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Running with a load increases leg stiffness

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ABSTRACT

Spring-mass models have been used to characterize running mechanics and leg stiffness in a variety of conditions, yet it remains unknown how running while carrying a load affects running mechanics and leg stiffness. The purpose of this study was to test the hypothesis that running with a load increases leg stiffness. Twenty-seven subjects ran at a constant speed on a force-measuring treadmill while carrying no load, and while wearing weight vests loaded with 10%, 20%, and 30% of body weight. We measured lower extremity motion and created a scaled musculoskeletal model of each subject, which we used to estimate lower extremity joint angles and leg length. We estimated dimensionless leg stiffness as the ratio of the peak vertical ground reaction force (normalized to body weight) and the change in stance phase leg length (normalized to leg length at initial foot contact). Leg length was calculated as the distance from the center of the pelvis to the center-of-pressure under the foot. We found that dimensionless leg stiffness increased when running with load ($p=0.001$); this resulted from an increase in the peak vertical ground reaction force ($p<0.001$) and a smaller change in stance phase leg length ($p=0.025$). When running with load, subjects had longer ground contact times ($p<0.020$), greater hip ($p<0.001$) and knee flexion ($p=0.048$) at the time of initial foot contact, and greater peak stance phase hip, knee, and ankle flexion ($p<0.05$). Our results reveal that subjects run in a more crouched posture and with higher leg stiffness to accommodate an added load.

1. Introduction

The mechanics of human running have often been characterized using a spring-mass model (e.g. Arampatzis et al., 1999; Blum et al., 2009; Donelan and Kram, 2000; Farley and Gonzalez, 1996; Lipfert et al., 2012; McMahon and Cheng, 1990). In a spring-mass model, the leg is treated as a massless linear spring, and the leg spring stiffness is related to the peak vertical ground reaction force and the change in stance phase leg length. Analyses of spring-mass models have suggested that leg stiffness increases in proportion to body mass among a wide range of animals (Farley et al., 1993). Running while carrying load is common in humans, but it is unknown how carrying load influences running mechanics and leg stiffness.

During the early stance phase of running, the distance between the center-of-mass and the foot decreases, as a result of flexion of the hip, knee, and ankle, and reaches a minimum near the middle of the stance phase (Cavagna et al., 1976; McMahon and Cheng, 1990). Leg stiffness is therefore related to lower extremity joint angles (Gunther and Blickhan, 2002; Kuitunen et al., 2002). Early studies of vertical hopping showed that leg stiffness decreased when subjects hopped with greater knee flexion angles (Greene and McMahon, 1979). Walking with progressively larger loads increases peak stance phase hip flexion (Silder et al., 2013), knee flexion (Birrell and Haslam, 2009; Silder et al., 2013), and ankle dorsiflexion angles (Silder et al., 2013), but it is unknown if subjects run with greater joint flexion when carrying a load.

Stance phase joint flexion angles and ground contact time can affect the peak vertical ground reaction force. McMahon et al. (1987) showed that when subjects ran with more lower extremity joint flexion (i.e. “Groucho running”) ground contact time increased and the peak vertical ground reaction force decreased. During both walking and running, the peak vertical ground reaction force increases less than the added load (Silder et al., 2013; Teunissen et al., 2007). For example, when subjects were asked to walk with load equal to 30% of their body weight, the peak vertical ground reaction force increased by an average of only 15% (Silder et al., 2013), and when asked to run with 30% of body weight, the peak vertical ground reaction force increased only 12%, compared to no load (Teunissen et al., 2007). During walking, subjects mitigate the increase in ground reaction force by increasing ground contact time and increasing flexion of the lower extremity joints (Silder et al., 2013), but the effects of load carriage

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on ground contact time and lower extremity joint angles during running are unknown.

We were interested to see whether subjects show similar adaptations when running with load as they do when walking with load. We expected that the peak vertical ground reaction force would increase and therefore hypothesized that leg stiffness would also increase when running with load. We further hypothesized that subjects would increase ground contact time and flex their hip, knee, and ankle joints more when running with load. We sought to test these hypotheses to understand how subjects adapt to running with load.

2. Methods

Twenty-seven recreational runners (16M, 11F; 33 ± 8 years; 70 ± 9 kg; 1.75 ± 0.09 m) provided informed consent to participate in this study according to a protocol approved by the Stanford University Institutional Review Board. Subjects were excluded if they could not run comfortably for a minimum of one hour at a speed of 3 m/s or faster.

All running trials were conducted on a split-belt force-instrumented treadmill (Bertec Corporation; Columbus, OH, USA) at each subject's self-reported 10 km training pace (mean ± SD = 3.34 ± 0.22 m/s). Subjects were not instructed to run with a particular foot strike pattern; inspection of each subject's running pattern during the data collection indicated that 25 of the 27 subjects ran with a heel–toe running pattern, and two ran with a forefoot strike pattern. Subjects completed four running trials; each trial was two minutes in duration. The trials were completed in random order and included carrying no load, or a load of 10%, 20%, or 30% of their body weight (BW). Subjects carried loads using an adjustable weight vest (HyperWare®, Austin, TX, USA). We chose this method of load carriage because it left the pelvis exposed for placement of motion capture markers, and the weight vests had approximately equal weight in the front and back, thereby producing a minimal change to the anterior–posterior center-of-mass location of the torso.

We estimated dimensionless leg stiffness, K_{leg}, as the ratio of the peak vertical ground reaction force normalized to body weight, $F_{\max}$, to the change in leg length during stance phase, normalized to leg length at foot contact, l_o

$$K_{\text{leg}} = \frac{F_{\max}}{(l_o - l_{\min})/l_o}, \qquad (1)$$

where $l_{\min}$ is the minimum leg length during stance phase. Leg length was estimated as the distance from the center-of-pressure (Bullimore and Burn, 2006) to the center of the pelvis in a model derived from the musculoskeletal model described by Delp et al. (1990) (Fig. 1).

Lower body motion (measured at 100 Hz) and ground reaction forces (measured at 2000 Hz) were analyzed for 10 consecutive left limb gait cycles for each trial. Motion was measured using 29 retro-reflective markers with an eight-camera optical motion-capture system (Vicon, Oxford Metrics Group, Oxford, UK). Thirteen markers were attached bilaterally to anatomical landmarks on the pelvis and lower extremities; an additional 16 markers were used to aid in segment tracking. We used a scaled model to represent the pelvis and lower limbs for each subject, derived from Delp et al. (1990). The pelvis was the base segment and had six degrees-of-freedom; the hip was represented as a spherical joint with three degrees-of-freedom; the knee was represented as a one degree-of-freedom joint in which non-sagittal rotations and tibiofemoral and patellofemoral translations were computed as a function of the sagittal knee angle (Walker et al., 1988); the ankle (talocrural) was represented as a revolute joint aligned with the anatomical axes (Delp et al., 1990). An upright static calibration trial and functional hip joint center trial (Piazza et al., 2004) were used to define body segment coordinate systems, marker locations, joint centers, and segment lengths for each subject. A global optimization inverse kinematics routine was used to compute pelvis position, pelvis orientation, and lower extremity joint angles at each time frame in the trials (Lu and O'Connor, 1999) using SIMM (Motion Analysis Corp, Santa Rosa, CA, USA; Delp and Loan, 2000).

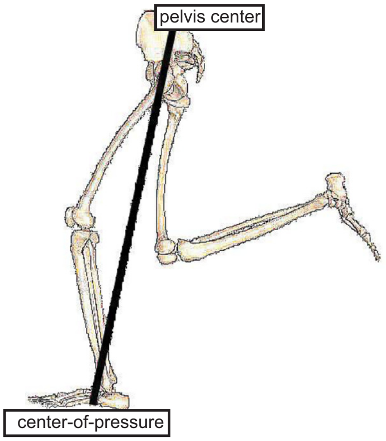

Fig. 1. Leg length was estimated by calculating the distance from the center-of-pressure to the center of the pelvis in a model derived from the musculoskeletal model described by Delp et al. (1990).

For each subject, we averaged data from 10 consecutive strides from each testing condition. We then compared the effect of load on leg stiffness, stance phase leg length (at foot contact, minimum length, and change in length), ground contact time, and the hip, knee, and ankle angles at the time of initial foot contact and the peak stance phase joint angles. Statistical analyses were performed using repeated measures ANOVA (SPSS, IBM, Armonk, NY, USA) with significance established at $p < 0.05$. We investigated the main effect of load on leg stiffness using Tukey's HSD post-hoc test.

3. Results

Dimensionless leg stiffness increased when running with load ($p = 0.001$, Table 1). Leg stiffness increased because the peak vertical ground reaction force increased ($p < 0.001$), and the change in stance phase leg length decreased ($p = 0.025$). Post-hoc analyses revealed that leg stiffness increased between running with no load and running with 20% ($p = 0.002$) and 30% ($p = 0.006$) of body weight. The only other significant pair-wise increase in leg stiffness was between the 10% and 30% load carriage conditions ($p = 0.046$). As the amount of load carried increased, leg length at initial foot contact decreased ($p = 0.007$) and minimum leg length during stance phase tended to decrease ($p = 0.051$) (Fig. 2B, Table 1).

The percent increase in the peak vertical ground reaction force (normalized to body weight) was less than the 10% increase in added load between testing conditions. With each 10% increase in load, the peak vertical ground reaction force increased an average of 5%, 4%, and 4% (Fig. 2A, Table 1). With each 10% increase in load, leg stiffness increased an average of 2%, 11%, and 10% (Fig. 3).

Ground contact time increased when running with load ($p < 0.020$, Table 1), and lower extremity joint kinematics were significantly altered. Flexion of the hip ($p < 0.001$) and knee ($p = 0.048$) increased at the time of initial foot contact, and peak stance phase hip flexion ($p = 0.021$), knee flexion ($p = 0.020$), and ankle dorsiflexion ($p = 0.004$) angles increased when running with load (Fig. 4). For all except five subjects, peak stance phase hip flexion occurred at the time of initial foot contact.

4. Discussion

This study tested the hypothesis that running at a constant speed while wearing weight vests with an additional 10%, 20%, and 30% of body weight would increase leg stiffness. In support of this hypothesis, dimensionless leg stiffness increased when running with load because of a simultaneous increase in the peak vertical ground reaction force and a decrease in the change in stance phase leg length. We also tested the hypothesis that running with load would increase ground contact time and peak stance phase lower extremity joint flexion angles. Our data support this hypothesis, showing that subjects ran with longer ground contact times and greater joint flexion when they carried a load.

Similar to our observations of walking with loads (Silder et al., 2013) and others' observations made of running with loads (Teunissen et al., 2007), the percent increase in the peak vertical ground reaction force was less than the added load (Fig. 2A, Table 1). When running with an additional 30% of body weight, the peak vertical ground reaction force increased an average of only 13%; this is similar to the 12% increase observed by

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Table 1
Mean (standard deviation) values from subjects running at the same speed with no load, and an additional 10%, 20% and 30% of body weight (BW). Dimensionless leg stiffness was estimated from the peak vertical ground reaction force (GRF) divided by body weight and the change in stance phase leg length. *p*-values indicate the main effect of load.

	No load	10%	20%	30%	*p*-Value
Dimensionless leg stiffness	35 (7)	36 (9)	40 (8)	44 (11)	0.001
Peak vertical GRF (BW)	2.5 (0.4)	2.6 (0.4)	2.7 (0.4)	2.8 (0.4)	<0.001
Change in stance phase leg length (% initial length)	7.3 (1.7)	7.7 (1.7)	7.0 (1.3)	6.7 (1.8)	0.025
Ground contact time (s)	0.24 (0.02)	0.25 (0.02)	0.25 (0.02)	0.26 (0.02)	0.020

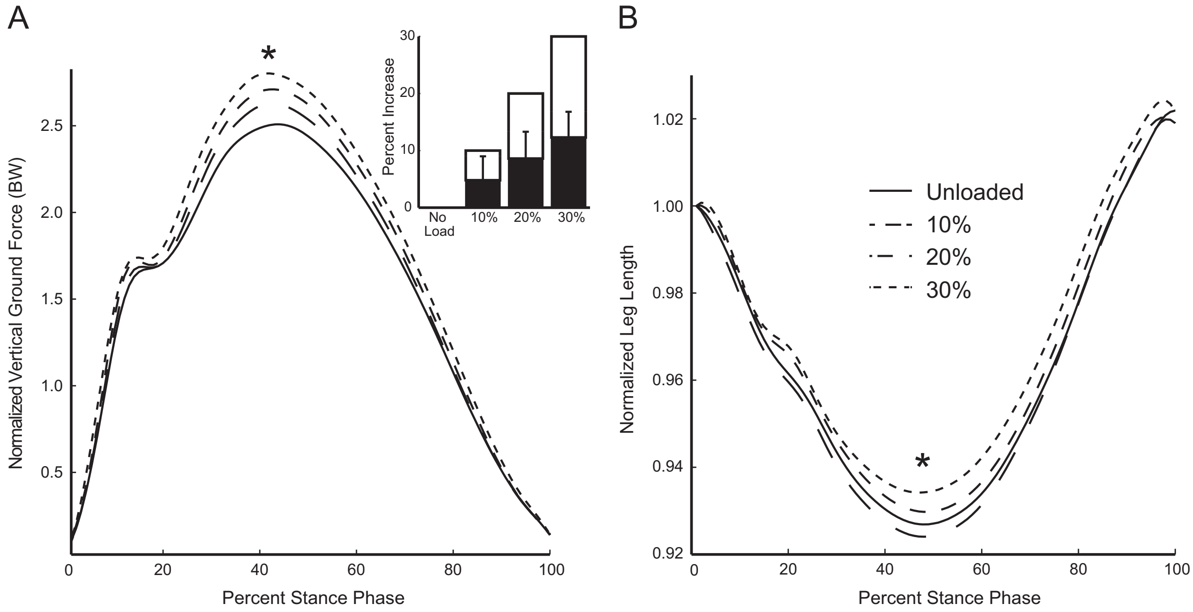

Fig. 2. Stance phase ensemble averaged (A) vertical ground force divided by body weight (BW) as subjects ran while carrying no load, and wearing weight vests loaded with 10%, 20%, and 30% of body weight. The solid bars of the inset figure represent the mean and standard deviation of the percent increase in the peak vertical ground reaction force, compared to unloaded running. As loads increased, the peak vertical ground force increased ($p<0.001$) less than the percent increase in added load, represented by the white bars. (B) Leg length divided by leg length at initial contact vs. percent stance phase decreased ($p=0.025$) when subjects ran with load. Significant trends indicated with *.

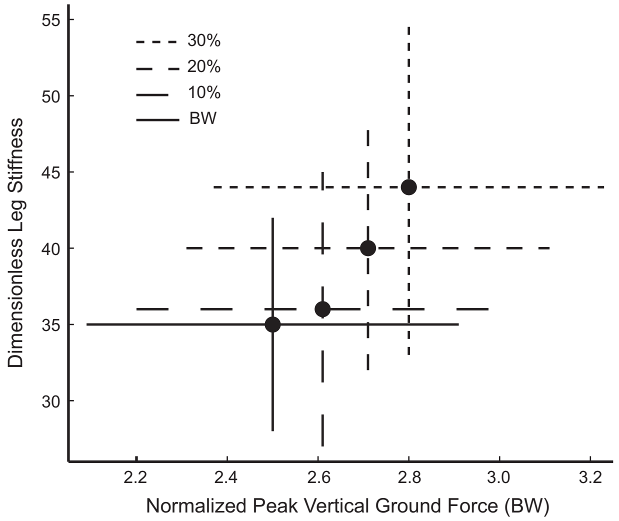

Fig. 3. Mean and standard deviation of dimensionless leg stiffness plotted vs. normalized peak vertical ground reaction force from subjects while running with no load and an additional 10%, 20%, and 30% of body weight (BW). The percent increase in leg stiffness (24%) was more than the percent increase in the peak vertical ground reaction force (13%) between running with no load and running with an additional 30% of BW.

Teunissen et al. (2007). Carrying load also caused an increase in ground contact time (Table 1) and peak stance phase hip flexion, knee flexion, and ankle dorsiflexion angles (Fig. 4). Groucho running is similarly characterized by an increase in lower extremity joint flexion angles, longer contact times, and lower peak vertical ground reaction forces (McMahon et al., 1987). The time integral of the ground reaction force across one step is a function of the product of contact time and total weight, including any additional weight being carried. Therefore, longer contact times may enable the peak vertical ground reaction force to increase less than the added load.

We observed an interesting relationship between the changes in leg stiffness, peak vertical ground reaction force, and stance phase leg length when running with load. Despite a relatively small increase in the peak vertical ground reaction force, the percent increase in leg stiffness was approximately equal to the added load when running with 20% and 30% of BW (Fig. 3, Table 1). Leg stiffness increased more than the peak vertical ground reaction force because stance phase leg compression decreased (Fig. 2B, Table 1).

We expect that increased joint flexion resulting from the added load necessitated greater muscle activity, which may, in turn, increase metabolic cost. For example, walking with increased joint flexion (Steele et al., 2010) and muscle activity (Hortobagyi et al., 2011) are associated with greater metabolic cost. Teunissen et al. (2007) found that when running with load equal to 30% of body weight, metabolic cost increased by an average of 38%. Although it is accepted that healthy adults tend to walk in an energetically optimal manner (Saunders et al., 1953), it is possible that a different optimization goal is chosen when running with load. The exact goal remains unclear, but the relatively large increase

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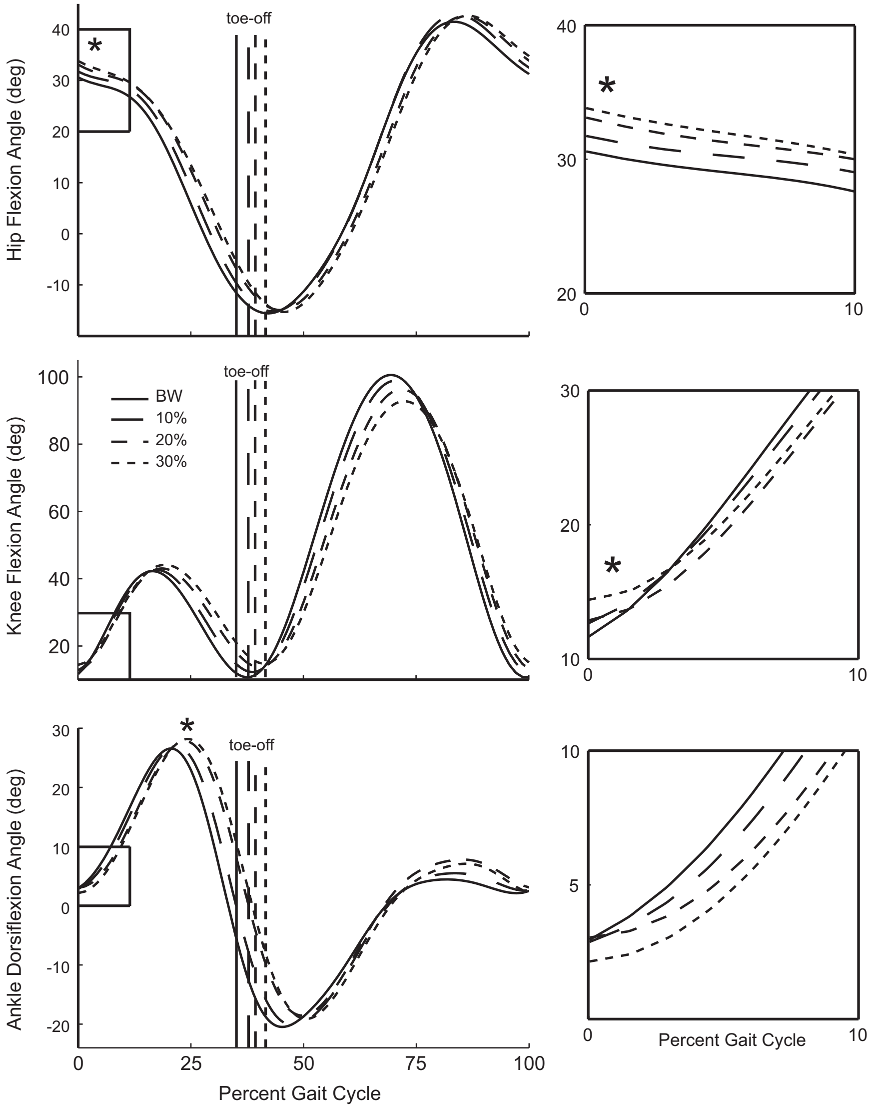

Fig. 4. Ensemble averaged hip, knee, and ankle angles vs. percent gait cycle from subjects carrying no load, or an additional 10%, 20%, and 30% of body weight. Peak stance phase hip flexion, knee flexion, and ankle dorsiflexion angles significantly increased ($p < 0.05$ indicated with *) when subjects ran with load. The insets to the right represent joint angles from the first 10% of the gait cycle, and correspond to the plots on the left. At the time of initial foot contact, flexion of the hip and knee increased when running with load ($p < 0.05$).

in metabolic cost measured by others (Teunissen et al., 2007) and the small increase in ground reaction force observed by us and others (Teunissen et al., 2007) suggests that individuals may be willing to increase metabolic cost to reduce the peak ground contact force.

Spring-mass models have been widely used to understand running mechanics (e.g. Blum et al., 2009; Bullimore and Burn, 2006; Farley and Gonzalez, 1996; Ferris et al., 1998; He et al., 1991; Lipfert et al., 2012). The theoretical model proposed by McMahon and Cheng (1990), and used in some previous studies, assumes the change in stance phase leg length can be estimated from running speed, ground contact time, and leg length at initial contact. In our experiments, running speed was the same for all load carriage conditions, and as the amount of load carried increased, ground contact time increased (Table 1) and leg length at initial contact decreased (Fig. 2B). Had we used the methods described by McMahon and Cheng (1990), the change in stance phase leg length would have increased when carrying load ($p < 0.01$), which is opposite to what we measured experimentally and similar to the findings of Arampatzis et al. (1999) who found that the spring-mass-model overestimates stance phase leg compression. We measured leg length directly across all of stance phase, thereby avoiding some of the assumptions made by McMahon and Cheng (1990).

A limitation of estimating leg stiffness using the spring-mass model combined with experimental data is that it is not possible to determine the body's true center-of-mass location. One solution is to estimate leg length and leg angle at initial contact, and then to twice integrate the vertical ground reaction force to get the change in center-of-mass position (Cavagna et al., 1976). We chose to estimate stance phase leg length as the distance from the center-of-pressure to the center of the pelvis, which eliminated the need to estimate contact angle, but assumes that the center of the pelvis sufficiently represents the center-of-mass (Saunders et al., 1953; Winter, 2005). To check our assumption, we compared vertical motion of the pelvis to vertical center-of-mass motion estimated by twice integrating the ground reaction force. The center-of-mass moved slightly less than the pelvis, similar to comparisons made during walking (Gard et al., 2004). When running with no load, stance phase vertical pelvis motion averaged 9.1 cm, compared to 8.1 cm for the center-of-mass; the average difference was 0.5 cm across all load carriage conditions. This

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difference would have resulted in leg stiffness values ~6% less had we used center-of-mass motion estimated by twice integrating the ground reaction force compared to motion capture. Finally, it is important to note that carrying load in the form of a weight vest raises the body center-of-mass. Had we increased initial leg length by the same amount as our estimated rise in center-of-mass location, leg stiffness values would have been ~4% greater when running with an additional 30% of body weight (1.8 cm, 3.2 cm, and 4.4 cm for the 10%, 20% and 30% conditions, respectively). This would not substantially change our conclusions that leg stiffness increases when running with load. Motion capture and musculoskeletal modeling, as used in our current study enabled us to characterize lower extremity joint kinematics across the gait cycle and measure the change in stance phase leg length directly.

Some experimental work has calculated leg stiffness by first measuring leg angle at contact, and subsequently estimating the change in stance phase leg length from running speed, contact time, and initial leg length (Arampatzis et al., 2007; Donelan and Kram, 2000; He et al., 1991). One assumption of this method is that the leg angle at contact is equal to the leg angle at toe-off. In agreement with others (Blum et al., 2009; Farley and Gonzalez, 1996; Grimmer et al., 2008; Lipfert et al., 2012), we found that when running with no load, the leg angle at contact was less than the leg angle at toe-off (contact 10°; toe-off 14°), with an average difference in contact and toe-off angles of 4° across all load carriage conditions. When combined with the theoretical spring mass model (McMahon and Cheng, 1990), assuming a symmetric gait cycle over-estimates contact angle, over-estimates leg compression and ultimately results in lower leg stiffness values. Many studies also assume that the point of contact, or center-of-pressure, does not translate throughout stance phase (Arampatzis et al., 2007; Donelan and Kram, 2000; Farley and Gonzalez, 1996; He et al., 1991). This can affect the magnitude of leg stiffness. Bullimore and Burn (2006) showed that accounting for the forward moving center of pressure during stance phase leads to higher estimates leg stiffness values. Not assuming a symmetric gait cycle or a fixed center-of-pressure likely contributed to the leg stiffness values reported in our study being higher than previously reported in previous studies that made these assumptions (Arampatzis et al., 2007; Blum et al., 2009; Lipfert et al., 2012).

One assumption that is common among ours and previous studies is that the peak vertical ground reaction force and minimum leg length occur at the same time. We found that peak force occurred at ~42% of stance phase (Fig. 2A), while minimum leg length occurred slightly later, at ~49% of stance phase (Fig. 2B). Calculating leg stiffness at the time of maximum force would have resulted in a lower estimate of leg stiffness (because the leg had not fully compressed), but would not have changed our conclusion that leg stiffness increases when running with load ($p < 0.001$). Calculating leg stiffness at the time of minimum leg length would also have resulted in a lower estimate of leg stiffness (because force had peaked and was declining), but would suggest that leg stiffness does not significantly change when running with load ($p = 0.284$). In addition, estimating leg stiffness using the peak vertical ground reaction force ignores the fore-aft and medial-lateral components. These would be important to consider if investigating how leg stiffness varies across stance phase. However, at the time of the peak vertical ground reaction force, the average resultant and peak vertical ground reaction force were approximately equal, with an average difference of 0.2 bodyweights across all load carriage conditions. This suggests that using the peak vertical ground reaction force is a reasonable measure when estimating leg stiffness using the methods described here.

Among a wide range of terrestrial animals, leg stiffness increases in proportion to body mass (Farley et al., 1993). In agreement with this idea, we showed how changes in running mechanics when carrying a load caused an increase in leg stiffness because of an increase in the peak vertical ground reaction force and a decrease in the change in stance phase leg length. Overall, subjects ran with greater flexion of lower extremity joints and longer ground contact times, resulting in the peak vertical ground reaction force increasing less than the added load. Carrying additional load and increasing lower extremity joint flexion necessitates an increase in muscle activity and higher metabolic cost. Although humans choose to walk in an energetically optimal manner without load, it is likely that a different strategy is used when running with load.

Conflict of interest

We, the authors, have no conflict of interest in the subject matter related to this work.

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