frontal plane measures may be of particular importance when comparing males and females and warrants exploration in future load carriage research. The chosen participants may also be a limitation. While all participants self-reported the ability to safely carry body borne loads, they were not required to have load carriage experience. Participants with previous load carriage experience may exhibit a substantial difference in leg stiffness and vGRFs compared to inexperienced load carriers when running with load.

5. Conclusion

In conclusion, adding body borne load may increase risk of MSI for military personnel. The current participants exhibited a significant increase in leg stiffness and vGRF measures, including peak magnitude, impact peak and loading rate, when running with 30 kg and 35 kg loads. Over-striding, however, did not further increase leg stiffness. Rather, the current participants decreased leg stiffness 4% and 13% with each incremental increase in stride length, but the ability to modulate leg stiffness differed between sexes. Males exhibited greater leg stiffness with the short strides and decreased leg stiffness with each incremental increase in stride length, whereas, female participants only exhibited a reduction in leg stiffness with the long strides. But, regardless of sex, using longer strides to run with body borne load may increase risk of MSI by placing greater mechanical stress on the limb. With each increase in stride length, the current participants exhibited a significant 8–28% increase in the impact peak and 6–22% increase in loading rate that the limb must safely attenuate.

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Conflict of Interest

None of the authors demonstrate any conflict of interest regarding this submission.

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