Relationships between anthropometric characteristics, block settings and block clearance technique during the sprint start

Valentina Cavedon[1], Neil Edward Bezodis[2], Marco Sandri[1], Mariola Pirlo[3], Carlo Zancanaro[1], Chiara Milanese[1]

[1]Department of Neurosciences, Biomedicine and Movement Sciences, University of Verona, Verona, Italy.

[2]Applied Sports, Technology, Exercise and Medicine Research Centre, Swansea University, Swansea, UK.

[3]OMR Automotive, Brescia, Italy.

Corresponding author:

Chiara Milanese

Department of Neurosciences, Biomedicine and Movement Sciences, University of Verona.

Strada Le Grazie, 8.

37134 Verona, Italy.

Tel. +39-0458425173 Fax: +39-0458425131

E-mail: chiara.milanese@univr.it.

Abstract

This study aimed to identify how body dimensions interact with anteroposterior block distances to influence lower limb joint angles in the "set" position, how these angles relate to block clearance kinetic and kinematic parameters, and how these biomechanical parameters influence sprint start performance in sprinters of both sexes and of different ability levels. Seventy-eight sprinters performed six maximal-effort 10 m sprints. Joint angles in the "set" position were quantified though 2D video analysis, and the forces generated during block exit were measured by dynamometric starting blocks. Lower limb length was associated with the front block-starting line distance ([FB/SL], partial correlation [r_{PC}] = 0.48) and was a significant predictor of FB/SL (R^2 = 0.39). The FB/SL was associated with front hip angle (r_{PC} = 0.38), which was consequently associated with numerous kinetic variables during block clearance (r_{PC} from -0.41 to -0.61). Coaches should be encouraged to explore the interactions between individual lower limb lengths and the FB/SL distance in both male and female sprinters to manipulate the front hip angle in the "set" position in an attempt to achieve more favourable block clearance kinetics.

Key words: sprint running, set position, biomechanics, anthropometrics, sex, ability level.

Introduction

The ability of sprinters to generate a large impulse over a short time during block clearance is strongly correlated with overall 100 m performance (Baumann, 1976; Mero, 1988; Bezodis et al., 2015; Willwacher et al., 2016). Higher levels of sprint start performance are related to greater ground reaction forces (resultant and horizontal component) during block clearance (Bezodis et al., 2019; Willwacher et al., 2016; Otsuka et al., 2014). Many biomechanical studies have therefore investigated and demonstrated the importance of technique during block clearance and the subsequent first and second steps (Čoh and Tormažin, 2006; Slawinski et al., 2012; Bezodis et al., 2015; Čoh et al., 2017). In several studies, particular attention has been given to the inclination of the block pedals and their positioning relative to each other and to the start line (Slawinski et al., 2013; Milanese et al., 2014; Bezodis et al., 2015; Otsuka et al., 2015; Cavedon et al., 2019). Block clearance technique is greatly influenced by these block spacings (Schot and Knutzen, 1992; Slawinski et al., 2012; Cavedon et al., 2019) because they affect the orientation of the body segments (and therefore joint angles) in the "set" position and beyond.

One of the most common adjustments modified by sprinters is the inter-block distance. The three main types of inter block spacing investigated in the literature are the bunched start (< 30 cm), the medium start (30 to 50 cm) and the elongated start (> 50 cm). A number of studies have suggested that the medium start provides the most favorable balance between total force generated and the increased time of force generation to enable sprinters to achieve their best sprint start performance levels (Sigerseth and Grinaker, 1962; Stock, 1962; Slawinski et al., 2012; Cavedon et al., 2019). However, the effects of the front-block starting line distance have not always been considered, despite the fact that this interacts with the inter-block distance and can affect the force producing capabilities of the rear leg (Cavedon et al., 2019), a factor which is known to influence block phase performance (Willwacher et al., 2016; Bezodis et al., 2019). Furthermore, individual anthropometry has also often been overlooked despite the fact that it is known that anthropometry plays an important role in sports where differences in body dimension may affect the biomechanics of movement and consequently the resulting levels of performance (e.g. gymnastics, track and field; Vucetic et al., 2008; Massidda et al., 2013). Definitive block spacing recommendations for sprinters and coaches therefore currently remain challenging because of the lack of individual-specific consideration as well as variation in the methods used for the inter-block and front block-start line spacings between these experimental studies. To help inform such recommendations, as well as the design of future experimental studies, it is crucial to obtain a more complete understanding of the potential influence of anthropometric characteristics on self-selected block settings, and how these interact to affect a sprinter's "set" position kinematics and block phase kinetics.

The starting block phase involves a closed kinematic chain of movements where the distal extremities commence from a fixed position. It is well known that individuals present different proportionality characteristics between their leg and trunk lengths, and a way to assess such proportionality is by using the Cormic Index (Ukwuma, 2009). The Cormic Index expresses sitting height as a proportion of total height, therefore representing a measure of the relative lengths of the trunk and lower limbs. Individuals are classified as brachycormic, metricormic and macrocormic according to a Cormic Index ≤51%, 51-53%, or ≥53%, respectively (Cagnazzo and Cagnazzo, 2009). These lower limb and trunk body dimensions, and their relative proportions have recently been shown to interact with the self-selected and experimentally manipulated anteroposterior block distances to affect block phase technique and performance (Cavedon et al., 2019). The study by Cavedon and colleagues (2019) identified the importance of anthropometry in selecting the block distances, but there are still several issues that require further investigation, including the need to understand the importance of a larger number of body dimensions (i.e. the thigh, shank, lower limb, trunk and the Cormic Index). Investigating how individual body dimensions interact with self-selected block settings provides a logical progression to extend the current understanding as well as valuable information for future experimental research focussing on manipulating anteroposterior block distances based on body dimensions.

The relationship between anthropometric characteristics and anteroposterior block spacing, and their combined effects on starting block technique, remains poorly understood. Moreover, investigating whether these combined anthropometric and technical factors are related to performance levels across a group of sprinters would be useful to help understand how a series of contributing factors lead to higher levels of block phase performance. As there appears to be no universal optimum body posture in the “set” position, a detailed investigation of the interactions between individual anthropometry and body configurations in the “set” position is required. This will provide athletes and coaches with new and valuable information regarding any potential connection between an individual’s body dimensions, block settings, and biomechanical parameters exhibited during a sprint start, which could inform their pursuit of ideal personal block spacings to ultimately enhance sprint start performance.

The first aim of this study was therefore to identify how individual body dimensions (length of body segments) and body proportionality (Cormic Index) interact with self-selected anteroposterior block distances to influence lower limb joint angles in the “set” position, and subsequently to determine how these joint angles relate to kinetic and kinematic parameters during block clearance. The second aim was to identify how these kinetic and kinematic parameters related to sprint start performance. Importantly, to enable consideration of whether ability level or sex influenced these effects, a cohort containing both well-trained and non-trained participants of both sexes were analyzed.

Methods

Participants

The minimum sample size required to achieve a desired power, while limiting the false discovery rate (FDR) below a specified threshold, was calculated using the method proposed by Pounds and Cheng (2005) and implemented in the FDRsampsize package for R (Pounds, 2016). The statistical test of interest was the t-test for non-zero correlation. The desired FDR and the average power were set to 0.1 and 0.8, respectively. The total number of planned tests was 372 and the population correlation coefficients were set to 0.4 for 20 (5%) of the 372 tests. Under these conditions, the minimum required sample size was 76.

Our study included 78 sprinters (50 well-trained and 28 non-trained sprinters). Well-trained sprinters (19 women and 31 men) had a competitive athletic career of at least two years in sprint running and their mean age, height and body mass (±SD) were 18.9 ± 2.5 and 19.3 ± 2.9 y, 165.3 ± 5.4 and 176.2 ± 5.3 cm, 55.5 ± 6.9 and 67.0 ± 9.9 kg for females and males, respectively. Their best time over 100 m ranged between 11.45 s and 13.64 s for women and between 10.45 s and 12.02 s for men. Non-trained sprinters' (9 women and 19 men) age, height and body mass were 21.1 ± 2.1 and 22.4 ± 3.5 y, 166.2 ± 5.5 and 176.3 ± 7.8 cm, 56.3 ± 3.6 and 70.9 ± 10.4 kg, respectively. All the non-trained sprinters were university exercise and sport sciences students who participated in sports such as soccer, baseball, cycling, and had only experienced block starts in four practice lessons on their degree course.

All participants gave their written informed consent to participate in the study, and the protocol was performed in accordance with the Declaration of Helsinki. Ethics approval was obtained from the Institutional Review Board.

Procedure

The sprint testing took place on an outdoor track (Olimpic Plast SWD surface, Olimpia Costruzioni, Forlì, Italy). One operator attached ten retro-reflective passive flat markers (14 mm diameter) bilaterally over specific anatomical landmarks on the participant's body (i.e., right [R] and left [L] acromion, R and L greater trochanter, R and L lateral epicondyle, R and L lateral malleolus, on the shoe lateral to the R and L 5th metatarsal head).

Following a warm-up consisting of jogging, dynamic stretching and sprints of submaximal intensity, all participants performed three maximal-effort 10 m sprints using their preferred block spacings and block obliquities. The well-trained sprinters were not allowed to use their spiked shoes so that assessment parameters could be compared across the two groups under the same conditions. For all trials, each sprint was initiated by the same experimenter, who provided standard “on your marks” and “set” commands. The experimenter then pressed a custom-designed trigger button to provide the auditory start signal through a sounder device. The rest period between trials was 5-7 minutes.

Anthropometric data

Anthropometric data were taken by one operator using conventional criteria and measuring procedures (Lohman et al., 1992). Body mass was assessed to the nearest 0.1 kg using a certified electronic scale (Tanita electronic scale BWB-800 MA, Wunder SA.BI. Srl, Milano, Italy). Standing height and sitting height were measured to the nearest 0.1 cm using a Harpenden portable stadiometer (Holtain Ltd., Crymych, Pembs. UK). For the sitting height, the participant was asked to sit on a flat stool of a known height, with the measurement obtained by subtracting the height of the stool from the reading on the stadiometer. The body dimensions were measured with a Harpenden anthropometer (Holtain Ltd., Crymych, Pembs. UK) to the nearest 0.1 cm, and the body circumferences were measured with a fiberglass tape (Figure 1).

The Cormic Index was calculated for each participant as sitting height/standing height ·100.

****Figure 1 near here****

Kinetic and kinematic data

Each trial was performed using a set of dynamometric starting blocks equipped with load cells (CU K5D and CU K1C models, GEFRAN SpA, Brescia, Italy) enabling the measurement of the magnitude and direction of forces generated. The acquisition frequency was 1 kHz and the sensitivity was 0.01 N. More detailed information concerning the starting block can be found in Cavedon et al. (2019).

Three tripod-mounted video cameras (Casio Exilim ex-zr 1000, Casio Europe Gmbh, Barcelona, Spain) captured the movement of each athlete in two dimensions during the starting block and acceleration phases (first and second stride lengths) at 200 Hz. The cameras collected images at a resolution of 1280 × 1024 pixels using a shutter speed of 1/1000 s, and were 5 m from the outside lane at a height of approximately 1 m. One camera (Camera 1) was positioned for the front block side view and another (Camera 2) for the rear block side view; both were perpendicular to the running lane in line with the approximate location of the respective hip joint in the "on your marks" position. The third camera (Camera 3) was positioned for a full-body view of the first and second strides approximately 1.5 m after the starting line and perpendicular to the running lane (Figure 2). Each video was calibrated with a 4 m horizontal bar positioned on the ground to the rear of the blocks, which also defined the X-axis.

Three pairs of photocells (Polifemo Light Radio, Microgate SRL, Bolzano, Italy) and a reflection system were used to measure the times at 5 m and 10 m in the sprint trials. The timing between the dynamometric starting blocks and the photocells system was synchronized using the digital output available from the block control system and connecting it to the available input for timing available in the Microgate unit.

****Figure 2 near here****

Data analysis

Raw kinetic data from the instrumented blocks were filtered using a low-pass Butterworth filter (fourth order) with a cutoff frequency of 120 Hz and analyzed using a custom program written in Matlab R2008a (MathWorks, Natick, MA, USA). Force signals were resolved into horizontal and vertical components. The x-axis pointed forward along the running surface (horizontal plane) and the y-axis pointed vertically upwards. Force data were used to define the force onset threshold (i.e., when the first derivative of the resultant force-time curve was greater than 500 Ns^{-1}) and block clearance (i.e., when the resultant force was lower than 50 N) for each block. The following temporal parameters were extracted for analysis from the instrumented blocks data: the reaction time (RT), defined as the time from the auditory signal to the first force onset threshold; the front block time (FBT), defined as the time from front block force onset threshold to front block clearance; the rear block time (RBT), defined as the time from rear block force onset threshold to rear block clearance and the total time block (TBT), defined from the first force onset threshold to front block clearance. The following kinetic variables obtained from the instrumented blocks data during the pushing phase were also measured: the front peak force (FPF), defined as the maximum resultant front block force value; the rear peak force (RPF), defined as the maximum resultant rear block force value; the horizontal and the vertical front peak force (H_FPF and V_FPF); the horizontal and the vertical rear peak force (H_RPF and V_RPF); the average total force (ATF: total resultant force from both blocks over the entire pushing phase duration). The front force impulse ($FF_{impulse}$), the rear force impulse ($RF_{impulse}$) and the total force impulse (Total $F_{impulse}$), as well as the horizontal and vertical $FF_{impulse}$ ($H\_FF_{impulse}$ and $V\_FF_{impulse}$, respectively) and the horizontal and vertical $RF_{impulse}$ ($H\_RF_{impulse}$ and $V\_RF_{impulse}$, respectively) were computed according to the procedures of Otsuka and colleagues (2014). All the kinetic variables were normalized to the body mass of each sprinter and expressed in kg. In addition, the following variables were computed: the ratio of horizontal to resultant force impulse for each leg and across both blocks (Ratio_front, Ratio_rear and Ratio_total, respectively) (Morin et al., 2011); the horizontal block velocity (H_BV) measured as the sum of the horizontal impulse on both blocks (in Ns) divided by the body mass of the sprinter (in kg); the normalized average horizontal external block power (NAHEP) calculated according to the procedures of Bezodis and colleagues (2010).

For each participant the video clips were digitized at full resolution with a zoom factor of 2.5 using freeware motion-analysis software (Kinovea; version 0.8.15, http://www.kinovea.org). One operator manually digitized the markers and quantified the joint angles and stride lengths at specific video frames on each video as outlined below. Firstly, the lower limb "set" position angles in the sagittal plane were measured to the nearest degree for the front (Camera 1) and rear (Camera 2) legs. In order to measure the length of the first two strides, the video clips from Camera 3 were stopped at the instant of foot contact and the horizontal distance between the front block and the toe of the rear foot at first foot strike (first stride length [SL_1]), and between the rear foot at the first toe off and the toe of the front foot at its first foot strike (second stride length [SL_2]), were determined. SL_1 and SL_2 were normalized to leg length to account for differences among participants and labelled as $NorSL_1$ and $NorSL_2$, respectively.

In order to limit the effects of any operator errors involved in 2D videography, the operator was familiar with the use of high-speed video to quantify joint angles in sprint running and in sprint starts, and the above procedures were repeated in three separate sessions, with a minimum of seven days between sessions. The mean value was recorded only when the coefficient of variation was <5%. As the markers can move in relation to the skin throughout the range of motion (Reinschmidt et al., 1997) despite being properly positioned prior to data collection, the operator paid close attention to this and visually adjusted for skin movement by only using the markers as a guide in line with the procedures of Bradshaw et al. (2007).

****Figure 3 near here****

Statistical analysis

The normality of the distribution of continuous variables was checked using the one-sample Kolmogorov-Smirnov equality-of-distributions test. All these variables analyzed in the study did not show significant deviations from the Gaussian distribution and were summarized as mean and standard deviation (SD). Categorical variables were described as absolute and relative frequencies. Differences between mean values and proportions in subgroups of participants were tested using Student t-test and Fisher's exact test, respectively.

The degree of association between two continuous variables, accounting for sex, age, and ability, was measured by partial correlation (r_{PC}). The partial correlation coefficient was considered small (0.00–0.30), moderate (0.31–0.49), large (0.50–0.69), very large (0.70–0.89), and almost perfect (0.90–1.00) as suggested by Hopkins (2009).

In order to control the expected proportion of rejected null hypotheses that are false (FDR) associated with multiple tests performed in our explorative analysis (on partial correlation), the Benjamini and Yekutieli procedure was used and adjusted p-values were estimated (P_{adj}) (Benjamini and Yekutieli, 2009).

The existence of sex- or ability-related differences in the relationship between a covariate and a response variable was tested by a likelihood-ratio (LR) test which compared the likelihood of a regression model containing the interaction term (sex × covariate or ability × covariate) with the likelihood of the regression model without interaction. When the interaction term was statistically significant, the partial correlation between the covariate and the response variable was estimated in the subgroups identified by the stratification variable (sex or ability).

Predictive variable importance measures (VIMs) of candidate predictors were estimated for each outcome before building multivariable linear regression models (Williamson et al., 2020). VIMs were estimated using random forests and the nonparametric method based on permutation importance (Breiman, 2001). This algorithm was implemented in the RandomForestSRC package of R (Ishwaran and Kolagur, 2021). For each outcome, variables with the highest VIMs were selected and used as explanatory variables in a multivariable linear regression model. The proportion of the variance in the dependent variable that is predictable from the model was assessed by estimating the adjusted coefficient of determination (R^2). Cohen's f squared (f^2) was calculated to estimate the effect size in the regression models and was interpreted as small ($f^2 \geq 0.02$), medium ($f^2 \geq 0.15$) and large ($f^2 \geq 0.35$) according to Cohen's guidelines (Cohen, 1988).

Statistical analyses were performed using Stata 16.1 (StataCorp. College Station, TX, USA) and R 4.0.4 (Foundation for Statistical Computing, Vienna). The statistical significance was set at $P \leq 0.05$.

Results

The demographic and anthropometric characteristics of the participants in the whole sample as well as the two ability level groups and two sex groups are summarized in Table 1. There was a significant difference in mean age between well-trained and non-trained groups (19 vs. 22 years, $P<0.001$); the difference was not significant between males and females. The mean values (± SD) of the anteroposterior block distances and the kinematic and kinetic outcomes from the whole sample and from the two ability level groups and two sex groups are reported in Table 2. In line with our rationale and aim, we will firstly present the investigation of the relationships between anthropometrics and anteroposterior block distances, followed by those between the block distances and body configurations in the "set" position, the body configurations and the biomechanical parameters measured during the block phase, and finally between these biomechanical parameters and performance. Any effects of ability level or sex, or other covariates in a multivariable setting, are presented in each subsection.

****Table 1 and 2 near here****

Relationships between anthropometric variables and block distances.

Across the whole sample, after accounting for the effect of sex, age and ability level, lower limb length and thigh length were both moderately and positively correlated with the front block-starting line distance (FB/SL distance) (r_{PC} = 0.48 and P_{adj} = 0.002, r_{PC} = 0.40 and P_{adj} = 0.003, respectively; Figure 4). There were no statistically significant differences of the associations between anthropometric variables and anteroposterior block distances when compared between males and females, and between non-trained and well-trained sprinters. Based on the VIMs (Supplementary Figure 1), the variable most predictive of the anteroposterior block distances was lower limb length followed by thigh length, sex and height. In the multivariable linear regression model using these covariates, only lower limb length was a predictor of the FB/SL distance (R^2 = 0.39, P < 0.001, f^2 = 0.67; Figure 5).

****Figure 4 and 5 near here****

Relationships between block distances and lower limb joint angles.

Across the whole sample, the FB/SL distance showed a positive and moderate partial correlation with front hip angle (r_{PC} = 0.38 and P_{adj} = 0.046; Figure 4). No lower limb joint angles showed a statistically significant relationship with the inter block distance (I-B distance), and there were no statistically significant differences between the associations of lower limb joint angles and block distances when stratifying by sex and by ability level. Based on the VIMs (Supplementary Figure 2), the FB/SL distance, age, and ability level were the most important potential predictors for both the front hip angle and the front ankle angle. The multivariable linear regression model using these covariates showed that only the FB/SL distance and ability level were predictive of the front hip angle (R^2 = 0.16, P < 0.001, f^2 = 0.19). When stratifying by ability level, FB/SL distance was only predictive of front hip angle in the well-trained group (Figure 6).

With ability level, age and FB/SL distance as covariates, only ability level was a predictor of front ankle angle (R^2 = 0.17, P = 0.003, f^2 = 0.20).

****Figure 6 near here****

Relationships between lower limb joint angles and biomechanical parameters.

Across the whole sample (Figure 4), both the front and rear hip angles were negatively associated with RBT (P_{adj} = 0.001 and 0.025, respectively), $RF_{impulse}$ (P_{adj} <0.001 for both), $H\_RF_{impulse}$ (P_{adj} = 0.007 and P_{adj} = 0.017, respectively), $V\_RF_{impulse}$ (P_{adj} <0.001 for both) and Total $F_{impulse}$ (P_{adj} = 0.017 and P_{adj} = 0.008, respectively) and positively associated with Ratio_total (P_{adj} = 0.006 for both). Statistically significant differences of the associations between RBT and the front and rear knee angles were found in the subgroups identified by ability level (P = 0.005 and P = 0.047, respectively); in the group of non-trained sprinters, both the front and the rear knee angles showed a statistically significant negative correlation with RBT (both r_{PC} = -0.61, P < 0.001), while in the group of well-trained sprinters these associations were not statistically significant. The relationship between rear knee angle and TBT was significantly different when comparing between the two ability level groups (P = 0.032); in the group of non-trained sprinters, rear knee angle was negatively associated with TBT (r_{PC} = -0.62, P <0.001), while in well-trained sprinters no association was found. A statistically significant difference was found when comparing the association between rear hip joint angle and Ratio_rear between sexes (P = 0.035); females showed a significant and positive correlation (r_{PC} = 0.58, P = 0.002), while no statistically significant association was found for males.

Finally, we investigated the ability of each lower limb joint angle to predict the biomechanical parameters in a multivariable setting (Supplementary Figure 3). The front and rear hip angles and ability level were the most important potential predictors for RBT, TBT, FPF, RPF, ATF, RF impulse, $H\_RF_{impulse}$, $V\_RF_{impulse}$, Ratio_total, H_BV and NAHEP. The multivariable linear regression model using these covariates showed that only the front hip angle was a predictor of RBT (R^2 = 0.25, P <

0.001, $f^2 = 0.33$), while both front hip angle and ability level were predictors of TBT ($R^2 = 0.28$, $P < 0.001$, $f^2 = 0.39$). In addition, rear hip angle and ability level were predictors of RF_impulse ($R^2 = 0.31$, $P < 0.001$, $f^2 = 0.45$), $H\_RF_{impulse}$ ($R^2 = 0.32$, $P < 0.001$, $f^2 = 0.47$) and $V\_RF_{impulse}$ ($R^2 = 0.37$, $P < 0.001$, $f^2 = 0.59$), while front hip angle and ability level were predictors of Ratio_total ($R^2 = 0.25$, $P < 0.001$, $f^2 = 0.33$). Ability level was the only predictor of the following biomechanical variables: FPF ($R^2 = 0.34$, $P < 0.001$, $f^2 = 0.52$), RPF ($R^2 = 0.36$, $P < 0.001$, $f^2 = 0.56$), ATF ($R^2 = 0.43$, $P < 0.001$, $f^2 = 0.75$), H_BV ($R^2 = 0.33$, $P < 0.001$, $f^2 = 0.49$) and NAHEP ($R^2 = 0.49$, $P < 0.001$, $f^2 = 0.96$).

Relationships between biomechanical parameters and starting block performance.

Across the whole sample accounting for sex, age and ability level, H_BV and NAHEP showed a positive partial correlation with several kinetic and kinematic parameters including: Total $F_{impulse}$ (r_{PC} = 0.81 and 0.44, respectively; P_{adj} = <0.001); ATF (r_{PC} = 0.59 and 0.81, respectively; P_{adj} = < 0.001), (Supplementary Figures 4 and 5); FPF (r_{PC} = 0.62 and 0.45, respectively; P_{adj} = < 0.001); RPF (r_{PC} = 0.39 and 0.46, respectively; P_{adj} = <0.001); $H\_RF_{impulse}$ (r_{PC} = 0.42 and 0.41, respectively; P_{adj} = <0.001). Moreover, the H_BV showed a positive and large partial correlation with $H\_FF_{impulse}$ and $FF_{impulse}$ (r_{PC} = 0.59 and 0.52, respectively; P_{adj} = < 0.001), whilst NAHEP showed a negative correlation with TBT (r_{PC} = -0.33; P_{adj} = 0.006). Finally, statistically significant negative correlations were found for time at both 5 m and 10 m with Ratio_front (r_{PC} = -0.26 and -0.34 with P_{adj} = 0.01 and 0.002, respectively), and with RPF (r_{PC} = -0.25 and -0.26 with P_{adj} = 0.018 and 0.01, respectively), (Figure 7). There were no statistically significant differences in the observed relationships between the biomechanical and performance parameters when stratifying by sex or by ability level.

The estimated predictive variable importance of the biomechanical parameters for the prediction of the four performance parameters are shown in Supplementary Figure 4. In the multivariable linear regression models using the variables with the highest VIMs, Total $F_{impulse}$, ATF,

$H\_FF_{impulse}$ and ability level were significant predictors of H_BV ($R^2 = 0.81$, $P < 0.001$, $f^2 = 4.3$), whilst the significant predictors of NAHEP were ATF, ability level and RPF ($R^2 = 0.84$, $P < 0.001$, $f^2 = 5.2$). The multivariable regression models for time at 5 m and 10 m include sex, Ratio_front and RPF ($R^2 = 0.27$ and 0.4, respectively, $P < 0.001$, $f^2 = 0.37$ and 0.67).

****Figure 7 near here****

Discussion

To the best of our knowledge, this is the first study investigating the relationships between a number of individual anthropometric characteristics and self-selected block settings. Results indicated that 1) lower limb length was a better predictor of the self-selected FB/SL distance than other anthropometric measurements, 2) the FB/SL distance was positively and significantly correlated with front hip angle in the "set" position, 3) front hip angle in the "set" position was significantly correlated with numerous kinetic variables during the subsequent block clearance phase, and 4) several kinetic and kinematic parameters were significantly correlated with block clearance and early acceleration performance.

When accounting for age, sex and ability level, lower limb length and thigh length are both moderately correlated to the FB/SL distance, and lower limb length is predictive of the FB/SL distance (Figure 5), irrespective of sex and ability level. Lower limb length is therefore a good anthropometric dimension for an initial FB/SL distances when exploring "set" position technique. However, athletes of both sexes and ability levels chose their I-B distance regardless of their anthropometric characteristics. The positive correlation between lower limb length and the FB/SL distance suggests that sprinters select this block distance according to their leg length, which may in part be a function of the traditional measurement of the FB/SL distance using steps determined by the length of the foot. However, for I-B distance, many sprinters preferred a small anteroposterior distance between the front and rear blocks irrespective their anthropometric characteristics. This agrees with recent studies (Otsuka et al., 2014; Willwacher et al., 2016; Ciacci et al., 2017; Čoh et al., 2017) showing that sprinters with different ability levels choose a bunched start (i.e., an I-B distance ranging from 25 to 30 cm) based on their sensations. The bunched start has been demonstrated to be the least effective from a biomechanical perspective because less force impulse is exerted on the starting blocks leading to a reduction in block velocity (Harland & Steele, 1997; Kraan et al., 2001; Slawinski et al., 2013; Cavedon et al., 2019), whilst several studies (Slawinski et al., 2010; Slawinski et al., 2013; Čoh et al., 2017; Cavedon et al., 2019) have highlighted that an intermediate I-B distance is associated with improvements in several kinetic and kinematic variables linked to the sprint start.

The results of our study support a previous investigation (Cavedon et al., 2019) that detailed the importance of body dimensions in identifying anteroposterior block distances, confirming that lower-limb length may play an important role when adjusting FB/SL distance. In our studied sample, participants self-selected average FB/SL and I-B distances of 63.8% and 33.7% of their lower limb length, respectively. Future research could explore whether block-setting manipulations driven by a sprinter's lower-limb leg length (including relative proportions of lower limb lengths) are able to improve performance during the block phase.

Our study provided further evidence of a positive association between front hip angle and the FB/SL distance, irrespective of sex and ability level. This suggests that adjusting the FB/SL distance will most likely affect the configuration of the front hip joint in the "set" position, and therefore the action of the hip extensors during block exit, rather than the other joints of the front leg. The importance of front hip extension for performance during the block phase has previously been highlighted (Brazil et al., 2017), and the current findings provide evidence to support the manipulation of the FB/SL distance for sprinters with a low front hip angular velocity. In addition, the multivariable linear model of anteroposterior block distances when predicting each lower limb joint angle showed that the FB/SL distance was predictive of the front hip angle only in the well-trained group (Figure 6), while the ability level was a predictor of the front ankle angle. A possible explanation for why the FB/SL distance was not predictive of the front hip angle in the non-trained group could be that the non-trained group have more variation in how they position their upper body in the “set” position (e.g., trunk angles relative to the horizontal and arm/shoulder angles down from the proximal end of the trunk). Furthermore, the non-trained group showed smaller hip and knee angles and larger ankle joint angles than the well-trained group (Table 2), suggesting that novice sprinters may position their centre of mass (CM) more upwards than forwards when in the “set” position. Several studies have reported that elite sprinters present a CM position closer to the starting line compared to slower sprinters (Harland & Steele, 1997; Slawinski et al., 2010), which has been linked to the generation of a greater start velocity (Slawinski et al., 2010; Čoh et al., 2017).

Our results showed that ability level was a predictor of the front ankle joint angle, which underlined another important difference in the technique used by sprinters between different ability level groups. It is important to note that the average value of the front ankle angle was lower for the well-trained compared to the non-trained sprinters (94.21 ± 7.83 vs. 101.42 ± 8.61°, respectively). This finding is consistent with previous studies showing smaller ankle joint angles in faster than slower sprinters, allowing for a greater range of motion over which the plantar flexors can contribute to the generation of velocity when leaving the blocks (Mero et al., 1983; Schrödter et al., 2017).

When we explored how the lower limb angles then correlated with kinetic parameters during block clearance, there were some clear findings. Both the front and rear hip joint angles were negatively associated with the RBT, $RF_{impulse}$, $H\_RF_{impulse}$, $V\_RF_{impulse}$ and Total $F_{impulse,}$ reinforcing previous suggestions regarding the importance of the hips for force impulse generation (Slawinski et al., 2010; Bezodis et al., 2015; Čoh et al., 2017; Cavedon et al., 2019), and suggesting that starting from a more flexed position in the hips was important for this.

In addition, the front hip was a predictor of RBT, suggesting that front hip angle can influence the pushing duration of the rear leg. Spending more time pushing with the rear leg against the blocks appears to be a feature of higher performing sprinters during the block phase, provided it does not elongate the total push phase duration (Fortier et al., 2005; Slawinski et al., 2010; Bezodis et al., 2015 and 2019). The association between the front hip joint angle and the rear leg push duration is a novel finding that extends the known importance of the role of the front hip joint during the block phase. Further research could directly investigate this relationship in an attempt to better understand this association.

The smaller hip joint angles and the lower rear force impulse with similar RBT in the non-trained sprinters compared to their well-trained counterparts (Table 2) suggests that smaller hip joint angles should potentially only be considered by sprinters with experience. This was supported by the linear regression analysis, where front hip angle and ability level were predictors of the TBT, as well as rear hip joint angle and ability level being predictors of the $RF_{impulse}$, $H\_RF_{impulse}$ and $V\_F_{impulse}$. More specifically, the well-trained group showed significantly higher mean vales for the impulses generated by the rear leg compared to the non-trained group. These findings suggest that, across different ability levels, sprinters adopt different technique strategies which ultimately influence their performance, with well-trained sprinters adopting a more “hip dominant” strategy during the pushing phase. It is possible that this relates to a higher level of hip extensor strength capacity, although more specific strength data are required to confirm this. The significant negative association between RBT and both knee joint angles as well as between the rear knee angle and TBT in the non-trained group suggests that novice sprinters may favour a more “knee dominant” strategy during the pushing phase. The non-trained group showed smaller knee joint angles and a greater TBT than the well-trained group in both legs, and this may have combined with their more extended ankles to play a role in many of the lower kinetic and kinematic parameters measured (Table 2). This is supported by the linear regression analysis which revealed that ability level is a predictor of FPF, RPF, ATF, H_BV and NAHEP with the non-trained sprinters showing lower values for all of these variables compared to well-trained sprinters. No effect of sex was found on the biomechanical parameters; both males and females showed similar values for all lower body joint angles, consistent with previous studies reporting no differences between sexes regarding hip and knee angles (Čoh et al., 1998; Ciacci et al., 2017).

Having established the importance of selected anthropometric variables (e.g. lower limb length) and block settings (e.g. FB/SL distance) for the kinematics adopted in the "set" position (e.g. front hip angle), and then the importance of "set" position joint kinematics (e.g. both hip angles) for numerous kinetic variables during the subsequent block phase, the final step in the causal order of our investigation was to investigate the relationships between these block phase parameters and sprint start performance in order to better understand how this series of interactions from anthropometrics, block settings, "set" position kinematics and block phase kinetics ultimately associate with sprint start performance. As could be expected mechanically, there was a large, significant association between Total (i.e. resultant) $F_{impulse}$ and H_BV. In contrast, the relationship between Total $F_{impulse}$ and NAHEP was only moderate; the largest relationship for NAHEP was with ATF. These findings provide further support to the idea that H_BV may not be the most appropriate measure of block phase performance as it is achieved through a larger impulse which can be achieved through longer block times or greater forces (Bezodis et al., 2010). In contrast, the mechanical variables significantly related to NAHEP show that it is more strongly associated with the production of larger average forces than total impulses, supporting previous cross-sectional studies (Willwacher et al., 2016; Bezodis et al., 2019). These previous studies have also shown that rear block force magnitudes are the strongest predictor of NAHEP (Willwacher et al., 2016; Bezodis et al., 2019), and the current results add further evidence to extend this importance of the rear leg action for NAHEP by identifying that whilst front block impulses show a large and significant correlation with H_BV, they are not related to NAHEP, likely because they extend TBT when force production is decreasing, and TBT is negatively related to NAHEP (Figure 7).

Our study has limitations that should be acknowledged. Firstly, 2D kinematic measurement was used which may have led to parallax error in the kinematic measurements given that the sprint start is not a perfectly planar movement. However, as all kinematic variables were reported from the "set" position or were stride lengths, this error would likely be small and the current data provide valuable new biomechanical evidence to further understand the relationships between anthropometrics and sprint start technique and performance. Secondly, as we prioritised identical conditions across all studied participants, the well-trained sprinters were not wearing spiked shoes and this must be considered in the application of the current findings. Finally, foot length was not measured in the present study, and future research may seek to investigate whether this dimension relates to the anteroposterior block distances given the way many sprinters traditionally set up their blocks.

In combination, the current findings regarding "set" position anthropometrics and biomechanical parameters across both sexes and different ability levels support previous suggestions that a single optimal "set" position for everybody is not recommended. The current study highlighted the relationship between lower limb length and the FB/SL distance, which consequently affected the front and rear hip angles, ~~and ultimately~~ and then demonstrated the relationships of these with several kinetic parameters during the block phase, which were then ultimately related to sprint start performance.

From a practical perspective, some important recommendations could be made. Firstly, whilst achieving an ideal starting block technique is likely a long-term process, coaches and athletes should pay attention to anthropometric characteristics from the earliest stages of learning. This may assist in the search for a more effective block start position given the series of relationships observed between anthropometry, block settings, "set" position kinematics, block phase biomechanical variables and performance. Secondly, specific exercises focusing on the function of the hip extensors could be considered in the training programme in an attempt to maximise the potential benefit of certain "set" positions in affecting the external kinetics during the block clearance phase, which ultimately influence block phase performance.

The results obtained in the present study provide comprehensive new information that can inform future studies, and can help inform coaches and athletes in their quest to identify the ideal personal block spacing to optimise performance at the start.

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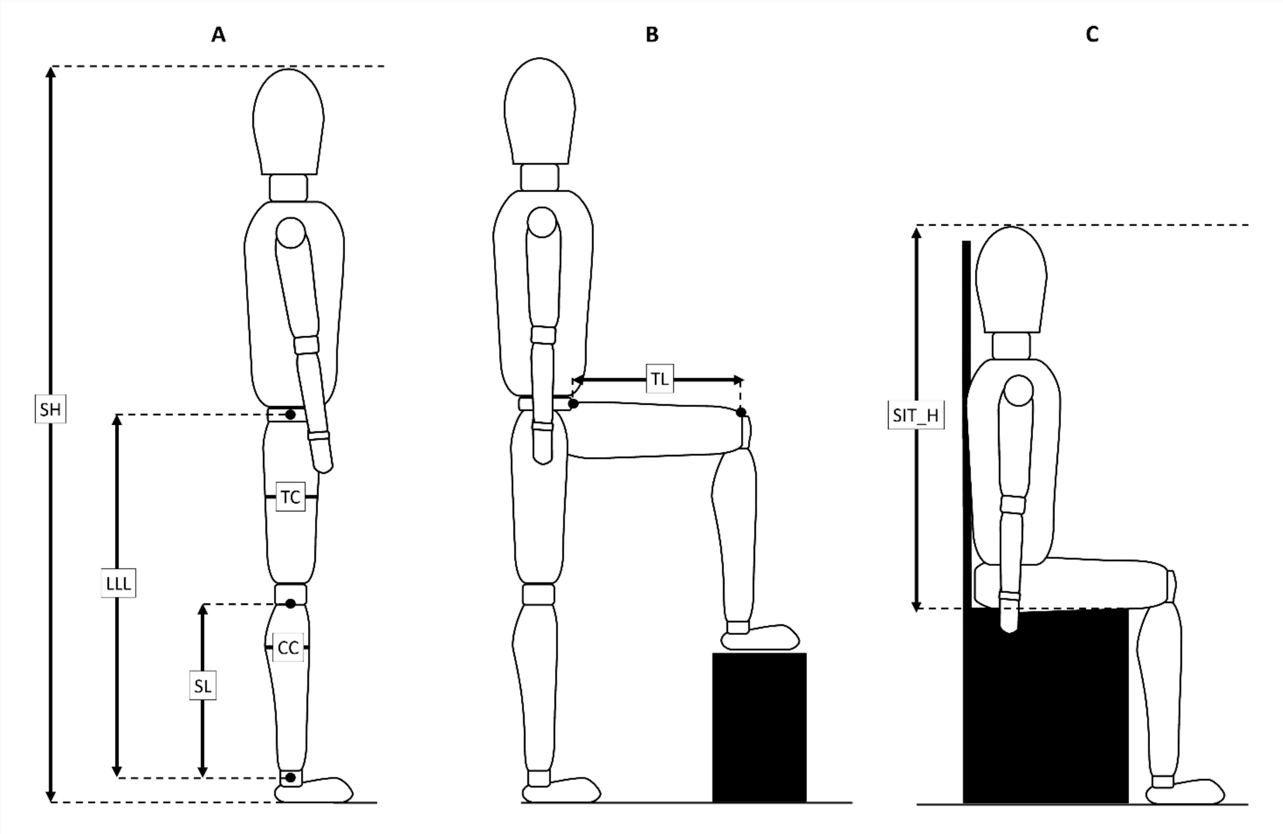

Figure 1. Procedures of anthropometric measurements.

Panel A: SH: standing height; LLL: lower-limb length (greater trochanter to lateral malleolus); SL: shank length (tibiale lateral to lateral malleolus); TC: thigh circumference (at the mid-thigh); CC: calf circumference (widest point of the calf). Panel B: TL: thigh length (from the midpoint of the inguinal ligament to the proximal edge of the patella). Panel C: SIT_H: sitting height.

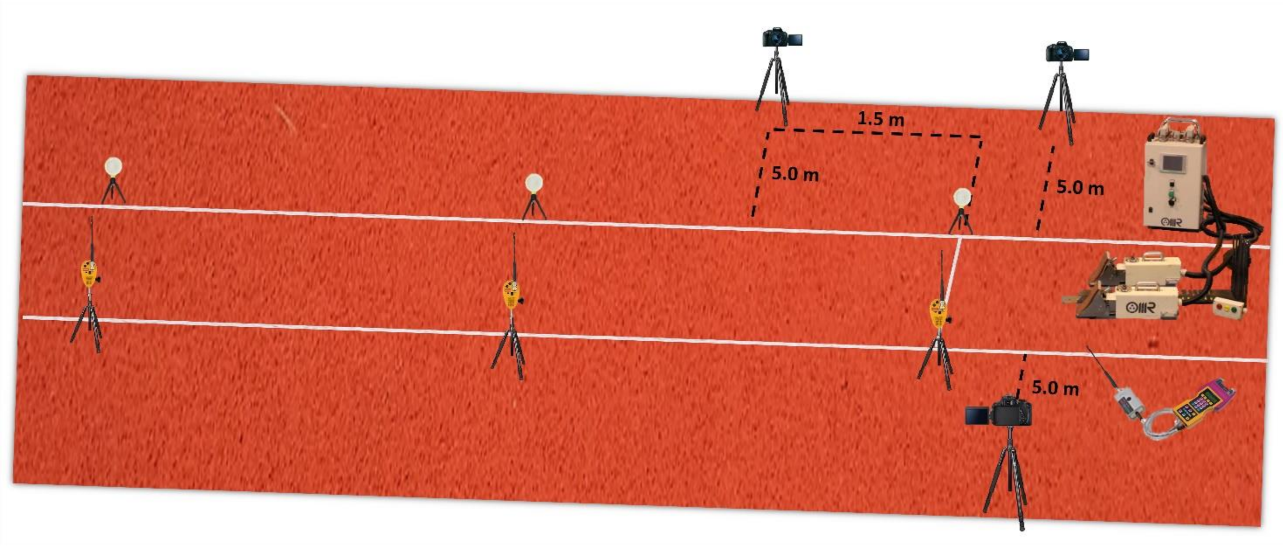

Figure 2. Experimental set-up.

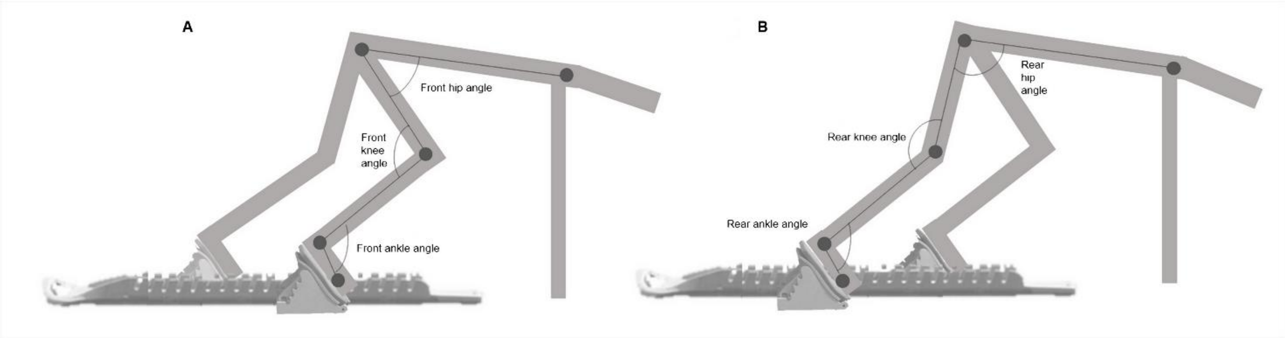

Figure 3. Two-dimensional functional representation of the joint angles on the front (Panel A) and rear blocks (Panel B) (Cavedon et al., 2019).

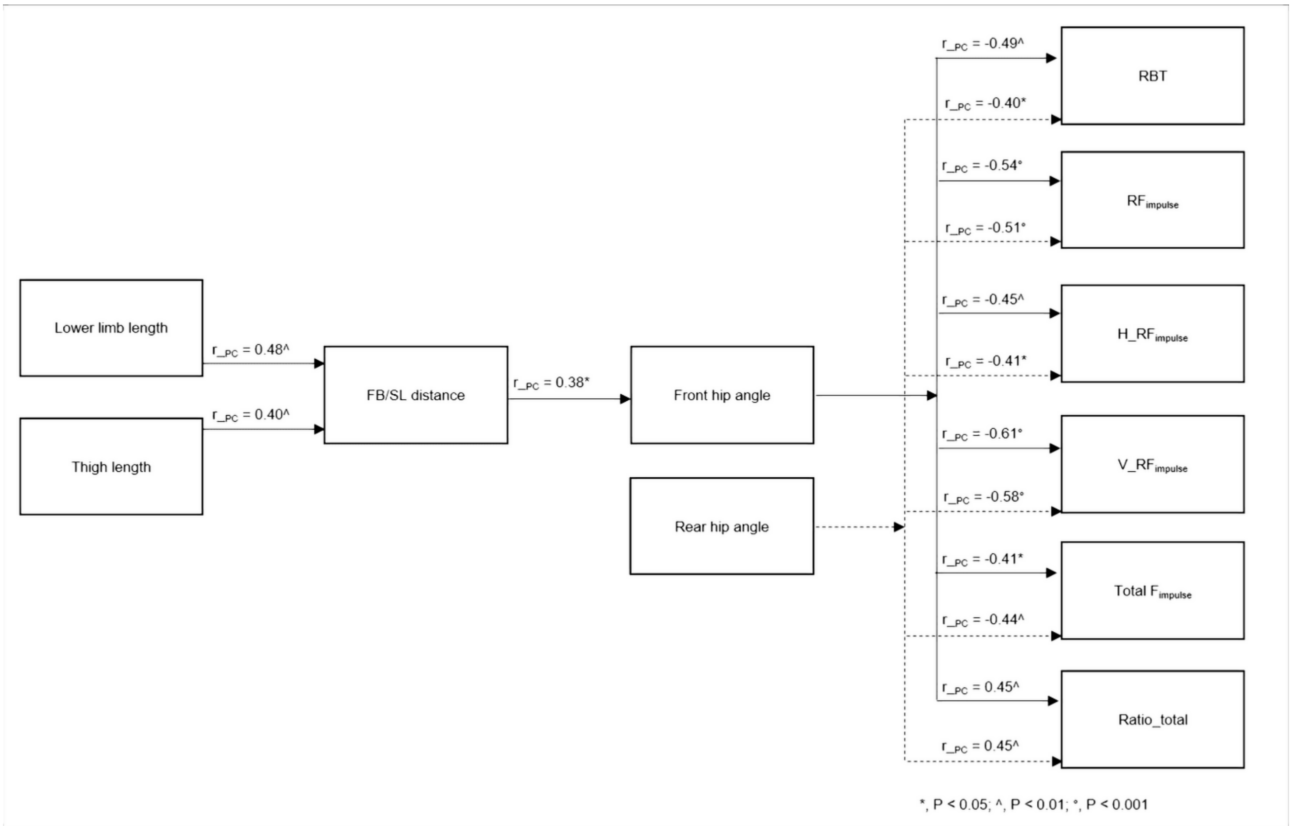

Figure 4. Schematic representation of the association (partial correlation) between anthropometry and block distances, between block distances and joint angles, and between joint angles and biomechanical variables measured by the instrumented starting blocks during the block clearance phase.

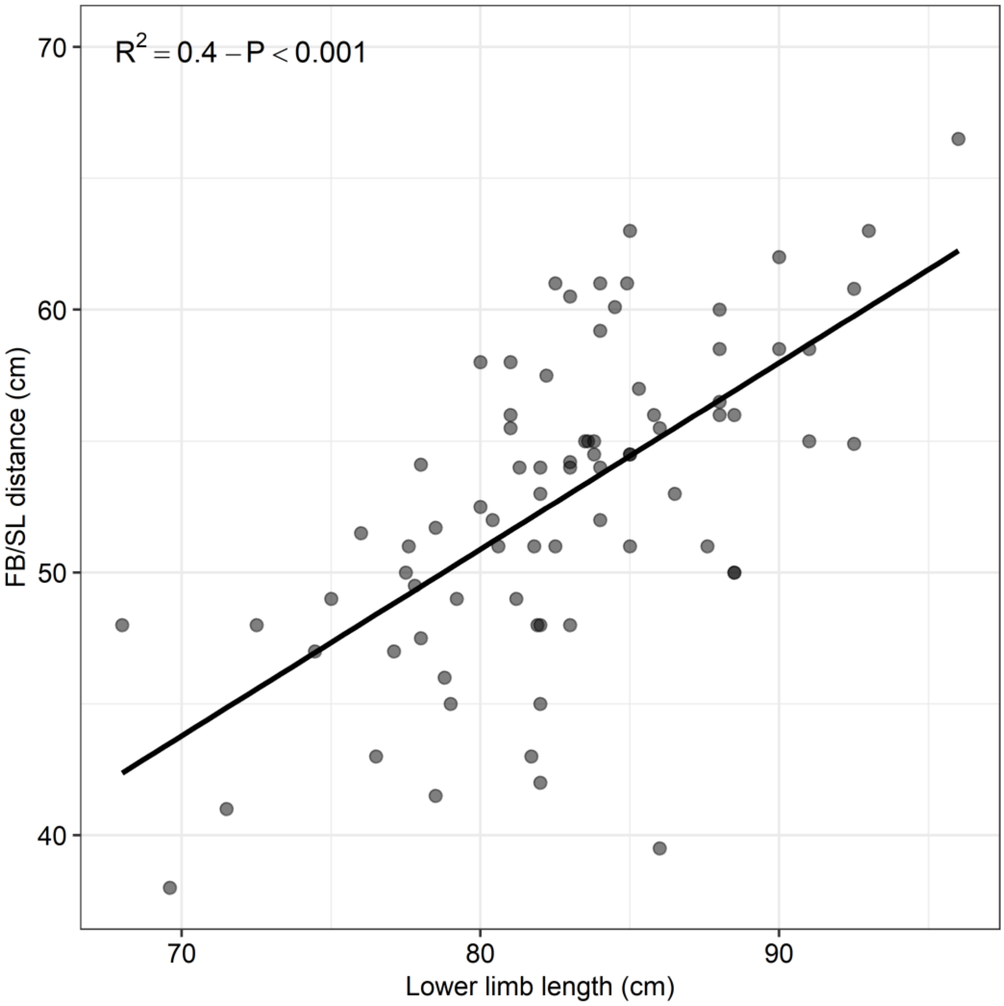

Figure 5. Relationship between the lower limb length and the front block-starting line distance.

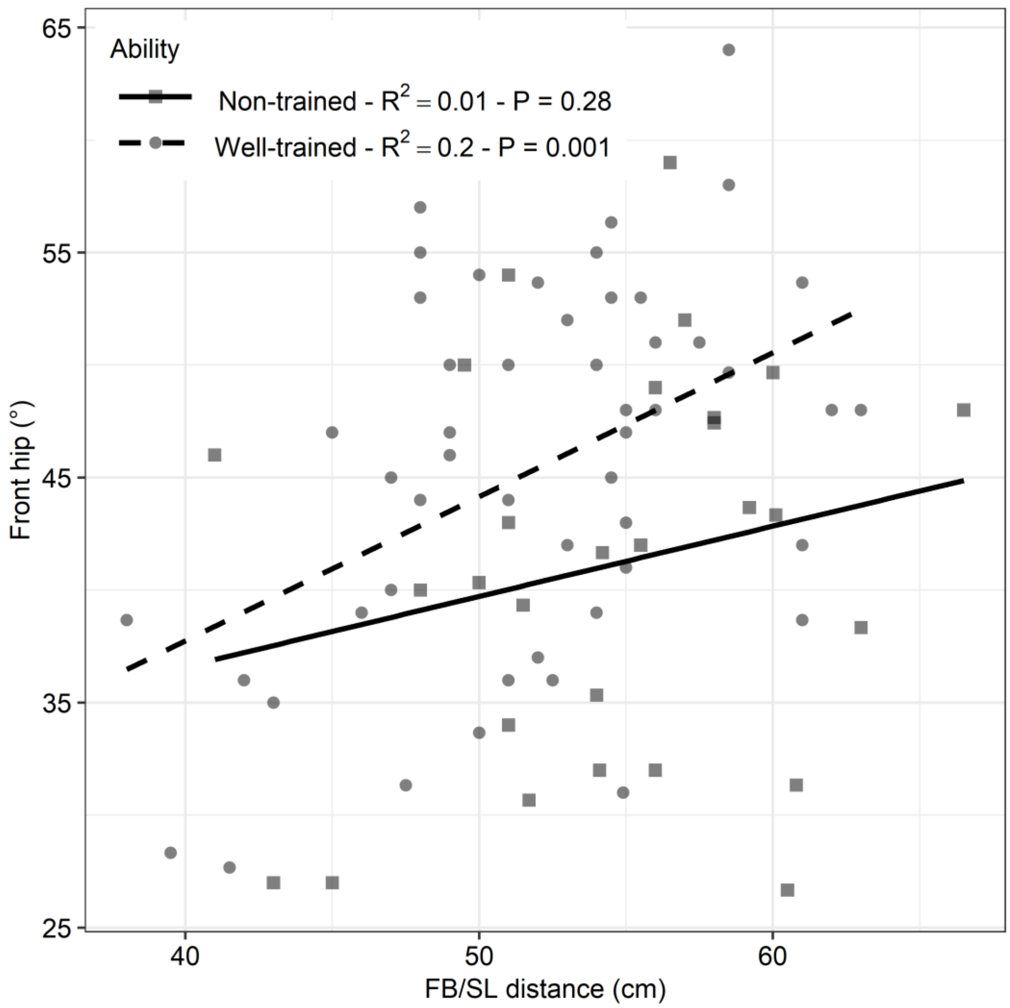

Figure 6. Relationship between the FB/SL distance and front hip joint angle across the two ability level groups.

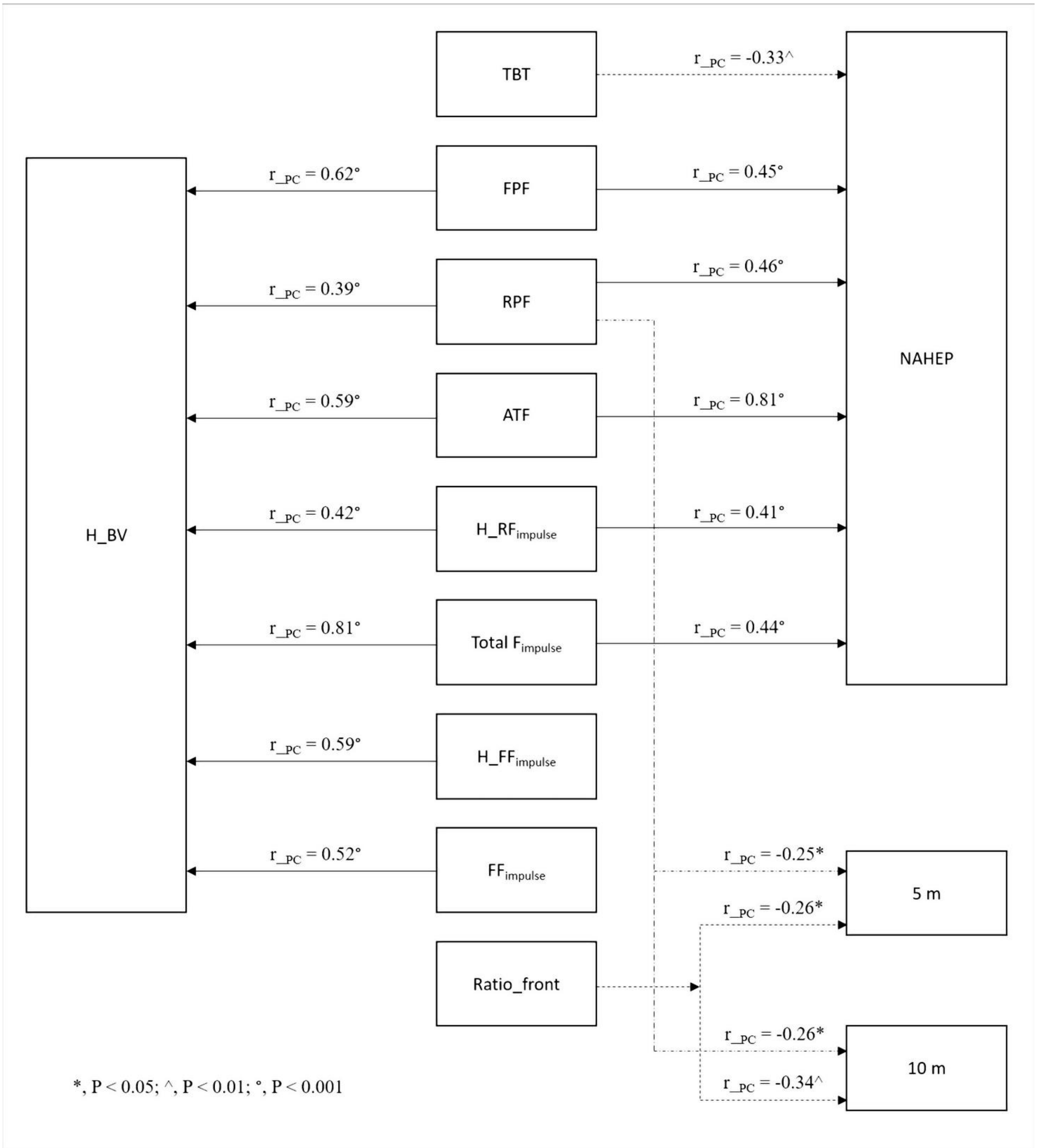

Figure 7. Schematic representation of the association (partial correlation) between biomechanical variables measured by the instrumented starting blocks during the block clearance phase and starting block performance.

Table 1. Characteristics of the participants in the whole sample and also when divided between the two ability level groups and the two sex groups. Data are means ± SD.

Variable	Whole sample (n=78)	Well-trained (n=50)	Non-trained (n=28)	Male (n=50)	Female (n=28)
Age (y)	20.15 ± 3.16	19.14 ± 2.70	21.96 ± 3.14	20.46 ± 3.48	19.61 ± 2.54
Body mass (kg)	63.94 ± 10.79	62.65 ± 10.46	66.24 ± 11.17	68.52 ± 10.16	55.75 ± 6.01
Height (cm)	172.44 ±7.83	172.09 ± 7.50	173. 07 ± 8.49	176.26 ± 6.28	165.64 ± 5.32
Sitting height (cm)	90.46 ± 4.81	90.28 ± 4.57	90.80 ± 5.28	92.59 ± 3.84	86.67 ± 3.97
Cormic Index	52.46 ± 1.49	52.46 ± 1.47	52.46 ± 1.54	52.54 ± 1.32	52.32 ± 1.76
Lower limb length (cm)	82.76 ± 5.28	82.66 ± 4.90	82.94 ± 6.00	85.04 ± 4.27	78.69 ± 4.44
Thigh length (cm)	40.50 ± 2.73	40.38 ± 2.71	40.78 ± 2.78	41.49 ± 2.32	38.80 ± 2.57
Shank length (cm)	40.08 ± 3.11	40.47 ± 2.86	39.39 ± 3.47	41.03 ± 2.92	38.38 ± 2.74
Thigh circumference (cm)	50.30 ± 4.24	49.46 ± 3.88	51.81 ± 4.49	50.88 ± 4.81	49.27 ± 2.74
Calf circumference (cm)	35.45 ± 2.72	34.76 ± 2.53	36.68 ± 2.67	36.32 ± 2.66	33.90 ± 2.11

Table 2. Block distances, set position joint angles, kinematic and kinetic data during the block clearance phase and performance and spatiotemporal data during the early acceleration phase for the whole sample and also when stratified between the two ability level groups and the two sex groups. Data are means ± SD.

Variable	Whole sample (n=78)	Well-trained (n=50)	Non-trained (n=28)	Male (n=50)	Female (n=28)
Block distances					
FB/SL distance (cm)	52.85 ± 5.93	52.00 ± 5.79	54.36 ± 5.97	55.16 ± 5.23	48.71 ± 4.78
I-B distance (cm)	27.86 ± 2.72	27.93 ± 2.74	27.75 ± 2.73	28.46 ± 2.63	26.80 ± 2.58
Set position joint angles					
Front hip (°)	43.87 ± 8.68	45.43 ± 8.33	41.09 ± 8.74	44.34 ± 8.90	43.04 ± 8.36
Rear hip (°)	74.94 ± 10.01	76.78 ± 9.93	71.64 ± 9.45	75.86 ± 9.95	73.30 ± 10.09
Front knee (°)	91.90 ± 9.07	92.20 ± 8.91	91.37 ± 9.50	91.35 ± 8.95	92.89 ± 9.37
Rear knee (°)	110.92 ± 11.90	112.41 ± 11.95	108.24 ± 11.53	111.04 ± 12.06	110.69 ± 11.82
Front ankle (°)	96.79 ± 8.78	94.21 ± 7.83	101.42 ± 8.61	97.25 ± 8.71	95.98 ± 9.01
Rear ankle (°)	90.26 ± 8.07	88.51 ± 7.78	93.39 ± 7.76	90.34 ± 8.47	90.13 ± 7.47
Block clearance phase					
RT (s)	0.20 ± 0.04	0.20 ± 0.04	0.22 ± 0.04	0.20 ± 0.04	0.20 ± 0.05
FBT (s)	0.41 ± 0.04	0.40 ± 0.04	0.42 ± 0.04	0.40 ± 0.04	0.42 ± 0.05
RBT (s)	0.22 ± 0.04	0.22 ± 0.04	0.23 ± 0.04	0.22 ± 0.04	0.22 ± 0.05
TBT (s)	0.44 ± 0.05	0.42 ± 0.05	0.47 ± 0.05	0.44 ± 0.05	0.44 ± 0.06
FPF (N/kg)	15.78 ± 2.55	16.90 ± 2.02	13.77 ± 2.16	15.71 ± 2.44	15.91 ± 2.78
RPF (N/kg)	11.13 ± 2.90	12.43 ± 2.28	8.80 ± 2.40	11.38 ± 3.11	10.67 ± 2.45
H_FPF (N/kg)	10.41 ± 1.48	11.04 ± 1.28	9.30 ± 1.10	10.51 ± 1.43	10.24 ± 1.59
V_FPF (N/kg)	11.82 ± 2.32	12.71 ± 1.99	10.24 ± 2.03	11.66 ± 2.27	12.11 ± 2.45
H_RPF (N/kg)	8.41 ± 2.47	9.48 ± 1.89	6.48 ± 2.21	8.61± 2.72	8.04± 1.96
V_RPF (N/kg)	7.54 ± 1.93	8.15 ± 1.70	6.44 ± 1.85	7.51 ± 2.00	7.58 ± 1.84
ATF (N/kg)	11.07 ± 1.46	11.78 ± 1.00	9.79 ± 1.28	11.13 ± 1.45	10.95 ± 1.51
$FF_{impulse}$ (Ns/kg)	3.45 ± 0.51	3.51 ± 0.49	3.35 ± 0.55	3.45 ± 0.46	3.47 ± 0.61
$RF_{impulse}$ (Ns/kg)	1.31 ± 0.40	1.41 ± 0.38	1.12 ± 0.37	1.32 ± 0.41	1.28 ± 0.39
Total $F_{impulse}$ (Ns/kg)	4.80 ± 0.54	4.94 ± 0.44	4.56 ± 0.64	4.82 ± 0.48	4.77 ± 0.65
H_ $FF_{impulse}$ (Ns/kg)	2.37 ± 0.31	2.42 ± 0.31	2.27 ± 0.29	2.40 ± 0.29	2.32 ± 0.34
V_ $FF_{impulse}$ (Ns/kg)	2.46 ± 0.46	2.49 ± 0.44	2.42 ± 0.51	2.43 ± 0.40	2.52 ± 0.56
H_$RF_{impulse}$ (Ns/kg)	0.94 ± 0.30	1.04 ± 0.28	0.77 ± 0.26	0.96 ± 0.31	0.91 ± 0.28
V_$RF_{impulse}$ (Ns/kg)	0.85 ± 0.29	0.89 ± 0.29	0.77 ± 0.28	0.86 ± 0.29	0.84 ± 0.30
Ratio_front	0.69 ± 0.05	0.69 ± 0.05	0.68 ± 0.04	0.70 ± 0.04	0.67 ± 0.06
Ratio_rear	0.72 ± 0.07	0.74 ± 0.05	0.69 ± 0.07	0.72 ± 0.07	0.72 ± 0.06
Ratio_total	0.70 ± 0.05	0.71 ± 0.04	0.67 ± 0.05	0.70 ± 0.04	0.69 ± 0.05
H_BV (m/s)	3.31 ± 0.36	3.47 ± 0.28	3.04 ± 0.32	3.36 ± 0.37	3.23 ± 0.33
NAHEP	0.44 ± 0.11	0.50 ± 0.08	0.34 ± 0.07	0.45 ± 0.11	0.43 ± 0.09
Early acceleration phase					
5 m (s)	1.31 ± 0.12	1.29 ± 0.11	1.33 ± 0.13	1.27 ± 0.12	1.37 ± 0.10
10 m (s)	2.06 ± 0.16	2.02 ± 0.14	2.11 ± 0.17	2.01 ± 0.15	2.15 ± 0.13
$NorSL_1$ (m)	1.06 ± 0.14	1.10 ± 0.13	0.99 ± 0.14	1.05 ± 0.16	1.08 ± 0.10
$NorSL_2$ (m)	1.16 ± 0.15	1.19 ± 0.14	1.10 ± 0.16	1.15 ± 0.16	1.16 ± 0.14

FB/SL, front block-starting line; I-B, inter-block; RT, reaction time; FBT, front block time; RBT, rear block time; TBT, total block time; FPF, front peak force; RPF, rear peak force; H_FPF, horizontal front peak force; V_FPF, vertical front peak force; H_RPF, horizontal rear peak force; V_RPF, vertical rear peak force; ATF, average total force; $FF_{impulse}$, front force impulse; $RF_{impulse}$, rear force impulse; Total $F_{impulse}$, total force impulse; $H\_FF_{impulse}$, horizontal front force impulse; $V\_FF_{impulse}$, vertical front force impulse; $H\_RF_{impulse}$, horizontal rear force impulse; $V\_RF_{impulse}$, vertical rear force impulse; Ratio_front, Ratio of horizontal to resultant force impulse of front leg; Ratio_rear, Ratio of horizontal to resultant force impulse of rear leg; NAHEP, normalized average horizontal external power; H_BV, horizontal block velocity; 5 m, time at 5 meters; 10 m, time at 10 meters; $NorSL_1$, first stride length normalized to leg length; $NorSL_2$, second stride length normalized to leg length.