Changes to horizontal force-velocity and impulse measures during sprint running acceleration with thigh and shank wearable resistance

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ABSTRACT

This study determined the effects of two wearable resistance (WR) placements (i.e. thigh and shank) on horizontal force-velocity and impulse measures during sprint running acceleration. Eleven male athletes performed 50 m sprints either unloaded or with WR of 2% body mass attached to the thigh or shank. In-ground force platforms were used to measure ground reaction forces and determine dependent variables of interest. The main findings were: 1) increases in sprint times and reductions in maximum velocity were trivial to small when using thigh WR (0.00–1.93%) and small to moderate with shank WR (1.56–3.33%); 2) athletes maintained or significantly increased horizontal force-velocity mechanical variables with WR (effect size = 0.32–1.23), except for theoretical maximal velocity with thigh WR, and peak power, theoretical maximal velocity and maximal ratio of force with shank WR; 3) greater increases to braking and vertical impulses were observed with shank WR (2.72–26.3% compared to unloaded) than with thigh WR (2.17–12.1% compared to unloaded) when considering the entire acceleration phase; and, 4) no clear trends were observed in many of the individual responses. These findings highlight the velocity-specific nature of this resistance training method and provide insight into what mechanical components are overloaded by lower-limb WR.

Keywords: limb loading, velocity, sport specificity, acceleration

INTRODUCTION

Sprint running is an important facet of many sports and the interest in understanding the mechanics of sprint running is evident by the extent of scientific literature addressing this topic.[1, 2] Mechanically, faster sprint running is determined by the athlete's technical ability (supported by sufficient strength and metabolic capacity) to produce high force production directed horizontally during acceleration[3, 4] and maintain high vertical support forces as contact times decrease during maximal velocity sprint running[5]. A deeper understanding of the mechanics of sprint running can be provided by evaluating kinetic information such as mechanical output characteristics (e.g. horizontal force-velocity profile)[6]; magnitude and duration of force application (i.e. impulse)[7]; and identifying the relationship between horizontal force to total force with increasing speed (i.e. ratio of forces)[3]. These kinetic factors provide an understanding of the underlying causes of sprint running performance and, thereby, offer pertinent information to be considered when reviewing and attempting to more thoroughly understand a training method's potential as a stimulus to generate improvements in sprint running performance.

Lower-limb wearable resistance (WR) training involves attaching "micro-loads" (e.g. 1–3% of body mass (BM)) to the lower-limb(s) of the body. The load is worn during sport-specific movement training as an application of the principle of training specificity. Based on this principle, training should replicate the characteristics of the sporting activity so any metabolic or mechanical adaptations will transfer directly to the performance of the movement itself. These contentions have formed the basis for using lower-limb WR as a training method for sprint running with the ultimate goal of improving sprint running performance.[8-10] An important consideration of using lower-limb WR is whether such loading influences sprint running kinetics. However, the influence of lower-limb WR on sprint running kinetics is not well understood.

Sprint running with lower-limb WR has been shown to alter the horizontal force-velocity (F-v) profile, which provides insight into an athlete's ability to generate horizontal force from zero to their theoretical maximal velocity (V_0). While the optimal profile for sprint running may vary based on sport-specific needs[11, 12], it has been established that faster short-distance sprint running is significantly correlated to the athlete's ability to maintain horizontal force production with increasing velocity and produce high levels of horizontal force and net horizontal power during each step.[3] When 3% BM WR was attached to the thigh and shank (thigh+shank) during overground sprint running, a ~10% more force dominant F-v profile was observed.[13, 14] This profile change resulted from a reduction in V_0 and an increase in relative theoretical maximal horizontal force (F_{0SM}; relative to system mass; 5.08–6.25%) with little corresponding change to total sprint running time.[13, 14] The time to sprint the 20 m distance used in these studies increased by 0.58% to 1.40% compared to unloaded sprint running. However, the same changes were not found when greater mass (5% BM) was attached to the thigh+shank during sprint running; sprint times over 20 m were significantly slower (−2.02%) and F_{0SM} only increased by 1.25%.[14] It would seem that different loading magnitudes may have varying effects and that more resistance does not always equate to more horizontal force production when using lower-limb WR during short-distance sprint running. It needs to be noted, however, that only a minimal number of loading magnitudes (i.e. 3% and 5% BM) have been investigated to date with no F-v profile information available on the effect of the WR placed solely on the shank.

Sprint running with lower-limb WR has also been shown to change the impulses generated during the acceleration phase of sprint running.[15] During unloaded sprint running, relative propulsive ($IMP_{P(BM)}$) and net anterior-posterior (IMP_{AP}) impulses have shown to significantly correlate (r = 0.52–0.87) to overground sprint running velocity[16], 40 m acceleration performance[17], and 10 m sprint time[18] with relative braking ($IMP_{B(BM)}$) and vertical impulses (IMP_{V}) having a corresponding weak or non-significant correlation (r = 0.04–0.50). However, sufficient vertical impulse is necessary to maintain upright body position when in contact with the ground and to elevate the body for the next flight phase; also, any increases in braking impulse must be met with an increase in propulsive impulse to maintain a given velocity. With 2% BM thigh WR, $IMP_{AP(SM)}$ has been shown to significantly decrease (−4.73%) during the acceleration phase of a 50 m sprint, which corresponded to a non-significant increase in $IMP_{B(SM)}$ (8.08%) and decrease in $IMP_{P(SM)}$ (−1.52%).[15] It would appear that 2% thigh WR alters the interplay of propulsive and braking forces during ground contact of the acceleration phase. These findings provide insight into how lower-limb WR may affect impulse production during sprint running and therefore assist in evaluating lower-limb WR as a training stimulus. However, these impulse values were averaged over steps 5-14 of the acceleration phase. A more detailed investigation of acceleration mechanics is warranted considering kinetic determinants of performance have been shown to shift as velocity increases.[7] It is also unknown if similar effects on impulse would occur with other lower-limb WR placements.

Researchers have started to uncover how lower-limb WR may alter horizontal F-v mechanical variables and impulse production during sprint running but further investigation is needed for coaches to better understand how to optimise lower-limb WR use to produce desired training adaptations. The information available to date is limited with minimal kinetic analyses that have only utilised two load placements (thigh and thigh+shank). Further information on how athletes respond to different load placements and how this affects the kinetics of sprint running is necessary. In particular, it is of interest to determine the effect of the same load magnitude placed on the thigh versus the shank as the more distal load placement produces a greater rotational overload (moment of inertia) to the lower-limb with the same load magnitude. This information will help coaches and strength and conditioning practitioners better understand what mechanical components can be influenced by lower-limb WR in an attempt to produce positive sprint running performance adaptations over time. Therefore, the purpose of this study was to determine the effect of two different WR placements (i.e. thigh versus shank) on horizontal F-v and impulse measures during sprint running acceleration. It was hypothesised that greater changes to the horizontal F-v and impulse measures would occur with shank WR due to the greater inherent rotational inertia.

MATERIALS AND METHODS

Experimental Procedures

Eleven male athletes volunteered to participate in this study (mean ± standard deviation; age = 21.2 ± 2.56 years, body mass = 69.1 ± 3.95 kg, stature = 1.75 ± 0.05 m). The athletes were university level, sprint specialists with a 100 m best time of 11.34 ± 0.41 s (range = 10.70–11.92 s) and sprint training experience of 9.73 ± 2.90 years (range = 7–16 years). Written informed consent was obtained before study participation. All study procedures were approved by the host University Institutional Review Board. The athletes reported to the testing facility on two occasions separated by a minimum of 72 hours. Upon arrival, the athletes completed a self-selected warm-up that included running drills, dynamic stretching, and a series of submaximal (e.g. 50%, 75%, and 90% of maximal effort) sprints. Following this, each athlete completed four maximal effort 50 m sprints that consisted of two repetitions under each experimental condition - loaded (WR attached to the thigh or shank) and unloaded (no WR). The sprints were completed in a randomised order separated by a minimum of five minutes of passive rest and each started from starting blocks. The thigh and shank WR experimental conditions were randomly assigned between the two testing occasions (i.e. each athlete completed two shank WR and two unloaded sprint during one session, and two thigh WR and two unloaded sprints during the other session). The athletes wore Lila™ Exogen™ (Sportboleh Sdh Bhd, Kuala Lumpur, Malaysia) weighted compression shorts or calf sleeves for the thigh and shank loaded trials, respectively. These specialised compression garments allow for Velcro backed "micro-loads" to be attached to the garment in a variety of different orientations and locations. The thigh WR was attached with a horizontal orientation on the distal aspect of the thigh with 2/3 of the load placed more anteriorly and 1/3 placed more posterior following previous thigh WR research[15, 19] (Figure 1A). The shank WR was attached in line with the long axis of the shank, equally encircling the shank (Figure 1B). A 2% BM load magnitude was used for each loaded trial (i.e. 1% BM attached to each limb) following previous research.[15, 19] Due to the loading increments available (100, 200, and 300 g), exact loading magnitudes ranged from 1.92-2.01% BM. All sprint trials were completed on an indoor athletic track surface (Taiiku, Hasegawa, Japan) with the athletes wearing their spiked running shoes. The sprint start was signalled with an electronic starting gun (Digi Pistol, Molten, Hiroshima, Japan). A series of 54 in-ground force platforms (TF-90100, TF-3055, TF-32120, Tec Gihan, Uji, Japan) were used to measure ground reaction forces (GRF) at 1000 Hz for a total distance of 52 m spanning from 1.50 m behind the starting line to the 50.5 m mark.

Data Processing

GRF data were filtered using a fourth-order Butterworth low-pass digital filter with a cut-off frequency of 50 Hz. Touch-down and take-off detection were identified in the filtered data by a 20 N vertical GRF threshold. The data from the initial movement in the blocks to the step at maximal velocity was used for the analysis. Horizontal centre of mass (COM) velocity (V_H, as a function of time) was calculated from the initial movement to maximal velocity per the methods outlined by Colyer, Nagahara and Salo [20]. Per this method, the impulse-momentum relationship was used to determine instantaneous V_H throughout the entire sprint from the IMP_{AP} and estimated aerodynamic drag[6]. The V_H was modelled with a mono-exponential fit and a series of horizontal F-v mechanical variables were calculated from the linear F-v relationship, the second-degree polynomial power-velocity relationship, and the linear relationship between the ratio of horizontal to total force and V_H for each trial.[6] These variables were used to describe the general mechanical ability of the athlete to produce horizontal external force during sprint running and included: theoretical maximal velocity (V_0); theoretical maximal horizontal force (F_0), peak power (P_{max}), maximal ratio of force (RF_{max}), and index of force application (D_{RF}).[21] These horizontal F-v mechanical variables, along with the slope of the F-v profile ($S_{FV(BM)}$; $-F_{0(BM)}/V_0$), were calculated consistent with the method previously validated.[6, 21] Further, sprint times (5, 10, 20, and 30 m) were derived from the integral of the V_H data. The maximal velocity (V_{max}) was determined from the step with the maximal toe-off velocity. The exponential modelling of the V_H data was well fit with all $R^2 > 0.99$.

The steps at 5 m, 10 m, 20 m, and 30 m were extracted to identify changes in impulse between the unloaded, thigh, and shank conditions. This was implemented by identifying the step in which the athletes' COM location at toe-off was closest to the metre mark of interest. Intra-individual consistency was ensured by using the same step for all trials. The step used for each condition along with the corresponding time, distance, and velocity at toe-off are reported in Table 3. This comparative approach was chosen since many coaches prescribe training repetitions based on set linear distances and pilot data suggests that athletes finish acceleration earlier when sprint running with WR. Impulse values were calculated by time integration of the respective directional component of force. Impulse values are reported as both absolute and normalised to BM.

Statistical Analysis

To represent each athlete's performance for each experimental condition, the data from the two trials for each loaded condition and the four trials for the unloaded condition were averaged. A series of preliminary analyses (paired-samples t-tests) were used to confirm there were no significant differences in sprint times between the two testing sessions for the unloaded condition before averaging the four trials (all $p > 0.05$). To determine the effect of thigh and shank WR on sprint times, mechanical output, and impulse, a one-way repeated measures ANOVA with pair-wise post hoc comparisons (Fisher's LSD) were conducted. An outlier was defined as a value greater than 3 box-lengths from the edge of the box in the IMP_{AP} 10 m, IMP_{B} 5 m and 20 m, and $IMP_{B(BM)}$ 20 m and 30 m data sets and in such cases was removed from the analysis. The differences between measures were normally distributed as assessed by Shapiro-Wilk's test ($p > 0.05$). Analyses were performed using SPSS Statistics (Version 26, IBM, Armonk, NY, USA). Significance was set at $p \leq 0.05$. Effect size (ES) statistics (Cohen's d) were calculated as the mean of the within-subjects difference scores divided by the average standard deviation of both repeated measures[22] and described as trivial (<0.20), small (0.20), moderate (0.50) and large (0.80)[23]. To describe individual responses to each loaded condition, the smallest worthwhile change (SWC) was calculated as 0.2 × pre-intervention between-subject standard deviation. Each response was then classified as an increase (> + SWC) or decrease (> – SWC) for each dependent variable if the absolute change from the unloaded condition was outside of the SWC, and a trivial change if it remained within the SWC.[23]

RESULTS

Sprint running times, maximal velocity, and horizontal F-v variables with post-hoc *p*-value and effect size statistics are presented in Table 1. Sprint running with thigh WR significantly increased 10 m, 20 m, and 30 m sprint times and decreased V_{max} (ES = 0.21–0.48), whilst sprint running with shank WR significantly increased all sprint times and decreased V_{max} (ES = 0.46–0.76). Sprint running with thigh WR significantly increased F_0 (ES = 0.32) and D_{RF} (ES = 0.78) and decreased V_0 (ES = 0.54), resulting in a more force dominant $S_{FV(BM)}$ (ES = 1.12). Sprint running with shank WR significantly increased D_{RF} (ES = 0.86) and decreased $P_{max(BM)}$ (ES = 0.26), V_0 (ES = 0.73) and RF_{max} (ES = 0.34), also resulting in a more force dominant $S_{FV(BM)}$ (ES = 1.23). When comparing thigh versus shank WR, 10 m, 20 m, and 30 m sprint times were significantly slower and $P_{max(BM)}$ and V_{max} (ES = 0.21–0.33) were significantly less with shank WR. The individual response to thigh and shank WR for $F_{0(BM)}$, $P_{max(BM)}$, V_0, and D_{RF}, reported as the absolute change from the unloaded condition (i.e. WR – unloaded), are presented in Figure 2. With thigh WR, the majority of athletes increased $F_{0(BM)}$ (7/11) and decreased V_0 (10/11), but for $P_{max(BM)}$ and D_{RF} a mixed response was observed. With shank WR, the majority of the athletes decreased $P_{max(BM)}$ (7/11) and all athletes decreased V_0, whilst a mixed response was observed for $F_{0(BM)}$ and D_{RF} measures.

The absolute and relative impulse measures with post-hoc *p*-value and effect size statistics are shown in Table 2. In the anterior-posterior direction, thigh WR increased IMP_B and $IMP_{B(BM)}$ by small effects at 5 m, 10 m, and 30 m (ES = 0.29–0.38, $p > 0.05$) and large effects at 20 m (ES = 1.17–1.35, $p < 0.05$). This coincided with trivial or small increases in IMP_P and $IMP_{P(BM)}$ (ES = 0.05–0.43, $p < 0.05$ at 30 m). Overall, trivial to small decreases in IMP_{AP} and $IMP_{AP(BM)}$ (ES = 0.04–0.47, $p > 0.05$) were observed. With shank WR, increases to IMP_B were small at 10 m (ES = 0.38, $p > 0.05$) and moderate to large at 5 m, 20 m, and 30 m (ES = 0.85–1.27, $p < 0.05$) and increases to $IMP_{B(BM)}$ were moderate to large through all distances measured (ES = 0.67–1.97, $p < 0.05$ at 20 m and 30 m). This coincided with trivial effects to IMP_P and $IMP_{P(BM)}$ (ES = 0.01–0.16, $p > 0.05$), which taken together, resulted in decreases to IMP_{AP} and $IMP_{AP(BM)}$ that were trivial at 5 m (ES = 0.13–0.16, $p > 0.05$), small at 10 m (ES = 0.23–0.34, $p > 0.05$) and moderate at 20 m and 30 m (ES = 0.63–0.72, $p < 0.05$ only at 30 m). In the vertical direction, IMP_V was increased by small effects (0.20–0.49, $p < 0.05$ at 10 m and 20 m) with thigh and shank WR. $IMP_{V(BM)}$ was increased by small to moderate effects (ES = 0.29–0.55, $p < 0.05$ at 20 m) with thigh WR and small to large effects (ES = 0.42–0.92, $p < 0.05$ at all distances) with shank WR.

The individual responses to thigh and shank WR for $IMP_{AP(BM)}$, reported as the absolute change from the unloaded condition (i.e. WR – unloaded) are presented in Figure 3. A variety of individual responses were recorded across the distance-matched steps and between the two loading conditions. Some athletes increased $IMP_{AP(BM)}$ at one step distance and decreased at another (e.g. participant 4). Also, some athletes responded in different directions between the two loading conditions, e.g. increase in $IMP_{AP(BM)}$ with thigh WR and decrease with shank WR. Individual responses to $IMP_{P(BM)}$, $IMP_{B(BM)}$, and $IMP_{V(BM)}$ are provided as supplementary material.

DISCUSSION

The effects of 2% BM lower-limb WR (attached to the thigh or shank) on sprint times, V_{max}, horizontal F-v mechanical variables, and impulse production during sprint running acceleration was quantified in this study. The main findings were: 1) increases in sprint times and reductions in maximum velocity were trivial to small when using thigh WR (0.00–1.93%) and small to moderate with shank WR (1.56–3.33%); 2) athletes maintained or significantly increased horizontal F-v mechanical variables while sprint running with WR (effect size = 0.32–1.23), except for V_0 during thigh WR and P_{max}, V_0, and RF_{max} during shank WR; 3) greater increases to braking and vertical impulses were observed with shank WR (2.72–26.3% compared to unloaded) than with thigh WR (2.17–12.1 % compared to unloaded) when considering the entire acceleration phase; and, 4) no clear trends were observed in many of the individual responses. These results support the hypothesis that the greater rotational inertia associated with the WR placed on the shank would result in greater changes to the horizontal F-v and impulse measures than the same WR load placed on the thigh.

Attaching an external load to the lower-limbs during sprint running will increase the rotational workload of the lower limbs in addition to increasing the total system mass.[19] Coaches and strength and conditioning practitioners interested in lower-limb WR training should be cognisant of the load placement with regards to the magnitude of the rotational overload desired. The same load magnitude placed further from the hip joint will increase the rotational overload (as quantified by the moment of inertia) by a function of the distance from this key axis of rotation (i.e. mass × $distance^2$). The impact of a load placement change is readily evident to the athlete based on sensory feedback but, also, the findings of this and previous research highlight the impact of a load placement change to athlete performance. In this study, V_{max} was significantly decreased by both thigh and shank WR but the decrease was to a greater effect with shank WR (moderate versus small). Previously, researchers have reported 1-3% BM thigh WR produced decreases in step velocity by -0.86 to -2.35%[15, 24, 25] but just ~0.6% BM shank WR has been shown to produce similar decreases in step velocity (-1.20% to -2.23%)[24, 26]. The significant changes to velocity and sprint time measures, along with the number of participants exceeding the V_0 SWC threshold (Figure 2), highlight the consistency in athlete response to the standardised limb load prescription by using a percent of BM. It is possible that other methods could be effective to standardise WR prescriptions such as using a velocity decrement. However, from a practical standpoint, the increases to sprint times in this study were < 0.10 s on average, reinforcing the principle that lower-limb WR allows for a velocity-specific form of resistance training for sprint running.[8, 27] It has also been confirmed that the rotational work at the hip joint is significantly increased with 2% BM thigh WR providing a means to increase the mechanical work of the lower-limbs specific to sprint running.[19]

Investigating acute kinetic changes that occur during the use of a training method can help coaches more thoroughly understand the training stimulus induced and determine how to use the training method to generate performance improvements. In this study, the athletes were able to maintain or increase some mechanical characteristics of external horizontal force production while loaded. Most notably F_0 and $F_{0(BM)}$ levels were maintained with shank WR and increased by small effects with thigh WR. Additionally, the athletes maintained $P_{max(BM)}$ and RF_{max} levels with thigh WR while the same WR load placed on the shank resulted in significant, small decreases to $P_{max(BM)}$ and RF_{max}. It appears that the WR encouraged a physiological (i.e. internal force production) or technical (i.e. orientation of force) response that allowed the athlete to maintain external horizontal force production during initial acceleration, especially with thigh WR where seven of the 11 participants experienced increases to $F_{0(BM)}$ beyond the smallest worthwhile change threshold. However, this was not preserved over the entire 30 m sprint as evident by the slowing of sprint times, decreased V_{max} and V_0, and increased D_{RF} values with both thigh and shank WR. This suggests a given WR load (e.g. 2% BM) provides a different overload magnitude based on the movement speed of the athlete. This has also been noted previously[8] and is supported by the angular work-energy relationship. As the angular velocity of the limb increases with increasing speed, so does the angular kinetic energy of the limb, which increases the muscular work required. Coaches and strength and conditioning practitioners could choose heavier WR loads to provide a greater overload for initial acceleration during initial acceleration-specific work (e.g. block clearance drills) and lighter WR loads to provide a comparable overload during higher velocity-specific work (e.g. "flying" sprint drills) if desired.

When comparing impulse production at the distance-matched steps, IMP_B was significantly greater (large ES) with shank WR compared to the unloaded sprint running at 5 m, 20 m, and 30 m and when calculated relative to BM, $IMP_{B(BM)}$ was significantly greater (large ES) at 20 m and 30 m. Considering IMP_B and $IMP_{B(BM)}$ were only significantly increased with thigh WR at 20 m, the increases to IMP_B and $IMP_{B(BM)}$ with shank WR were primarily due to the location of the WR placement rather than the increase in system mass as the latter was consistent between the two WR conditions. For impulse to increase, there must be greater force magnitudes, a greater duration of force application (i.e. longer contact times), or some combination of the two. Considering the greater rotational overload with the shank WR placement, it is likely that the limb had greater angular momentum at the end of the forward swing phase. This would increase the challenge to stop and reverse the motion of the limb in preparation for the next ground contact. The energy of the limb at the end of the swing phase is absorbed by the work of the hip and knee joints.[28] If the greater momentum is not fully countered by the work of the hip and knee joints, the horizontal velocity of the foot at touchdown could be altered or the distance between the foot and COM at touchdown (i.e. increased touchdown distance) could be increased. Both have been suggested to be related to horizontal ground reaction forces[16, 29], and thus, could result in greater horizontal impact forces, greater time spent reversing braking forces to transition to propulsion, or a combination of the two. Future studies could attempt to determine the effect of lower-limb WR on the magnitude of horizontal force across the duration of ground contact to better understand this.

Although $IMP_{B(BM)}$ is not a strong predictor of sprint acceleration velocity[16, 17], more detailed analyses have revealed the importance of attenuating braking forces as acceleration progresses for improving sprint running performance.[4, 7, 20] Athletes that better attenuated braking forces also produced greater horizontal external power[20] and differences between sprinters and soccer players show sprinters better attenuate braking forces during the latter portion of the braking phase[4]. From these findings, it has been suggested that a component of training for sprint running should include working to improve the athlete's ability to resist and reverse braking forces.[4, 20] Lower-limb WR may provide a unique training stimulus to overload $IMP_{B(BM)}$ during acceleration especially when WR placement is located on the shank.

With shank WR, IMP_V and $IMP_{V(BM)}$ were significantly increased at each of the distance-matched steps except for IMP_V at 5 m (small to large ES). With thigh WR, the only significant increases were found at 10 m (IMP_V, small ES) and 20 m (IMP_V and $IMP_{V(BM)}$, small and moderate ES, respectively). The greater rotational overload of shank WR likely increased the challenge to reposition the limb during swing and athletes may have subsequently used longer flight times to reposition the limb. To achieve longer flight times a greater vertical take-off velocity would be required and this would need to be accomplished with greater vertical impulse production during the preceding ground contact. It has been speculated that during acceleration the magnitude of $IMP_{V(BM)}$ should be only that needed to produce sufficient flight time to reposition the limb, otherwise, force production should be oriented horizontally.[16] However, considering ground contact time decreases with increasing speed[30], an athlete's ability to produce sufficient $IMP_{V(BM)}$ to maintain flight time as ground contact time decreases must come from increased vertical force production. Shank WR, in particular, appears to encourage greater $IMP_{V(BM)}$ during sprint running acceleration although this may be a consequence of how the athlete handles the load during the flight phase. It is also possible that the greater $IMP_{V(BM)}$ is a result of increased vertical impact forces. In accordance with the two-mass model of human running[31, 32], the addition of mass to the shank with WR could result in greater impact forces upon ground contact. Future studies could therefore attempt to understand the underlying influence of force magnitude and ground contact time on observed changes in vertical impulse during sprint running with lower-limb WR.

This study aimed to determine the effect of thigh and shank WR on horizontal F-v and impulse measures. An important next step is to detail the change to ground reaction force time-histories to determine if the greater impulses with lower-limb WR are a result of greater ground contact times, altered time spent in braking or propulsion, increased force magnitudes at a particular part of stance or throughout the entire stance phase, or a combination of some or all of the above factors. The WR loading schemes used in this study did not equate the magnitude of rotational overload between the two placement locations. While it appears that the placement of the shank WR might uniquely affect mechanical output and impulse during sprint running over thigh WR, this cannot be fully confirmed without first equating the magnitude of the rotational overload between the two placement locations. This has been investigated with lighter WR loads during maximal velocity sprint running[24], looking only at spatiotemporal and angular kinematic measures, but this has yet to be investigated during acceleration or with rotational overload equated to the 2% BM shank WR used in this study. Finally, training studies that elucidate the longitudinal kinematic and kinetic adaptations to WR training need to be prioritized.

Conclusion

This study provided further evidence that 2% BM WR placed on the thigh or shank overloads sprint running acceleration. However, the minimal changes to sprint times (i.e. on average < 0.10 s at 30 m) highlighted the velocity-specific nature of this resistance training method. Alterations to impulse production occurred at 20 m and 30 m distances with thigh WR but were present as early as 5 m with shank WR. Although braking and vertical impulses were increased with WR, athletes were able to largely maintain propulsive and net anterior-posterior impulse levels relative to BM at the distance matched steps with external resistance. The analysis of the individual data, for the most part, reinforces the notion that athletes adapt differentially to the same loading and programming for performance change can be complex. These findings provide insight into what mechanical competencies are overloaded by lower-limb WR and may be influenced overtime to produce positive speed adaptations.

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Table 1. Mean and standard deviation for sprint running times, maximal velocity, and horizontal force-velocity variables for each sprint running condition with post-hoc *p*-value and effect size (ES) statistics.

	Unloaded	**Thigh**	**Shank**	**Thigh - Unloaded**	**Shank - Unloaded**	**Thigh - Shank**
	$\bar{x}$ **(SD)**	$\bar{x}$ **(SD)**	$\bar{x}$ **(SD)**	***p*-value; ES**	***p*-value; ES**	***p*-value; ES**
5 m time (s)	1.28 ± 0.04	1.28 ± 0.05	1.30 ± 0.05	0.07; 0.00	<0.01*; 0.44	0.06; 0.40
10 m time (s)	1.98 ± 0.07	2.00 ± 0.07	2.02 ± 0.07	0.02*; 0.29	<0.01*; 0.57	0.03*; 0.29
20 m time (s)	3.19 ± 0.11	3.22 ± 0.12	3.25 ± 0.12	0.01*; 0.26	<0.01*; 0.52	0.04*; 0.25
30 m time (s)	4.31 ± 0.16	4.36 ± 0.16	4.40 ± 0.17	<0.01*; 0.31	<0.01*; 0.55	0.04*; 0.24
V_{max} ($m{\cdot}s^{-1}$)	9.31 ± 0.40	9.13 ± 0.36	9.00 ± 0.44	<0.01*; 0.47	<0.01*; 0.74	0.03*; 0.33
F_0 (N)	583 ± 37.4	596 ± 42.7	585 ± 38.0	<0.01*; 0.32	0.51; 0.06	0.04; 0.27
$F_{0(BM)}$ ($N{\cdot}kg^{-1}$)	8.47 ± 0.52	8.62 ± 0.57	8.53 ± 0.53	0.01; 0.28	0.24; 0.11	0.24; 0.16
$P_{max(BM)}$ ($W{\cdot}kg^{-1}$)	20.3 ± 2.12	20.2 ± 2.06	19.7 ± 2.16	0.50; 0.05	<0.01*; 0.26	0.05*; 0.21
V_0 ($m{\cdot}s^{-1}$)	9.62 ± 0.44	9.39 ± 0.40	9.29 ± 0.47	<0.01*; 0.55	<0.01*; 0.73	0.09; 0.23
D_{RF} ($\%{\cdot}s{\cdot}m^{-1}$)	-7.82 ± 0.21	-8.02 ± 0.30	-8.04 ± 0.30	0.01*; 0.78	0.01*; 0.86	0.83; 0.07
RF_{max} (%)	55.2 ± 2.11	54.9 ± 2.19	54.5 ± 2.14	0.14; 0.13	<0.01*; 0.34	0.13; 0.20
$S_{FV(BM)}$ (%)	-0.88 ± 0.03	-0.92 ± 0.04	-0.92 ± 0.04	<0.01*; 1.14	<0.01*; 1.14	0.87; 0.00

F_0 = theoretical maximal horizontal force; $F_{0(BM)}$ = theoretical maximal horizontal force relative to body mass; $P_{max(BM)}$ = peak power relative to body mass; V_0 = theoretical maximal velocity; D_{RF} = index of force application, RF_{max} = maximal ratio of force; $S_{FV(BM)}$ = slope of the force-velocity profile; * = significant post hoc comparison ($p \leq 0.05$) coinciding with a significant main test effect.

Table 2. Mean and standard deviation of impulse measures for each sprint running condition with post-hoc *p*-value and effect size statistics.

	Unloaded	Thigh	Shank	Thigh - Unloaded	Shank - Unloaded	Thigh - Shank
	$\bar{x}$ (SD)	$\bar{x}$ (SD)	$\bar{x}$ (SD)	*p*-value; ES	*p*-value; ES	*p*-value; ES
Impulse (N·s)						
IMP_{AP}						
5 m	43.2 ± 6.21	43.6 ± 6.47	42.3 ± 5.93	0.40; 0.06	0.07; 0.16	0.10; 0.21
10 m	24.9 ± 2.63	24.6 ± 3.22	23.9 ± 2.93	0.50; 0.08	0.04; 0.34	0.24; 0.23
20 m	12.9 ± 1.86	12.0 ± 2.30	11.6 ± 1.64	0.14; 0.40	0.01; 0.69	0.52; 0.20
30 m	7.90 ± 1.55	7.98 ± 2.10	6.60 ± 2.05	0.79; 0.04	0.01*; 0.72	0.01*; 0.67
IMP_{P}						
5 m	46.6 ± 5.75	47.3 ± 6.03	46.4 ± 5.85	0.10; 0.11	0.54; 0.05	0.21; 0.15
10 m	30.6 ± 3.50	30.5 ± 3.59	30.1 ± 3.66	0.87; 0.01	0.10; 0.14	0.18; 0.13
20 m	22.8 ± 2.35	23.0 ± 2.75	22.9 ± 2.19	0.48; 0.10	0.79; 0.03	0.68; 0.07
30 m	19.3 ± 1.64	19.9 ± 1.69	19.5 ± 1.68	0.02*; 0.35	0.47; 0.08	0.05*; 0.27
IMP_{B}						
5 m	-3.23 ± 0.89	-3.52 ± 0.42	-4.08 ± 1.10	0.28; 0.43	0.02*; 0.85	0.11; 0.74
10 m	-4.83 ± 0.80	-5.14 ± 0.83	-5.19 ± 1.08	0.24; 0.38	0.10; 0.38	0.89; 0.06
20 m	-10.1 ± 1.14	-11.3 ± 0.96	-11.6 ± 1.16	<0.01*; 1.17	<0.01*; 1.27	0.41; 0.23
30 m	-11.4 ± 1.42	-12.0 ± 1.53	-12.9 ± 1.65	0.15; 0.35	0.01*; 0.94	0.02*; 0.59
IMP_{V}						
5 m	156 ± 18.5	161 ± 14.6	160 ± 18.2	0.06; 0.28	0.02; 0.23	0.85; 0.03
10 m	153 ± 18.9	156 ± 18.2	158 ± 16.1	0.03*; 0.20	0.01*; 0.34	0.25; 0.13
20 m	159 ± 17.9	164 ± 16.2	163 ± 19.1	<0.01*; 0.35	<0.01*; 0.29	0.72; 0.03
30 m	153 ± 14.0	158 ± 12.6	160 ± 16.6	0.10; 0.34	0.05*; 0.49	0.24; 0.20
Impulse relative to body mass (m·s^{-1})						
$IMP_{AP(BM)}$						
5 m	0.63 ± 0.08	0.63 ± 0.08	0.62 ± 0.08	0.62; 0.04	0.18; 0.13	0.25; 0.17
10 m	0.37 ± 0.05	0.37 ± 0.05	0.36 ± 0.05	0.24; 0.13	0.06; 0.23	0.53; 0.10
20 m	0.19 ± 0.03	0.17 ± 0.03	0.17 ± 0.03	0.11; 0.47	0.01; 0.63	0.67; 0.14
30 m	0.11 ± 0.02	0.12 ± 0.03	0.10 ± 0.03	0.90; 0.04	0.01*; 0.72	0.02*; 0.67
$IMP_{P(BM)}$						
5 m	0.68 ± 0.07	0.68 ± 0.07	0.68 ± 0.08	0.20; 0.10	0.92; 0.01	0.48; 0.10
10 m	0.44 ± 0.04	0.44 ± 0.04	0.44 ± 0.05	0.62; 0.05	0.20; 0.14	0.51; 0.09
20 m	0.33 ± 0.03	0.33 ± 0.03	0.33 ± 0.03	0.65; 0.07	0.54; 0.07	0.97; 0.00
30 m	0.28 ± 0.02	0.29 ± 0.02	0.28 ± 0.02	0.03*; 0.43	0.24; 0.16	0.13; 0.28
$IMP_{B(BM)}$						
5 m	-0.05 ± 0.01	-0.05 ± 0.01	-0.06 ± 0.02	0.23; 0.31	0.04; 0.67	0.23; 0.46
10 m	-0.07 ± 0.01	-0.08 ± 0.01	-0.08 ± 0.01	0.41; 0.29	0.04; 0.70	0.53; 0.36
20 m	-0.15 ± 0.01	-0.16 ± 0.01	-0.17 ± 0.01	<0.01*; 1.35	<0.01*; 1.97	0.27; 0.37
30 m	-0.17 ± 0.02	-0.17 ± 0.02	-0.19 ± 0.02	0.17; 0.34	<0.01*; 1.05	0.02*; 0.66
$IMP_{V(BM)}$						
5 m	2.26 ± 0.18	2.33 ± 0.12	2.33 ± 0.15	0.07; 0.42	0.01*; 0.42	0.84; 0.04
10 m	2.21 ± 0.18	2.26 ± 0.16	2.31 ± 0.14	0.06; 0.29	0.01*; 0.62	0.01*; 0.33
20 m	2.30 ± 0.16	2.37 ± 0.14	2.38 ± 0.17	0.01*; 0.53	<0.01*; 0.51	0.78; 0.04
30 m	2.22 ± 0.11	2.28 ± 0.11	2.33 ± 0.14	0.13; 0.55	0.04*; 0.92	0.11; 0.43

IMP_{AP} = net anterior posterior impulse; IMP_{P} = propulsive impulse; IMP_{B} = braking impulse; IMP_{V} = vertical impulse; * = significant post-hoc comparison ($p \leq 0.05$) coinciding with a significant main test effect.

Table 3. Mean and standard deviation for time, distance, velocity, percent of maximal velocity and the step number used at each distance of interest for the unloaded, thigh, 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 max toe-off velocity (%)
5 m	**U**	3 (n = 2), 4 (n = 8), 5 (n = 1)	1.27 ± 0.07	4.96 ± 0.43	6.47 ± 0.31	69.5 ± 2.10
	T		1.28 ± 0.09	5.00 ± 0.44	6.45 ± 0.27	70.6 ± 2.61
	S		1.29 ± 0.08	5.00 ± 0.39	6.40 ± 0.28	71.1 ± 2.28
10 m	**U**	6 (n = 2), 7 (n = 7), 8 (n = 2)	1.98 ± 0.09	9.94 ± 0.44	7.79 ± 0.30	83.7 ± 1.25
	T		1.99 ± 0.09	9.91 ± 0.40	7.70 ± 0.28	84.4 ± 1.32
	S		2.00 ± 0.09	9.91 ± 0.37	7.64 ± 0.30	84.9 ± 1.70
20 m	**U**	11 (n = 2), 12 (n = 4), 13 (n = 3), 14 (n = 2)	3.21 ± 0.13	20.1 ± 0.42	8.87 ± 0.36	97.1 ± 1.64
	T		3.23 ± 0.14	20.1 ± 0.54	8.70 ± 0.32	95.3 ± 0.94
	S		3.26 ± 0.15	20.1 ± 0.46	8.64 ± 0.37	96.0 ± 1.00
30 m	**U**	16 (n = 2), 17 (n = 4), 18 (n = 3), 19 (n = 2)	4.33 ± 0.17	30.2 ± 0.65	9.23 ± 0.39	99.1 ± 0.39
	T		4.39 ± 0.15	30.3 ± 0.46	9.07 ± 0.37	99.4 ± 0.27
	S		4.42 ± 0.17	30.2 ± 0.26	8.95 ± 0.43	99.5 ± 0.37

U = unloaded condition, T = thigh condition, S = shank condition

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

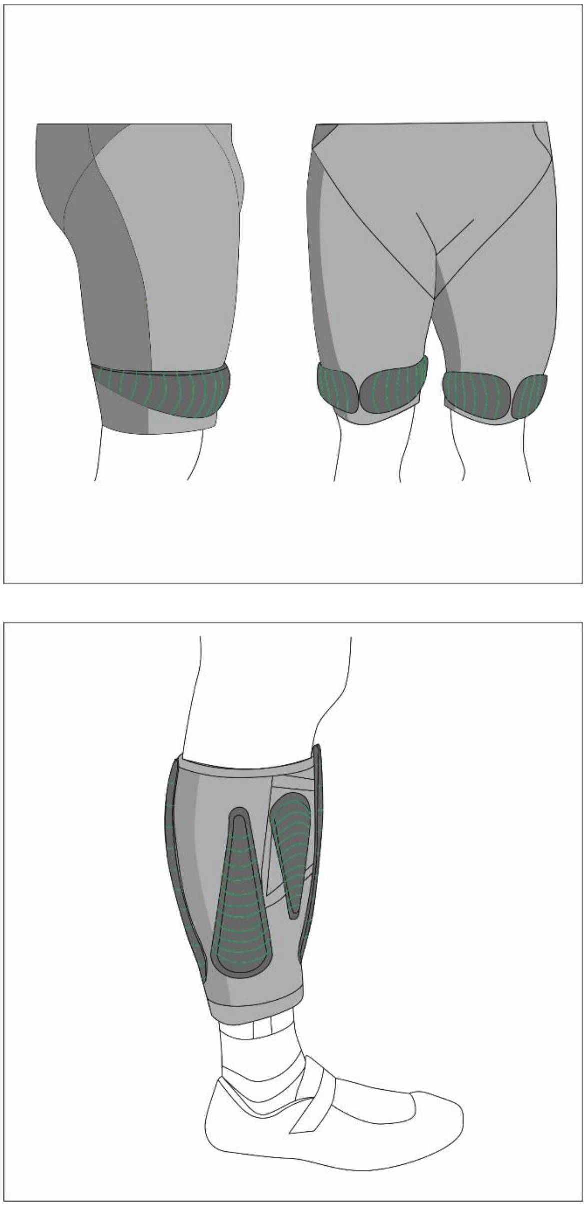


Figure 2. Absolute change in horizontal force-velocity mechanical variables from the unloaded condition with thigh (black) and shank (grey) wearable resistance for each participant. Dashed lines indicate the smallest worthwhile change threshold (± 0.20 × unloaded condition between-subject standard deviation). $F_{0(BM)}$ = theoretical maximal horizontal force relative to body mass; $P_{max(BM)}$ = peak power relative to body mass; V_0 = theoretical maximal velocity; and D_{RF} = index of force application.

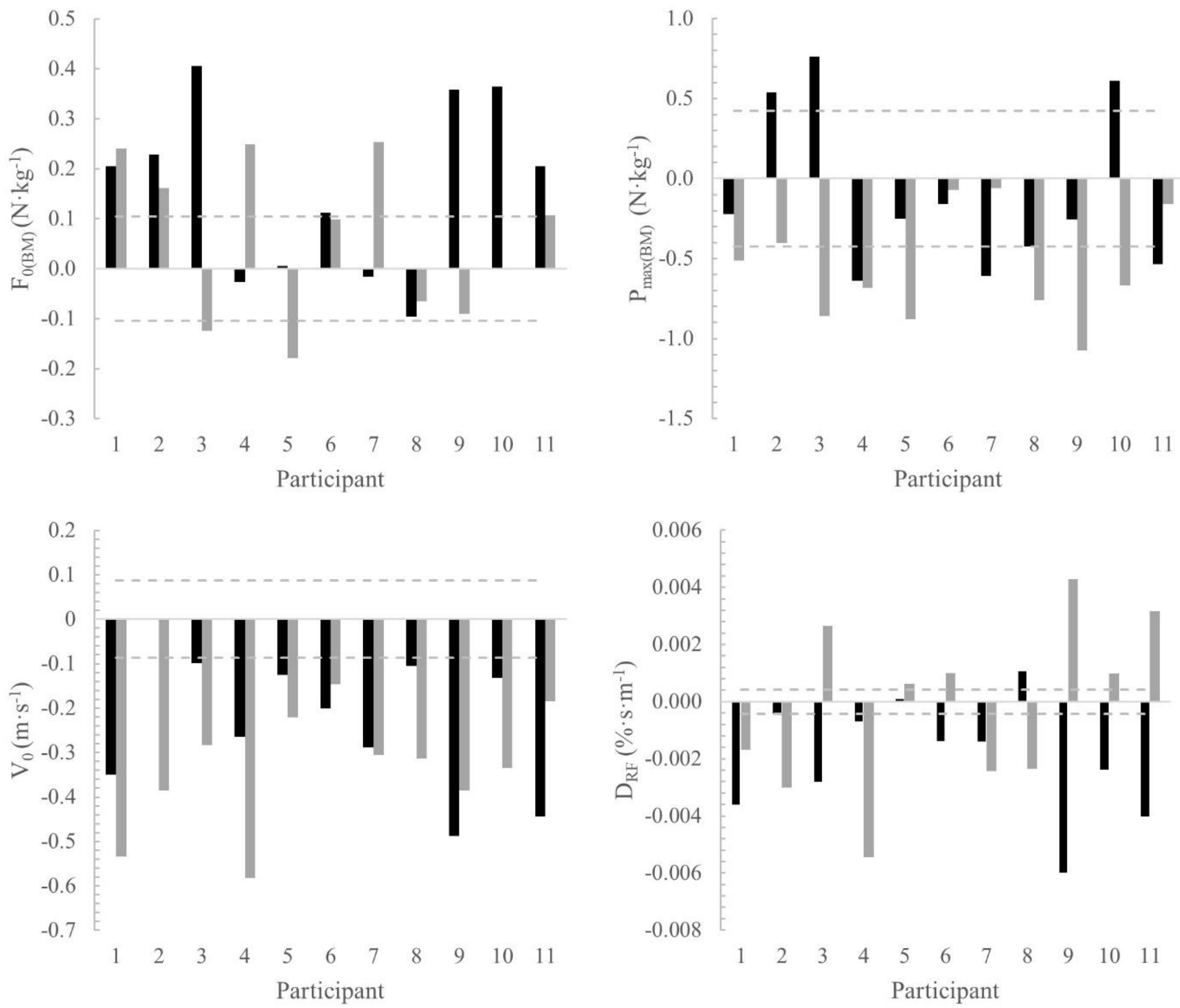
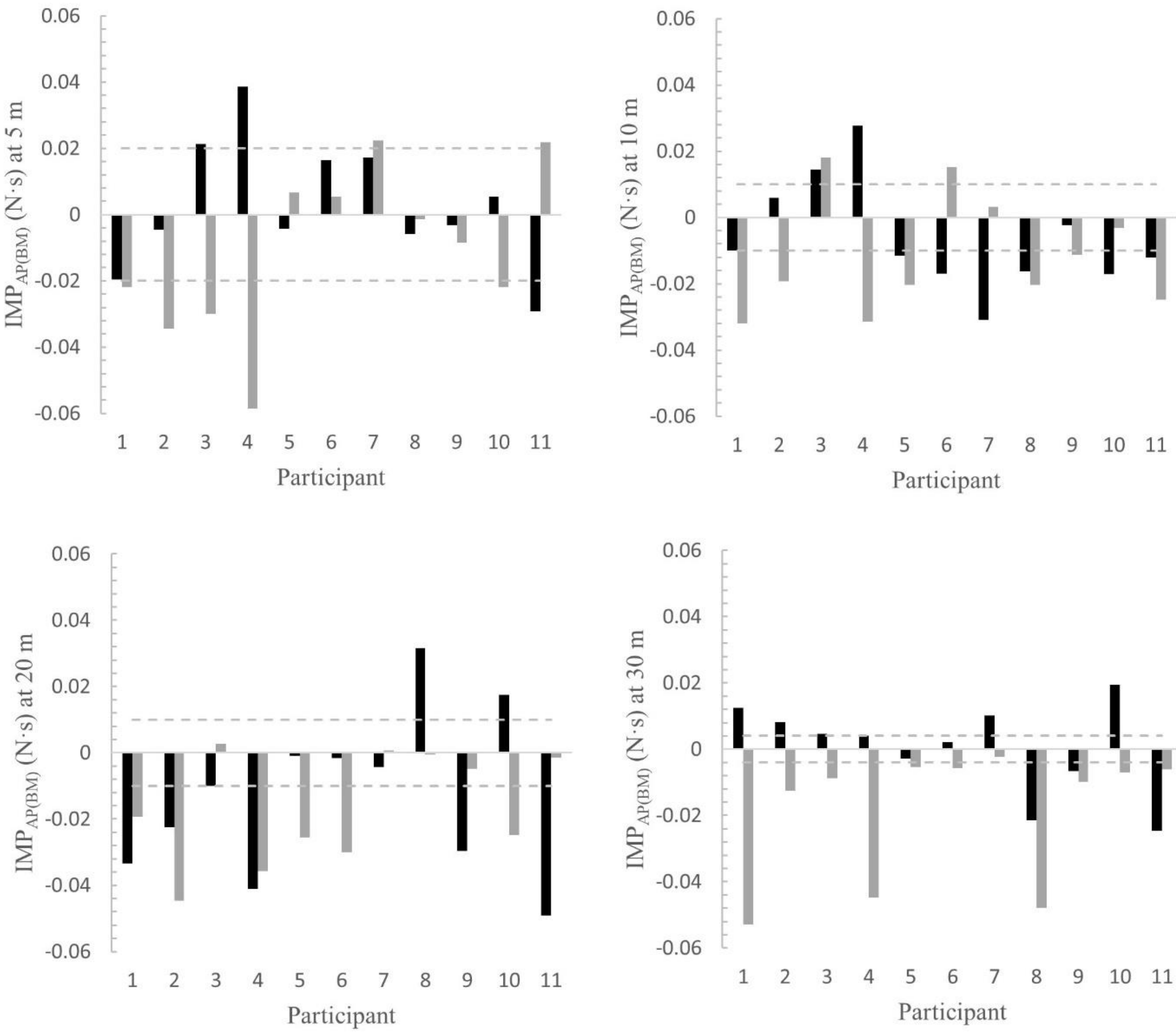
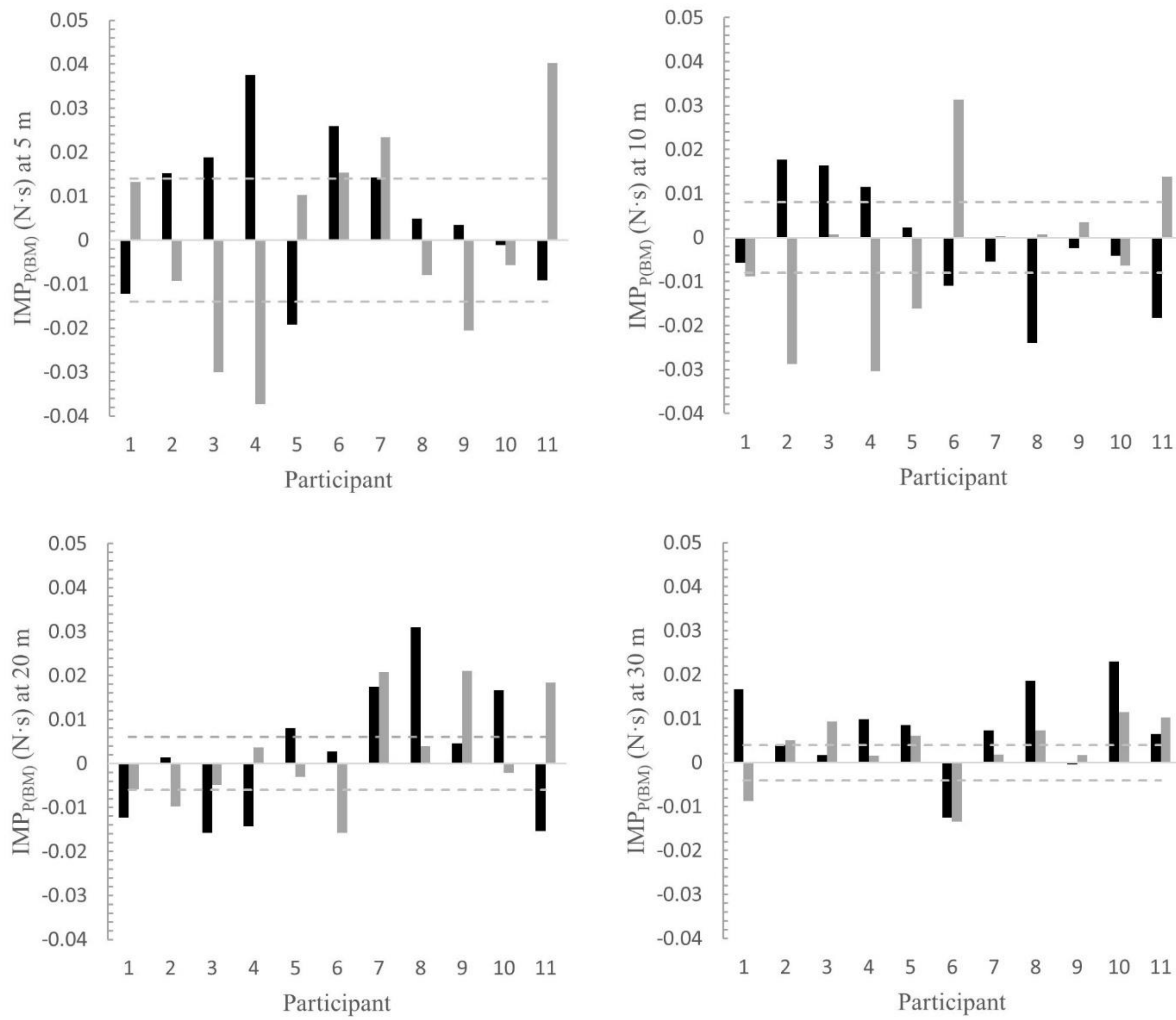


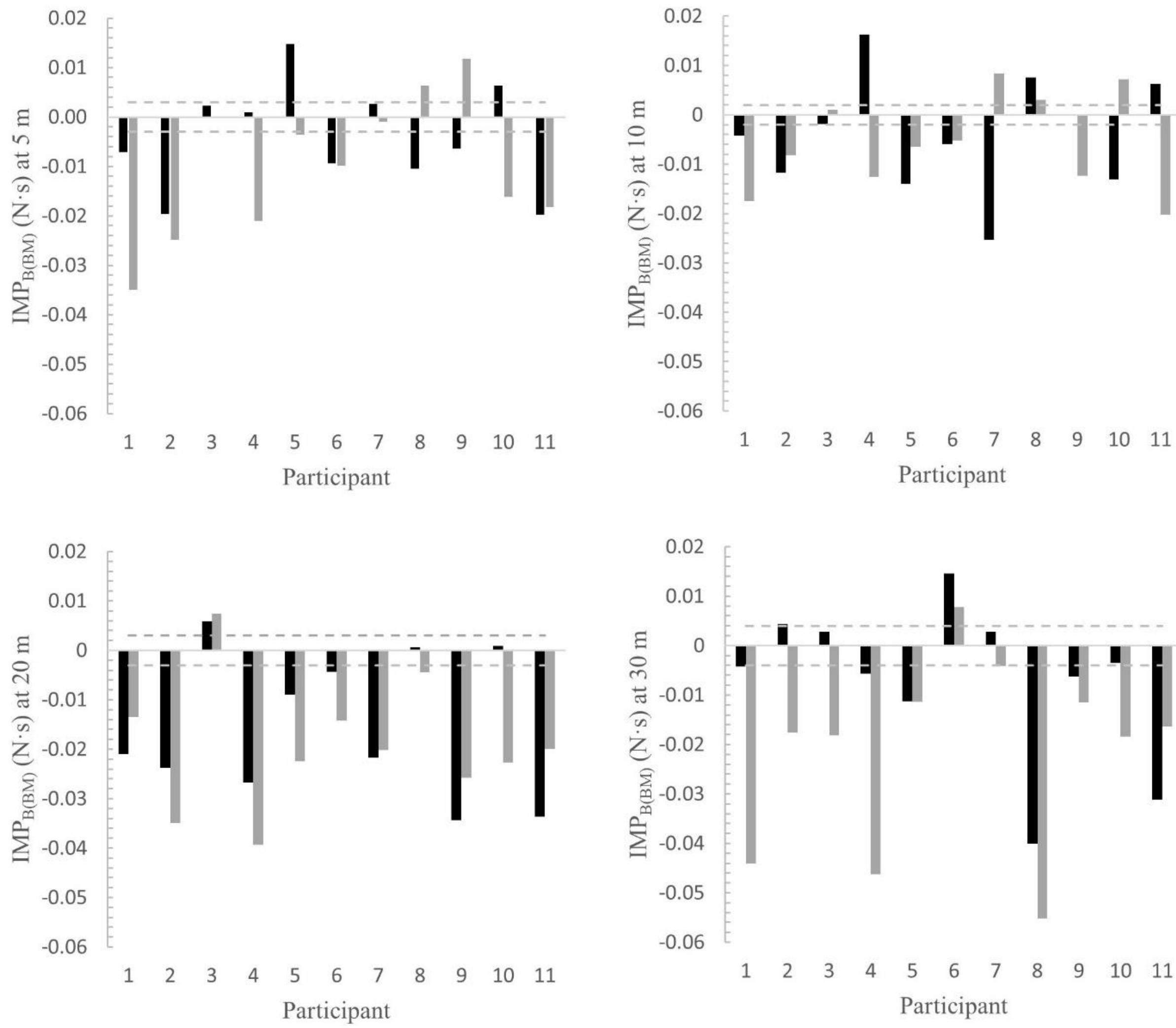
Figure 3. Absolute change in relative anterior-posterior impulse from the unloaded condition with thigh (black) and shank (grey) wearable resistance for each participant at each distance-matched step (5, 10, 20, and 30 m). Dashed lines indicate the smallest worthwhile change threshold (± 0.20 × unloaded condition between-subject standard deviation). IMP_{AP} = net anterior-posterior impulse.



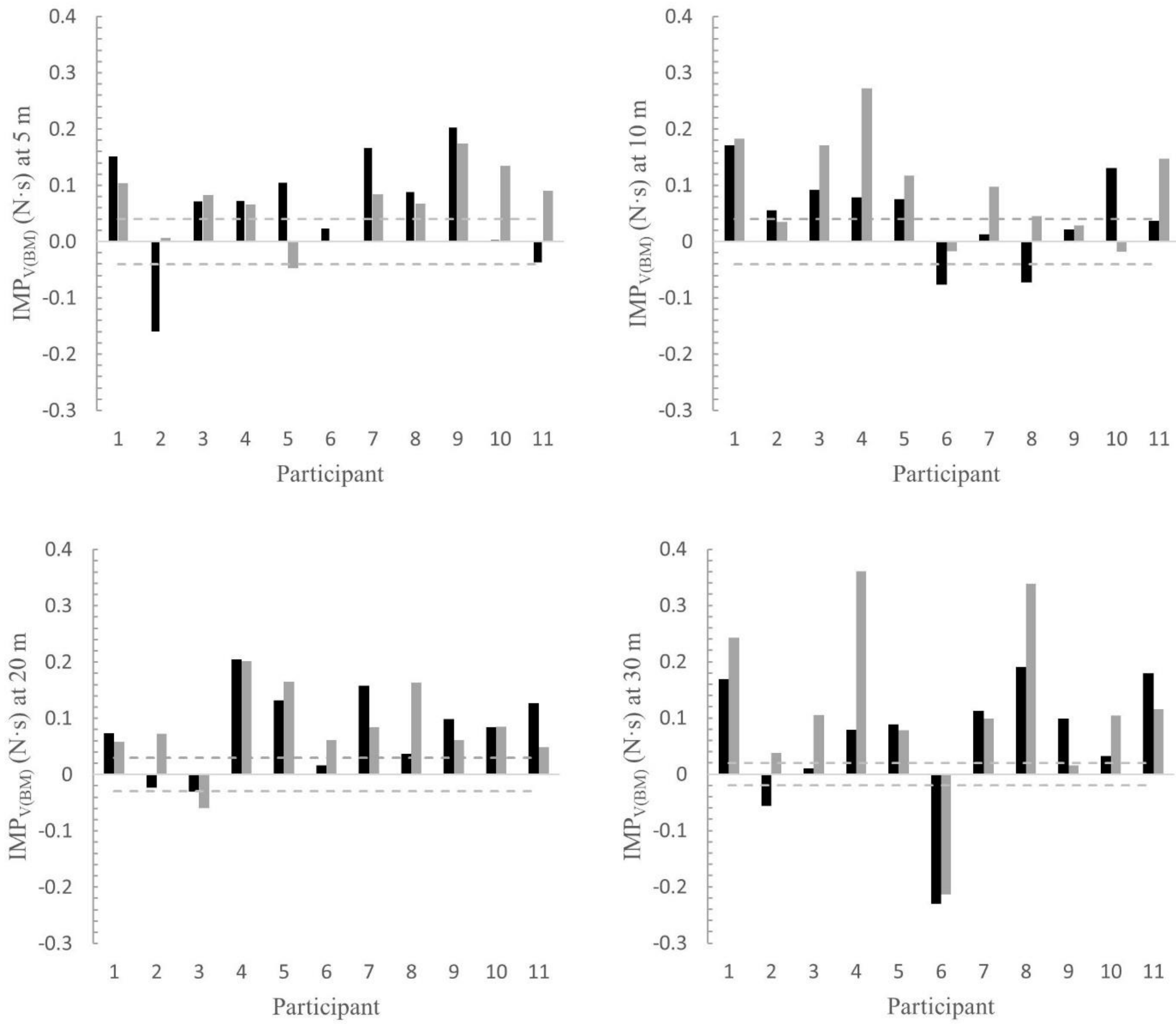
APPENDIX A. SUPPLEMENTARY MATERIAL

Figure 4. Absolute change in propulsive (A), braking (B), and vertical (C) impulse from the unloaded condition with thigh (black) and shank (grey) wearable resistance for each participant at each distance-matched step (5, 10, 20, and 30 m). Dashed lines indicate the smallest worthwhile change threshold (± 0.20 × unloaded condition between-subject standard deviation). IMP_P = propulsive impulse; IMP_B = braking impulse; IMP_V = vertical impulse.





IMPB(BM) (N·s) at 5 m
IMPB(BM) (N·s) at 10 m
IMPB(BM) (N·s) at 20 m
IMPB(BM) (N·s) at 30 m
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
1 2 3 4 5 6 7 8 9 10 11
Participant



0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
IMP$_{V(BM)}$ (N·s) at 5 m
1 2 3 4 5 6 7 8 9 10 11
Participant
IMP$_{V(BM)}$ (N·s) at 10 m
IMP$_{V(BM)}$ (N·s) at 20 m
IMP$_{V(BM)}$ (N·s) at 30 m

515