Waveform analysis of shank loaded wearable resistance during sprint running acceleration

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Abstract (198 words)

Lower-limb wearable resistance (WR) provides a specific and targeted overload to the musculature involved in sprint running, however, it is unknown if greater impact forces occur with the additional limb mass. This study compared the contact times and ground reaction force waveforms between sprint running with no load and 2% body mass (BM) shank-positioned WR over 30 m. Fifteen male university-level sprint specialists completed two maximum effort sprints with each condition in a randomised order. Sprint running with shank WR resulted in trivial changes to contact times at 5 m, 10 m, and 20 m (effect size [ES] = < 0.20, $p > 0.05$) and a small, significant increase to contact time at 30 m by 1.94% (ES = 0.25, $p = 0.03$). Significant differences in ground reaction force between unloaded and shank loaded sprint running were limited to the anterior-posterior direction and occurred between 20–30% of ground contact at 10 m, 20 m, and 30 m. Shank WR did not result in greater magnitudes of horizontal or vertical forces during the initial impact portion of ground contact. Practitioners can prescribe shank WR training with loads ≤ 2% BM without concern for increased risk of injurious impact forces.

Keywords: GRF, SPM, injury prevention, training modality

Introduction

Wearable resistance (WR) can be used for high-velocity resistance training of sport-specific movement patterns.[1-4] The load magnitude used for limb WR training is often very low (e.g. ≤ 3% of body mass[BM]), which allows the resistance training to take place at or near typical movement speeds.[2] When WR is attached to the limb, the overload can be modulated by moving the load proximal-distal from the axis of rotation, thus increasing the rotational inertia of the limb. The loads can be positioned to increase the mechanical work of particular joints and, therefore, target specific musculature.[5,6] For sprint running, WR can be positioned on the shank to overload the muscles spanning the hip and knee joints. This provides a specific and targeted overload to the movements involved in sprint running[5,6], making shank WR training of great interest for improving sprint running speed. However, practitioners should be cognisant of how the athlete responds to rotational inertial changes consequent to a specific WR placement and magnitude to ensure the resulting overload adheres to the training stimulus intended.

Shank WR has been shown to increase vertical and horizontal braking impulse during sprint running acceleration.[7] Specifically, 2% BM shank WR resulted in small to large increases in relative vertical impulse (3.05–5.23%, effect size [ES] = 0.42–0.92, $p < 0.05$) and moderate to large increases in relative horizontal braking impulse (9.63–20.8%, ES = 0.67–1.97, $p < 0.05$) compared to unloaded sprint running for steps at 5 m, 10 m, 20 m, and 30 m.[7] These findings led to the suggestion that shank WR provides a unique stimulus which may be used to improve an athlete's ability to resist and reverse horizontal braking forces during acceleration[7] which is thought to be a distinguishing characteristic of faster sprint running.[8,9]

It is possible however, that greater horizontal and/or vertical impact forces occur with the addition of mass to the shank. In the vertical direction, a contributing factor to the forces at impact corresponds to the deceleration of the foot and shank.[10,11] The addition of mass to the shank could have a direct effect on the vertical impact forces by imposing greater deceleration needs, especially at faster speeds when the sprinter is inevitably in a more upright position following in accordance with the two-mass model of human running[11,12]. In the horizontal direction, the added shank mass could result in greater forward velocity (relative to the ground) of the foot at touchdown especially if the sprinter cannot fully counter the increased forward momentum of the limb at the end of the swing phase. The horizontal velocity of the foot at touchdown has been suggested to be related to the horizontal braking forces during sprint running.[13] Thus, if the forward velocity of the foot at touchdown is increased with shank WR, the athlete could experience greater impact forces in the horizontal direction. If sprint running with shank WR results in higher impact forces, there could be concern for risk of repetitive stress injuries. While repetitive stress injury rates may not be as high in sprinters compared to distance runners, sprinters have been reported to sustain bone stress injuries during training[14] and ground reaction force magnitude and rate have been considered one of the biomechanical risk factors of bone stress injury[15]. Practitioners would need to exercise caution when prescribing shank WR training to ensure an accumulation of training volume that could be injurious does not occur.

The research available to date does not provide the necessary details to determine if the higher vertical and horizontal braking impulse values seen with shank WR are a result of longer contact times, altered proportions of time spent in braking and propulsion, greater force magnitudes at a particular part of stance or throughout the entire stance phase, or some combination thereof. A more detailed investigation into the ground reaction forces produced when sprint running with shank WR is warranted to better understand the underlying cause(s) for increased horizontal braking and vertical impulse. A force waveform analysis and contact time comparison provides the further detail needed to better understand impulse production during each step. Specifically, a systematic analysis of the force waveforms enables a deeper understanding of ground reaction force production than that available with a discrete variable analysis. Therefore, the purpose of this study was to compare the contact times and force waveforms between sprint running with no load and 2% BM shank WR. Given increased contact times are commonly reported with lower-limb WR[2] but in this study a relatively light loading scheme was employed, it was hypothesised that shank WR would result in longer contact times but not greater horizontal or vertical impact forces.

Materials and Methods

Participants

Fifteen male university-level sprint specialists volunteered to participate in this study (age = 21.1 ± 2.22 years, mass = 67.2 ± 4.58 kg, height = 1.74 ± 0.05 m). The athletes had an average 100 m best time of 11.44 ± 0.42 s and training experience of 9.33 ± 2.74 years. Study procedures were approved by the host University Institutional Review Board and written informed consent was obtained before study participation.

Experimental Procedures

Athletes reported to an indoor training facility and began the testing protocol by completing a self-selected warm-up which included dynamic stretching, running drills, and a series of submaximal effort sprints (i.e. 50%, 75%, and 90% of maximal effort). Following the warm-up, each athlete completed four maximal effort 50 m sprint trials from starting blocks wearing their own spiked running shoes. The sprint trials consisted of two repetitions with WR attached to the shank and two repetitions unloaded (no WR) completed in a randomised order. For all sprint trials, the athletes wore Lila™ Exogen™ (Sportboleh Sdh Bhd, Kuala Lumpur, Malaysia) calf sleeves which allowed for Velcro backed "micro-loads" to be attached to the garment for the loaded trials. The loads were attached in line with the long axis of the shank and totalled in magnitude 2% BM (i.e. 1% BM attached to each limb) per Feser, Bezodis, Neville, Macadam, Uthoff, Nagahara, Tinwala, Clark, Cronin [7] (Figure 1). The exact loading magnitudes ranged from 1.90–2.11% due to the loading increments available (100, 200, and 300 g). The sprint trials were completed on an indoor track surface (Hasegawa Sports Facilities Co., Hasegawa, Japan) which housed a series of in-ground force platforms (TF-90100, TF-3055, TF-32120, Tec Gihan, Uji, Japan) that covered a total distance of 52 m. This allowed for ground reaction force measurement at 1000 Hz across the entire acceleration phase (defined here as following block clearance to 30 m). Each sprint start was signalled with an electronic starting gun (Digi Pistol, Molten, Hiroshima, Japan).

Data Analysis

The ground reaction force data were filtered with a fourth-order Butterworth low-pass digital filter, cut-off frequency 50 Hz. Movement onset was defined as the time point where the resultant ground reaction force increased and remained above two standard deviations greater than the mean value during the initial stationary period. Individual steps were identified from the filtered ground reaction force data by detecting the touchdown and take-off with a 20 N vertical ground reaction force threshold. The horizontal centre of mass velocity was calculated from the initial movement to maximal velocity[9] by determining the instantaneous horizontal velocity throughout the entire sprint from the anterior-posterior impulse and estimated aerodynamic drag.[16] From the horizontal centre of mass velocity-time data, a distance-time relationship was derived for each sprint trial. This was done so the steps at 5 m, 10 m, 20 m, and 30 m could be extracted per Feser, Bezodis, Neville, Macadam, Uthoff, Nagahara, Tinwala, Clark, Cronin [7] and used for analysis. The step number used for each experimental condition along with the corresponding time, distance, velocity at toe-off, and percent of maximal toe-off velocity are reported in Table 1.

Statistical Analysis

A series of paired-samples t-tests were used to test for differences in contact time between the shank and unloaded conditions at the distance-matched steps of 5 m, 10 m, 20 m, and 30 m. No outliers, were found as defined by a value greater than 3 box-lengths from the edge of a boxplot. The differences between the shank loaded and unloaded contact time measures were normally distributed, as assessed by Shapiro-Wilk's test ($p > 0.05$) and Normal Q-Q Plot visual inspection. 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 as the mean of the within-subjects difference scores divided by the average standard deviation of the two conditions[17] and described as trivial (<0.20), small (0.20), moderate (0.50) and large (0.80).[18] Individual response to the shank WR was classified as an increase or decrease if the individual change from the unloaded condition was $> \pm 0.2 \times$ unloaded between-subject standard deviation (i.e. smallest worthwhile change).[18]

The vertical and anterior-posterior components of the ground reaction force waveforms at each of the distance-matched steps underwent a curve analysis using Statistical Parametric Mapping[19] (SPM, version 0.4, http://www.spm1d.org/) in MATLAB (MATLAB R2019b, The MathWorks, Inc., Natick, Massachusetts, USA). This method allowed for identification of differences throughout ground contact rather than focussing just on discrete events. The force waveforms were temporally normalised to 0% to 100% of ground contact (i.e. each step was time normalised to 1000 data points) using an inbuilt cubic spline function. The time normalised waveforms for the two trials within each experimental condition were then averaged to represent athlete performance at each distance-matched step. As part of the statistical parametric mapping analysis process, a paired-samples t-test was used to test for differences between the shank loaded and unloaded conditions in anterior-posterior force and vertical force (both body weight normalised) at the distance-matched steps of 5 m, 10 m, 20 m, and 30 m in accordance with previous research.[7] Significance was set at $p \leq 0.05$.

Results

Sprint running with shank WR resulted in 30 m sprint times that were 1.80% slower than unloaded sprint running. Shank WR produced trivial changes to contact times at 5 m, 10 m, and 20 m (ES < 0.20, $p > 0.05$) and a small, significant increase to contact time at 30 m by 1.94% (ES = 0.25, $p = 0.03$) (Table 2). Individual change in contact time between the unloaded and shank loaded conditions (i.e. shank loaded contact time – unloaded contact time) at each distance-matched step are shown in Figure 2. The majority of participants (6/10) that experienced a change in contact time at 5 m demonstrated a reduction in contact time. The majority of participants that experienced a change in contact time at 10 m, 20 m, and 30 m demonstrated an increase in contact time (7/11, 6/8, and 8/10, respectively).

There were significant differences in the anterior-posterior force waveforms during the early-mid (i.e. 20–30%) part of stance for the steps analysed from 10 m onwards. Specifically, propulsive force was significantly decreased when sprint running with shank WR from 20.8–24.2% of ground contact for the step at 10 m. Horizontal braking force was significantly increased when sprint running with shank WR from 21.4–26.0% and 23.9–28.3% of ground contact for the steps at 20 m and 30 m, respectively (Figure 3). There were no significant differences in vertical force between unloaded and shank WR sprint running (Figure 4).

Discussion

Understanding the mechanical effects of shank loaded WR is important to determine its potential as a training tool, but also to determine if the user needs to be aware of the possibility of increased force magnitudes which may be associated with injury risk. This study, therefore, compared the force waveforms and contact times between sprint running with no load and 2% BM shank WR, for the distance-matched steps at 5 m, 10 m, 20 m, and 30 m. The hypothesis that sprint running with shank WR would result in longer contact times but not greater horizontal or vertical impact forces was partially supported. The main findings were: 1) group-mean changes to contact time with shank WR were non-significant and trivial until 30 m where contact time was significantly increased by 1.94% (ES = 0.25); and, 2) significant differences in ground reaction force between unloaded and shank WR were limited to the anterior-posterior direction and occurred between 20.8–28.3% of ground contact, around the period of transition from braking to propulsion, for the distance-matched steps at 10 m, 20 m, and 30 m. Therefore, sprint running with 2% BM shank WR does not result in greater horizontal or vertical forces during the impact portion of ground contact beyond that seen with unloaded sprint running.

The WR used in this study did not significantly alter contact times until the distance-matched step at 30 m, in which contact time was increased by 1.94% (ES = 0.25). The individual changes in contact time (Figure 2) show a larger proportion of the athletes increasing contact time at greater movement velocities. Thus, it appears changes in contact time are sensitive to movement velocity when sprint running with 2% BM shank WR. The effect of shank WR on contact times during maximal velocity sprint running has been previously investigated. Researchers reported increases to contact time with ~0.60% BM shank WR by 0.88% ($p > 0.05$)[20] and 1.1% BM shank WR by 10.0% ($p < 0.01$)[21]. Although the athletes in the current study were close to maximal velocity speeds for the step at 30 m (i.e. 99.4% of maximal velocity, Table 1), the change in contact time was much less than that reported in Zhang, Yu, Yang, Yu, Sun, Wang, Yin, Zhuang, Liu [21] who reported a 0.01 s (10%) increase with 1.1% BM shank WR (contact time = 0.10 s unloaded; 0.11 s loaded). However, it should be noted that Zhang, Yu, Yang, Yu, Sun, Wang, Yin, Zhuang, Liu [21] reported contact time to only the hundredths place (rather than thousandths) which possibility has removed the precision needed to accurately compare their results to the findings in this study. It is likely the small, significant increase in contact time at 30 m with shank WR in this study contributes to the greater horizontal braking and vertical impulse values reported previously by researchers who used the same loading scheme.[7] Otherwise, the greater impulse values at steps 5, 10, and 20 m also reported previously with shank WR[7] must primarily come from greater magnitudes of force production across the stance phase as trivial changes to contact times were measured for the steps at these distances in this study.

The relationship between anterior-posterior force production and performance has been shown to differ throughout the stages of acceleration. During the earlier stages of acceleration (i.e. the first 11 steps), the positive relationship between anterior-posterior force production and sprint performance occurred during the propulsive phase, placing importance on concentric force production for these steps (e.g. 58–92% of ground contact at step two).[9] In the later stages of acceleration, the positive relationship with performance occurred during the second part of the braking phase and the transition in to propulsion, emphasising the importance of being able to attenuate braking forces for improving sprint performance during these steps (e.g. 19–25%, 28–35%, and 38–64% of ground contact at step nineteen).[9] In this study, with shank WR, significantly lower propulsive forces were found at 10 m from 20.8–24.2% of ground contact. At 20 and 30 m, representing the later stages of acceleration, significantly greater braking forces were found at a similar relative time within ground contact (21.4–26.0% and 23.9–28.3%, respectively). Thus, it appears 2% shank WR provides a direct overload to anterior-posterior force production during the early-mid part of stance around the time where the ground reaction force vector transitions between braking and propulsion, and that this appears to closely align with the features of the ground reaction forces that align with performance as the athlete travels from 10 m onwards. Considering the increase to braking force magnitudes and duration during the later parts of acceleration, it is possible that shank WR directly challenges the athlete to maintain their lower-limb stiffness resulting in the athletes experiencing greater braking forces before they can transition to propulsion. This may potentially serve as a mechanism for shank WR to improve sprint acceleration performance by enabling athletes to better attenuate braking forces following training exposure. Whilst the significant effects of shank WR on anterior-posterior forces occurred at a very similar part of the step cycle to where the magnitudes of the anterior-posterior force are known to relate to performance[9], it should be noted that these effects only occurred for ~5% of the stance phase and it remains unknown if this overload would be sufficient as a training stimulus. Future longitudinal studies could investigate if this overload would be sufficient as a training stimulus.

The waveform analysis revealed no difference ($p > 0.05$) in vertical force production between the shank loaded and unloaded sprint trials across the ground contact of each of the distance-matched steps. It is possible the athletes altered end-swing phase or touchdown mechanics to prevent substantial increases in vertical impact forces. The initial rising edge of the vertical force waveform at impact is influenced by three factors during upright sprint running; mass, vertical touchdown velocity, and deceleration time of the shank.[11] Athletes can alter two of the three variables (velocity and deceleration time) when sprint running with shank WR to limit an increase in vertical impact force. The findings here suggest these athletes were able to maintain touchdown kinetics with 2% BM shank WR to not incur large vertical impact forces and likely did so by altering vertical touchdown velocity and/or deceleration time of the shank. Visual inspection of the entire force waveforms shows slightly greater forces at midstance with shank WR which, although non-significant, are possibly a function of the greater system mass. It has been hypothesized that greater vertical forces than those during unloaded sprint running are needed to produce a greater vertical take-off velocity and, thus, greater flight times.[7] The greater flight times are thought to be needed to allow for more time to reposition the limb during swing in preparation of the next ground contact due to the constraint of increased rotational inertia. The athletes in this study were able to perform sprint running acceleration with the 2% BM shank WR without a need to significantly increase vertical force production across the stance phase. Thus, it is possible that the addition of 2% BM shank WR does not necessitate greater flight times to allow for limb repositioning.

This study was the first to investigate ground reaction force waveforms over the entire stance phase during sprint running with WR. It was found that the only significant differences between the loaded and unloaded force waveforms occurred the anterior-posterior direction during the period of transition from braking to propulsion. Future studies could consider investigating the stance by sub-phases, including direction- or feature-specific waveform analyses and contact time comparisons. A possible limitation to the findings of this study includes any influence of acute performance effects that could occur from the use of shank WR. The acute performance effects of lower-limb WR on sprint running performance have only been investigated using a combined thigh and shank WR loading scheme (1–5% BM).[22-24] No significant changes to sprint running times were reported in these studies. However, Simperingham, Cronin, Pearson, Ross [22] reported substantial changes (i.e. greater than two standard deviations from the baseline mean) in a single-subject analysis for the start and acceleration phase contact times (2.1–2.9%) following 40 m sprints with 1%, 3%, and 5% BM WR. Therefore, in effort to minimize any influence of potential acute performance effects for measures in this study, the athletes were provided five to ten minutes of passive rest between sprint trials and the experimental conditions were randomised.

Lower-limb WR can be used to provide a specific and targeted overload to the muscles involved in sprint running. This has made lower-limb WR training of great interest for improving sprint running speed. To-date, only a small variety of load placements and magnitudes have been investigated.[2] However, it is unknown how different load magnitudes and placements may alter ground reaction force production across the stance phase compared to the loading scheme used in this study. Practitioners should still be watchful when using different lower-limb WR schemes for any negative individual responses that may occur, especially when using loading schemes that induce greater rotational inertial changes to that studied here. This will help to ensure the appropriateness of the WR training with respect to desired training outcomes and limit the potentially injurious impact forces.

Conclusions

This study builds upon the current WR research and identifies specific kinetic effects which may render shank WR as a potentially effective training tool for sprint acceleration performance. Sprint running with 2% shank WR produced a small, significant increase to contact time at 30 m by 1.94% (ES = 0.25, $p = 0.03$). Significant differences in the anterior-posterior component of the ground reaction force between unloaded and shank WR occurred between 20–30% of ground contact at 10 m, 20 m, and 30 m. The overload provided to anterior-posterior force production coincided closely with the performance demands at these stages within acceleration. In addition, this study assists practitioners in determining if caution needs to be exercised when prescribing shank WR to reduce injury risk. The results of this study do not indicate that greater horizontal braking or vertical forces occur during the impact portion of ground contact when sprint running with 2% BM shank WR up to 30 m. Therefore, practitioners can prescribe shank WR training with loads ≤ 2% BM for sprint running training matching the speeds and distances used in this study with little concern such loading will cause injury.

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Table 1. Time, distance, velocity, percent of maximal velocity (mean ± SD) and the step number used at each distance of interest for the unloaded and shank conditions' distance-matched steps.

Step (#)			Time at toe-off (s)	Distance at toe-off (m)	Velocity at toe-off ($m \cdot s^{-1}$)	Percent of maximal velocity at toe-off (%)
5 m	3 (n = 2), 4 (n = 12), 5 (n = 1)	**U**	1.29 ± 0.08	5.07 ± 0.46	6.49 ± 0.28	70.0 ± 2.45
		S	1.30 ± 0.07	5.02 ± 0.35	6.38 ± 0.25	71.1 ± 1.99
10 m	6 (n = 2), 7 (n = 11), 8 (n = 2)	**U**	1.98 ± 0.09	9.90 ± 0.53	7.75 ± 0.31	83.5 ± 1.55
		S	2.01 ± 0.08	9.87 ± 0.35	7.60 ± 0.30	84.8 ± 1.45
20 m	11 (n = 2), 12 (n = 6), 13 (n = 5), 14 (n = 2)	**U**	3.20 ± 0.15	20.0 ± 0.72	8.81 ± 0.38	95.0 ± 1.02
		S	3.26 ± 0.15	19.9 ± 0.57	8.60 ± 0.36	95.9 ± 0.94
30 m	16 (n = 2), 17 (n = 5), 18 (n = 5), 19 (n = 3)	**U**	4.36 ± 0.20	30.3 ± 0.84	9.19 ± 0.41	99.0 ± 0.44
		S	4.44 ± 0.18	30.2 ± 0.42	8.92 ± 0.41	99.4 ± 0.37

Note: U = unloaded condition, S = shank loaded condition

Table 2. Contact time mean and standard deviation measures for each sprint running condition with paired-samples t-test *p*-value and Cohen's *d* effect size statistics.

	Unloaded	**Shank loaded**	**Shank loaded - Unloaded**
	$\bar{x}$ (SD)	**$\bar{x}$ (SD)**	***p*-value; ES**
5 m CT (ms)	143 ± 12.0	141 ± 13.9	0.18; 0.15
10 m CT (ms)	125 ± 7.58	126 ± 8.87	0.42; 0.12
20 m CT (ms)	110 ± 8.01	111 ± 8.60	0.15; 0.13
30 m CT (ms)	103 ± 7.11	105 ± 6.67	0.03*; 0.25

Note: CT = contact time; * = significant difference between unloaded and shank loaded; ES = effect size

Figure 1. Example wearable resistance load placement.

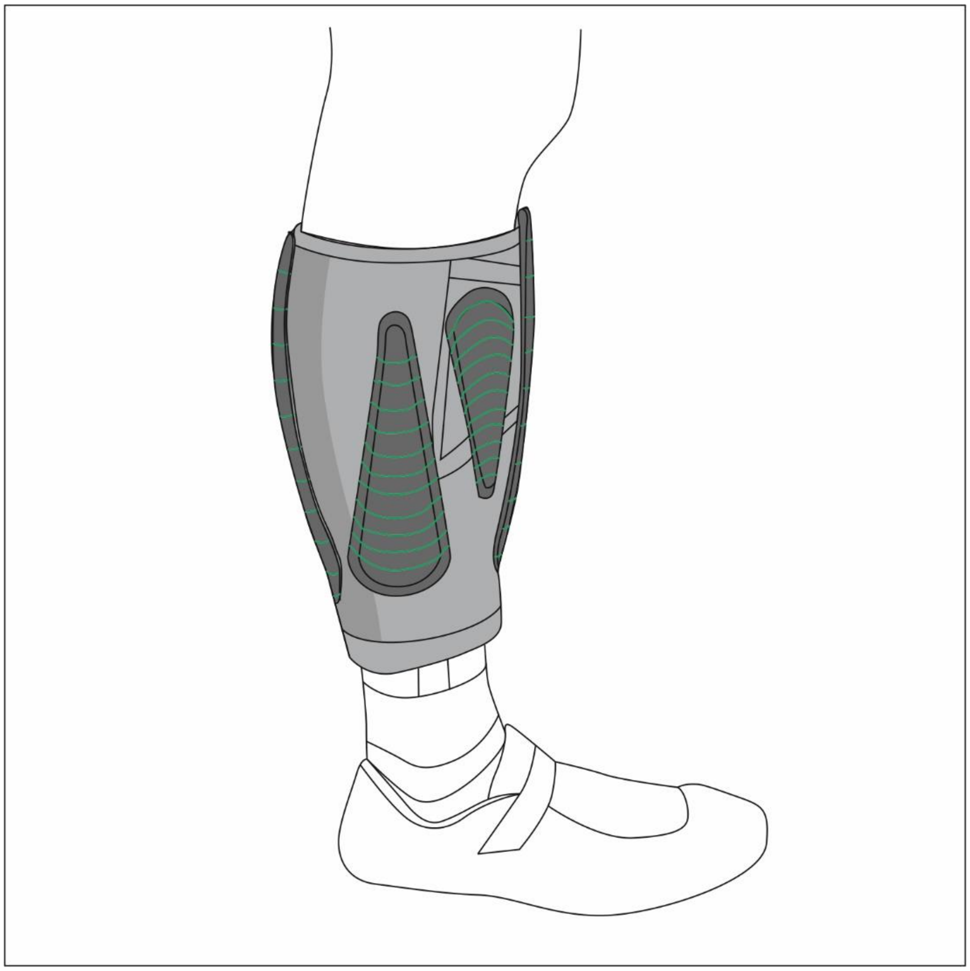

Figure 2. Individual change in contact time between the unloaded and shank loaded conditions for each participant (n = 15) at each distance-matched step; A = 5 m, B = 10 m, C = 20 m, D = 30 m. The values are ranked in order of magnitude. A positive value indicates a higher contact time in the shank loaded condition. Dashed lines indicate the smallest worthwhile change threshold (± 0.20 × unloaded condition between-subject standard deviation).

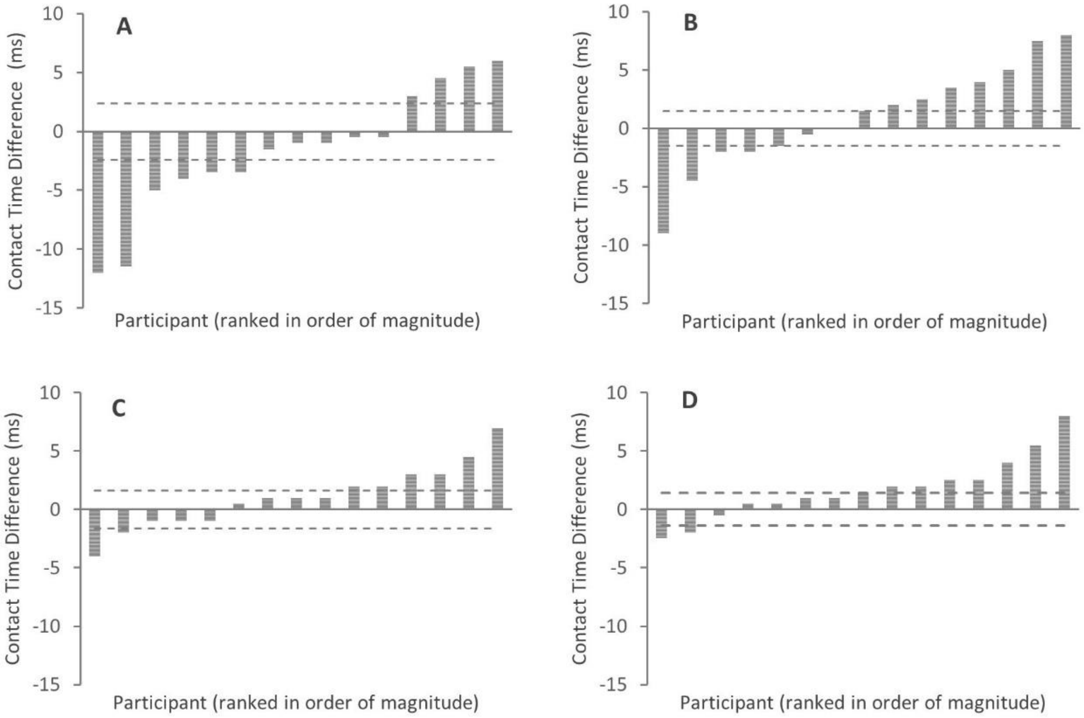

Figure 3. Anterior-posterior force waveforms (force units standardised to body weight) for the step at 5 m, 10 m, 20 m, and 30 m during unloaded (black) and shank loaded (red) sprint running. The left column shows average force waveforms for each participant at 5 m (A), 10 m (B), 20 m (C), and 30 m (D). The right column shows mean (solid line) and standard deviation (dotted line) for each condition at 5 m (E), 10 m (F), 20 m (G), and 30 m (H). The gray bar indicates the sections of the waveform where the SPM curve exceeded the critical threshold representing a statistically significant difference between the two conditions ($p < 0.05$).

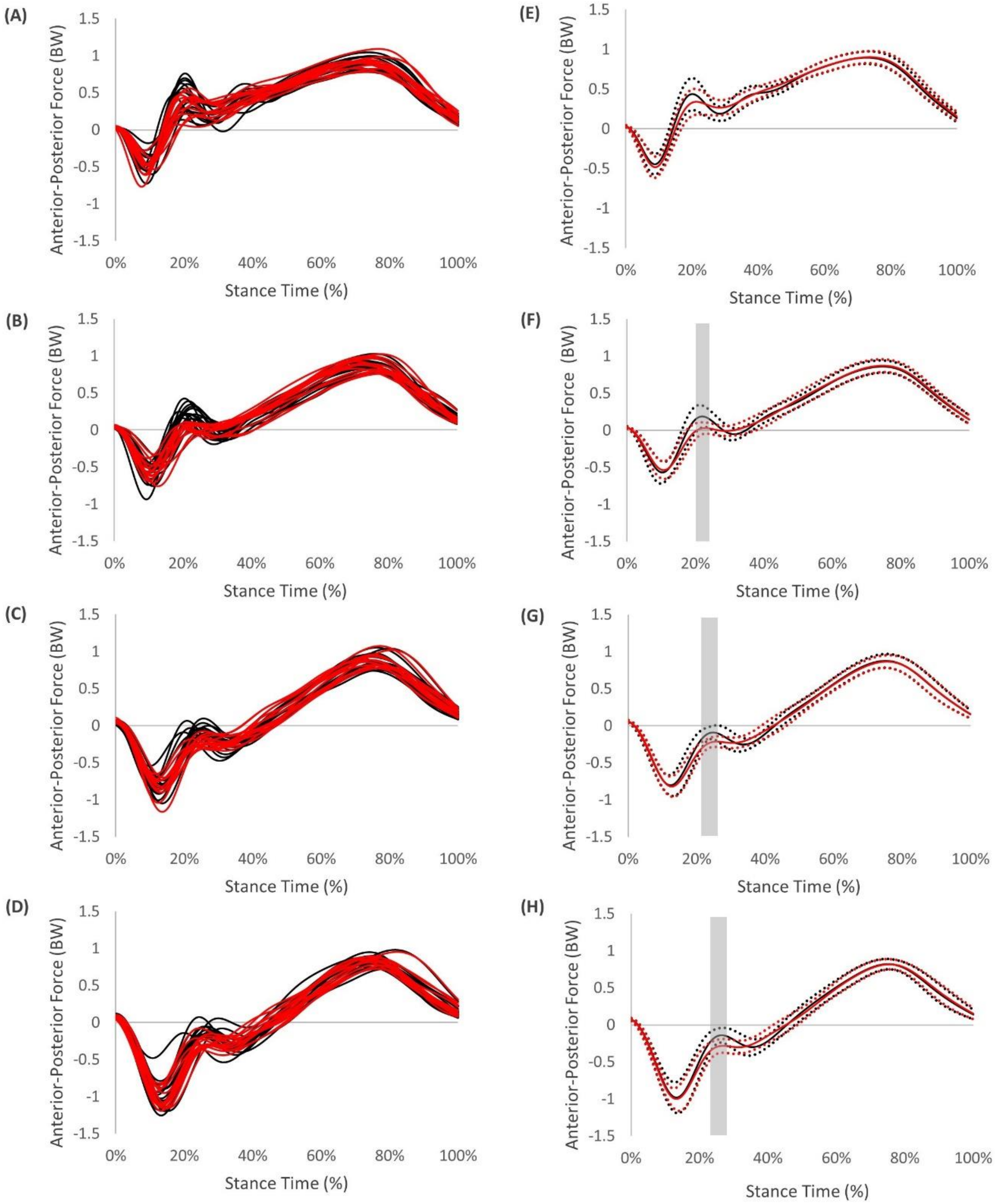

Figure 4. Vertical force waveforms (force units standarised to body weight) for the step at 5 m, 10 m, 20 m, and 30 m during unloaded (black) and shank loaded (red) sprint running. The left column shows average force waveforms for each participant at 5 m (A), 10 m (B), 20 m (C), and 30 m (D). The right column shows mean (solid line) and standard deviation (dotted line) for each condition at 5 m (E), 10 m (F), 20 m (G), and 30 m (H). No statistically significant differences were present between the two conditions at any of the step distances ($p > 0.05$).