# Changes in sprint performance and sagittal plane kinematics after heavy resisted sprint training in professional soccer players

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**Background.** Sprint performance is an essential skill to target within soccer, which can be likely achieved with a variety of methods, including different on-field training options. One such method could be heavy resisted sprint training. However, the effects of such overload on sprint performance and the related kinetic changes are unknown in a professional setting. Another unknown factor is whether violating kinematic specificity via heavy resistance will lead to changes in unloaded sprinting kinematics. We investigated whether heavy resisted training (HS) affects sprint performance, kinetics, sagittal plane kinematics, and spatiotemporal parameters in professional soccer players. **Methods.** After familiarization, training-induced changes in sprint split-times and force-velocity-profiles were computed before and after a nine-week protocol. Out of the two recruited homogenous soccer teams (N = 32, age: 24.1 ± 5.1 years: height: 180 ± 10 cm; body-mass: 76.7 ± 7.7 kg, 30-meter split-time: 4.63 ± 0.13 s), one was used as a control group continuing training as normal with no systematic non-specific acceleration training (CON, N = 13), while the intervention team was matched into two subgroups based on their sprint performance. Subgroup one trained with a resistance that induced a 60% velocity decrement from maximal velocity (N = 10, HS60%) and subgroup two used a 50% velocity decrement resistance (N = 9, HS50%) based on individual load-velocity profiles . **Results.** Both intervention subgroups improved significantly all 0-30-m split times ($p < 0.05$, d = -1.25; -0.62), however, the 0-5-m split time improvement remained under the minimal detectable change. Post-hoc showing HS50% improving significantly compared to CON in 0-10-m split (d = 1.03) and peak power (d = 1.16). Initial maximal theoretical horizontal force capacity and sprint FV-sprint profile properties showed a significant moderate relationship with F*0* adaptation potential ($p < 0.05$). Within-group spatiotemporal analysis showed that HS50% increased maximal velocity step rate ($p < 0.05$, $d = 1.50$), however, the improvement remained under the minimal detectable change . No differences in sprinting kinematics were observed. **Conclusion.** With appropriate coaching, heavy resisted sprint training could be one pragmatic option to assist improvements in sprint performance without adverse changes in sprinting kinematics in professional soccer players. Assessing each player's initial individual sprint FV-profile may assist in predicting adaptation potential. More studies are needed that compare heavy resisted sprinting in randomized conditions.

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# Abstract

**Background.** Sprint performance is an essential skill to target within soccer, which can be likely achieved with a variety of methods, including different on-field training options. One such method could be heavy resisted sprint training. However, the effects of such overload on sprint performance and the related kinetic changes are unknown in a professional setting. Another unknown factor is whether violating kinematic specificity via heavy resistance will lead to changes in unloaded sprinting kinematics. We investigated whether heavy resisted training (HS) affects sprint performance, kinetics, sagittal plane kinematics, and spatiotemporal parameters in professional soccer players. **Methods.** After familiarization, training-induced changes in sprint split-times and force-velocity-profiles were computed before and after a nine-week protocol. Out of the two recruited homogenous soccer teams (N = 32, age: 24.1 ± 5.1 years: height: 180 ± 10 cm; body-mass: 76.7 ± 7.7 kg, 30-meter split-time: 4.63 ± 0.13 s), one was used as a control group continuing training as normal with no systematic non-specific acceleration training (CON, N = 13), while the intervention team was matched into two subgroups based on their sprint performance. Subgroup one trained with a resistance that induced a 60% velocity decrement from maximal velocity (N = 10, HS60%) and subgroup two used a 50% velocity decrement resistance (N = 9, HS50%) based on individual load-velocity profiles. **Results.** Both intervention subgroups improved significantly all 0-30-m split times ($p < 0.05$, d = -1.25; -0.62), however, the 0-5-m split time improvement remained under the minimal detectable change. Post-hoc showing HS50% improving significantly compared to CON in 0-10-m split (d = 1.03) and peak power (d = 1.16). Initial maximal theoretical horizontal force capacity and sprint FV-sprint profile properties showed a significant moderate relationship with F*0* adaptation potential ($p < 0.05$). Within-group spatiotemporal analysis showed that HS50% increased maximal velocity step rate ($p < 0.05$, d = 1.50), however, the improvement remained under the minimal detectable change. No differences in sprinting kinematics were observed. **Conclusion.** With appropriate coaching, heavy resisted sprint training could be one pragmatic option to assist improvements in sprint performance without adverse changes in sprinting kinematics in professional soccer players. Assessing each players initial individual sprint FV-profile may assist in predicting adaptation potential. More studies are needed that compare heavy resisted sprinting in randomized conditions.

Keywords: strength, resistance training, horizontal force, velocity-based training, technique

# Introduction

Sprinting performance has been shown to be effective in distinguishing different levels of soccer players [1,2]. Accordingly, it makes sense that there exists an interest in finding optimal methods to improve sprint performance in high level settings[1]. This likely also explains the fact that articles on soccer and sprinting have increased exponentially in the last two decades [3]. However, there still seems to be a lack of sprint performance intervention articles, especially in professional settings. Therefore, researching the usefulness of different training options for sprint performance enhancement within a professional soccer setting seem warranted.

One option that may provide a beneficial stimulus for sprint performance is resisted sprint training [4–12]. Different forms of resisted sprint training have been used with the aim to improve sprint performance by overloading different parts of the sprint acceleration phase, both from a intermuscular coordination and structural standpoint [12]. Recently, there has been a growing interest in exploring the value of heavy resistance in assisting improvements in sprint performance[6–8]. Based on the available literature, a definitive definition for heavy resisted sprinting does not seem to exist. One definition for heavy resistance could be that it prioritizes within moderation overloading kinetic properties (force application) over kinematic specificity (technical similarity) [12]. Thus, this would be considered "specific traditional overload" [13]. According to cross-sectional biomechanical studies, this corresponds to all loads clearly decreasing maximal velocity capacity more than 10% [14]. This has also been reported to be around a less accurate measure of 7.5-15% of body mass (BM), a method that is highly biased towards frictional components and does not consider the relative strength of the athlete [15]. The idea behind heavy loading is to focus on the early acceleration phase of the Force-Velocity (FV) spectrum. Thus from a kinetic standpoint, the focus is on highly overloading the horizontal component of the resultant ground reaction force vector [6,16,17]. This stimulus could affect to different degrees both mechanical effectiveness of the ground force orientation during the step (i.e. what ratio of anterior-posterior and vertical forces is the resultant force built upon) and absolute force output, which could lead to improved sprint performance. Interventions with heavy loads have shown mixed results, possibly to some degree due to different methodology. Three studies showed positive effects on early sprint performance [4–6], another showed split time improvements between 10-30 m, while instead a lighter load group improved also at 0-20 m [7], and one study showed trivial to small effects on performance from both heavy and light resisted sprinting [8]. Evident methodological differences include large differences in what is considered heavy (range ~20% - 50% velocity decrement), not standardizing each subjects load to a specific velocity decrement (using the less accurate % of BM method) [18], using 1 vs. 2 training sessions per week, initial level and amount of familiarization of subjects, and timing between training completion and post-testing and associated tapering [19]. Limitations have also been discussed, such as not considering each subjects degree of loading needs in terms of initial sprint FV-characteristics in the start of the study [8].

Furthermore, potential negative effects of violating kinematic specificity by using heavy resistance in sprinting have also been discussed in literature [9,10,20]. These discussions have possibly created uncertainty among coaches, with regards to whether such immediate kinematic and spatiotemporal changes would then lead to detrimental long-term transference to unloaded sprinting. One theory is that training with increased loading may lead to excessive trunk lean [10], or create unwanted lower body flexion mechanics [20]. However, only two intervention studies have addressed the long-term effects of resisted sprint training on technique and both using only light resistance (7.5 – 10% velocity decrement), while comparing to a unresisted sprint training group [10,11]. Despite the light loading, both interventions showed that resisted sprint training led to a very slight increase in trunk lean during initial acceleration, while one of the studies showed that even the unresisted group increased trunk lean [11]. Increased trunk lean has been associated with improved force production in the anterior-posterior direction [21], thus making it less clear when it is a unwanted adaptation and whether it is dependent on the training modality. Therefore, one possible explanation for why the unresisted group in Alcaraz et al.[10] did not increase trunk lean could be related to the fact that there was no improvement in early acceleration performance, unlike the unresisted group in Spinks et al. [11]. However, adaptations to kinematics should be carefully interpreted to whether it is a cause or an effect and as such may not be directly related.

Therefore, the aim of this study is to investigate changes in sprint performance and the potential underlying mechanical changes (kinematics, spatiotemporal variables, ground force orientation efficiency, and main kinetic outputs) after integrating two different heavy resisted sprint training loading protocols within a professional soccer setting. The aim of the first heavy load is to follow the same maximal mechanical power parameters as in previous literature, which corresponds to a 50% velocity decrement relative to maximal velocity [8,15,29]. The aim of the second heavy load is to have a slightly higher focus on maximal strength and early acceleration, which corresponds to a 60% velocity decrement. Our first hypothesis was that both heavy loads will improve early split-time sprint performance, with the heavier load being even more effective at early acceleration. Our second hypothesis was that both loads will increase early acceleration center of mass (CM) distance and CM angle at toe-off.

# Materials and methods

## Study design and participants

32 male professional soccer athletes from two teams in the premier division in Finland, volunteered to participate in the study using convenience sampling (age: 24.1 ± 5.1 years: body-height: 180 ± 10 cm, body-mass: 76.7 ± 7.7 kg). Inclusion criteria included being a professional soccer athlete competing within the Finnish Premier soccer league. An exclusion criterion was placed for goalkeepers due to the lower amounts of linear sprinting. No exclusion criterion was placed for age, but under 18-year-old athletes were required to have parental consent. Both teams were in initial pre-season and trained on average of 7-10 sessions per week (which included strength training twice per week) and competed an average of once per week. More detailed scheduling can be found in the supporting information (tables 1-2 in S2 tables). One professional soccer team was used as two intervention groups and the other professional soccer team as a control group. The soccer team selected to function as the control group did not train early or late acceleration separately from sport-specific practice in their pre-season protocol, including no resisted sled training. Therefore, they were instructed to continue training as normal. The intervention team was further randomly matched into two homogenous subgroups in terms of sprint performance with different heavy sled loading schemes. These loading schemes corresponded either to a heavy sled (HS) load that decreased the athlete's maximal velocity by 50% (HS50%) or 60% (HS60%). A total of 15 training opportunities were provided within 9 weeks (Fig 1). Including two training sessions each week was not possible because of the teams scheduling conflicts. This corresponded

to 6 out of 9 weeks including two sessions per week. Furthermore, tapering was initiated on week 10 and continued to week 11 where post testing was performed. Therefore, both the control and intervention group were tested for sprint performance and kinematic changes 11 weeks apart. Testing was performed on the same day of the week (end of the week, after a low intensity day), but one week apart. The intervention groups had the opportunity to complete two weeks of pretesting on sprint performance and technique analysis, while due to scheduling issues, the control group was available for one week of testing. All training and testing sessions were completed inside on artificial turf, with an exception made for post testing, which was performed outside on the same type of artificial turf on the same time and day of the week. Wind conditions were still (1 $m.s^{-1}$) on the outdoor post testing day with a highly similar temperature (14 vs. 15 C). Written informed consent was obtained from all athletes on the first day of familiarization, and approval for this study was granted by the University of Jyvaskyla Ethical Committee and was performed in the accordance with the Declaration of Helsinki.

**Insert figure 1 here**

# Group allocation

Athletes in the intervention soccer team were ordered from the lowest to highest 30-m split times derived during two weeks of familiarization and, thereafter, matched in a pairwise manner into either of the following heavy sled groups: HS50% or HS60% to balance variance. The best 30-m performance was used from the two familiarization weeks. The 0-30-m split time was used as it has a lower measurement error compared to smaller split-times [22], and because it was the maximal split-time distance used in our testing protocol. There was no ordering of the control group, however, the sprint performance was predicted to be similar due to earlier consultation work with the team. The initial aim was to recruit an equal amount of soccer athletes within the control team. However, only 13 were available to volunteer and were considered healthy by the team physiotherapist to perform sprint testing at this point of the early pre-season. The final group size and respective highly homogenous 30-m performance times were the following:

HS60%, N = 10, 4.65 s, CI95%: 4.55; 4.77 vs. HS50%, N = 9, 4.62 s, CI95%: 4.56; 4.69 vs. CON, N: 13, 4.63 s, CI95%: 4.55; 4.70, p = 0.88.

# Testing procedures and data analysis

## Sprint Force-Velocity profile and performance tests

After warm-up, all athletes performed two 30-m maximal sprints from a standing stance start with three minutes of passive recovery between sprints. For the best time trial, sprint performance (split times 0-5,0-10,0-20, and 0-30 m), kinetic outputs and mechanical efficiency were computed pre- and post-training using a validated field method measured with a radar device (Stalker ATS Pro II, Applied Concepts, TX, USA) as reported previously [22–24]. Individual linear sprint Force-Velocity (FV) profiles were then extrapolated to calculate relative theoretical maximal force (*F0:* $N.kg^{-1}$), velocity (*v0*: $m.s^{-1}$), and maximal power (Pmax: *W*.$kg^{-1}$) capabilities in the antero-posterior direction. Despite the use of an approximate measurement of "maximal power", that is only derived from the forward running velocity and the anterior-posterior force, which should be called a pseudo-power [25], we will use the term maximal power output in this study. Mechanical efficiency was calculated based on the maximal ratio of forces (RFmax in %) and the average ratio of forces for the first 10-m (Mean RF on 10-m in %).These RF values are a ratio of the step-averaged horizontal component of the ground-reaction force to the corresponding resultant force, i.e. these values aid the interpretation of mechanical effectiveness with which the ground force is oriented in early acceleration [26]. RFmax depicts the theoretical maximal effectiveness of directing force forwards in the first step of the sprint (within the constraints of sprint running stance, the higher the value of RFmax, the more forward, horizontally-oriented the ground push during the stance phase). Mean RF on 10-m focuses on the same parameter, but is an average of the forward force application effectiveness over the first 10-m.

## Load-velocity tests

The final sled familiarization session was combined with load-velocity testing. Load-velocity tests were completed under one unloaded and 3 loaded conditions with one sprint per load (50%, 75%, 100% of BM) for both HS groups, outlined in previous literature [27]. The load-velocity data was then fit with a least-square linear regression to generate an individualized load-velocity profile for each athlete. Thereafter, the individual load corresponding to a 60% and 50%-velocity decrement of maximal velocity was calculated.

Sled velocity was verified with the radar on the first week of training to be within a 5% range of the targeted velocity. A total of 3 athletes' loads had to be modified with an increase of 2.5-7.5 kg, that were verified again the following week (Final ranges, HS%60: -58.4%, CI95%: -59.4; -57.5, HS50%: -49.4%, CI95%: -51.4; -47.5).

## Sprint spatiotemporal and kinematics assessment

For all FV-profile sprints, video images were obtained at 240 Hz with a smart phone video camera at a HD resolution of 720p (Iphone6, Apple Inc, Cupertino, Ca). The kinematic sprint sequences of interest were the touchdown (first frame the foot was visibly in contact with the ground) and toe-off (first frame the foot had visibly left the ground) across the first extension and three steps of early acceleration and 3 steps in upright sprinting of the sprint using 6 × zoom in Kinovea (v.0.8.15), similar to previous literature [28]. The same leg sequence was analyzed pre-post, with a secondary effort to analyze the sequence as close to the midpoint of the camera as possible. The cameras were placed 9-m perpendicular at the 1.5-m mark and the 22.5-m mark along a 0-30-m line, at a 1.1 m height, allowing approximately a 9-m field of view. 1.5-m was chosen based on that the first three steps have been considered unique to early acceleration [29], taking place within around three meters in this population. Upright mechanics were analyzed at 22.5 m based on that team sport athletes are at around 95% or at maximal velocity at this phase [30].

Furthermore, an additional data analysis was performed in the second week of the study to observe the immediate effects of the resisted sprint training on early acceleration mechanics. The second week was chosen so that the athletes had time to react to the used coaching cues, which are defined in the intervention section. According to our data, sleds at this resistance magnitude reach maximal velocity around 5-m, therefore going into a velocity maintenance phase for the remaining meters (~10-m for HS60%, ~15-m for HS50%). Thus, this was considered the main stimuli zone for each sprint, and therefore, it was used to compare to early acceleration of the unloaded sprint. This was done by having the sled sprint start 5-m before the calibration zone for unloaded early acceleration.

All filming zones were calibrated to a 5-m horizontal distance along the midpoint of the camera at the line. The human body was modelled as 18 points. This required manual digitization of the following: vertex of the head, halfway between the suprasternal notch and the 7th cervical vertebra, shoulder, elbow, and wrist joint centers, head of third metacarpal, hip, knee, and ankle joint centers, and the tip of the toe.

The following spatiotemporal and kinematic step characteristics were determined after exporting the digitalized coordinates to Excel (Microsoft Office 2016): contact time (s), step length (m; horizontal displacement between initial contact of one foot and the point of initial contact of the opposite foot, measured from the toe tips), and step rate (Hz; calculated as 1/step time, where step time was determined as the sum of contact time and the subsequent aerial time). Whole-body center of mass (CM) location was calculated using de Leva's et al. [31] segmental data. This allowed for the calculation of touchdown and toe-off distances (m; horizontal distance between the toe and the CM, with positive values representing the toe ahead of the CM). Furthermore, angles of the trunk (relative to the horizontal) and the hips (ipsilateral and contralateral) were quantified. All distances of CM were normalized to the height of the athlete and reported as (m/body length) [28]. All sprints were analyzed twice to improve reliability with the digital marker method.

# Intervention

Training protocols are outlined in Figure 1. Familiarization within the intervention group for sled training was initiated two weeks before the training intervention and was combined with the sprint Force-Velocity (FV)-profile tests (2x30 m sprints), including group allocation based on sprint performance. A load of 80% of BM (2 x 15 m sprints) was selected for familiarization. A total of 15 heavy resisted sprint training session opportunities were planned within 9 weeks and an additional two-week taper (two sessions total) across the 11-week pre-season. This 11-week interval included a break week in the form of an international training camp. Therefore, resisted sprint training sessions were, in general, twice per week, transitioning from a total of six resisted sprints per week up to eight at the midway point (week 5). All training sessions included 20-m free sprints, which were in the start of the program two per session, transitioning to one free sprint per session after the midway point. All athletes were harnessed at their waist, using the 21 kg sprint sleds (DINOX, customized sled, Finland). To standardize the stimuli between athletes within both intervention subgroups, a velocity-based training approach was utilized, where all athletes used a load that adapted their velocity to the desired threshold. In this case HS60% used a load leading to a 60% velocity decrement from maximal velocity and HS50% used a load leading to a 50% decrement from maximal velocity. The 50% load was chosen to simulate power properties as it has been shown that external maximal power is reached approximately at 50% of maximal velocity in a maximal acceleration sprint [27]. The heavier 60% velocity decrement load was chosen with the aim to stay within proximity to the 50% load but stimulate more maximal strength properties, thus an even higher bias towards early acceleration. On the artificial training surface, this 10% velocity difference corresponded to the average relative mass of 120% of BM in the HS60% group and 94% of BM in the HS50% group (including the mass of the sled), equating to a group average difference of 26 kg. A sled sprint distance of 0-15-m for the HS60% group and 0-20-m for the HS50% group was used to standardize time under tension (HS60%: 4.26 s, CI95%: 3.74; 4.77, HS50%: 4.73 s, CI95%: 4.39; 5.08, $p = 0.15$). Training was supervised by the team strength and conditioning coach and completed after the warm-up for technical and/or tactical training on field. Pre-training warm-up (~15min) included light running, dynamic full-body stretches, muscle and dynamic movement pattern activation, and low to high intensity sprint exercises. Between-sprint rest was three minutes. Both groups were given the same coaching cues, that is, prioritizing stride power (or push) over stride frequency and high arm movement with aligned posture. Finally, post testing was completed at the end of a two-week tapering period, by reducing the modality specific volume down from eight sprints a week to two, with one session of two free sprints per week.

## Statistical analysis

Normality of the data was ensured using Shapiro-Wilk’s test of normality. Levene's test was used to examine the homogeneity of variance for variables of interest.

To answer the question whether sled training was statistically different from control, a one-way between subjects ANCOVA was calculated to examine the effect of sled training as a whole (HS, irrespective of load) vs. no sled training (CON) on sprint performance while controlling for the effect of initial sprint performance (covariate in ANCOVA model). Thereafter, post-hoc testing with a 3-group one-way ANCOVA was used to verify whether the specific sled stimulus (HS60% vs HS50%) was statistically different from control. Sprint performance was defined mechanically (Pmax, F*0*, RFmax, Mean RF on 10-m, v*0*, and Sprint FV-profile), by split-times (5-m,10-m,20-m, and 30-m), spatiotemporally (contact time, step rate, step length at initial acceleration and maximal velocity) and kinematically (hip angle, trunk angle, CM distance). Independent and paired two-tailed t-tests were used to examine between sled group and within group differences. For each individual the sprint with the best 30-m time within pre and post testing was compared statistically for both mechanical-, split times- and sprint technique variables.

All above mentioned tests were performed using SPSS software version 22.0 (SPSS Inc., Chicago, IL, USA). Effect sizes (ES) were calculated using pooled SD using a custom spreadsheet allowing interpretation of our data against Hopkins' benchmarks to assign small (≥ 0.2), moderate (≥ 0.6), large (≥ 1.2) effects [32]. In the effort to account for normal fluctuations in athletes' weekly sprint performance and sprint technique during the season, minimum detectable change (MDC) at a 95% confidence interval was calculated as Typical Error (TE) • $1.96\sqrt{2}$ from the difference in best performance sprint FV-profile variables completed during pre-test week -1 and 0. The MDC% was defined as $(MDC/\bar{X}) \cdot 100$. Test-retest reliability for each variable analyzed was assessed by intraclass correlation coefficient (ICC), coefficient of variation (CV%), TE with 95% confidence intervals, and MDC, using Hopkins spreadsheet [33]. ICCs were defined as poor (ICC < 0.40), fair ($0.40 \leq ICC < 0.60$), good ($0.60 \leq ICC < 0.75$), and excellent ($0.75 \leq ICC \leq 1.00$). Alpha was set at $p < 0.05$. Descriptive data are presented as mean ± standard deviation (SD).

# Results

A total of four subjects could not complete the required pre post measurements. Due to sustaining a flu, one athlete within the HS60% group could not perform final testing, making a total of nine out of 10 subjects completing the protocol. Due to injuries, three subjects in the control group could not participate in the post testing, making a total of 10 subjects measured. Furthermore, although participating in the sprint performance measurements, there was one camera malfunction during the HS50% group post-testing, leading to a loss of pre-post kinematics of one subject.

Out of 15 possible sessions, within the 9-week window the HS60% completed an average of 10.6 (CI95%: 9.57; 11.54), while HS50% completed an average of 10.3 (CI95%: 9.30; 11.37). For HS60%, this corresponded to a resisted sprint volume of 38.2 (CI95%: 35.5; 40.9) and for HS50% 37.4 (CI95%: 34.2; 40.7), $p = 0.72$.

## Group Characteristics at Baseline

All variables were normally distributed. At baseline population variance was not significantly different for any variables, including age, height, mass, kinetic and kinematic variables ($p > 0.09$), with all split-times being highly similar (Table 1, $p > 0.55$).

## Reliability

All reliability statistical values can be found in supporting information (tables 1-8 in S1 tables), including MDC%, TE, CV% and ICC. For the sprint FV-profile and performance variables, within and between session ICC ranged from good – to excellent (0.60 – 0.98, CI95%: -0.09; 0.99), except for sprint FV-profile slope and mean RF on 10-m, showing poor between session reliability (0.23 - 0.49, CI95%: -0.33; 0.89). For the spatiotemporal and kinematic variables, within and between session ICC ranged from fair to excellent (0.41 – 0.99, CI95%: 0.03; 0.99), except for maximal velocity contact time, showing poor between-session reliability (0.34, CI: -0.37; 0.80).

## Between and within group statistics

### Body mass

No significant differences were found at baseline and pre and post for BM in the 3 groups ($p > 0.05$).

## Sprint Split-times

All descriptive and inferential statistics for sprint performance can be found in table 1 and visualized in Figure 2. The two group one-way ANCOVA indicated a main effect for the following sprint performance variables significantly decreasing in the HS group compared to the CON group: 10 m ($p = 0.01$, $F(1, 25) = 7.57$, $d = 1.16$), and 20 m ($p = 0.04$, $F(1, 25) = 4.47$, $d = 0.88$), after controlling for initial values. The three-group one-way ANCOVA with Bonferroni post-hoc test for 10-m split time revealed significant differences between HS50% and CON ($p = 0.03$, $d = 1.03$) but not for 20 m ($p > 0.05$).

Within group t-test comparisons, both HS60% and HS50% groups reached statistical significance for reductions in all 5-30-m split times ($p < 0.04$, $t(8) < -2.54$, $d < -0.61$). However, only 0-10-m, 0-20-m, and 0-30-m split time improvements surpassed the between-session minimal detectable change threshold (Figure 2).

**Insert figure 2 here**

**Insert table 1 here**

## Sprint Force-Velocity profile variables

All within and between group statistics for mechanical variables can be found in table 2 and visualized in Figure 3. The two group one-way ANCOVA indicated a main effect for the following mechanical variables significantly increasing in the HS group compared to the CON group: $F0$ ($p = 0.03$, $F(1, 25) = 5.21$, $d = 1.03$), and Pmax ($p = 0.023$, $F(1, 25) = 5.86$, $d = 1.00$), after controlling for initial values. The three-group one-way ANCOVA with Bonferroni post-hoc test revealed significant differences between HS50% and CON in Pmax ($p = 0.02$, $d = 1.00$) but not for $F0$ ($p = 0.09$). Correlations between mechanical variables can be found in Figure 4.

Within group t-test comparisons, both HS60% and HS50% groups reached statistically greater F*0* ($p < 0.02$, $t(8) < -3.18$, $d > 0.99$), RFmax ($p < 0.01$, $t(8) < -3.392$, $d > 1.00$), and Pmax ($p < 0.003$, $t(8) < -4.35$, $d > 0.87$). All groups reached statistically greater Mean RF on 10-m ($p < 0.03$, $t(9) < -2.64$, $d > 0.64$). However, the F*0* changes (HS60%: 7.83, HS50%: 9.23 %) were under the between-session minimal detectable change threshold (9.53 %).

**Insert figure 3 here**

**Insert figure 4 here**

**Insert table 2 here**

## Sprint kinematic and spatiotemporal variables

*Cross-sectional analysis of immediate effects of sled on early acceleration*

All significant results for immediate effects of sled are visualized in Figure 5. All descriptive and inferential statistics can be found in table 3. Due to timetable issues, 8 out 9 subjects were available for kinematic filming of the sled from the HS60% group and 6 out of 9 from the HS50% group.

Between group t-tests showed no differences ($p > 0.05$). Within group t-test comparisons showed that using the sled led to significant changes in all spatiotemporal variables, with a significant increase in contact time in both groups (HS60%: $p = 0.003$, $t(7) = -4.52$, $d = 2.10$, HS50%: $p = 0.03$, $t(5) = -3.01$, $d = 1.71$), and with a significant decrease in step rate and step length in HS60% ($p < 0.009$, $t(7) > 3.67$, $d > -1.57$) and HS50% ($p < 0.05$, $t(5) > 2.74$, $d > -2.09$). Toe-off CM distance increased significantly only in HS50% ($p = 0.03$, $t(5) = -3.01$, $d = 1.34$), while both sled loads decreased touchdown CM distance (HS60%: $p = 0.003$, $t(7) = -4.48$, $d = 1.99$, HS50%: $p = 0.003$, $t(5) = -5.21$, $d = 3.50$). For CM angle at touchdown, both groups decreased their angle significantly (HS60%: $p = 0.005$, $t(7) = 4.01$, $d = -2.30$, HS50%: $p = 0.005$, $t(5) = 5.14$, $d = -3.00$), while only HS60% decreased significantly Toe-off CM angle ($p = 0.04$, $t(7) = 2.48$, $d = -1.49$). All significant variables were above the between-session minimal detectable change threshold. No other variables reached significance ($p > 0.05$).

**Insert figure 5 here**

**Insert table 3 here**

*Pre-Post intervention changes in kinematic and spatiotemporal variables*

All descriptive and inferential statistics for sprint technique can be found in table 4 and visualized in Figure 6. The two-group one-way ANCOVA (HS vs. CON) found no significant main effects between pre and post sprint kinematic variables for both early acceleration and upright sprinting ($p > 0.05$).

Within group t-test comparisons, the HS50% group reached statistical significance for an increase in maximal velocity step rate ($p = 0.01$, $t(8) = -3.26$, $d = 1.50$). However, the step rate change (HS50%: 4.00%) was under the between-session minimal detectable change threshold (6.60%). All other within group comparisons did not reach significance ($p > 0.05$).

**Insert figure 6 here**

**Insert table 4 here**

# Discussion

The main results of this study were that, although both heavy load conditions (50% and 60% velocity decrement) improved sprint performance in soccer players, the HS50% was the only group showing changes in sprint parameters that were significantly different from CON. A clear favoring towards improvements in early acceleration performance and sprint kinetics were present in both HS50% and HS60% groups, showing moderate to large effect size differences compared to CON. Furthermore, although both loads produced significant immediate changes in early acceleration at toe-off and touchdown, no long-term changes on early acceleration and upright sprint technique were observed that surpassed minimal detectable change based on the 2D analysis. These results suggest that heavy resisted sprinting can be successfully integrated in a professional soccer setting.

Our initial hypothesis was partly met, with heavy resisted sprinting leading to improved early acceleration sprint performance. It is important to mention that the reported 5-m within-group improvements fell under the minimal detectable change threshold and, thus, still could be interpreted as remaining within the measurement error thresholds (Figure 2). This is a logical result based on previous literature on 5-m split time measurements [34]. However, we expected to see differences between loads in improving specific parts of early acceleration sprint performance. Specifically, we expected the HS60% group to mostly improve the 0-5-m split-times, whereas the HS50% group would mostly improve the 0-10-m split times. This is because the first steps of acceleration are considered to be more dependent on maximal force capacity, with its importance reducing with increasing velocity [17,35.] Hence the larger load was thought to provide a higher transfer in this area. However, both heavy loads affected early acceleration performance in a similar manner (Figure 2). Although the HS50% group was the only group to reach significantly lower split times compared to CON and had a large effect size (0-10-m split-time). The most evident reasons for the lack of differences in loads can be a combination of a too small difference in loading parameters and that the total training volume was possibly not high enough.

The underlying kinetic reasons to the performance improvements were also of interest in this study. Therefore, we analyzed the ratio of forces at the first step and over the first 10-m (RFmax and mean RF on 10-m). The analysis showed that when considering initial values, there was a lack of clear difference in effect size between the two ratio of force variables and F*0* compared to the control group. Therefore, it seems that the intervention groups improved both their maximal ground reaction force capacity and their capability to orient this force more horizontally. However, as Pmax was the only kinetic variable to show significant improvements compared to CON (HS50%), the ability to produce higher forces at higher velocities (i.e. maximal mechanical power), seemed to be the main driver for the improved sprint performance. Furthermore, caution should also be considered within the interpretation of mean RF on 10-m, showing poor between-session reliability within this population.

The most important aim of improving sprint performance was met, an essential part in preparing soccer athletes for the season [1,2.] This contradicted previous literature with similar loading parameters. Specifically, the main methodological strengths of this study compared to previous literature was that the present groups were evenly divided based on their initial sprint performance, training was done mostly twice per week instead of once, and tapering was completed [7,8]. Furthermore, in the study by Pareja-Blanco et al. [7] loads were not standardized and individualized to a specific velocity decrement, but rather to body mass (80% of BM). Therefore, one conclusion is that if a time slot of roughly 20 minutes is accepted for velocity-based resisted sprint training within field practice conditions twice per week, it will likely be beneficial, assuming the athlete has been assessed for lacking early acceleration capacity (Figure 4). Furthermore, our results may indicate that heavy loading parameters are not highly sensitive, indicating that staying within a 45-65% velocity decrement is acceptable if sprinting technique is monitored. However, our study did not have a group completing non-resisted sprint training, only a control group completing sport-specific training. Therefore, we do not know if just the mere systematic focus on early acceleration, regardless of load, is enough. Measuring a force-velocity and load-velocity profile for everyone might be an issue for some as there may be time constraints and lack of access to technology. However, this can be done relatively quickly and at a low cost with the help of accurate apps [36], while saving some time with a shorter load-velocity protocol (3 loads: 0, 25 and 75% of BM is sufficient to obtain the linear individual load-velocity profile, see Figure 2 in Cross et al. [8]), although this still needs to be validated.

Our second hypothesis was that both loads would improve early acceleration toe-off CM distance (more triple extension of the body) and CM angle (increased forward body lean). The results showed no changes in the kinematics or any other variables in early acceleration, which is in contrast to previous light load literature showing slight increases in trunk lean [10,11]. However, moderate effect sizes were seen in some early acceleration kinematic parameters, including decreased touchdown CM distance and CM angle in HS50%, corresponding to potentially less time spent in the breaking phase due to contact times not changing. These changes make sense with our cross-sectional sled measurements (Fig 5), as these were the two variables that showed the largest effect sizes for changes in movement. However, we found no relationships between changes in these variables and improvements in sprint performance, thus more accurate methodological approaches and/or larger sample sizes are likely needed for such short interventions. Furthermore, no negative effects of heavy resisted sprinting were observed on either early acceleration or upright sagittal plane sprint kinematics as speculated to some degree by previous literature [9,10,14,20]. This was potentially influenced by the coaching cues used in the current study by helping to maintain good posture.

As an additional observation, our data showed that initial F*0* capacity and sprint FV-profile orientation seems to explain moderately adaptation potential (Fig 4), corresponding to previous literature [37]. Thus, if an athlete already has a high force production capacity, or a force-oriented FV-relationship/profile, it should logically reduce adaptation potential to a high force – low velocity stimulus. This sample size does not allow for clear cut-off thresholds for training, however, a recent study using heavy resisted sprints in high-level rugby players showed nearly identical results. Therefore, an initial F*0* value around 8.4 $N.kg^{-1}$, or a sprint FV-profile lower than -0.95 will likely not respond well to heavy resisted sprint training [37]. Future studies should explore if varying from individualized (velocity decrement) heavy to light loads based on initial FV-qualities is of further value.

*Limitations*

The control group and the intervention groups were two different teams with inevitable differences in their training culture. Therefore, although initial sprint performance was highly homogenous, differences in training and recovery methods may have contributed to the results. Furthermore, inclusion of a control group that performs unloaded systematic acceleration training should be compared in future studies. The 2D motion analysis was only based on two time points, therefore caution is advised in their interpretation and future studies are implored to use more rigorous approaches. We did not have access to a high-resolution slow-motion camera, which likely contributed a couple of variables showing lower reliability. Similar to previous resisted sled training literature our sled study used a single time point method (toe-off, touchdown). A more ideal approach would likely be the analysis of waveforms, such as with the statistical parametric mapping method [38].

# Conclusion

Providing efficient evidence-based options to enhance sprint performance training is crucial for strength and conditioning coaches in high level soccer settings. It seems that in a time span of 11 weeks, one of the underlying reasons for heavy resisted sprint training improving sprint performance is increased force production (both directional and absolute). As this took place in a similar step time, the main driver seems to be improved mechanical power and likely rate of force development. Thus, our findings suggest that heavy resisted sprint training can improve sprint performance in professional soccer players. Based on the average amount of resisted sprints that were conducted during this study, the target should be to achieve at least 38 sprints divided over 2 months, preferably twice per week, including a final taper. After familiarization, this stimulus can be integrated efficiently into field conditions, with a session duration lasting ~20 minutes for the entire team with 4+ sleds. Our results support the assertion that coaches do not have to worry about potential adverse effects on sprint technique if appropriate familiarization, cueing and supervision is used. Furthermore, coaches should be aware that heavy resisted sprint training will very likely not work for the entire team, which can be to some extent predicated by appropriate initial performance tests, including sprint FV-profiling.

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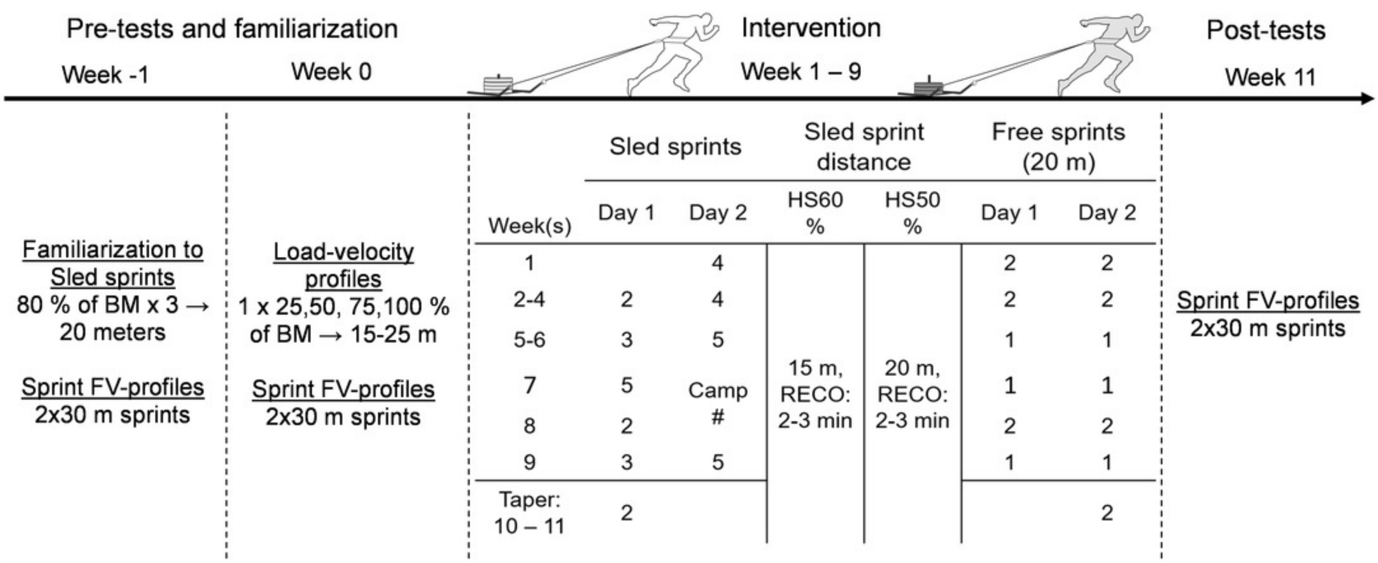
# Figure 1

Training program design

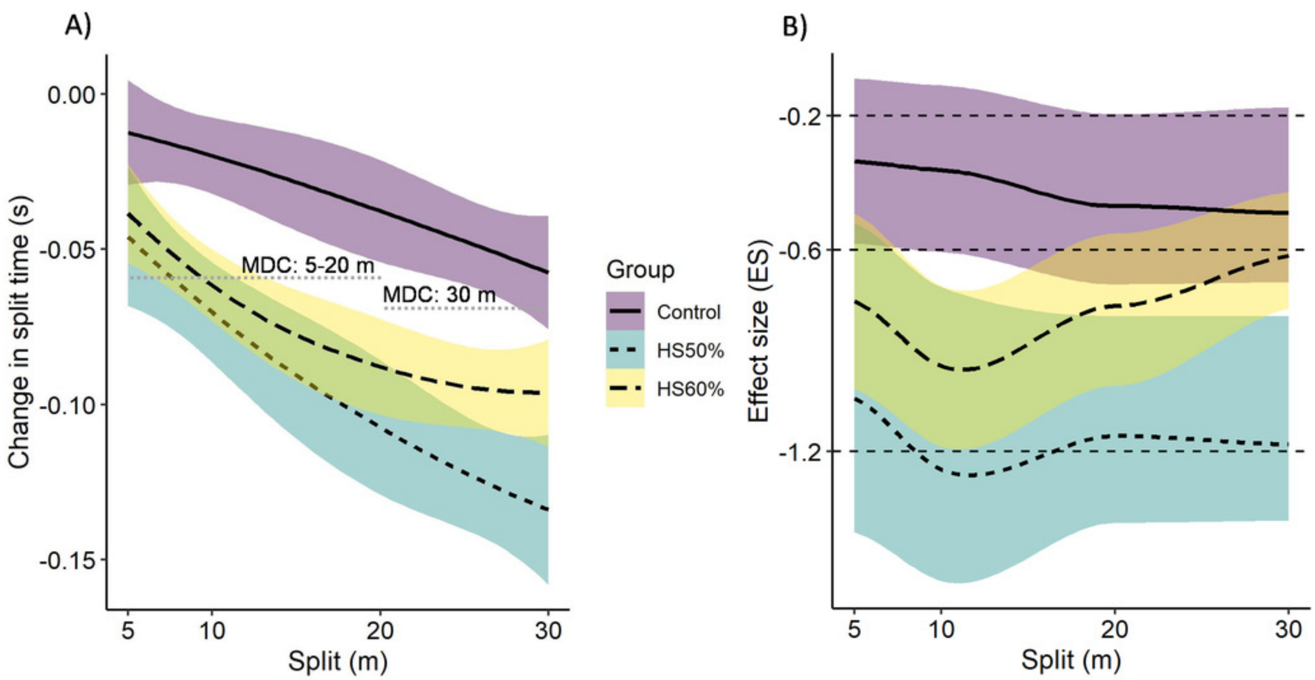
HS: Heavy Sled, *: sled velocity verification was completed on week 1, filming of sled technique on week 2, RECO: recovery time between sprints, m: meters, FV: Force-velocity, #: camp training included two sprints with rubber bands and 2x2 free sprints on separate days.



# Figure 2

Sprint split-time changes.

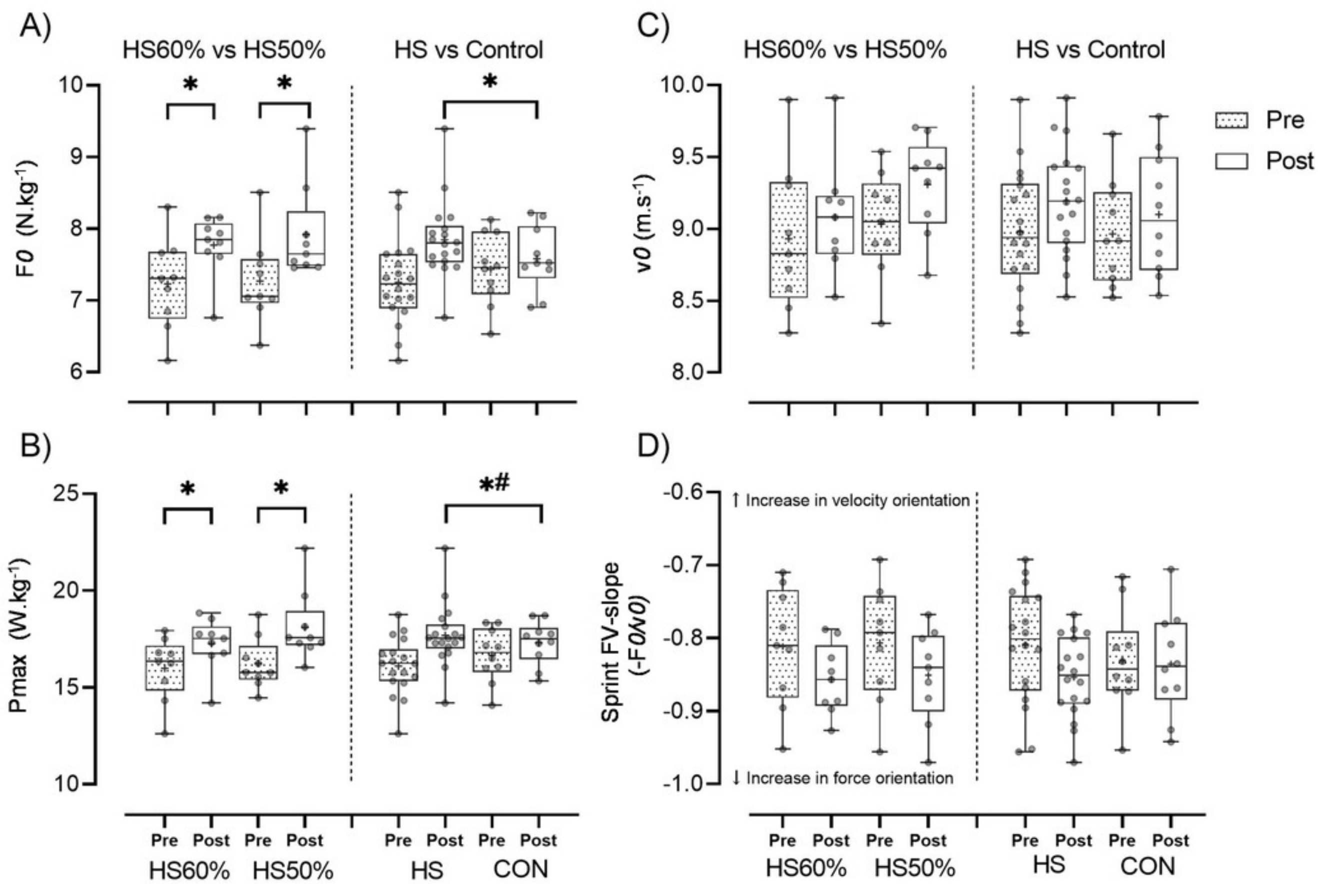
Raw Changes in split time performance with MDC thresholds (A) and their corresponding effect sizes within each group with ES thresholds (B). The lines between the four split-time measurements (0-5, 0-10, 0-20, 0-30) have been smoothed. The error ribbons represent standard error via bias corrected and accelerated bootsrapping at 0.68 confidence intervals, corresponding to +/- 1 standard deviation. HS: Heavy sled, CON: control group, MDC: Minimal detectable change.



# Figure 3

Sprint mechanical variable changes.

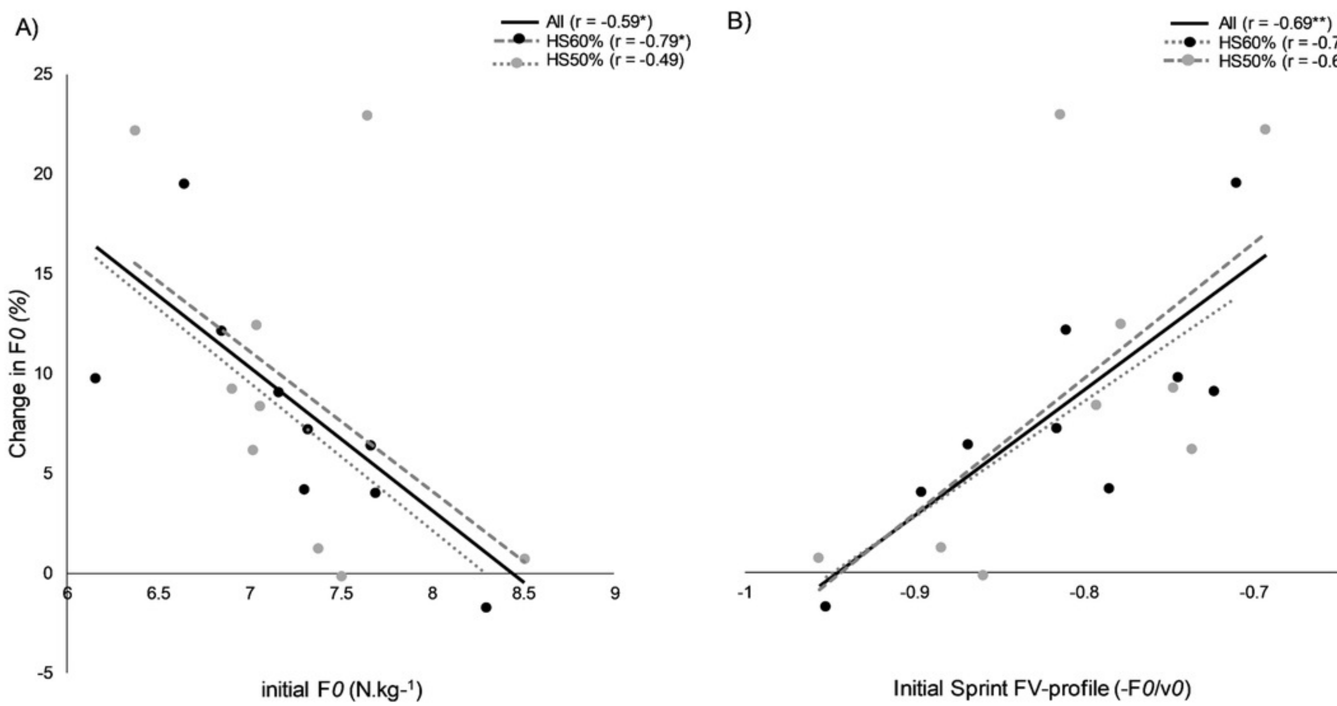
Boxplots of within and between group comparisons for F*0* (A), Pmax (B), v*0* (C), and Sprint FV-profile (D). Sled training is compared for between group statistics both as pooled stimuli and separate stimuli based on % velocity decrement. HS: Heavy sled, CON: Control group, *: p < 0.05, #: significant difference between HS50% and CON, +: mean.



# Figure 4

Mechanical variable correlations.

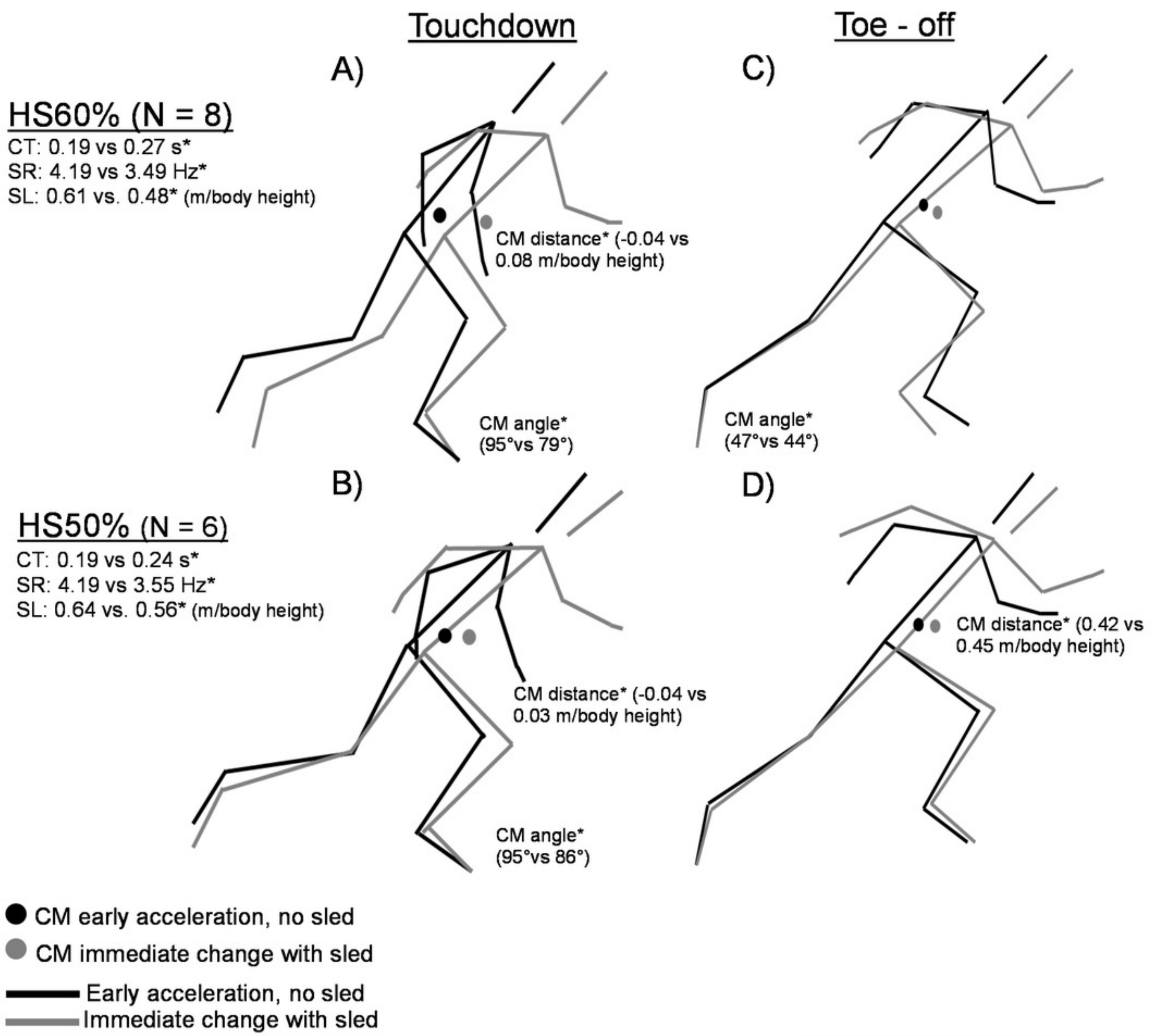
Correlation coefficients between initial values in A) maximal theoretical horizontal force (F*0*) production, B) initial Sprint FV-profile (-F*0*/v*0*), and respective changes post intervention. HS: Heavy sled, CON: control group, *: p < 0.05, **: p < 0.01.



# Figure 5

Sprint kinematic and spatiotemporal changes, immediate effects of sled.

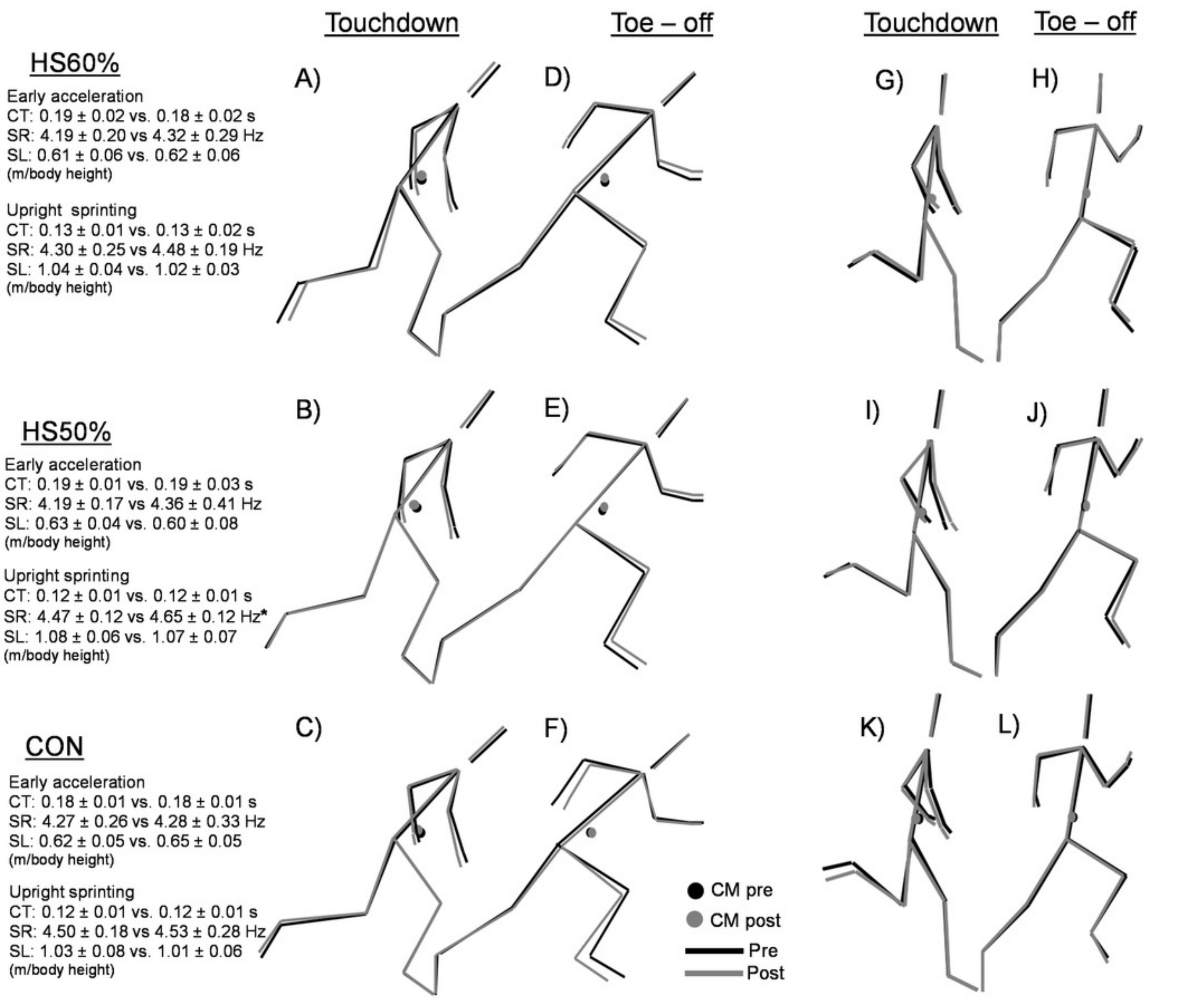
Immediate kinematic and spatiotemporal differences between early acceleration (black) and sled sprinting (gray). Touchdown (A, B) and toe – off (C, D) within HS60% and HS50% groups. Toe-off HS: Heavy sled, CT: Contact time, SR: Step Rate, SL: Step Length relative to body height, CM: Center of Mass, IPSI: Ipsilateral (ground contact leg), m: meter, *: $p < 0.05$. No group differences were found ($p < 0.05$).


Touchdown
Toe - off
A)
HS60% (N = 8)
CT: 0.19 vs 0.27 s*
SR: 4.19 vs 3.49 Hz*
SL: 0.61 vs. 0.48* (m/body height)
CM distance* (-0.04 vs 0.08 m/body height)
CM angle* (95°vs 79°)
C)
CM angle* (47°vs 44°)
B)
HS50% (N = 6)
CT: 0.19 vs 0.24 s*
SR: 4.19 vs 3.55 Hz*
SL: 0.64 vs. 0.56* (m/body height)
CM distance* (-0.04 vs 0.03 m/body height)
CM angle* (95°vs 86°)
D)
CM distance* (0.42 vs 0.45 m/body height)
CM early acceleration, no sled
CM immediate change with sled
Early acceleration, no sled
Immediate change with sled

# Figure 6

Pre-post intervention sprint kinematic changes in early acceleration and upright sprinting.

Touchdown (A, B, C, J, I, K) and toe – off (D, E, F, H, J, L) within HS60%, HS50%, and CON groups. In early acceleration, toe-off is based on the average of the first push toe-off from the sprint start and the first two steps toe-off. The touchdown is based on the first 3 steps. Upright sprinting toe-off and touchdown are analyzed from 2 steps during upright sprinting at our close to maximal velocity (~22.5 m). No kinematic variables for within and between-group comparisons reached significance. Toe-off HS: Heavy sled, CT: Contact time, SR: Step rate, SL: Step Length relative to body height, CM: Center of Mass.


Touchdown
Toe – off
Touchdown
Toe – off
HS60%
Early acceleration
CT: 0.19 ± 0.02 vs. 0.18 ± 0.02 s
SR: 4.19 ± 0.20 vs 4.32 ± 0.29 Hz
SL: 0.61 ± 0.06 vs. 0.62 ± 0.06
(m/body height)
Upright sprinting
CT: 0.13 ± 0.01 vs. 0.13 ± 0.02 s
SR: 4.30 ± 0.25 vs 4.48 ± 0.19 Hz
SL: 1.04 ± 0.04 vs. 1.02 ± 0.03
(m/body height)
A)
D)
G)
H)
HS50%
Early acceleration
CT: 0.19 ± 0.01 vs. 0.19 ± 0.03 s
SR: 4.19 ± 0.17 vs 4.36 ± 0.41 Hz
SL: 0.63 ± 0.04 vs. 0.60 ± 0.08
(m/body height)
Upright sprinting
CT: 0.12 ± 0.01 vs. 0.12 ± 0.01 s
SR: 4.47 ± 0.12 vs 4.65 ± 0.12 Hz*
SL: 1.08 ± 0.06 vs. 1.07 ± 0.07
(m/body height)
B)
E)
I)
J)
CON
Early acceleration
CT: 0.18 ± 0.01 vs. 0.18 ± 0.01 s
SR: 4.27 ± 0.26 vs 4.28 ± 0.33 Hz
SL: 0.62 ± 0.05 vs. 0.65 ± 0.05
(m/body height)
Upright sprinting
CT: 0.12 ± 0.01 vs. 0.12 ± 0.01 s
SR: 4.50 ± 0.18 vs 4.53 ± 0.28 Hz
SL: 1.03 ± 0.08 vs. 1.01 ± 0.06
(m/body height)
C)
F)
K)
L)
CM pre
CM post
Pre
Post

## Table 1(on next page)

Results for sprint split-times.

HS: Heavy sled, CON: Control, s: seconds, ES: Effect size (Small: 0.2 – 0.59, Moderate: 0.60 – 1.19, Large 1.19 >), SD: Standard deviation, Δ: alpha (change pre post). **: Post-Hoc tests were only performed for all subgroups (HS60% vs CON, HS50% vs CON, HS60% vs HS50%) when HS vs CON reached significance . Effect size calculations are presented irrespective of post-hoc testing. *: $p < 0.05$.

| Variable | Group | Pre (SD) | Post (SD) | %∆ (95%CI) | Within group Statistics (p-value, ES) | Between group statistics |
|---|---|---|---|---|---|---|
| 5 m split time (s) | HS60% | 1.39 (0.05) | 1.35 (0.04) | -2.54 (-3.56; -1.52) | p = 0.002*, ES: -0.74 | HS vs CON : p = 0.08, ES: 0.82 |
| | HS50% | 1.39 (0.04) | 1.34 (0.04) | -3.14 (-5.63; -0.65) | p = 0.03*, ES: -1.04 | HS60% vs CON: ES: 0.87<br>HS50% vs CON: ES: 0.72 |
| | CON | 1.38 (0.04) | 1.36 (0.04) | -0.90 (-2.17; 0.88) | p = 0.40, ES: -0.33 | HS60% vs HS50%: ES: -0.20 |
| 10 m split time (s) | HS60% | 2.15 (0.08) | 2.09 (0.06) | -3.05 (-4.07; -2.03) | p = 0.001*, ES: -0.96 | HS vs CON: p = 0.01*, ES: 1.16, Post-hoc**: |
| | HS50% | 2.14 (0.06) | 2.07 (0.06) | -3.37 (-5.29; -1.46) | p = 0.008*, ES: -1.25 | HS60% vs CON: p = 0.18, ES: 1.26 |
| | CON | 2.12 (0.06) | 2.10 (0.04) | -0.87 (-1.95; - 0.52) | p = 0.42, ES: -0.37 | HS50% vs CON: p = 0.03*, ES: 1.03<br>HS60% vs HS50%: p = 1.00, ES: -0.13 |
| 20 m split time (s) | HS60% | 3.45 (0.12) | 3.36 (0.10) | -2.45 (-3.37; -1.54) | p = 0.001*, ES: -0.77 | HS vs CON: p = 0.04*, ES: 0.88, Post-hoc**: |
| | HS50% | 3.43 (0.08) | 3.32 (0.10) | -3.07 (-4.64; -1.51) | p = 0.005*, ES : -1.15 | HS60% vs CON: p = 0.61, 0.82 |
| | CON | 3.41 (0.09) | 3.37 (0.08) | -1.10 (-2.22; -0.03) | p = 0.31, ES : -0.47 | HS50% vs CON: p = 0.08, 0.93<br>HS60% vs HS50%: p = 1.00, -0.31 |
| 30 m split time (s) | HS60% | 4.65 (0.17) | 4.56 (0.14) | -2.04 (-3.03; -1.06) | p = 0.006*, ES: -0.62 | HS vs CON: p = 0.09, ES: 0.62 |
| | HS50% | 4.62 (0.10) | 4.49 (0.12) | -2.89 (-4.15; -1.64) | p = 0.002*, ES: -1.18 | HS60% vs CON: ES: 0.46<br>HS50% vs CON: ES: 0.87 |
| | CON | 4.62 (0.12) | 4.56 (0.11) | -1.23 (-2.47; -0.26) | p = 0.28, ES: -0.48 | HS60% vs HS50%: ES: -0.48 |

# Table 2(on next page)

Results for sprint mechanical variables.

F*0*: Maximal Horizontal force, RF: Ratio of Forces, m: meters, HS: Heavy sled, CON: Control, ES: Effect size (Small: 0.2 – 0.59, Moderate: 0.60 – 1.19, Large 1.19 >), SD: Standard deviation, Δ: alpha (change pre post). **: Post-Hoc tests were only performed for all subgroups (HS60% vs CON, HS50% vs CON, HS60% vs HS50%) when HS vs CON reached significance. Effect size calculations are presented irrespective of post-hoc testing. *: p < 0.05.

| Variable | Group | Pre (SD) | Post (SD) | %Δ (95%CI) | Within group Statistics (p-value, ES) | Between group statistics |
|---|---|---|---|---|---|---|
| F*0* (N.kg$^{-1}$) | HS60% | 7.23 (0.63) | 7.77 (0.42) | 7.83 (4.16; 11.5) | p = 0.003*, ES: 1.00 | HS vs CON: p = 0.03*, ES: 1.03, Post-hoc**: |
| | HS50% | 7.27 (0.59) | 7.91 (0.65) | 9.23 (3.58; 14.9) | p = 0.01*, ES: 1.04 | HS60% vs CON: p = 0.36, ES: 0.99 |
| | | | | | | HS50% vs CON: p = 0.09, ES: 0.98 |
| | CON | 7.43 (0.50) | 7.58 (0.45) | 1.89 (-1.60; 5.39) | p = 0.50, ES: 0.30 | HS60% vs HS50%: p = 0.69 ES: 0.18 |
| RFmax (%) | HS60% | 47.9 (2.57) | 50.8 (1.88) | 6.03 (4.01; 8.03) | p < 0.001*, ES: 1.25 | HS vs CON: p = 0.39, ES: -0.75 |
| | | | | | | HS60% vs CON: ES: -0.81 |
| | HS50% | 47.9 (3.51) | 51.2 (2.91) | 7.12 (2.59; 11.7) | p = 0.009*, ES: 1.01 | HS50% vs CON: ES: -0.72 |
| | CON | 50.1 (2.39) | 51.6 (2.58) | 3.00 (0.42; 5.58) | p = 0.06, ES: 0.55 | HS60% vs HS50%: ES: 0.20 |
| Mean RF on 10-m (%) | HS60% | 27.7 (1.71) | 28.9 (1.42) | 4.70 (2.83; 6.58) | p = 0.001*, ES: 0.80 | HS vs CON: p = 0.22, ES: -0.68 |
| | | | | | | HS60% vs CON: ES: -0.45 |
| | HS50% | 27.9 (1.59) | 29.8 (1,61) | 6.58 (4.00; 9.17) | p = 0.001*, ES: 1.14 | HS50% vs CON: ES: -0.88 |
| | CON | 28.6 (1.61) | 29.3 (1.36) | 3.20 (0.95; 5.45) | p = 0.02*, ES: 0.65 | HS60% vs HS50%: ES: 0.53 |
| Pmax (W.kg$^{-1}$) | HS60% | 16.0 (1.66) | 17.3 (1.35) | 8.36 (5.11; 11.6) | p = 0.01*, ES: 0.84 | HS vs CON: p = 0.02*, ES: 1.00, Post-hoc**: |
| | HS50% | 16.2 (1.31) | 18.1 (1.82) | 11.64 (6.40; 16.9) | p = 0.02*, ES: 1.18 | HS60% vs CON: p = 0.55, ES: 0.88 |
| | | | | | | HS50% vs CON: p = 0.02*, ES: 1.16 |
| | CON | 16.5 (1.27) | 17.0 (1.08) | 4.05 (0.94; 7.15) | p = 0.29, ES: 0.49 | HS60% vs HS50%: p = 0.47, ES: -0.48 |
| v*0* (m.s-$^{1}$) | HS60% | 8.93 (0.51) | 9.08 (0.39) | 1.79 (-0.21; 3.78) | p = 0.49, ES: 0.32 | HS vs CON: p = 0.44, ES: 0.11 |
| | | | | | | HS60% vs CON: ES: 0.06 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | HS50% | 9.03 (0.36) | 9.31 (0.33) | 3.08 (1.44; 4.72) | p = 0.11, ES: 0.78 | HS50% vs CON: ES: 0.45 |
| | CON | 8.96 (0.36) | 9.10 (0.42) | 2.04 (-0.45; 4.54) | p = 0.38, ES: 0.34 | HS60% vs HS50%: ES: -0.44 |
| Sprint FV-profile (-F*0*/v*0*) | HS60% | -0.81 (0.08) | -0.86 (0.05) | 6.07 (1.54; 10.62) | p = 0.17, ES: -0.67 | HS vs CON: ES: -0.69<br>HS60% vs CON: ES: -0.66 |
| | HS50% | -0.81 (0.08) | -0.85 (0.06) | 6.11 (-0.30; 12.5) | p = 0.22, ES: -0.60 | HS50% vs CON: ES: -0.57 |
| | CON | -0.83 (0.07) | -0.83 (0.07) | 0.12 (-5.31; 5.56) | p = 0.83, ES: -0.06 | HS60% vs HS50%: ES: 0.00 |

## Table 3(on next page)

Results for kinematic variables from immediate effects on early acceleration of sled loads.

HS: Heavy sled, CON: control, TO: Toe-off, TD: Touchdown, CM: Center of Mass, m: meter, s: seconds, Hz: Hertz, ES: Effect size (Small: 0.2 – 0.59, Moderate: 0.60 – 1.19, Large 1.19 >), SD: Standard deviation, Δ: alpha (change pre post). **: Post-Hoc tests for HS60% & HS50% vs. CON run only if HS vs. CON reached significance, *: $p < 0.05$.

| Variable | Group | Toe-off wihtout sled | Toe-off with sled | %Δ ± CI95% | Within group Statistics (P-value, ES) | Touchdown without sled | Touchdown with sled | %Δ ± CI95% | Within group Statistics (P-value, ES) |
|---|---|---|---|---|---|---|---|---|---|
| CM distance (m/body length) | HS60% | 0.42 (0.04) | 0.45 (0.03) | 7.74 (-0.53; 16.0) | p = 0.15, ES: 0.85 | -0.04 (0.03) | 0.08 (0.08) | -820 (-1670; 29.3) | p = 0.003*, ES: 1.99 |
| | HS50% | 0.43 (0.01) | 0.46 (0.03) | 7.18 (3.31; 11.0) | p = 0.03*, ES: 1.34 | -0.04 (0.02) | 0.03 (0.02) | -847 (-1751; 55.9) | p = 0.003*, ES: 3.50 |
| CM angle (°) | HS60% | 46.8 (1.77) | 44.1 (2.21) | -5.79 (-9.90; -1.67) | p = 0.04*, ES: -1.49 | 95.3 (4.19) | 79.8 (8.59) | -16.1 (-22.9; -11.0) | p = 0.005*, ES: -2.30 |
| | HS50% | 46.6 (1.22) | 44.7 (1.49) | -4.46 (7.41; -1.52) | p = 0.06, ES: -2.33 | 95.2 (3.30) | 86.2 (2.60) | -8.46 (-11.0; -5.97) | p = 0.005*, ES: -3.00 |
| Hip-angle Ipsilateral (°) | HS60% | 171 (7.61) | 173 (10.6) | 2.05 (-1.91; 6.01) | p = 0.41, ES: 0.10 | 101 (7.30) | 108 (20.3) | 7.67 (-9.25; 24.6) | p = 0.40, ES: 0.41 |
| | HS50% | 174 (2.95) | 181 (4.82) | 4.22 (1.33; 7.11) | p = 0.07, ES: 1.70 | 105 (8.10) | 108 (4.04) | 3.18 (-1.40; 7.78) | p = 0.28, ES: 0.60 |
| Hip-angle Contralateral (°) | HS60% | 85.7 (6.72) | 90.3 (7.16) | 6.01 (-3.30; 15.3) | p = 0.19, ES: 0.57 | 161 (8.81) | 159 (13.1) | -0.34 (-6.44; 5.76) | p = 0.71, ES: -0.18 |
| | HS50% | 86.7 (4.08) | 84.7 (6.09) | -3.81 (-7.58; -0.02) | p = 0.45, ES: -0.59 | 164 (6.59) | 164 (10.2) | 2.56 (-2.08; 7.21) | p = 0.91, ES: 0.00 |
| Trunk angle (°) | HS60% | 46.3 (5.20) | 42.7 (8.37) | -6.09 (-19.0; 6.82) | p = 0.29, ES: -0.60 | 46.8 ( 6.18) | 42.0 (8.11) | -7.54 (-21.2; 6.11) | p = 0.18, ES: -0.85 |
| | HS50% | 47.9 (2.87) | 49.4 (2.76) | 1.12 (-4.25; 6.50) | p = 0.31, ES: 0.33 | 49.1 (3.97) | 48.4 (2.40) | -1.77 (-6.45; 2.90) | p = 0.66, ES: --0.19 |
| Spatiotemporel variables | Group | Early acceleration, no sled | | Early acceleration, with sled | | %Δ ± CI95% | | Within group Statistics (P-value, ES) | |

| | | | | | |
|---|---|---|---|---|---|
| Contact time (s) | HS60% | 0.19 (0.02) | 0.27 (0.05) | 40.0 (24.5; 55.4) | p = 0.003*, ES: 2.10 |
| | HS50% | 0.19 (0.01) | 0.24 (0.04) | 28.2 (13.3; 43.1) | p = 0.03*, ES: 1.71 |
| Step Rate (Hz) | HS60% | 4.19 (0.20) | 3.49 (0.51) | -16.5 (-23.3; -9.70) | p = 0.004*, ES: -1.90 |
| | HS50% | 4.19 (0.17) | 3.55 (0.41) | -14.8 (-23.6; -6.12) | p = 0.041*, ES: -2.09 |
| Step Length (m/body length) | HS60% | 0.61 (0.06) | 0.48 (0.10) | -21.9 (-32.3; -11.5) | p = 0.008*, ES: -1.58 |
| | HS50% | 0.64 (0.04) | 0.56 (0.04) | -11.3 (-16.7; -5.97) | p = 0.02*, ES: -.2.00 |

## Table 4(on next page)

Results for kinematic and spatiotemporal variables in early acceleration (ACC) and upright sprinting (MAX).

HS: Heavy sled, CON: Control, TO: Toe-off, TD: Touchdown, CM: Center of Mass, m: meter, s: seconds, Hz: Hertz, ES: Effect size (Small: 0.2 – 0.59, Moderate: 0.60 – 1.19, Large 1.19 >), SD: Standard deviation, Δ: alpha (change pre post). **: Post-Hoc tests for HS60% & HS50% vs. CON run only if HS vs. CON reached significance, *: $p < 0.05$.

| Variable | Group | ACC Toe-off pre (SD) | ACC Toe-off post (SD) | %Δ (95%CI) | Within group Statistics (p-value, ES) | ACC Touchdown pre (SD) | ACC Touchdown post (SD) | %Δ (95%CI) | Within group Statistics (p-value, ES) |
|---|---|---|---|---|---|---|---|---|---|
| CM distance (m/body length) | HS60% | 0.42 (0.03) | 0.42 (0.04) | -0.01 (-1.56; 1.36) | p = 0.97 , ES: -0.01 | -0.04 (0.03) | -0.03 (0.03) | 39.0 (-79.2; 157) | p = 0.42 , ES: 0.39 |
| | HS50% | 0.43 (0.01) | 0.43 (0.01) | 0.16 (-1.22; 1.56) | p = 0.93, ES: 0.04 | -0.04 (0.02) | -0.02 (0.03) | 35.0 (-420; 490) | p = 0.19, ES: 0.70 |
| | CON | 0.43 (0.02) | 0.44 (0.01) | 1.04 (-0.82; 2.10) | p = 0.85, ES: 0.16 | -0.03 (0.03) | -0.03 (0.02) | 156 (-227; 540) | p = 0.94, ES: 0.00 |
| CM angle (°) Relative to horizontal | HS60% | 46.8 (1.77) | 47.4 (1.38) | 1.32 (-0.59; 3.23) | p = 0.44, ES: 0.36 | 95.3 (4.19) | 93.7 (3.37) | -1.63 (-3.02; -0.25) | p = 0.38, ES: -0.42 |
| | HS50% | 46.6 (1.22) | 46.8 (1.08) | 0.46 (-0.64; 1.57) | p = 0.72, ES: 0.17 | 95.2 (3.30) | 92.6 (4.18) | -2.66 (-6.16; 0.82) | p = 0.18, ES: -0.69 |
| | CON | 47.7 (1.97) | 47.5 (1.24) | 0.45 (-0.81; 1.71) | p = 0.68, ES: 0.11 | 93.7 (4.99) | 93.3 (3.13) | -0.32 (-2.36; 1.72) | p = 0.86, ES: -0.10 |
| Hip-angle Ipsilateral (°) 180° = full EXT | HS60% | 171 (7.61) | 169 (6.72) | -1.19 (-3.07; 0.68) | p = 0.54, ES: -0.30 | 101 (7.30) | 103 (5.28) | 1.94 (-2.25; 6.14) | p = 0.59, ES: 0.26 |
| | HS50% | 174 (2.95) | 175 (2.69) | 0.12 (-1.59; | p = 0.92, ES: 0.05 | 104 (8.10) | 105 (6.14) | 0.74 (-3.27; 4.75) | p = 0.90, ES: 0.07 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 1.82) | | | | | |
| | CON | 170 (5.28) | 171 (3.18) | 0.41 (-0.51; 1.33) | p = 0.73, ES: 0.14 | 103 (8.73) | 103 (5.95) | 1.22 (-2.01; 4.44) | p = 0.86, ES: 0.12 |
| Hip-angle Contralateral (°) 180° = full EXT | HS60% | 85.7 (6.72 | 82.8 (3.98) | -3.03 (-5.91; -0.15) | p = 0.29, ES: -0.51 | 161 (8.81) | 154 (7.49) | -4.01 (-5.97; - 2.05) | p = 0.11, ES: -0.80 |
| | HS50% | 86.7 (4.08) | 85.6 (5.74) | -1.25 (-4.62; 2.10) | p = 0.66, ES: -0.22 | 164 (6.59) | 162 (4.87) | -1.57 (-4.68; 1.56) | p = 0.35, ES: -0.48 |
| | CON | 85.1 (8.98) | 84.6 (8.04) | -0.47 (-2.39; 1.46) | p = 0.93, ES: -0.06 | 159 (7.18) | 155 (5.36) | -3.13 (-4.65; -1.61) | p = 0.09, ES: -0.80 |
| Trunk angle (°) Relative to horizontal | HS60% | 46.3 (5.20) | 45.3 (3.03) | -1.48 (-6.44; 3.47) | p = 0.63, ES: -0.23 | 46.8 (6.18) | 45.9 (2.59) | -0.73 (-7.25; 5.79) | p = 0.70, ES: -0.18 |
| | HS50% | 47.9 (2.87) | 48.6 (3.77) | 1.44 (-2.54; 5.41) | p = 0.70, ES: 0.20 | 49.1 (3.97) | 48.8 (4.25) | -0.39 (-4.50; 4.21) | p = 0.90, ES: -0.07 |
| | CON | 46.5 (5.29) | 46.6 (4.29) | 0.59 (-2.10; 3.28) | p = 0.94, ES: 0.03 | 47.3 (5.50) | 46.0 (4.24) | -2.26 (-6.25; 1.73) | p = 0.50, ES: -0.26 |

| Spatiotemporel variables ACC | Group | Pre (SD) | Post (SD) | %Δ (95%CI) | Within group Statistics (p-value, ES) |
|---|---|---|---|---|---|
| Contact time (s) | HS60% | 0.19 (0.02) | 0.18 (0.02) | -5.48 (-9.12; -1.83) | p = 0.25, ES: -0.56 |
| | HS50% | 0.19 (0.01) | 0.19 (0.03) | -0.97 (-13.0; 11.01) | p = 0.82, ES: -0.12 |
| | CON | 0.19 (0.01) | 0.18 (0.01) | -2.34 (-6.50; 1.82) | p = 0.49, ES: -0.34 |

| | | | | | |
|---|---|---|---|---|---|
| Step Rate (Hz) | HS60% | 4.19 (0.20) | 4.32 (0.29) | 3.25 (-0.56; 7.07) | p = 0.27, ES: 0.54 |
| | HS50% | 4.19 (0.17) | 4.36 (0.41) | 4.45 (-3.09; 12.0) | p = 0.28, ES: 0.56 |
| | CON | 4.27 (0.26) | 4.28 (0.33) | 0.54 (-2.61; 3.69) | p = 0.98, ES: 0.08 |
| Step Length (m/body length) | HS60% | 0.61 (0.06) | 0.62 (0.06) | 1.52 (-3.21; 6.26) | p = 0.79, ES: 0.13 |
| | HS50% | 0.63 (0.04) | 0.60 (0.08) | -4.56 (-14.3; 5.21) | p = 0.33, ES: -0.50 |
| | CON | 0.62 (0.05) | 0.64 (0.05) | 5.38 (1.11; 9.64) | p = 0.19, ES: 0.28 |

| Variable | Group | MAX Toe-off pre (SD) | MAX Toe-off post (SD) | %Δ (95%CI) | Within group Statistics (p-value, ES) | MAX Touchdown pre (SD) | MAX Touchdown post (SD) | %Δ (95%CI) | Within group Statistics (p-value, ES) |
|---|---|---|---|---|---|---|---|---|---|
| CM distance to toe (m/body length) | HS60% | 0.35 (0.01) | 0.34 (0.01) | -2.09 (-3.76; -0.41) | p = 0.32, ES: -0.48 | -0.23 (0.02) | -0.21 (0.02) | -5.84 (-10.9; -0.83) | p = 0.15, ES: 0.71 |
| | HS50% | 0.34 (0.02) | 0.36 (0.03) | 3.67 (-1.51; 8.85) | p = 0.39, ES: 0.44 | -0.22 (0.02) | -0.21 (0.01) | -2.81 (-6.77; 1.16) | p = 0.40, ES: 0.44 |
| | CON | 0.33 (0.02) | 0.33 (0.02) | -0.19 (-1.57; 1.19) | p = 0.95, ES:-0.02 | -0.21 (0.02) | -0.21 (0.02) | -1.11 (-4.75; 2.53) | p = 0.88, ES: 0.09 |
| CM angle (°) | HS60% | 56.6 (2.13) | 57.1 (1.87) | 0.95 (0.19; 1.71) | p = 0.58, ES: 0.26 | 114 (2.11) | 112 (2.11) | -1.23 (-2.27; -0.20) | p = 0.17, ES: -0.67 |
| | HS50% | 57.6 (2.77) | 56.1 (2.63) | -2.48 (0.19; 0.44) | p = 0.29, ES: -0.54 | 112 (1.64) | 112 (2.01) | -0.44 (-1.16; 0.28) | p = 0.60, ES: -0.27 |
| | CON | 56.4 (2.38) | 57.7 (2.17) | 2.40 (0.77; 4.03) | p = 0.24, ES: 0.58 | 112 (2.37) | 112 (2.49) | 0.03 (-0.83; 0.90) | p = 0.87, ES: 0.01 |
| Hip-angle Ipsilateral (°) | HS60% | 201 (4.46) | 201 (5.14) | 0.13 (-0.99; 1.25) | p = 0.91, ES: 0.05 | 134 (6.15) | 136 (5.40) | 1.69 (-0.18; 3.56) | p = 0.43, ES: 0.38 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | HS50% | 202 (5.38) | 202 (4.22) | -0.34 (-1.51; 0.82) | p = 0.76, ES: -0.15 | 141 (14.3) | 140 (3.81) | -0.39 (-2.46; 1.67) | p = 0.93, ES: -0.04 |
| | CON | 202 (5.84) | 201 (5.79) | -0.27 (-0.87; 0.32) | p = 0.83, ES: -0.10 | 135 (5.57) | 136 (5.82) | 0.41 (-1.51; 2.33) | p = 0.79, ES: 0.08 |
| Hip-angle Contralateral (°) | HS60% | 105 (3.42) | 106 (4.94) | 0.52 (-1.29; 2.33) | p = 0.78, ES: 0.13 | 176 (4.69) | 173 (4.92) | -1.64 (-3.77; 0.49) | p = 0.21, ES: -0.61 |
| | HS50% | 107 (8.24) | 104 (4.26) | -2.08 (-5.21; 1.04) | p = 0.45, ES: -0.39 | 174 (7.85) | 172 (4.80) | -1.37 (-3.38; 0.64) | p = 0.44, ES: -0.39 |
| | CON | 106 (4.54) | 107 (5.79) | 1.13 (-1.17; 3.44) | p = 0.70, ES: 0.23 | 171 (11.6) | 169 (13.2) | -1.40 (-3.44; 0.64) | p = 0.73, ES: -0.19 |
| Trunk angle (°) | HS60% | 78.7 (4.37) | 79.3 (4.36) | 0.87 (-0.74; 2.51) | p = 0.75, ES: 0.15 | 79.9 (3.92) | 80.4 (3.99) | 0.61 (-1.66; 2.89) | p = 0.81, ES: 0.11 |
| | HS50% | 78.9 (5.48) | 77.6 (3.48) | -1.48 (-4.23; 1.27) | p = 0.57, ES: -0.29 | 78.6 (4.43) | 78.5 (3.86) | -0.09 (-2.22; 2.03) | p = 0.95, ES: -0.03 |
| | CON | 78.0 (5.54) | 79.4 (3.73) | 2.03 (-1.60; 5.68) | p = 0.52, ES: 0.28 | 77.9 (4.47) | 79.0 (3.74) | 1.52 (-0.96; 4.01) | p = 0.59, ES: 0.26 |

| Spatiotemporel variables MAX | Group | Pre (SD) | Post (SD) | %∆ (95%CI) | Within group Statistics (p-value, ES) |
|---|---|---|---|---|---|
| Contact time (s) | HS60% | 0.13 (0.01) | 0.13 (0.02) | -0.75 (-8.48 – 6.97) | p = 0.83, ES: -0.10 |
| | HS50% | 0.12 (0.01) | 0.12 (0.01) | -2.70 (-6.64 – 1.23) | p = 0.32, ES: -0.51 |
| | CON | 0.12 (0.01) | 0.12 (0.01) | 0.56 (-2.47 – 3.59) | p = 0.75, ES: 0.09 |
| Step Rate (Hz) | HS60% | 4.30 (0.25) | 4.48 (0.19) | 4.38 (1.62 – 7.14) | p = 0.10, ES: 0.82 |

| | | | | | |
|---|---|---|---|---|---|
| | HS50% | 4.47 (0.12) | 4.65 (0.12) | 4.00 (1.66 – 6.33) | p = 0.009*, ES: 1.51 |
| | CON | 4.50 (0.18) | 4.53 (0.28) | 0.67 (-2.82 – 4.17) | p = 0.89, ES: 0.12 |
| Step Length (m/body length) | HS60% | 1.04 (0.04) | 1.02 (0.03) | -1.39 (-3.07 – 0.28) | p = 0.41, ES: -0.39 |
| | HS50% | 1.08 (0.06) | 1.07 (0.07) | -1.37 (-3.75 – 1.00) | p = 0.65, ES: -0.23 |
| | CON | 1.03 (0.08) | 1.01 (0.06) | -1.38 (-5.26 – 2.50) | p = 0.68, ES: -0.23 |