Sprint mechanical differences at maximal running speed: effects of performance level

Giorgos Paradisis[a], Athanassios Bissas[b], Panagiotis Pappas[a], Elias Zacharogiannis[a], Apostolos Theodorou[a], Olivier Girard[c]

[a]Athletics Sector, School of Physical Education & Sport Science, National & Kapodistrian University of Athens, Athens, Greece
[b]Carnegie School of Sport, Leeds Beckett University
[c]School of Psychology and Exercise Science, Murdoch University, Perth, Australia

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Corresponding author: Giorgos P Paradisis
Athletics Sector, Faculty of Physical Education & Sport Science, National & Kapodistrian University of Athens, Ethn. Antistasis 41, Dafni, Athens, 172 37, Greece
Tel: + 30 210 727 6167
E-mail: gparadi@phed.uoa.gr

Running title: Mechanical differences between sprinters of different performance level

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Abstract

As the effect of performance level on sprinting mechanics has not been fully studied, we examined mechanical differences at maximal running speed (MRS) over a straight-line 35 m sprint amongst sprinters of different performance levels. Fifty male track and field sprinters, divided in Slow, Medium and Fast groups (MRS: 7.67 ± 0.27 $m \cdot s^{-1}$, 8.44 ± 0.22 $m \cdot s^{-1}$, and 9.37 ± 0.41 $m \cdot s^{-1}$ respectively) were tested. A high-speed camera (250 Hz) recorded a full stride in the sagittal plane at 30-35 m. MRS was higher ($p < 0.05$) in Fast vs. Medium (+11.0%) and Slow (+22.1%) as well as in Medium vs. Slow (+10.0%). Twelve, eight and seven out of twenty one variables significantly distinguished Fast from Slow, Fast from Medium and Medium from Slow sprinters, respectively. Propulsive phase was significantly shorter in Fast vs. Medium (-17.5%) and Slow (-29.4%) as well as in Medium vs. Slow (-14.4%). Fast sprinters had significantly higher vertical and leg stiffness values than Medium (+44.1% and +18.1% respectively) and Slow (+25.4% and +22.0% respectively). MRS at 30-35 m increased with performance level during a 35-m sprint and was achieved through shorter contact time, longer step length, faster step rate, and higher vertical and leg stiffness.

Introduction

The ability to achieve maximum running speed (MRS) is essential to success in many sports and is crucial in track-and-field events such as the 100-200 m sprint races (Brüggemann, Koszewski, & Müller, 1999). Sprinting speed is the product of step length (SL) and step rate (SR) and an increase in one of these two variables, or both, will consequently result in the attainment of faster sprinting speed as long as the other one does not undergo a proportionately similar or larger decrease (Hunter, Marshall, & McNair, 2004). There are inconsistencies in the literature regarding the relative importance of developing longer SL (Gajer, Thepaut-Mathieu, & Lehenaff, 1999; Hunter et al., 2004; Maćkała & Mero, 2013; Mero & Komi, 1985) over higher SR (Bezodis, Kerwin, & Salo, 2008; Mero, Komi, & Gregor, 1992) to reach top speeds. In order to improve MRS through specifically designed training protocols (e.g. resisted, assisted, and supramaximal sprints (Mero & Komi, 1985; Paradisis & Cooke, 2006), it is first vital to identify the most decisive mechanical differences, associated with the attained MRS during a straight line sprint, among athletes of different performance levels.

To date, there is a paucity of studies examining potential mechanical differences among sprinters of various performance levels. In one study, elite sprinters produced greater MRS, SR and SL (9.3%, 3.0% and 2.3%, respectively) compared with sub-elite sprinters (e.g. 100 m best time 9.95-10.29 s vs. 10.40-10.60 s) over a 40-m sprint run (Rabita et al 2015); however, only four elite and five sub-elite sprinters have been included in this analysis. Also, faster sprinters (e.g. 100 m: 11.6 s vs. 12.3 s) have been found to produce +2.8% faster MRS and +2.1% greater SR over an 80 m sprint run (Monte, Muollo, Nardello, & Zamparo, 2017). Finally, elite sprinters have been found to produce greater net rates of force development compared to slower sprinters (e.g. 100 m = 10.27 s *vs.* 11.31 s) during the starting block phase and the two subsequent steps (Slawinski et al., 2010). However, surprisingly no other studies have examined mechanical differences among sprinters of various performance levels.

In terms of ground contact characteristics in sprinting, it is known that higher running speeds are achieved through reduced contact times (Morin, Tomazin, Samozino, Edouard, & Millet, 2012; Paradisis & Cooke, 2006; Weyand, Sandell, Prime, & Bundle, 2010; Weyand, Sternlight, Bellizzi, & Wright, 2000) and by producing greater amounts of horizontal net force at each step, in particular during the early acceleration phase (Morin et al., 2012; Rabita et al., 2015). Reportedly, exerting a large propulsive force during the entire acceleration phase, suppressing braking force when approaching maximal speed, and producing a large vertical force during the maximal speed phase are essential for achieving greater acceleration and maintaining higher maximal speed (Morin et al., 2015; Nagahara, Mizutani, & Matsuo, 2018; Nagahara, Mizutani, Matsuo, Kanehisa, & Fukunaga, 2018). It is also known that sprinting performance determinants of acceleration shift from higher concentric propulsion to lower eccentric braking forces as velocity increases (Colyer, Nagahara, & Salo, 2018).

The “spring-mass model” (SMM), which represents a runner as a point mass supported by a single linear leg spring, has been proposed to model the biomechanics of running (Alexander, 1995; Blickhan, 1989; Farley & Gonzalez, 1996; Morin, Dalleau, Kyröläinen, Jeannin, & Belli, 2005). During running, leg stiffness (K_{leg}) is defined as the ratio of the peak vertical GRF to the peak displacement of initial leg length during contact phase (Morin et al., 2005), while effective vertical (K_{vert}) is defined as the ratio of the peak vertical GRF to the vertical displacement of the center of the mass (CM) during the same phase (Farley & Gonzalez, 1996; McMahon & Cheng, 1990). In the running literature, K_{vert} and K_{leg} are increasingly used to represent the mechanical function of the lower limbs as these parameters have demonstrated relationships with both performance and injury risk (Brughelli & Cronin, 2008; Butler, Crowell, & Davis, 2003). It has been suggested that high levels of stiffness could be beneficial to maximum speed running (Bret, Rahmani, Dufour, Messonnier, & Lacour, 2002), and training-induced improvements in K_{vert} (+56.4%) and MRS (+5.7%) have been observed in sprinters (Nagahara & Zushi, 2017). Additionally, it has been shown that K_{vert} or K_{leg} moderately correlate significantly with 100 m performance (Bret et al., 2002; Chelly & Denis, 2001), even though this is not an universal finding (Morin, Jeannin, Chevallier, & Belli, 2006). Furthermore, it has been demonstrated that K_{vert} increases with running speed but this observation is limited in so far to the 2 – 6.5 $m.s^{-1}$ speed range (Arampatzis, Brüggemann, & Metzler, 1999; Cavagna, 2005; Kuitunen, Ogiso, & Komi, 2011; Morin et al., 2006). All the above studies however, have not categorically established a robust relationship between mechanical stiffness and sprinting as stiffness behaviour has been either determined during a hoping test (Bret et al., 2002; Chelly & Denis, 2001) or in a cohort of non-specialized sprint runners (i.e., with no direct comparison with sprinters of higher performance) (Morin et al., 2006).

A level of indirect support to the hypothesis that MRS is accompanied by high stiffness values, however, comes from our study (Girard, Brocherie, Tomazin, Farooq, & Morin, 2016) showing that reduced running speed in the last 50 m distance interval of a 100 m run was accompanied by reductions in both SR (-5.8%) and K_{vert} (-12.3%). Other studies have also discovered significant relationship between decrements in both SR and K_{vert} and a progressive slowing in running speed after the repetition of four 100-m sprints on a track (Morin et al., 2006), three sets of five 5-s sprints on a sprint treadmill (Girard et al., 2017), and six 35-m sprints (Brocherie, Millet, & Girard, 2015) on artificial turf. Participants recruited in those studies, however, were not sprint running specialists but physical education students or team sports players who possibly possess different technical sprint ability compared to 'true' sprinters (Wild, Bezodis, North, & Bezodis, 2018). In team sports, for instance, achieving faster acceleration (first few steps) rather than faster top speeds is probably more important. To the authors' knowledge, no previous study has assessed the nature of the relationship between mechanical stiffness and MRS in sprinters of various performance levels.

Our intention was therefore to identify how performance level affects several key running mechanical factors (i.e., spatiotemporal characteristics, body angles, K_{vert} and K_{leg}) during the MRS phase of a short (35 m), straight-line overground sprint. A second aim was to investigate the association of the main mechanical variables with MRS in order to discuss recent suggestions about key mechanical determinants of sprint performance. It was hypothesized that faster sprinters would display more favorable mechanical characteristics – reinforcing the importance of K_{vert} and SR in particular - compared to their slower counterparts at MRS.

Methods

Participants

Fifty male track and field sprinters, from club to sub-elite level, participated in the study (mean ± SD age 24.3 ± 2.5 years, training year experience 5.6 ± 1.2 years, mass 77.9 ± 8.4 kg, height 1.79 ± 0.05 m, MRS 8.53 ± 0.72 m.s^{-1}. Their 100-m competition or training time at the time of testing was 12.39 ± 0.71 s. Ethical approval was gained from the Institutional Research Ethics Committee, and each participant provided written informed consent before commencement of the study.

Experimental design

Video recordings were collected during a 35-m straight-line track running sprint, between 30-35 m (MRS phase) to determine how performance level affects key running mechanical factors. Participants were classified *a priori* as Slow (13.24 ± 0.26 s, ranged from 13.78 to 13.05 s, N = 13), Medium (12.48 ± 0.22 s, ranged from 12.87 to 12.03 s, N = 21) and Fast (11.57 ± 0.40 s, ranged from 11.92 to 10.60 s, N = 16) based on their competition or training time in 100-m (above 13 s, between 13 and 12 s and below 12 s).

Data collection took place on an indoor synthetic track surface (60-m long and 2.5-m wide) at an ambient temperature of 25^{o} C. All data collection procedures took place in the autumn and during the athletes' usual practice time of day, which was between 4.00 and 7.00 pm. After completion of a standardized 20-min warm-up (8-min jogging, 6-min stretching exercises, and 4-6 sprints at gradually increased intensity), the participants performed 3 maximal straight-line 35-m sprint runs (10 min recovery between efforts). Participants used a standing start and started sprinting upon hearing an audible signal. For subsequent analysis, we selected the best of the three trials in terms of achieving maximum running speed (MRS). Participants were asked to wear the same shoes and clothing during all trials, and to consume only a light meal at least 4 hours before testing. The participants were asked not to undertake any other sport activity during the last two days leading up to the data collection day.

Data collection

A Kodak EktaPro 1000 high-speed video camera (Kodak, Hamburg, Germany) sampling at 250 Hz was used (Paradisis, Bissas, & Cooke, 2009, 2015; Paradisis & Cooke, 2001). The camera was fixed on a tripod at a distance of 10 m from the runway with its optical axis perpendicular to the plane of motion. The field of view of the camera zoomed so as to record the final two consecutive steps (i.e. one full stride) of each run, however, participants were required to continue sprinting after the finish line for 5 m in order to avoid abrupt slowing down or an unconventional running technique with trunk tilting actions on the finish line. Calibration for the 2D-DLT kinematic and kinetic analysis was conducted by placing a 6 m x 2.5 m frame with 16 control markers perpendicular to the camera axis. The X-axis represented the direction of the runway. Y-axis was vertical and perpendicular to the X-axis (Paradisis & Cooke, 2001).

Data analysis

Seventeen segment endpoints were manually digitized using SIMI Motion 9.2 (Munich, Germany). A 14-segment body parameter model (De Leva, 1996) was used to obtain data for the whole-body centre of mass (CM) and limb segments. Surface markers were identified in the digitization process and the magnification factor was utilised (≤400%) to assist with the identification of markers. When the markers were not clearly visible, the identification of the points for digitization was based on superficial anatomical landmarks and an understanding of axes of rotation at the joints (Challis, Bartlett, & Yeadon, 1997). For each running sequence, digitizing started 3 frames before the touchdown of the one foot and ended 3 frames after the touchdown of the opposite foot. The video recordings were smoothed using a cross-validated quintic spline (Giakas & Baltzopoulos, 1997).

In order to ensure reliability of the digitizing process, repeated digitizing (two trials) of one running sequence was performed with an intervening period of 48 hours. Three statistical methods for assessing reliability were used: 95% limits of agreement, coefficient of variation and intraclass correlation coefficient. The data for each tested variable were assessed for heteroscedasticity by plotting the standard deviations against the individual means of the two trials. If the data exhibited heteroscedasticity a logarithmic transformation of the data (loge) was performed prior to the calculation of absolute reliability measures (Bland & Altman, 1986). Therefore, depending on the presence of heteroscedasticity the coefficient of variation and limits of agreement values were expressed in either original or ratio scale. The results showed minimal systematic and random errors and therefore confirmed the high reliability of the digitizing process with regard to the overall group of participants.

Spatio-temporal characteristics

The step cycle had as a starting point the touchdown of the ipsilateral foot, it continued through the flight phase, and terminated at touchdown of the contralateral foot. Touchdown was defined as the instant at which the foot of the participant made contact with the ground and takeoff as the instant at which the participants' foot left the ground.

The appropriate frames defining touchdown and take-off were identified through visual inspection by the researcher who digitized all the trials (Paradisis & Cooke, 2001). The following variables were calculated: Step time: from touchdown of the ipsilateral foot to the touchdown of the contralateral foot. Contact time (CT): the time that the foot is in contact with the ground. Braking phase (BP): the time period of the downward movement of the CM with a decreasing knee and ankle angle. Propulsive phase (PP): the time period of the upward movement of the CM with an increasing knee and ankle angle. Flight time (FT): time from take-off of the ipsilateral foot to touchdown of the contralateral foot. Stride time (SDT): time between consecutive touchdowns of the same foot. Swing time (SWT): time that foot was not in contact with the ground during a stride, and was determined by subtracting the contact time from stride time. Step length (SL): horizontal distance traveled by the CM during a step. Flight length (FL): horizontal distance traveled by the CM from the take-off of the ipsilateral foot to the touchdown of the contralateral foot. Contact length (CL): horizontal distance traveled by the CM during the contact time. Step rate (SR): the number of steps per second. MRS was calculated according to the formula:

$$MRS = \frac{SL}{(CT + FT)} \tag{1}$$

Angles

At touchdown and take-off, the following angles were measured: knee joint angle (α, the angle between the thigh and the lower leg), hip joint angle (β, the angle between the trunk and the thigh), shank to running surface (γ, The angle of the lower leg relative to the running surface), trunk to running surface angle determined by the line between the hip and glenohumeral joints of the right side of the body (δ) (Figure 1); additionally the distance parallel to the running surface between a line perpendicular to the running surface which passes through the CM and the contact point at touchdown and take-off were measured (DCM, Figure 1).

*** FIGURE 1 NEAR HERE ***

Spring-mass model parameters

The average CT and FT values of the left and right foot were used for the estimation of K_{vert} and K_{leg}, according to the "sine-wave" method (Morin et al., 2005). This method allows estimating K_{vert} and K_{leg} during running based on a few simple variables (body mass, forward speed, leg length, FT and CT). This method is not without limitations (Coleman, Cannavan, Horne, & Blazevich, 2012) and relies on several assumptions; *i.e.*, CM vertical displacement values i) reach a maximum at the middle of the stance phase and ii) are of equivalent magnitude before and after mid-stance. However, this simple method remains a reliable and acceptable descriptor of stance-limb mechanics for the range of running velocities achieved in this study (Clark, Ryan, & Weyand, 2014; Girard et al., 2017; Pappas, Paradisis, Tsolakis, Smirniotou, & Morin, 2014). Moreover, the estimations of K_{vert} and K_{leg} obtained during treadmill running (for a range of speeds 4.4 - 6.7 $m.s^{-1}$) have been reported as highly reliable for both intra-session and inter-session designs (ICCs: 0.87 – 0.99) (Girard, Brocherie, Morin, & Millet, 2016; Pappas, Dallas, & Paradisis, 2017; Pappas et al., 2014). The estimation of K_{vert} and K_{leg} was made according to the following formulae (Morin et al., 2005):

$$K_{vert} = \frac{F_{max}}{\Delta y} \quad (2)$$

$$F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c} + 1\right) \quad (3)$$

$$\Delta y = -\frac{F_{max} {t_c}^2}{m\pi^2} + g\frac{{t_c}^2}{8} \quad (4)$$

$$K_{leg} = \frac{F_{max}}{\Delta L} \quad (5)$$

$$\Delta L = L - \sqrt{L^2 - \left(\frac{vt_c}{2}\right)^2} + \Delta y \quad (6)$$

where g = acceleration of gravity (9.81 m.s^{-2}), π constant (3.14159), F_{max} is the maximal ground reaction force during contact, Δy is the vertical displacement of the COM, m is the participant's body mass (in kg), ΔL is the leg length variation, and L is the resting leg length and is modeled from each athlete's stature according to Winter, (1979) L = 0.53 x participants' height (in m). Prior to further analysis the K_{leg} and K_{vert} values were corrected with the correction factor (1.0496 K), which was suggested to improve the accuracy of the method (Coleman et al., 2012).

The force applied perpendicular to the running surface (PF) and the effective force (EF) were calculated according to(Weyand et al., 2000):

$$PF = FOG + EF \quad (7)$$

$$FOG = \frac{ST}{CT} \quad (8)$$

$$EF = FOG - 1 \quad (9)$$

$$EI = EF \cdot CT \quad (10)$$

where FOG is the average mass-specific force applied to oppose gravity during foot-ground contact and EI is the effective impulse.

Statistical analysis

A one-way analysis of variance (ANOVA) was used to establish if there was any significant difference among the three subgroups. For ANOVA, the assumption of sphericity was examined using Mauchly's test. In the event of significant overall group differences, Bonferroni post hoc tests were used to identify the specific group differences. Effect sizes, using the Cohen's criterion (d) (Cohen, 1988) were defined as "small, d = 0.2," "Medium, d = 0.5," and "large, d = 0.8". Additionally, all kinematic and kinetic variables were analyzed by simple linear regression. The relative importance of all variables to MRS was assessed by the factorial change in each variable provided by the respective regression equation for all participants tested as well as across each of the three sub-categories. SPSS software (SPSS Inc., version 22, Chicago, IL) was used for all statistical analyses. The significance level for all the tests was set at $p < 0.05$ with all data reported as mean ± SD.

Results

Spatiotemporal parameters

In our cohort of 50 participants, MRS was on average 8.53 ± 0.72 $m.s^{-1}$ and ranged from 7.12 to 10.35 $m \cdot s^{-1}$ (Slow: 7.12 to 7.99 $m.s^{-1}$, Medium: 8.05 to 8.94 $m.s^{-1}$, and Fast: 9.01 to 10.35 $m.s^{-1}$, Table 1). MRS values were significantly ($F = 104.5$, $p < 0.05$) higher in Fast *vs*. Medium (+11.0%) and Slow (+22.1%) as well as in Medium *vs*. Slow (+10.0%) (Tables 1 and 4). Compared to Slow, SR values were significantly higher ($F = 13.56$, p <

0.05) in Fast (+13.1%) and Medium (+8.1%) (Tables 1 and 4). SL and FL values were significantly (F =7.24 and 17.59, respectively, $p < 0.05$) higher in Fast than in Slow (+8.2% and +19.6%, respectively) and Medium (+6.0% and +16.7%, respectively) (Tables 1 and 4). Compared to Slow, SDT, ST, and SWT values were significantly lower (F = 14.72, 14.22 and 7.47, respectively, $p < 0.05$) in Fast (-11.3%, -11.4% and -8.2%, respectively) and Medium (-7.5%, -7.3% and -7.4%, respectively) (Tables 1 and 4). CT and PP values were significantly lower (F = 29.08 and 14.93, respectively) in Fast *vs*. Medium (-13.5% and -17.5% respectively) and Slow (-20.2% and -29.4% respectively) as well as in Medium *vs*. Slow (-7.8% and -14.4% respectively) (Tables 1 and 4). CL, FT, and BP values did not differ between groups (Tables 1 and 4). Finally, none of the joint angle values differed between groups ($p>0.05$, Table 2).

*** TABLES 1 & 2 NEAR HERE ***

Kinetic and spring-mass model parameters

Fast had significantly higher K_{vert}, K_{leg}, and FOG values (F = 22.21, 6.50, and 18.53, respectively) than Medium (+44.1%, +18.1%, and +10.8%, respectively) and Slow (+25.4%, +22.0%, and +10.4%, respectively) (Tables 3-4).

*** TABLES 3 & 4 NEAR HERE ***

Regression analysis

Regression analysis revealed significant association of MRS with most of the analyzed variables (r ranging 0.46 to 0.80, $p < 0.05$), with highest correlation coefficients measured for CT (r = -0.80), PP (r = -0.70), K_{vert} (r = 0.74), and K_{leg} (r = 0.77) (Figures 2 and 3, Table 5). For each group separately, regression analysis revealed significant ($p < 0.05$) associations with MRS only for CT (r = -0.58) in Slow and for CT (-0.53), PP (-0.51), K_{vert} (r = 0.54) and K_{leg} (r = 0.57) in Fast (Table 5).

*** FIGURES 2 & 3 AND TABLE 5 NEAR HERE ***

Discussion

The aim of this study was to identify how performance level affects several key running mechanical factors during the MRS phase of a 35 m straight-line overground sprint. Our *a priori* categorisation into Fast, Medium and Slow sprinters indicates that twelve, eight and seven out of twenty one variables significantly distinguished Fast from Slow, Fast from Medium and Medium from Slow sprinters, respectively. Also, Medium sprinters displayed significantly different mechanical charactersitics in 7 variables compared to Slow sprinters. Our first hypothesis, stating that faster compared to slower sprinters at MRS would produce favorable mechanical characteristics, is therefore verified. Additionally, high associations of MRS with both K_{vert} and K_{leg} (both for the whole sample and the Fast group) would support our second hypothesis that these mechanical features are key to generate faster top speed during a short sprint.

The present results indicated significant differences for MRS values among Slow, Medium and Fast performance groups (7.67±0.27, 8.44±0.22 and 9.37±0.41 $m.s^{-1}$, respectively). Overall, the range of values corresponded to those attained by physicallyactive students (7.40 – 8.1 $m.s^{-1}$) (Paradisis et al., 2015; Paradisis & Cooke, 2001, 2006), sprinters with average performance level (8.37 – 9.08 $m.s^{-1}$) (Paradisis et al., 2015), and sprinters with higher performance level (9.38 – 10.37 $m.s^{-1}$) (Bezodis et al., 2008; Paradisis et al., 2015; Rabita et al., 2015), respectively. The importance of achieving high MRS values for achieving best sprint race performance is supported by high correlation coefficients (0.91 – 0.96) reported elsewhere between MRS and 100-m performance (Brüggemann et al., 1999). In particular, the speed which was achieved at the 30-40 m distance interval during the 2017 World Athletics Championship 100 m men's final was significantly correlated (0.98) with the final race time, which also corresponded to 96 ± 2% of the maximum speed (Bissas et al 2018). As expected, MRS is a variable that clearly discriminates sprinters between different performance levels.

Attainment of distinct MRS values among the three performance level groups was accompanied by key differences in most of spatiotemporal characteristics. In particular, SL was greater in Fast than in Slow and Medium (+8.2% and +6.0%, respectively), but not between Slow and Medium. This indicates that the fastest sprinters compared to their counterparts of lower performance level adopted a longer step pattern strategy in order to produce faster running speeds near the 30-35-m distance mark. Additionally, SR was greater in Fast and Medium than in Slow (+13.1% and +8.1%, respectively). Whilst sprinters of lower performance level are not capable of producing high SR values at peak speeds, a lack of difference for SR between Fast and Medium sprinters reinforces that SL is probably more important in this particular context to explain difference in MRS between these two groups. Furthermore, our results indicated that CT is a temporal characteristic that differed among all three performance level groups (Table 4). Hence, faster sprinters spent less time in contact with the ground compared to sprinters of lower performance level, whereas FT was comparable between groups. Our findings therefore strengthen the suggestion that higher running speeds are achieved through reduced contact times, as opposed to shorter flight times (Morin et al., 2012; Paradisis & Cooke, 2006; Weyand et al., 2010; Weyand et al., 2000). Using group level comparisons, our unique data set indicate that SR could explain MRS differences between Slow and Fast-Medium sprinters, while longer SL values differentiated Fast from Medium and Slow sprinters. However, CT, but not FT, helps differentiating performance among all three groups. Practically, progressing from one performance level to the next one (from Slow to Medium and from Medium to Fast) can occur through either different distinct pathways (i.e. improve only one of the key parameters) or a combination of improvements. However, as all three factors (SR, SL, CT) are mechanically interrelated ((Paradisis & Cooke, 2001) it would not be wise to target only one of them through specific training whilst removing the focus from the others. In theory, one could employ resistance and flexibility drills to improve SL but this on its own, without reducing the CT and therefore increasing SR, could lead to suboptimal increases in MRS. A crucial aspect is therefore to generate large impulses onto the ground, something that governs both SL and SR and subsequently MRS (Weyand et al., 2000).

Our analysis of the relationships between selected mechanical variables and MRS for all participants regardless of performance group indicated a moderate contribution of SR to the achieved MRS at 30-35 m during a 35 m sprint, as it only accounted for 43% of MRS variance. The contribution of SL (26%) was even smaller. Different views exist in the literature regarding the relative importance of developing longer SL (Gajer et al., 1999; Hunter et al., 2004; Maćkała & Mero, 2013; Mero & Komi, 1985) over higher SR (Bezodis et al., 2008; Mero et al., 1992) to reach top speeds. While individual strategies to reach MRS were also evident in our tested sample, it has previously been demonstrated that there is a large variation in running speed patterns among elite sprinters since SR and SL are highly individual qualities (Salo, Bezodis, Batterham, & Kerwin, 2011). Our observation of a moderate contribution of SR to the achieved MRS at 30-35 m during a 35 m sprint, partially support conclusions of previous studies (Bezodis et al., 2008; Mero et al., 1992), which suggest that SR is the main limiting factor at maximal speed. However, as SR will not compensate for insufficient stride lengths, its limiting role becomes apparent only once mechanically adequate SL values have been achieved. The definition of “adequate” will differ between individuals and groups of sprinters due to a range of differences including those in segment lengths. Our findings that the Fast group exhibited longer SL values than the other two highlight the prerequisite role of SL in the speed advantages gained through high SR values.

A unique observation was also that the PP became shorter as performance level increased, with significant differences observed among the three groups. In contrast, the duration of BP was similar. It appears that PP is the discriminative variable of performance level when the foot is in contact with the ground. Indirect support for this interpretation comes from studies showing that 6 – 8 weeks of specific sprint training improved MRS by decreasing propulsive phase duration (Paradisis, Bissas, & Cooke, 2013; Paradisis et al., 2015). Our novel findings indicate that shorter CT could explain 64% of the variance in MRS and was mainly due to shorter PP since braking phase duration was similar between the three groups. The combination of shorter PP with longer SL in the Fast group seems to be the result of more powerful actions of lower limbs when pushing-off against the ground in sprinters of higher performance level. The attainment of shorter CT in Fast sprinters, while SL remains optimal, could theoretically be explained by the capacity of better performers to generate large propulsive impulses driven by the production of large horizontal forces (Weyand et al., 2000; Weyand, et al., 2010) in limited time periods. In support, the faster runners in our study also produced greater forces to oppose gravity (FOG) compared to their slower counterparts indicating that faster sprinters can reach greater MRS by applying greater support forces to the ground; similar results have been reported previously (Weyand et al., 2000; Weyand et al., 2010). The relative smaller contribution of FOG to the development of higher running speed (it represented 39% of the MRS variance) leads us to suggest that the ground force-step rate combination that maximizes forward speed is set largely by contacting the ground faster (short CT) with greater peak vertical force.

Despite the fact that significant differences occurred in the spatio-temporal characteristics among the three groups, the angles of the body segments (i.e., similar ankle, knee and hip joints) during contact and take off phases were similar. This would indicate that more experienced sprinters achieve faster MRS without the necessity to adopt a different body positioning of their lower extremities, but through the generation of greater propulsive impulses. In line with this, previous research indicated that specific sprint training improved MRS and the related spatio-temporal characteristics, without altering the body segment angles in a population cohort ranging from physical education students to experienced sprinters (Paradisis et al., 2009, 2013, 2015; Paradisis & Cooke, 2006). This supports the suggestion that the faster sprinters in our study had improved neural and/or the contractile characteristics, probably due to years of training. This assumption remains speculative since our study did not include any specific neuromuscular function profiling of tested athletes.

Our spring-mass modelling indicates that both K_{vert} and K_{leg} values were greater in Fast than in Slow (+44.1% and +18.1% respectively) and Medium (+25.4% and +22.0% respectively) sprinters. These differences are remarkable and underpin the notion that high stiffness values are needed for higher MRS. Besides, previous studies have shown that K_{vert} values typically increase with running speed (Arampatzis et al., 1999). Past research on world class sprinters (100 m time = 9.58 - 9.84 s) has calculated K_{vert} values in the region of 355.8 - 541.8 kN·m^{-1} (Taylor & Beneke, 2012), so the K_{vert} values (118.42 kN·m^{-1}) for the fastest sprinter of this study (100 m = 10.60 s) are in a realistic zone within the stiffness continuum.

Another unique observation was that K_{vert} and K_{leg} explained 55% and 59% of the variance in MRS (N = 50), respectively. It has been argued that mechanical stiffness regulation is a vital component for setting SR (Farley & Gonzalez, 1996). The strong correlation observed between changes in K_{vert} and SR with fatigue induced by repetition of "all-out" running efforts (Girard et al., 2017; Morin et al., 2006) and in maximal treadmill sprints of different distances (Girard et al., 2016; Hobara et al., 2010) indicates that a decreased K_{vert} leads to lower SRs. In our study, an increase in K_{vert} in the Fast group would enable the spring-mass system of quicker sprinters to recoil in a shorter time (Farley & Gonzalez, 1996), something essential for quicker absorption and generation of power and kinetic energy during ground contact (Hobara et al., 2010). In line with previous results (Arampatzis et al., 1999; Farley, Glasheen, & McMahon, 1993; Kuitunen et al., 2011), the current study demonstrated a clear association of mechanical stiffness with running speed, indicating that producing elevated K_{vert} and K_{leg} values are associated with increased MRS (especially for Fast sprinters), higher SR and lower CT. Therefore producing larger stiffness values would in turn participate to improve MRS. This is reinforced by observation of shorter CT and larger impulses when stiffness values are also higher. However, due to the multifactorial nature of the process modulating stiffness it is challenging to break down accurately training elements purely responsible for stiffness conditioning. Nevertheless, as some of the stiffness determinants are known, there are already training methods available aiming to manipulate those factors. For instance, training involving high stretching velocities (e.g. plyometrics, downhill sprinting, loaded sprints, bounding) could provide sufficient stimuli to reinforce several stiffness regulating mechanisms (e.g. muscle preactivation, tendon-aponeurosis behavior, Golgi tendon organs and muscle spindles) (Kubo et al., 2007; Kubo, Ishigaki, & Ikebukuro, 2017; Muñiz, Virgen-Ortiz, Huerta, Trujillo, & Marin, 2008).

Limitations and additional considerations

The present study has some limitations. First, the data collected were specifically focusing on the 30-35 m distance interval in order to emphasize the few steps when running speed is peaking. As such, our results must remain specific to the 30–35-m distance interval of a 35-m sprint and should not be extrapolated to other phases of the sprint (i.e. early acceleration or/and deceleration) or shorter/longer sprint durations. For future research the comparison of different distance intervals and the determination of possible even larger differences across different performance level groups would be novel. Second, as the present results were obtained in male adult athletes with a sprint-training background, the conclusions should not be extrapolated to other age groups, genders, or populations, Indeed, age-related differences in spatio-temporal parameters and ground reaction forces during sprinting have been observed in 99 boys aged 6.5 - 15.4 years (Nagahara, Takai, et al., 2018). Third, the stiffness estimations are based on a number of assumptions associated with the spring-mass model (Blickhan, 1989; McMahon & Cheng, 1990). However, these mechanical simplifications are necessary as the complexity of the human body mechanics during running makes any totally accurate macroscopic approach impossible. These are also surpassed by useful information derived from the analysis using the spring mass model, which successfully describe the general characteristics of locomotion (Blickhan, 1989).

Conclusions

Our findings based on a large sample and distinct subpopulations of sprinters demonstrate that maximal running speed at 30-35 m increased with sprinting performance level and was achieved through shorter contact time and propulsive phase, longer step length, faster step rate, and higher vertical and leg stiffness. Therefore, the attainment of maximal running speed during a 35-m straight-line sprint is influenced by key mechanical charactersitics which clearly differ amongst sprinters of various abilities. Knowledge of how performance level, reached through a combination of trainable and non-trainable factors, influences the production of effective running mechanics and the nature of the association between these variables with running velocity may provide a basis for coaches when developing individualised sprint training protocols.

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Figure 1. Location of the body landmarks and visualization of the angles: knee (α), hip (β), shank to running surface (υ), trunk to running surface (δ), thigh to running surface (ε), the angle between the two thighs (ζ) DCM = distance from the center of mass.

Figure 2. Swing time (A), propulsive phase (B), contact time (C), step time (D), flight length (E), step length (F), and step rate (G) as a function of maximum running speed for all participants (N-50).

Figure 3. Leg stiffness (A), vertical stiffness (B) and FOG = average mass-specific force applied to oppose gravity during contact (C) as a function of maximum running speed for all participants (N-50).

Table 1. Spatiotemporal characteristics of the three groups.

	Slow (N = 13)	Medium (N = 21)	Fast (N = 16)
Maximum running speed ($m \cdot s^{-1}$)	7.67±0.27	8.44±0.22*	9.37±0.41*#
Step length (m)	2.00±0.10	2.04±0.12	2.17±0.15*#
Step rate (Hz)	3.83±0.18	4.14±0.28*	4.34±0.29*
Contact length (m)	1.03±0.07	1.05±0.08	1.00±0.07
Flight length (m)	0.97±0.09	1.00±0.10	1.16±0.11*#
Contact time (ms)	134±12	124±11*	107±8*#
Braking phase (ms)	55±6	56±8	51±8
Propulsive phase (ms)	79±14	68±11*	56±9*#
Flight time (ms)	127±10	118±12	124±11
Step time (ms)	261±13	242±17*	232±16*
Swing time (ms)	390±16	361±29*	358±25*
Stride time (ms)	525±22	485±34*	466±31*

* Significantly different from Slow and # significant different from Medium ($p < 0.05$)

Table 2. Postural characteristics of the three groups.

	Slow (N = 13)	Medium (N = 21)	Fast (N = 16)
Contact instant			
Knee (°)	145±7	147±6	145±7
Shank (°)	91±4	92±4	91±5
Hip (°)	134±6	133±6	135±5
Trunk (°)	80±5	79±4	81±4
DCM (cm)	30.4±41	31.0±40	28.8±43
Take off instant			
Knee (°)	161±7	162±7	161±7
Shank (°)	42±3	42±3	41±4
Hip (°)	203±8	202±7	204±8
Trunk (°)	83±5	83±4	84±4
DCM (cm)	58.8±47	59.2±40	58.8±56

Knee=knee joint angle; Hip= hip joint angle; Shank= shank to running surface; Trunk= trunk to running surface angle (determined by the line between the hip and glenohumeral joints of the right side of the body) (δ); DCM= distance from the center of mass.

Table 3. Spring mass model characteristics of the three groups.

	Slow (N = 13)	Medium (N = 21)	Fast (N = 16)
FOG (Wb)	1.952±0.123	1.959±0.108	2.163±0.108*#
Effective impulse (Wb·s)	0.127±0.010	0.118±0.012	0.124±0.011
Vertical stiffness (kN·m^{-1})	73.8±9.7	83.8±11.7	105.1±16.8*#
Leg Stiffness (kN·m^{-1})	13.1±2.3	12.7±2.3	15.5±2.7*#

** Significantly different from Slow and # significant different from Medium ($p < 0.05$). FOG= average mass-specific force applied to oppose gravity during contact.*

Table 4. Comparison matrix of all examined variables with % differences and effect sizes among the three groups and the fold changes with the changes of maximum running speed.

	Fast-Slow (%, d)	Fast-Medium (%, d)	Medium-Slow (%, d)	Fold change with 1.45 change of MRS
MRS	22.1%, 4.95*	11.0%, 2.84*	10.0%, 3.15*	-
Step rate	13.1%, 2.09*	4.7%, 0.63	8.1%, 1.32*	1.25
Step length	8.2%, 1.34*	6.0%, 0.93*	2.0%, 0.30	1.16
Contact length	-2.6%, 0.37	-4.1%, 0.59	1.5%, 0.21	-
Flight length	19.6%, 1.92*	16.7%, 1.63*	2.5%, 0.26	1.42
Stride time	-11.3%, 0.74*	-4.1%, 0.60	-7.5%, 0.57*	-1.25
Step time	-11.4%, 1.99*	-4.4%, 0.63	-7.3%, 1.30*	-1.26
Flight time	-2.0%, 0.29	5.1%, 0.52	-6.7%, 0.81	-
Contact time	-20.2%, 2.65*	-13.5%, 1.77*	-7.8%, 0.87*	-1.55
Braking phase	-7.1%, 0.57	-8.7%, 0.63	1.8%, 0.14	-
PP	-29.4%, 1.95*	-17.5%, 1.19*	-14.4%, 0.87*	-2.06
Swing time	-8.2%, 1.52*	-0.9%, 0.11	-7.4%, 1.24*	-1.17
Vertical stiffness	44.1%, 2.28*	25.4%, 1.47*	14.9%, 1.01	1.93
Leg stiffness	18.1%, 0.95*	22.0%, 1.11*	-3.2%, 0.18	2.41
FOG	10.8%, 1.83*	10.4%, 1.90*	0.4%, 0.815	1.22
EI	-2.0%, 1.83	5.1%, 1.90	-6.7%, 0.06	-

** Significantly different between the groups ($p < 0.05$), MRS = maximum running speed, PP = propulsive phase of contact time, FOG = average mass-specific force applied to oppose gravity during contact, EI = effective impulse.*

Table 5. Association (Pearson's correlation coefficient) of maximum running speed with all the analyzed variables for all the participants and for each group separately.

	All participants (N = 50)	Slow (N = 13)	Medium (N = 21)	Fast (N = 16)
Step rate	0.66*	0.38	0.41	0.32
Step length	0.51*	0.36	0.08	0.30
Contact length	-0.15	-0.19	0.05	0.03
Flight length	0.65*	0.53	0.07	0.39
Stride time	-0.65*	-0.33	-0.40	-0.29
Step time	-0.66*	-0.38	-0.39	-0.34
Flight time	-0.08	0.53	0.07	-0.09
Contact time	-0.80*	-0.58*	-0.34	-0.53*
Braking phase	-0.19	0.15	-0.03	0.02
PP	-0.70*	-0.54	-0.27	-0.51*
Swing time	-0.46*	-0.03	-0.35	-0.18
Vertical stiffness	0.74*	0.24	0.17	0.54*
Leg stiffness	0.77*	0.26	0.15	0.57*
FOG	0.62*	0.45	0.03	0.38
EI	-0.08	0.19	-0.24	-0.09

** = $p < 0.05$, PP = propulsive phase of contact time, FOG = average mass-specific force applied to oppose gravity during contact, EI = effective impulse.*

Figure 1

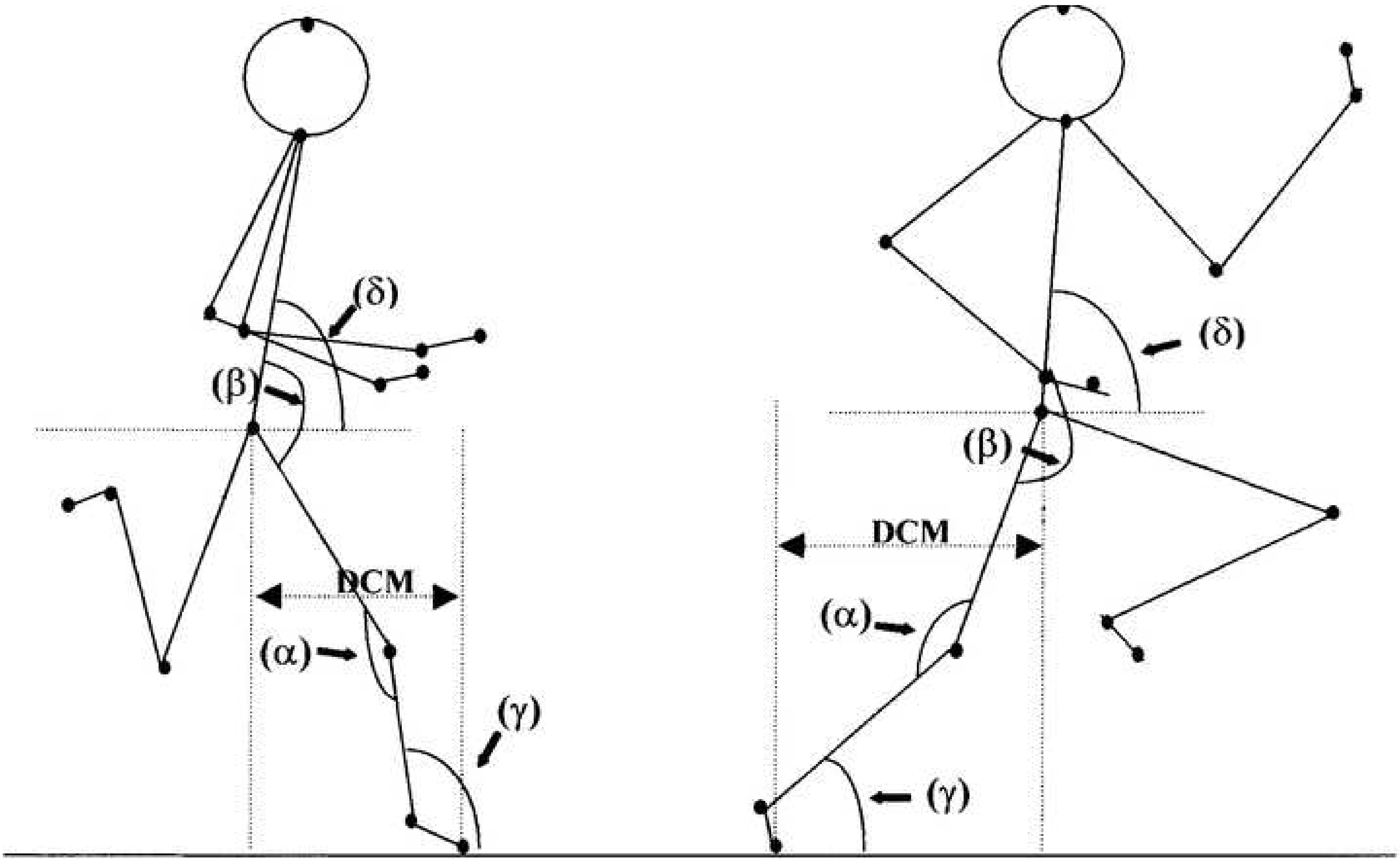
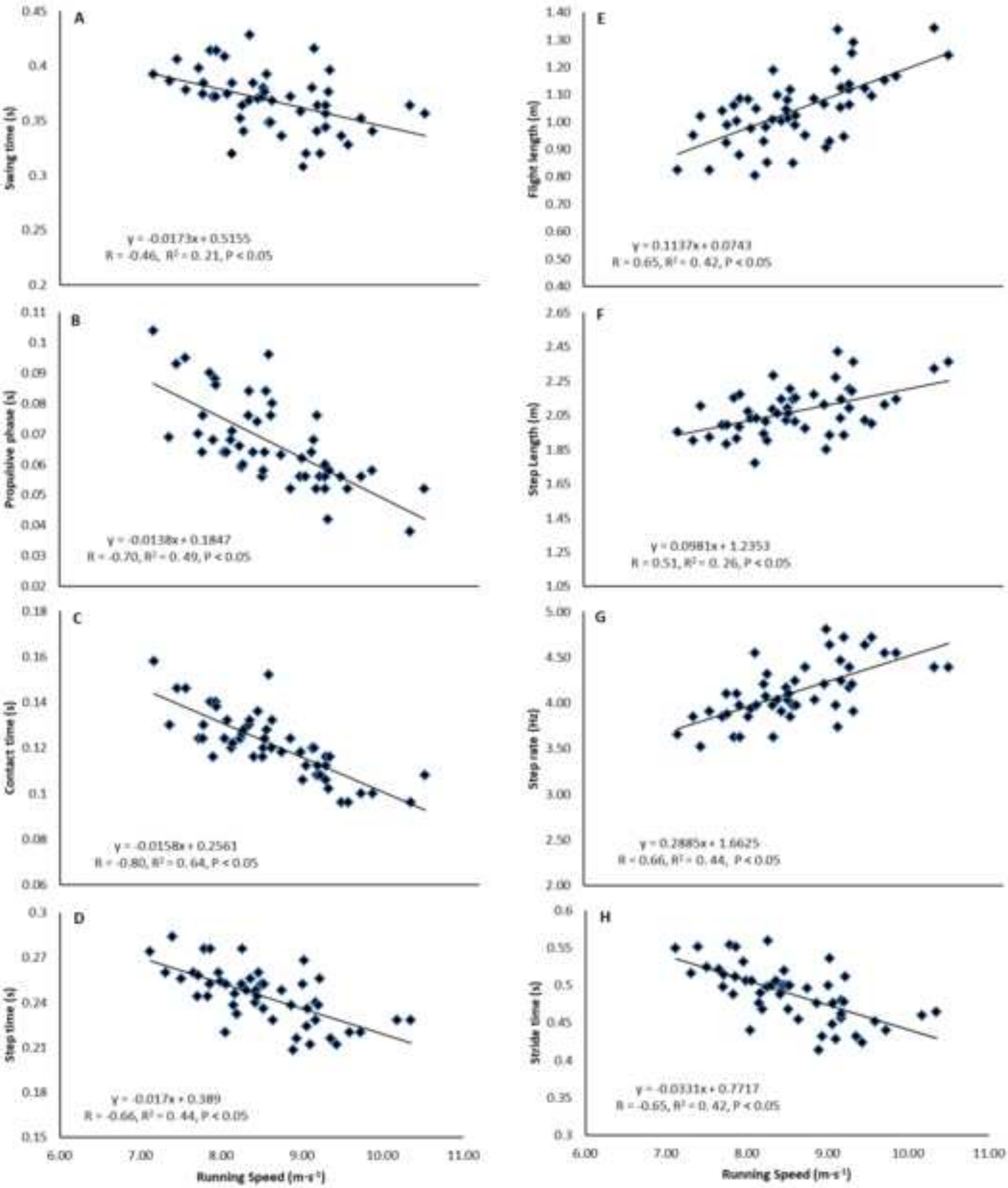
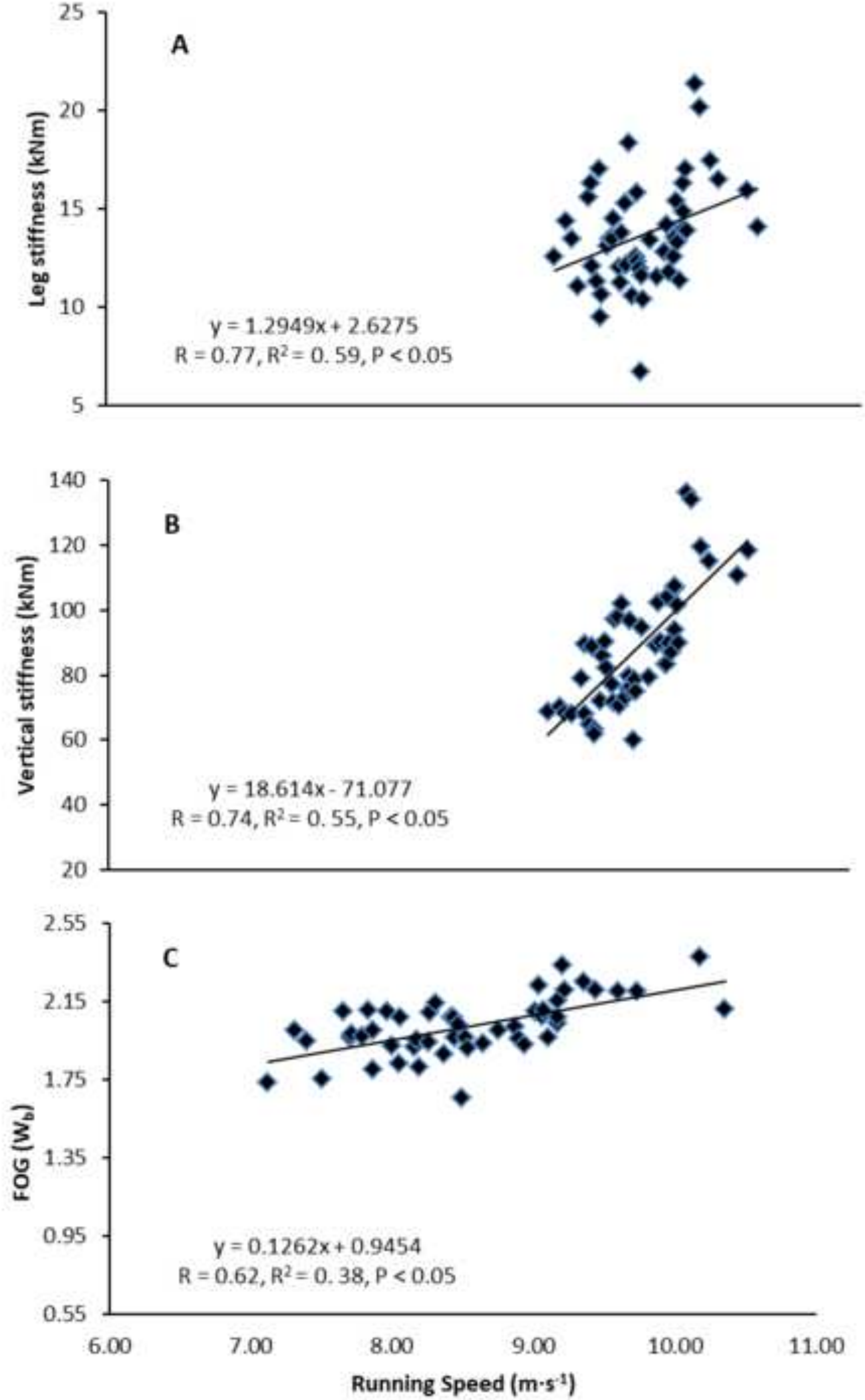


Figure 2



A
Swing time (s)
y = -0.0173x + 0.5155
R = -0.46, R² = 0.21, P < 0.05
B
Propulsive phase (s)
y = -0.0138x + 0.1847
R = -0.70, R² = 0.49, P < 0.05
C
Contact time (s)
y = -0.0158x + 0.2561
R = -0.80, R² = 0.64, P < 0.05
D
Step time (s)
y = -0.017x + 0.389
R = -0.66, R² = 0.44, P < 0.05
Running Speed (m·s⁻¹)
E
Flight length (m)
y = 0.1137x + 0.0743
R = 0.65, R² = 0.42, P < 0.05
F
Step Length (m)
y = 0.0981x + 1.2353
R = 0.51, R² = 0.26, P < 0.05
G
Step rate (Hz)
y = 0.2885x + 1.6625
R = 0.66, R² = 0.44, P < 0.05
H
Stride time (s)
y = -0.0331x + 0.7717
R = -0.65, R² = 0.42, P < 0.05
Running Speed (m·s⁻¹)

Figure 3



A
Leg stiffness (kNm)
y = 1.2949x + 2.6275
R = 0.77, R² = 0. 59, P < 0.05
B
Vertical stiffness (kNm)
y = 18.614x - 71.077
R = 0.74, R² = 0. 55, P < 0.05
C
FOG (W_b)
y = 0.1262x + 0.9454
R = 0.62, R² = 0. 38, P < 0.05
Running Speed (m·s⁻¹)