Lower-limb wearable resistance overloads joint angular velocity during early acceleration sprint running

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Abstract

Lower-limb wearable resistance (WR) facilitates targeted resistance-based training during sports-specific movement tasks. The purpose of this study was to determine the effect of two different WR placements (thigh and shank) on joint kinematics during the acceleration phase of sprint running. Eighteen participants completed maximal effort sprints while unloaded and with 2% body mass thigh- or shank-placed WR. The main findings were: 1) the increase to 10 m sprint time was small with thigh WR (effect size [ES] = 0.24), and with shank WR the increase was also small but significant (ES = 0.33); 2) significant differences in peak joint angles between the unloaded and WR conditions were small (ES = 0.23–0.38), limited to the hip and knee joints, and < 2° on average; 3) aside from peak hip flexion angles, no clear trends were observed in individual difference scores; and, 4) thigh and shank WR produced similar reductions in average hip flexion and extension angular velocities. The significant overload to hip flexion and extension velocity with both thigh- and shank-placed WR may be beneficial to target the flexion and extension actions associated with fast sprint running.

Keywords

Specificity, motion analysis, limb loading, sprinting

INTRODUCTION

Wearable resistance (WR) loading involves attaching an external load to one or more of the segments of the body [1]. The low load magnitude used with this training method (e.g. ≤ 5% of body mass [BM] [2]) allows for targeted resistance-based training during sports-specific movement tasks. Practitioners can selectively place a WR load to overload specific joints, and therefore, target specific muscles and specific muscular adaptations. This has made thigh- or shank-placed WR an attractive training option for improving sprint running performance. However, an external load attached to a limb changes the limb's inertial properties and can potentially alter joint kinematics during movement training. This is an important consideration for using lower-limb WR for sprint running.

The influence of thigh or shank WR on leg joint kinematics during sprint running has primarily been investigated during maximal velocity overground sprint running. Researchers have reported mean changes to joint position and limb segment displacement measures to be within ± 3° with thigh (~1.7% BM) [3] and shank (~0.6–1.1% BM) [3,4] WR. These reported measures were non-significant [3,4], with the exception of knee joint angle at touchdown, where sprint running with 1.1% BM shank WR resulted in a small, significant decrease in knee flexion (–1.7°, effect size [ES] = 0.28, $p = 0.03$) [4]. The loading schemes evaluated to-date do not appear to produce aberrant movement patterns during maximal velocity sprint running. However, the characteristics of typical joint kinematics during unloaded sprint running change as an athlete transitions through acceleration to maximal velocity [5]. Therefore, the effects of thigh and shank WR on joint kinematics during acceleration should also be investigated.

The available research on the acute effects of lower-limb WR on acceleration phase joint kinematics is limited to one study published to-date. Researchers investigated the effect of sprint running with 2% BM thigh WR compared to unloaded sprint running on thigh kinematics and found non-significant increases in thigh flexion and extension displacement ranging from 0.8° to 2.8° across the acceleration phase (ES = 0.10–0.27, all $p > 0.05$) [6,7]. It seems that thigh angular displacement is minimally affected by the increase in rotational inertia from 2% BM thigh WR. Although thigh angular velocity was significantly decreased during all step phases measured (–2.3 to –8.0%, ES = 0.26–0.51, $p < 0.05$; steps 1-2, 3-6, and 7-10), the rotational work at the hip joint was significantly increased with the thigh WR (9.8–18.8%, ES 0.09–0.55, $p < 0.01$) [6]. However, the joint kinematic measures at the knee and ankle joints were not reported, nor is there currently any information available on the effects of shank WR on acceleration phase joint kinematics during overground sprint running. Comparing the effect of thigh versus shank WR is especially important considering the progressive increase to the moment of inertia about the hip joint as a given WR load is placed more distally during sprint running [8].

Researchers have begun to establish how lower-limb WR may influence joint kinematics during sprint running but further investigation is needed to better understand the effect of thigh and shank WR on hip, knee, and ankle joint kinematics during sprint running acceleration. The information available to date is limited for the acceleration phase since only one WR load placement (thigh) has been used and one joint (hip) has been analysed. The outcomes of this study will help improve practitioner understanding of how changing the limb's inertial properties with shank or thigh WR influences joint kinematics across the whole leg, enabling them to make more informed decisions when programming training with lower-limb WR. Therefore, the primary purpose of this study was to determine the effect of two different WR placements (thigh and shank) on hip, knee, and ankle joint kinematics during the acceleration phase of sprint running. It was hypothesised that any significant changes to the joint position when loaded would be of a small effect and any significant changes to angular velocity would be classified as small or moderate.

METHODS

Participants

Eighteen male, university-level sprinters volunteered to participate in this study (age = 20.9 ± 2.05 years, mass = 66.3 ± 5.06 kg, height = 1.74 ± 0.05 m). The athletes had a combined training experience of 9.17 ± 2.57 years and a mean 100 m best time of 11.46 ± 0.40 s. All study procedures were approved by the host University Institutional Review Board. Each athlete provided written informed consent prior to study participation.

Experimental Procedures

Athletes reported to the testing facility for two randomly ordered testing sessions, separated by a minimum of 72 hours. The testing occurred during the athletes' late off-season at a time of day that represented their normal training hours (between 10am to 3pm). One testing session utilised thigh WR for the loaded experimental condition while the other utilised shank WR. Each testing session began with the athletes completing a prescribed warm-up and then four maximal effort 50 m sprints from the starting blocks wearing spiked shoes. During the warm-up, the athletes were asked to spend the first five minutes performing low intensity dynamic movements (e.g. jogging and skipping variations) and muscle activation exercises (e.g glute bridges), then five minutes of dynamic stretching to target the primary lower-limb muscles, and finally five minutes of sprint specific drills (e.g. A-skips) and submaximal runs at ~70% and ~90% effort in both the unloaded and loaded experimental conditions. Each sprint trial was separated by a minimum of five minutes rest. Two sprints were completed under each experimental condition – loaded (with thigh or shank WR) and unloaded (no WR). The order of the sprints and the loading conditions were randomly assigned.

Each sprint trial was completed on an indoor track surface (Hasegawa Sports Facilities Co., Hasegawa, Japan). An electronic starting gun (Digi Pistol, Molten, Hiroshima, Japan) was used to signal the start of each sprint. A retro-reflective marker set to record three-dimensional kinematics of the lower limb and torso was affixed to the athletes. The position of the WR limited the placement of markers on the loaded segment, so two marker sets were developed, one for each condition (Appendix A). The relevant marker set applied was a modified version of the University of Western Australia (UWA) lower limb marker set [9]. At the start of each testing session, the athletes performed a static pose calibration trial to determine anatomical landmark positions of the knee and ankle. The marker data were recorded at 250 Hz by a high-speed motion capture system (Motion Analysis Corporation, Santa Rosa, California, USA, 21 Raptor-E cameras) to capture the first 9 m of the acceleration phase of the sprint. The 10 m sprint times were measured using a photocell system (TC Timing System; Brower Timing Systems, Draper, UT, USA), initiated by the electric starting gun.

The WR was attached to the limb with a specialised form-fitting garment (Lila™ Exogen™, Sportboleh Sdh Bhd, Kuala Lumpur, Malaysia) that allows for Velcro backed micro-loads to be attached to the garment. The Exogen™ garments were worn for all sprint trials. For the thigh-loaded experimental condition, WR was attached to the Exogen™ shorts in a horizontal orientation on the distal aspect of the thigh. Consistent with previous thigh WR research, 2/3 of the load was placed more anteriorly and 1/3 placed more posteriorly (Figure 1A) [6,10]. For the shank-loaded experimental condition, WR was attached to the Exogen™ calf sleeves along the long axis of the shank in a manner to balance the loading around the limb (Figure 1B). The exact loading magnitudes ranged from 1.92 – 2.06% of BM due to the load increments available (50, 100, and 200 g).

[Figure 1 here]

Data Analysis

Marker trajectory data was filtered by a fourth-order Butterworth low-pass digital filter at participant-specific cutoff frequencies (13-18 Hz) via residual analysis performed on a tibia-mounted marker [11]. The data were modelled using the UWA lower-limb model [9], modified to be compatible with the adjusted marker sets. All data modelling was performed using Vicon Nexus 2 (Vicon, Oxford Metrics, Oxford, UK).

Modelled kinematic outputs were exported from Vicon Nexus 2 into CSV format and imported in MATLAB (MATLAB R2019b, The MathWorks, Inc., Natick, Massachusetts, USA) for post-processing and feature extraction. A custom algorithm was developed to extract the joint angle vector data associated with the sagittal plane of movement, specifically hip flexion and extension, knee flexion and extension, and ankle dorsiflexion angles, for the stride cycles of interest. The short presence of ankle plantar flexion that occurs prior to weight acceptance was used to help identify the start of the stance phase. Specifically, the timepoint of the transition back to dorsiflexion marked the start of the stance phase and subsequent stride cycle. The stride cycles commencing from the start of the first and third ground contacts on the track after clearing the starting blocks were identified for each athlete's trials and used for the analysis. For each stride, the peak hip flexion and extension, knee flexion and extension, and ankle dorsiflexion angles were identified for the limb that made first ground contact. Therefore, data from only one limb was used for the analysis. The angles corresponded with the late stance phase (i.e. peak hip and knee extension), late swing phase (i.e. peak hip and knee flexion), and the early-mid stance phase (i.e. peak ankle dorsiflexion). The average flexion and extension velocities were calculated for the hip and knee joints across each stride from the time points of peak joint angle values (e.g. hip extension velocity was calculated from the time point of peak hip flexion to peak hip extension). The average ankle joint dorsiflexion velocity was calculated from the onset of dorsiflexion at the start of the stance phase to the time point of peak dorsiflexion, thus corresponding to the weight acceptance portion of the early-mid stance phase. To represent average athlete performance for each sprint condition, the mean values for all dependent variables across the two trials were used for statistical analysis.

Statistical Analysis

Athletes that were only able to attend one testing session due to scheduling conflicts were included in the analysis of the testing session in which they participated. A paired-samples t-test was used to test for differences between the thigh WR and unloaded conditions (*n* = 14) and between the shank WR and unloaded conditions (*n* = 15). For the athletes that attended both testing sessions (*n* = 11), a paired-samples t-test was also used to test for differences between the thigh and shank WR conditions. The between condition difference scores were inspected for normality and outlier data samples. Outliers classified as extreme (>3 box-lengths from the edge of the boxplot) or those that prevented a normal distribution (assessed by Shapiro-Wilk's test) were removed from the final analysis. Marker failure resulted in missing angle data at the knee and ankle for the thigh testing session (*n* = 1 and 2, respectively) and the shank testing session (*n* = 1 and 2, respectively). Analyses were performed using SPSS Statistics (Version 25, IBM, Armonk, NY, USA). Significance was set at $p \leq 0.05$. ES statistics (Cohen's d) were calculated and described as trivial (<0.20), small (0.20), moderate (0.50) and large (0.80) [12].

Results

The 10 m sprint times increased with thigh WR by a mean difference of 0.02 s compared with unloaded sprinting (unloaded = 2.16 ± 0.09 s and loaded = 2.18 ± 0.08 s, ES = 0.24, *p* = 0.13). Shank WR significantly increased 10 m sprint times by a mean difference of 0.03 s compared with unloaded sprinting (unloaded = 2.15 ± 0.09 s and loaded = 2.18 ± 0.09 s, ES = 0.33, *p* = 0.02).

All group-averaged changes to peak joint angles with thigh and shank WR were classified as trivial or small (ES = 0.00–0.38) and < ± 2°. The peak joint angles for each experimental condition are presented in Table 1 and 2. With thigh WR, significantly less hip flexion occurred at the end of the forward swing phase during stride 1 and stride 3 and significantly less knee extension occurred at the end of the stance phase during stride 3 compared with unloaded sprinting (ES = 0.27–0.32). With shank WR, significantly less hip flexion occurred at the end of the forward swing phase during stride 1 and significantly less hip extension occurred at the end of the stance phase during stride 3 compared with unloaded sprinting (ES = 0.23–0.38). A visual display of the individual response to each experimental condition for the peak hip and knee joint angles is given in Figure 2. With the exception of hip flexion, where the majority of athletes responded to the WR loading by reaching smaller peak hip flexion angles at the end of the forward swing, no clear trends in individual responses were identified across both strides within an experimental condition (i.e. stride 1 versus stride 3) or between experimental conditions (i.e. thigh versus shank WR).

All group-averaged changes in angular velocity ranged from trivial to moderate with thigh WR (ES = 0.00–0.70) and shank WR (ES = 0.06–0.50) across stride 1 and 3. The average angular velocities for each experimental condition are presented in Tables 1 and 2. Thigh WR significantly reduced hip and knee extension velocity and hip flexion velocity during stride 1 and 3 compared with unloaded sprinting (ES = 0.43–0.70). Shank WR significantly reduced hip extension and flexion velocity during stride 1 and 3 and significantly increased knee flexion velocity during stride 3 compared with unloaded sprinting (ES = 0.22–0.50).

When comparing the thigh versus the shank loaded conditions, with thigh WR, athletes reached significantly less knee extension at the end of the stance phase during stride 1 by a mean difference of 4.34 ± 6.17° (ES = 0.73, $p = 0.05$). Also, with thigh WR, the average knee extension and ankle dorsiflexion velocities were significantly slower during stride 1 by 30.8 ± 25.1°/s (ES = 0.93, $p < 0.01$) and 29.1 ± 38.7°/s (ES = 0.70, $p = 0.05$), respectively.

[Table 1 and 2 here]

[Figure 2 here]

Discussion

This study determined the effect of 2% BM WR placed on two different lower-limb segments (thigh and shank) on hip, knee, and ankle joint kinematics during the early acceleration phase of sprint running. The hypothesis that any significant changes to the peak joint angles would be of a small effect and any significant changes to angular velocity would be classified as small or moderate was supported. The main findings were: 1) the increase to 10 m sprint time was small with thigh WR (ES = 0.24), and with shank WR the increase was also small but significant (ES = 0.33); 2) significant differences in peak joint angles between the unloaded and WR conditions were small (ES = 0.23–0.38), limited to the hip and knee joints, and < 2° on average; 3) aside from peak hip flexion angles, no clear trends were observed in individual difference scores between the WR and unloaded conditions for peak joint angles; and, 4) thigh and shank WR produced similar reductions in average hip flexion and extension angular velocities, while thigh WR decreased average knee extension velocity and shank WR increased average knee flexion velocity compared with unloaded sprint running (all < ± 27°/s, ES = 0.22–0.70, $p < 0.05$).

Lower-limb WR has been purported as a movement- and speed-specific training option for sprint running [2,8,13] and initial evidence appears to favour training with WR compared to training with no load for maintaining[14] and improving sprint running performance [15]. However, it is important to ascertain if global changes to movement speed when loaded maintain specificity to the maximal speeds associated with sprint running. In this study, sprint running with WR increased 10 m sprint times by < 1.5%. This indicates that the athletes were moving at near maximal acceleration speeds through the early acceleration phase under resistance. This is similar to changes reported previously where thigh and shank WR of ≤ 2% BM has been shown to affect sprint running speed and time measures by 0.9–2.23% (ES = 0.22–0.55) [3,4,6,10]. These measures were taken across early acceleration to maximal velocity, with the largest changes occurring at maximal velocity [3,4,6,10]. In the current study, the significant increase to sprint time occurred when the WR was placed on the shank, which corresponded to the experimental condition with the greater rotational overload about the hip given the increased distance between this joint and the applied load. A method to increase the rotational overload with WR therefore, is to move the load distally from the primary joint axis of rotation [8]. As a result, the same load magnitude moved from the thigh to the shank will create a greater rotational overload about the hip joint and additionally overload the knee joint during sprinting.

The athletes in this study were able to achieve similar ranges of motion to unloaded sprint running with thigh or shank WR with all changes to peak joint angles < ± 2°. These findings confirm that the WR placement schemes deployed in this study do not produce appreciably different movement patterns across the early acceleration phase of sprint running. However, it is important to note the variation in individual responses. Other than the exception of hip flexion, where the majority of athletes responded to the WR loading by reaching smaller peak hip flexion angles at the end of the forward swing phase, no clear trends in responses to a WR condition can be observed. Additionally, the effects for some athletes were upwards of ± 8°. Given the clear variation in individual responses (direction and magnitude), coaches are encouraged to assess the acute effects of lower-limb WR loading on their athletes on an individual basis to determine whether the addition of the WR is having the desired effect for the individual's training needs. Research continuing in this topic may consider kinematic waveform analysis to provide a more complete analysis across the entire stride and further context for discrete variable analysis.

The effect of WR loading had a greater overall influence on the average angular velocities than the average peak joint angles of the lower-limb joints with significant changes from unloaded sprint running considered small to moderate. This highlights the specific overload to the speed of the stride cycle (i.e. stride frequency) that occurs with this resistance training method. The stride cycle of sprint running encompasses open kinetic-chain and closed kinetic-chain movements for the joints of the lower-limb, the swing and stance phases, respectively. With thigh WR, the significant overload to the average hip joint velocity occurred during the open kinetic-chain (hip flexion) and closed kinetic-chain (hip extension) portions of the movement. However, the significant overload to the average knee joint velocity only occurred during knee extension which primarily occurs during the closed kinetic-chain portion of the stride cycle. Considering, there was no load placed distal to the knee joint in the thigh-loaded condition, it would be expected that the knee joint wouldn't experience significant changes to the measures associated with the swing phase. With shank WR, athletes responded similarly at the hip joint, i.e. the velocity at the hip joint was significantly decreased during the open kinetic-chain and closed kinetic-chain portions of the stride cycle. However, shank WR did not significantly alter the average knee or ankle velocities during the closed kinetic-chain portion of the stride cycle (i.e. knee extension and ankle dorsiflexion). Thus, the athletes did not experience the knee extension overload during stance that was evident in the thigh-loaded condition. Further, there were no consequent effects further down the chain at the ankle joint even though the shank load placement was proximal to the joint. Conversely, athletes increased average knee flexion velocity ($p < 0.05$ at stride 3) during the forward swing phase. The increased average knee flexion velocity at stride 3 coincided with a greater peak knee flexion angle (by 1.72°, ES = 0.21, $p > 0.05$). This may indicate a kinematic mechanism to reduce the rotational inertia about the hip joint in an effort to maintain swing phase timing and have the limb prepared for next touchdown.

The findings of this study further highlight the movement-specificity of placing the WR load on the lower-limbs compared to other load placement options, such as the torso with vest loading, for sprint running. With lower-limb placed WR, the resistance must be overcome during both the open and closed kinetic-chain portions of the movement pattern, whereas a specific lower-limb overload is only incurred during the closed kinetic-chain portion of the movement pattern with vest loading. Recent research has demonstrated a strong correlation between running speed and thigh angular velocity during both the swing and ground contact phases of the stride cycle during upright running [16]. Thus, training should work to produce adaptations to both the flexion and extension actions to support the necessary reciprocal action of the thighs and contribute to the vertical forces necessary to produce faster running speeds [16]. Given that both shank and thigh WR reduced the average angular velocities about the hip joint, programmatic use of lower-limb WR may be a method to develop the speed-specific strength associated with the fast flexion and extension actions at hip joint during sprint running.

Although it was not the primary purpose of this study, 11 of the athletes participated in both the thigh and shank loaded testing sessions. Direct comparison between the two loaded conditions (i.e. thigh versus shank loading) revealed that with thigh WR athletes performed less knee extension at the end of the stance phase and average knee extension and ankle dorsiflexion velocities were reduced ($p \leq 0.05$, ES = 0.70–0.93). However, these effects were limited to stride 1. These findings provide further insights to the effects of thigh- and shank-placed WR on sprint running, which in tandem with future research, can be used to better inform WR placement.

A limitation to this research is that only a snapshot of the joint kinematics (i.e. 2 strides) during early acceleration were able to be included due to motion capture volume limitations. It is unknown how the joint kinematics of the remainder of the acceleration phase compares to unloaded sprint running. Further, ankle joint kinematics were used to identify the onset of the stance phase. And although the same identification method was used for every trial, it is unknown if any differences between the method used here and a more direct stance phase identification method (such as using force plates) exist. Another limitation is that training intensity prior to the study was not controlled. Additionally, the athletes that participated in this study were not familiarised to lower-limb WR outside of what was provided for this study. It is unknown how the joint kinematics when sprint running with WR might change following repeated exposure to lower-limb WR. Similarly, the kinematic adaptations that occur following sprint running training with lower-limb WR and potential differences present between the leading and trailing legs during the early steps of acceleration requires investigation.

Conclusion

Sprint running with 2% BM thigh and shank WR produced small changes to 10 m sprint times (< 1.50%; ES = 0.24–0.33) and lower-limb joint angles (all < 2° on average; ES = 0.23–0.38). It appears that lower-limb WR of ≤ 2% BM does not significantly disrupt the movement patterns associated with sprint running, however, individual responses will likely vary and can be considered on a case-by-case bases to determine whether the addition of the WR is having the desired effect for the individual's training needs. The effect of WR loading had a greater overall influence on angular velocity compared to the influence on the peak joint angles at the hip and knee joints with significant changes considered small to moderate (≤ ± 27°/s, ES = 0.22–0.70). This highlights the specific overload to the movement speed of the stride cycle that occurs with this training method. Further, the significant overload to hip flexion and extension velocity with both thigh and shank-placed WR may be especially helpful to target the flexion and extension actions associated with fast sprint running.

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Table 1. Peak joint angle and average velocity of the hip, knee, and ankle for the unloaded and thigh wearable resistance conditions during the first and third stride of sprint acceleration.

	Peak Joint Angle (°)				Average Velocity (°/s)			
	Unloaded	Thigh-loaded	Difference	Effect Size	Unloaded	Thigh-loaded	Difference	Effect Size
Stride 1								
Hip Extension	3.35 ± 5.18	4.07 ± 4.86	0.72	0.14	–360 ± 26.0	–343 ± 30.5*	16.6	0.60
Hip Flexion	98.7 ± 5.04	97.0 ± 5.56*	–1.81	0.32	445 ± 37.6	423 ± 39.4*	–22.6	0.57
Knee Extension	17.8 ± 5.78	18.3 ± 5.11	0.47	0.09	–311 ± 30.1	–301 ± 24.8*	10.8	0.36
Knee Flexion	126 ± 7.75	125 ± 10.2	–0.82	0.11	657 ± 50.3	648 ± 65.0	–8.44	0.16
Ankle Dorsiflexion	30.0 ± 5.98	29.2 ± 5.41	–0.81	0.14	168 ± 41.5	160 ± 38.7	–8.11	0.20
Stride 3								
Hip Extension	–3.20 ± 4.87	–2.15 ± 4.83	1.05	0.22	–422 ± 28.2	–407 ± 24.5*	14.8	0.57
Hip Flexion	98.0 ± 6.43	96.4 ± 5.28*	–1.53	0.27	459 ± 41.8	442 ± 37.9*	–16.8	0.43
Knee Extension	15.0 ± 5.40	16.8 ± 5.86*	1.81	0.32	–381 ± 37.7	–354 ± 39.6*	26.7	0.70
Knee Flexion	136 ± 7.93	134 ± 9.32	1.33	0.23	736 ± 53.0	722 ± 47.3	14.6	0.28
Ankle Dorsiflexion	28.8 ± 4.26	28.5 ± 5.11	0.24	0.06	232 ± 30.5	232 ± 35.2	0.89	0.00

Note: Values reported as mean ± standard deviation, Difference score reported as mean difference of the thigh-loaded – unloaded conditions, * = significantly different from the unloaded condition at $p \leq 0.05$.

Table 2. Peak joint angle and average velocity of the hip, knee, and ankle for the unloaded and shank wearable resistance conditions during the first and third stride of sprint acceleration.

	Peak Joint Angle (°)				Average Velocity (°/s)			
	Unloaded	Shank-loaded	Difference	Effect Size	Unloaded	Shank-loaded	Difference	Effect Size
Stride 1								
Hip Extension	1.46 ± 6.81	1.60 ± 6.90	0.14	0.02	–368 ± 23.5	–359 ± 22.3*	8.64	0.39
Hip Flexion	99.5 ± 4.16	97.8 ± 4.85*	–1.76	0.38	454 ± 39.2	445 ± 41.5*	–8.76	0.22
Knee Extension	12.5 ± 6.23	12.2 ± 5.66	–0.27	0.05	–340 ± 44.3	–335 ± 34.7	4.79	0.13
Knee Flexion	129 ± 7.99	129 ± 6.53	–0.21	0.00	686 ± 85.9	694 ± 64.5	7.69	0.11
Ankle Dorsiflexion	28.9 ± 3.82	29.9 ± 4.16	0.97	0.25	178 ± 47.3	192 ± 43.5	13.6	0.31
Stride 3								
Hip Extension	–5.31 ± 6.48	–3.98 ± 5.14*	1.33	0.23	–432 ± 28.1	–418 ± 28.4*	14.4	0.50
Hip Flexion	98.3 ± 4.52	97.2 ± 5.17	–1.05	0.23	466 ± 39.1	450 ± 31.4*	–15.5	0.45
Knee Extension	11.7 ± 6.38	11.9 ± 6.76	0.20	0.03	–402 ± 57.0	–394 ± 41.9	7.57	0.16
Knee Flexion	136 ± 4.43	137 ± 5.13	1.72	0.21	740 ± 56.4	763 ± 58.8*	23.4	0.40
Ankle Dorsiflexion	28.8 ± 4.08	29.1 ± 2.93	0.29	0.09	244 ± 34.1	242 ± 35.3	–1.59	0.06

Note: Values reported as mean ± standard deviation, Difference score reported as mean difference of the shank-loaded – unloaded conditions, * = significantly different from the unloaded condition at $p \leq 0.05$.

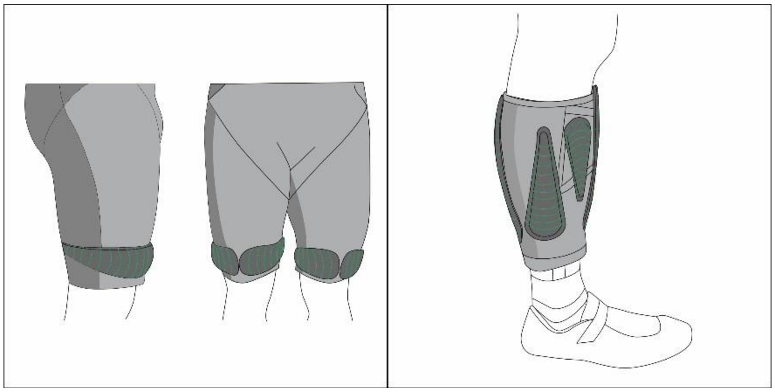
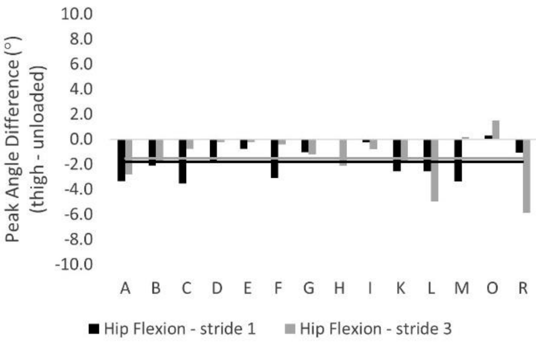
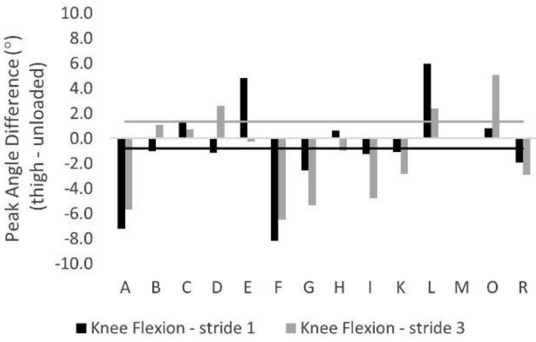


Figure 1. Example wearable resistance load placements for (A) the thigh wearable resistance experimental condition and (B) the shank wearable resistance experimental condition.

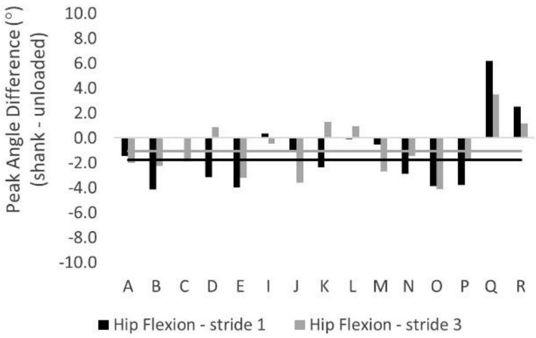

Peak Angle Difference (°)
(thigh - unloaded)
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
A B C D E F G H I K L M O R
■ Hip Extension - stride 1
■ Hip Extension - stride 3


Peak Angle Difference (°)
(thigh - unloaded)
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
A B C D E F G H I K L M O R
■ Hip Flexion - stride 1
■ Hip Flexion - stride 3


Peak Angle Difference (°)
(thigh - unloaded)
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
A B C D E F G H I K L M O R
■ Knee Extension - stride 1
■ Knee Extension - stride 3


Peak Angle Difference (°)
(thigh - unloaded)
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
A B C D E F G H I K L M O R
■ Knee Flexion - stride 1
■ Knee Flexion - stride 3


Peak Angle Difference (°)
(shank - unloaded)
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
A B C D E I J K L M N O P Q R
■ Hip Extension - stride 1
■ Hip Extension - stride 3


Peak Angle Difference (°)
(shank - unloaded)
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
A B C D E I J K L M N O P Q R
■ Hip Flexion - stride 1
■ Hip Flexion - stride 3


Peak Angle Difference (°)
(shank - unloaded)
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
A B C D E I J K L M N O P Q R
■ Knee Extension - stride 1
■ Knee Extension - stride 3

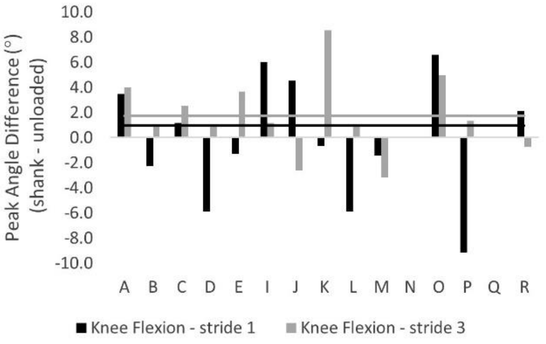

Peak Angle Difference (°)
(shank - unloaded)
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
A B C D E I J K L M N O P Q R
■ Knee Flexion - stride 1
■ Knee Flexion - stride 3

Figure 2. Individual difference scores (loaded – unloaded) for the thigh WR (column A) and shank WR (column B) experimental conditions. Group average difference scores represented with the horizontal lines.

Note: Values are organised by the athlete. A positive difference score means a decrease in hip extension, while a negative difference score means a decrease in knee extension, hip flexion, and knee flexion for the loaded condition. Horizontal lines indicate the group mean difference score for stride 1 (black) and stride 3 (grey). No knee data was available for athlete M in the thigh WR experimental condition and athlete N and Q in the shank WR experimental condition due to marker failure.

Appendix A

Marker Set Descriptions

Prefixes R and L denote right and left side of body

Italic font denotes markers used during the calibration process and removed for dynamic trials

Regular font denotes markers in place for the entire duration of the data collection session

Thigh Loading Condition:

Pelvis, right/left
- Anterior superior iliac spine (RASI, LASI)
- Posterior superior iliac spine (RPSI, LPSI)
- Iliac crest (RILC, LILC)

Thigh, right/left
- *Standard thigh cluster (RTH1-4, LTHI-4) – calibration only*

Knee, right/left
- *Lateral Femoral condyle (RLFC, LLFC) – static calibration only*
- *Medial Femoral condyle (RMFC, LMFC) – static calibration only*

Tibia, right/left
- Custom proximal 4-mkr cluster (pRTB1-4, pLTB1-4)
- Custom distal 3-mkr cluster (RTB1-3, LTB1-3)

Ankle, right/left, medial/lateral
- *Lateral Malleolus (RLMAL, LLMAL) – static calibration only*
- *Medial Malleolus (RMMAL, LMMAL) – static calibration only*

Foot, right/left
- Head of Metatarsal 1 (RMT1, LMT1)
- Head of Metatarsal 5 (RMT5, LMT5)
- Calcaneus (RCAL, LCAL)

Trunk
- Mid-point of Clavicles (CLAV)
- Xiphoid Process (STRN)

- Spinous Process C7 Vertebra (C7)
- Spinous Process T10 Vertebra (T10)

Note: Images also depict locations of inertial sensors (with markers mounted upon them) on the sacrum, each thigh, and each tibia. These markers and inertial sensors were not used in the research presented in this manuscript. The markers mounted on the weights (green-striped items at bottom of shorts) were also not used for this manuscript.

Shank Loading Condition:

Pelvis

- Anterior superior iliac spine (RASI, LASI)
- Posterior superior iliac spine (RPSI, LPSI)
- Iliac crest (RILC, LILC)

Thigh

- Standard thigh cluster (RTH1-4, LTHI-4)

Knee

- *Lateral Femoral condyle (RLFC, LLFC) – static calibration only*
- *Medial Femoral condyle (RMFC, LMFC) – static calibration only*

Tibia

- *Standard 4-mkr cluster (RTB1-4, LTB1-4) – calibration only*
- Custom distal 3-mkr cluster (RTB1-3, LTB1-3)

Ankle

- *Lateral Malleolus (RLMAL, LLMAL) – static calibration only*
- *Medial Malleolus (RMMAL, LMMAL) – static calibration only*

Foot

- Head of Metatarsal 1 (RMT1, LMT1)
- Head of Metatarsal 5 (RMT5, LMT5)
- Calcaneus (RCAL, LCAL)

Trunk

- Mid-point of Clavicles (CLAV)
- Xiphoid Process (STRN)
- Spinous Process C7 Vertebra (C7)
- Spinous Process T10 Vertebra (T10)

Note: Images also depict locations of inertial sensors (with markers mounted upon them) on the sacrum, each thigh, and each tibia. These markers and inertial sensors were not used in the research presented in this manuscript. The markers mounted on the weights (green-striped items at bottom of shorts) were also not used for this manuscript.