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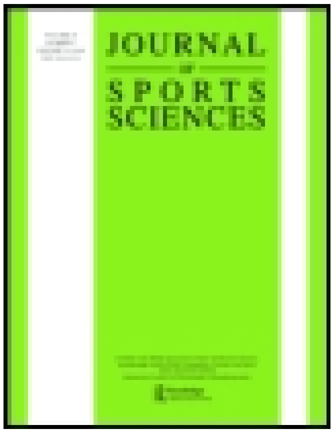

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Mechanical determinants of acceleration and maximal sprinting speed in highly trained young soccer players

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Abstract
The aim of the present study was to examine, in highly trained young soccer players, the mechanical horizontal determinants of acceleration (Acc) and maximal sprinting speed (MSS). Eighty-six players (14.1 ± 2.4 year) performed a 40-m sprint to assess Acc and MSS. Speed was measured with a 100-Hz radar, and theoretical maximal velocity (V_0), horizontal force (F_0) and horizontal power (P_{max}) were calculated. Within each age group, players were classified as high Acc/fast MSS (>2% faster than group mean), medium (between −2% and +2%), and low/slow (>2% slower). Acc and MSS were very largely correlated (−0.79; 90% confidence limit [−0.85; −0.71]). The determinants (multiple regression r^2 = 0.84 [0.78; 0.89]) of Acc were V_0 (partial *r*: 0.80 [0.72; 0.86]) and F_0 (0.57 [0.44; 0.68]); those of MSS (r^2 = 0.96 [0.94; 0.97]) were V_0 (0.96 [0.94; 0.97]) and P_{max} (0.73 [0.63; −0.80]). High/Med have likely greater F_0 (Cohen's d: +0.8 [0.0; 1.5]), V_0 (+0.6 [−0.1; 1.3]) and P_{max} (+0.9 [0.2; 1.7]) than Low/Med. High/Fast have an almost certainly faster V_0 (+2.1 [1.5; 2.7]) and a likely greater P_{max} (+0.6 [−0.1; 1.3]) than High/Med, with no clear differences in F_0 (−0.0 [−0.7; 0.6]). Speed may be a generic quality, but the mechanical horizontal determinants of Acc and MSS differ. While maximal speed training may improve both Acc and MSS, improving horizontal force production capability may be efficient to enhance sprinting performance over short distances.

Keywords: *football association, force-velocity profile, horizontally oriented force*

Introduction

The ability to perform high-speed running actions is believed to be an important prerequisite for successful participation in soccer (Haugen, Tonnessen, & Seiler, 2013). Professional players have become faster over time (Haugen et al., 2013), indicating that sprinting skills are paramount in modern soccer. For example, recent analyses have shown that sprinting is the most frequent action in goal situations in the first German national league, both for the scoring and assisting player (Faude, Koch, & Meyer, 2012). In addition, acceleration and maximum sprinting speed have been reported to distinguish players from different standards of play (Haugen et al., 2013). While both a high acceleration and a fast maximal sprint speed might allow players to overtake opponents and win balls, a fast maximal speed may also allow reduced relative neuromuscular load during match play (Mendez-Villanueva, Buchheit, Simpson, & Bourdon, 2013). This has likely direct implications for fatigue development and potential injury risk during games.

Acceleration and maximum sprinting speed are two distinct components of sprint running and are considered by many researchers and practitioners to be determined by a combination of specific physiological, metabolic, biomechanical and morphological factors. The magnitude of the correlations between acceleration and maximum sprinting speed (0.56–0.87 (Harris, Cronin, Hopkins, & Hansen, 2008; Little & Williams, 2005; Mendez-Villanueva et al., 2011; Vescovi & McGuigan, 2008)) suggests that they may be specific qualities and, therefore, require different training approaches (Haugen et al., 2013). In fact, it is generally considered that acceleration is

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mainly influenced by concentric force development, impulse and knee and hip extensor activity (Dorn, Schache, & Pandy, 2012). In contrast, maximum sprinting speed may be more related to greater stretch-shortening cycle, lower-limb stiffness and hip extensor activity aimed at producing great vertical ground reaction forces per unit body mass (Harris et al., 2008; Sleivert & Taingahue, 2004; Weyand, Sandell, Prime, & Bundle, 2010).

Understanding the specific mechanical determinants of acceleration and maximum sprinting speed is pivotal to design optimal training programs, especially in developing soccer players. However, to date, most researchers have mainly focused their investigations on non-locomotor-specific determinants and/or vertical force application capability (e.g., lower limb muscles force characteristics (Hoff, 2005), jumping performance (Buchheit, Mendez-Villanueva, Delhomel, Brughelli, & Ahmaidi, 2010)), which limits a possible transfer to locomotor performance. There is growing evidence that horizontal force production may be a stronger determinant of sprinting performance than vertical forces (Brughelli, Cronin, Levin, & Chaouachi, 2008; Morin, Edouard, & Samozino, 2011; Morin et al., 2012), especially during acceleration phases (Hunter, Marshall, & McNair, 2005). It has therefore been suggested that horizontally oriented resistance exercises may be particularly efficient to enhance sprinting performance over short distances (Los Arcos et al., 2014; Meylan, Cronin, Oliver, Hopkins, & Contreras, 2014; Randell, Cronin, Keogh, & Gill, 2010).

Horizontal force production is often assessed in athletes using (single leg) horizontal jumps (Brughelli et al., 2008; Meylan et al., 2014), sprint running on motorised (Morin et al., 2012; Weyand, Sternlight, Bellizzi, & Wright, 2000) or non-motorised (Nummela, Keränen, & Mikkelsson, 2007) treadmills, or ground sprinting while stepping on a force plate (Hunter et al., 2005; Nummela et al., 2007). Nevertheless, sprinting on a treadmill may lack specificity with regard to field-based locomotor performance, and force plates only allow capturing a portion of speed performance (i.e., a couple of steps while either accelerating or sprinting at max speed). To overcome these limitations, a promising approach was recently developed, based on the instantaneous speed changes during a maximal sprint in the field (Mendiguchia et al., 2014; Samozino, Morin, et al., 2013). As previously shown for jumping performance (Samozino, Rejc, Di Prampero, Belli, & Morin, 2012), this modelling technique allows determining each individual mechanical properties of sprint running propulsion: theoretical maximal horizontal force (F_0), maximal horizontal power ($P_{\max}$), theoretical maximal speed (V_0), and in turn, a force/velocity profile (Morin et al., 2012; Samozino et al., 2012; Samozino, Edouard, et al., 2013). The respective impact of these latter variables on acceleration and maximum sprinting speed, is however, still unknown. The aim of the present study was therefore to examine, in highly trained young soccer players, the horizontal mechanical determinants of acceleration and maximum sprinting speed.

Methods

Participants

Eighty-six highly trained soccer players (14.1 ± 2.4 years, 161.2 ± 11.1 cm and 50.1 ± 11.7 kg) representing U13 to U17 teams from an elite academy were involved. All the players, irrespective of age groups, participated on average in ~14 h of combined soccer-specific training and competitive play per week (6–8 soccer training sessions, 1 strength training session, 1–2 conditioning sessions, 1 domestic game per week and 2 international club games every 3 weeks). All players had a minimum of 3 years prior soccer-specific training. The study was approved by the local research ethics committee and conformed to the recommendations of the Declaration of Helsinki.

Experimental overview

Players were tested in the afternoon (4 PM) during the competitive season, after at least two days of easy technical/tactical training (i.e., neither high-intensity running nor resistance training). They sprinted on a synthetic track in an indoor facility maintained at standard environmental conditions (23–24°C), wearing sport shoes (i.e., no football boots). The testing was preceded by a 10-min standardised warm-up including athletic drills (e.g., skipping, high knee runs), five short bursts of progressive accelerations on the track and two maximal 15-m sprints. Players were all very familiar with all test procedures.

Speed measures

Acceleration (10-m sprint time, Acc) and maximal sprinting speed (best 10-m split over a 40-m sprint, MSS) were measured with timing gates (Swift Performance Equipment, Lismore, Australia) (Buchheit & Mendez-Villanueva, 2013). Split times were measured to the nearest 0.01 s. Players commenced each sprint from a standing start with their front foot 0.5 m behind the first timing gate. The players started when ready and completed two trials with the best performances retained for analysis (i.e., to assess the horizontal mechanical determinants of Acc and MSS). Results from both sprints were used to assess intra-day reliability of the different variables. In a similar population, the typical error has been reported to be of 2.2% (90% confidence limits, 1.9; 2.5) and 1.4% (1.2; 1.6) for Acc and MSS, respectively (Buchheit & Mendez-Villanueva, 2013).

Horizontal mechanical profile

Instantaneous speed was measured continuously throughout the entire sprint via a 100-Hz laser (Laveg 300 C, Jenoptik, Germany) and used to derive, for each individual, linear horizontal force–velocity relationships, from which horizontal force–velocity profile (F–V profile, slope of the F–V relationship), theoretical maximal velocity (V_0), horizontal force (F_0) and horizontal power (P_{max}) were calculated (Mendiguchia et al., 2014; Samozino, Morin et al., 2013) (Figure 1).

Statistical analyses

Data in the text and figures are presented as means with 90% confidence limits (CL) and intervals (CI), respectively. All data were first log-transformed to reduce bias arising from non-uniformity error. The reliability of each mechanical variable was assessed while calculating both the typical error of measurement, expressed as a coefficient of variation (CV,

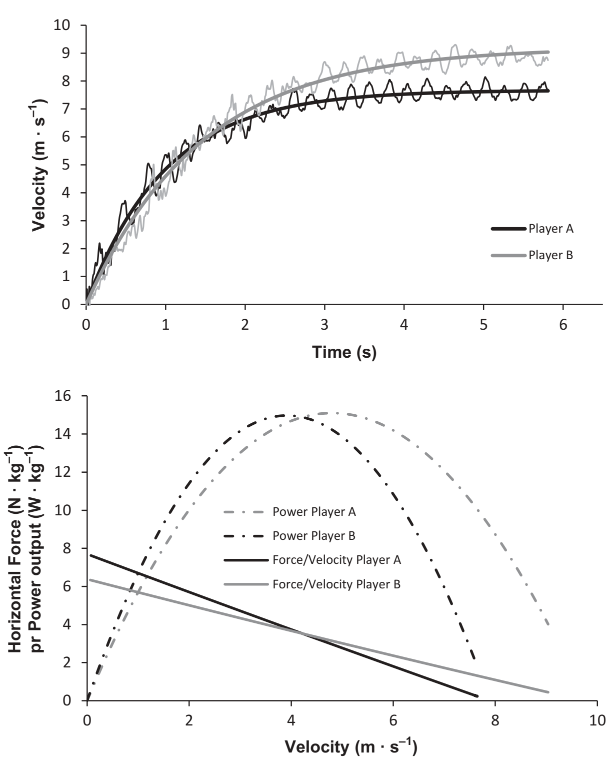

Figure 1. Actual and modelled velocity profiles of two representative players throughout the 40-m sprint (upper panel) and their associated mechanical horizontal profiles (lower panel).

90% CL), and the intraclass correlation coefficient (ICC, 90% CL) (Hopkins, Marshall, Batterham, & Hanin, 2009). To allow the analysis of the relationships between the different variables for all players pooled together, despite the age-related differences in absolute performances, data were expressed as a percentage of each age group mean (Buchheit, 2012). First, the respective horizontal mechanical determinants of Acc and MSS were assessed using multiple linear regression models (stepwise backward elimination procedure), with Acc and MSS as the dependent variables and V_0, F_0, P_{max} and F–V profile as the independent variables. In the backward procedure, variables with F value <4 were removed from the model. The following criteria were adopted to interpret the magnitude of the correlation (r, 90% CI): ≤0.1, trivial; >0.1–0.3, small; >0.3–0.5, moderate; >0.5–0.7, large; >0.7–0.9, very large; and >0.9–1.0, almost perfect. If the 90% CI overlapped small positive and negative values, the magnitude was deemed unclear; otherwise that magnitude was deemed to be the observed magnitude (Hopkins et al., 2009). Within each age-group, players were also classified as High Acc/Fast MSS (>2% faster than group mean), medium (between −2% and +2% of group mean), and Low/Slow (>2% slower than group mean). The 2% threshold was based both on within-player CV for Acc and MSS (Buchheit & Mendez-Villanueva, 2013) and was within the range of a fifth of the between-player SD within each age group (i.e., the so-called smallest worthwhile change (Hopkins et al., 2009)). Between speed group, standardised differences in horizontal mechanical determinants were calculated using pooled standard deviations. Threshold values were >0.2 (small), >0.6 (moderate), >1.2 (large) and very large (>2) (Hopkins et al., 2009). Uncertainty in each effect was expressed as 90% CL and as probabilities that the true effect was substantially positive and negative. These probabilities were used to make a qualitative probabilistic mechanistic inference about the true effect: if the probabilities of the effect being substantially positive and negative were both >5%, the effect was reported as unclear; the effect was otherwise clear and reported as the magnitude of the observed value. The scale was as follows: 25–75%, possible; 75–95%, likely; 95–99%, very likely; >99%, almost certain. Data for groups with limited sample size (High/Slow, n = 2 and Med/Fast, n = 4) are presented in the results, but were not included in the group comparison analysis.

Results

For the reliability analysis, we observed a CV of 1.6% (90% CL, 1.4;1.9) and an ICC 0.97

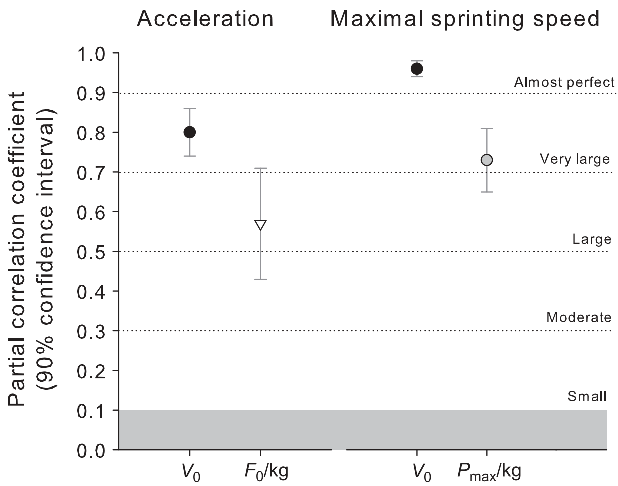

Figure 2. Associations between acceleration (left) or maximal sprinting speed (right) and theoretical maximal velocity (V_0), horizontal force (F_0) and horizontal power (P_{max}) obtained from the multiple stepwise regression analysis. For simplicity, a positive outcome is represented using a positive correlation coefficient – the correlation coefficient for acceleration (10-m sprint time) was therefore changed from a negative to a positive value. The variables not presented (i.e., force–velocity profile) were those excluded from the regression model. The grey area represents trivial correlation coefficients.

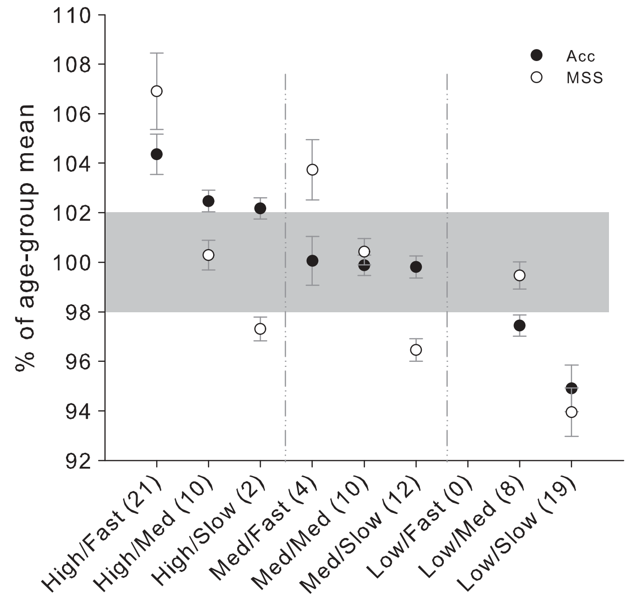

Figure 3. Acceleration (Acc) and maximal sprinting speed (MSS, upper panel) for players grouped by level of Acc and MSS, receptively: High, Medium (Med) and Low for Acc and Fast, Med and Slow for MSS. The grey area represents Med values (see the "Methods" section).

(0.96;0.99) for V_0, 7.8% (6.9;9.1) and 0.64 (0.52;0.74) for F_0/kg, 7.1% (6.2;8.2) and 0.87 (0.82;0.91) for P_{max}/kg, 8.9% (7.8;10.4) and 0.88 (0.83;0.92) for F–V profile, and 1.1% (1.0;1.3) and 0.98 (0.98;0.99) for 40-m sprint time.

Acc and MSS were very largely correlated (r = −0.79, 90% confidence limits [−0.85;−0.71]). The significant determinants (r^2 = 0.84 [0.78;0.89] for the overall multiple regression) of Acc were V_0 and F_0 (Figure 2). The significant determinants of MSS (r^2 = 0.96 [0.94;0.97]) were V_0 and P_{max}. All other variables were excluded from the models (Figure 2).

Twenty-four percent of the players were rated as High/Fast, 12% High/Med, 2% High/Slow, 5% Med/Fast, 12% Med/Med, 14% Med/Slow, 9% Low/Med and 22% Low/Slow (Figure 3). There was no Low/Fast player.

When comparing players with similar MSS but different Acc, players with greater Acc tended to have greater F_0, V_0 and P_{max}, while the difference in F–V profile were inconsistent (Figure 4). When comparing players with similar Acc but different MSS, players with greater MSS tended to have faster V_0 and P_{max}, with no clear differences in either F_0 or force/velocity profile (Figure 4). The magnitude of the difference in V_0 tended to be greater for players differing in MSS than in Acc. In contrast, the magnitude of the difference in P_{max} tended to be greater for players differing in Acc than in MSS.

Discussion

In the present study, we examined for the first time the mechanical horizontal determinants of sprint performance (i.e., Acc and MSS) in highly trained young soccer players. The main results were as follow: (1) acceleration was very-largely and largely associated with V_0 and F_0, respectively; (2) MSS was almost perfectly and very-largely correlated with V_0 and P_{max}, respectively; (3) for players matched for MSS, those with greater acceleration had moderately to largely greater V_0, F_0 and P_{max}; (4) for players matched for acceleration, those with faster MSS had very-largely greater V_0 and moderately greater P_{max}, with no substantial difference in F_0; and (5) there was no consistent association between acceleration/MSS profile and the F–V profile.

While the non-perfect correlation between Acc and MSS (r = −0.79, shared variance between the two tests ~60%) may highlight the specificity of these two capabilities (Little & Williams, 2005; Mendez-Villanueva et al., 2011; Vescovi & McGuigan, 2008), a shared variance >50% is generally interpreted as a proof of a generic quality (Clarke & Clarke, 1970). In fact, the first determinant of both Acc and MSS was V_0 (Figure 2), and the majority of players who displayed a high Acc also tended to have a fast MSS (12%). Similarly, the majority of the players with a moderate Acc also tended to have a moderate MSS (14%), and finally, those with a low Acc, a slow MSS

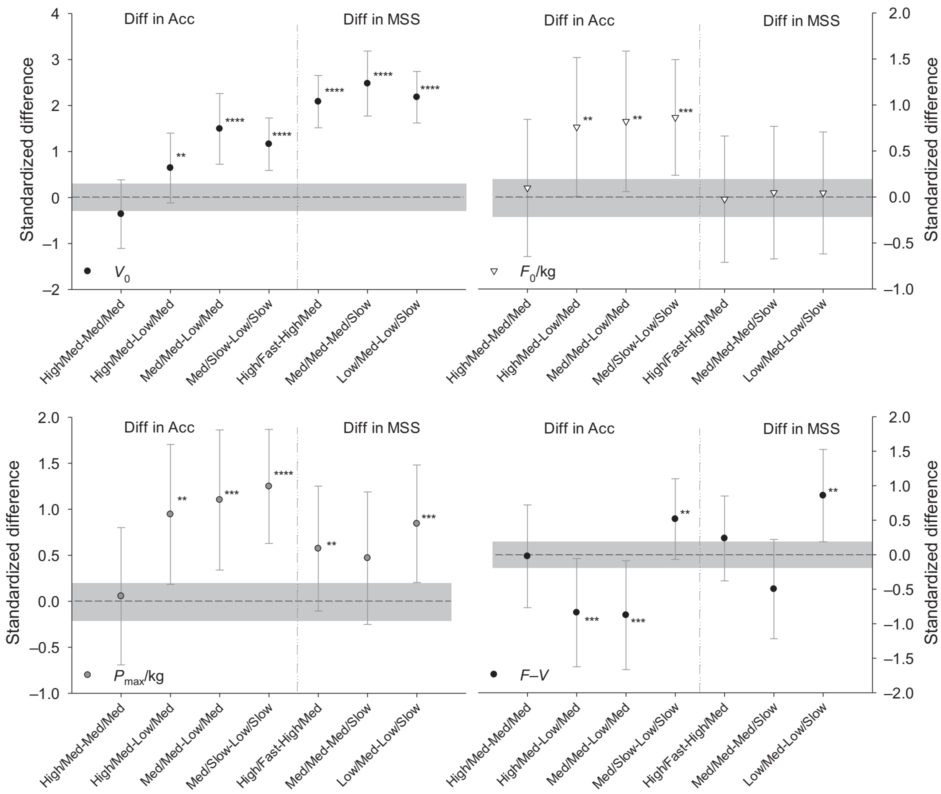

Figure 4. Standardised differences in theoretical maximal velocity (V_0), horizontal force (F_0), horizontal power (P_{max}) and horizontal force/velocity profile (F–V) in players grouped by level of acceleration (Acc) and maximal sprinting speed (MSS): High, Medium (Med) and Low for Acc and Fast, Med and Slow for MSS. The grey area represents trivial between-group differences (see the "Methods" section). The number of * symbol refers to possible (2), likely (3) and very likely (4) between-group differences.

(22%). The remaining 52% of the players had a more "mixed" profile, but clearly opposite profiles were absent (Low/Fast, 0%) or very poorly represented (High/Slow, 5%). The main practical application of this finding is that sprinting speed (over both short and longer distances) could be considered as a generic neuromuscular quality. Differences in technical ability of force application (Morin et al., 2011), stride mechanics and mechanical vertical (Weyand et al., 2000) and mechanical horizontal force/velocity profile may explain the remaining individual differences in Acc vs. MSS performances.

The present results show for the first time in young soccer players that the mechanical horizontal determinants of acceleration and MSS may differ. Once "adjusted" for differences in V_0 (multiple regression analysis), Acc was largely correlated with F_0, while MSS, very-largely with P_{max}. Similarly, players with greater Acc tended to have moderately to largely greater F_0, V_0 and P_{max}, while players with greater MSS had very-largely greater V_0 and moderately greater P_{max}, with no difference in F_0 (Figure 4). The beneficial impact of F_0 on Acc, but not MSS, is in accordance with the results reported by Hunter et al. (2005) where the stronger determinant of 16-m sprint time was horizontal impulse. During the acceleration phase, the human body is in a situation in which gravitational constrains are such that the total force is predominantly produced in a direction that is not that of their displacement. Therefore, only the horizontal component of the total force is directed forward, and the other (vertical) component can be considered as ineffective in producing forward acceleration, although necessary to keep moving forward (Morin et al., 2011). These results suggest that improving horizontal force production capability (for instance using horizontally oriented resistance exercises) may be efficient to enhance sprinting performance over short distances (Los Arcos et al., 2014; Meylan et al., 2014; Randell et al., 2010). The lack of association between horizontal F_0 and MSS is consistent with the findings of Weyand et al. (2000, 2010), who showed that during maximal constant-speed sprinting, there is no or very little horizontal resistance to overcome and that the propulsive forces that increase the body's velocity before take-off simply offset the braking forces that decrease the body's velocity on landing (Weyand et al., 2000). Since it is the vertical portion of the stride that needs assistance to overcome the gravity, applying greater vertical force allows a player to run at a faster velocity ("all is about hitting the ground hard and fast”). While the ability to apply high vertical forces might be improved with vertically oriented resistance exercises (e.g., squat, loaded counter movement jumps, drop jumps) and better running technique (i.e., using shorter periods of foot-ground force application, repositioning the swing limbs more rapidly, and thereby taking less time in the air between steps), whether athletes' performance would actually benefit from an increased capacity to produce vertical forces is not straightforward. In fact, since the limit to speed is believed to be reached “when foot-ground contact times and effective vertical impulses (i.e., the product of foot-ground contact time and the vertical force exceeding the athlete's body mass) decrease to the minimums that provide just enough aerial time to reposition the swing limb for the next step” (Weyand et al., 2010), excessively high level of vertical strength may not obligatory transfer into faster sprinting speed. Additionally, the ability to apply high vertical forces to the ground and reposition the swing limb is likely related to body mass and dimensions (Weyand & Davis, 2005; Weyand et al., 2010), which are moderately (body mass) to non- (height) trainable physical attributes. Finally, in the absence of any association with F_0, the very large association between MSS and P_{max}, as well as the higher P_{max} in players with faster MSS, is likely exclusively related to their greater V_0. Along the same lines, while the fastest player in Figure 1 (i.e., B) presented with the greatest V_0, his P_{max} was actually similar to that of his slower teammate, despite his lower F_0. The practical application of these findings is that while an improved maximal power is likely beneficial for MSS in this specific context of 40-m sprints in young soccer players, maximal power may need to be developed more through velocity- than force-oriented exercises (i.e., light loads at high-to-maximal speed) (Cronin & Sleivert, 2005). Finally, the F–V profile was excluded from the stepwise regression models, and the differences in F–V profiles between players with different Acc/MSS profiles were inconsistent (i.e., while some players with greater Acc had more force-oriented F–V profiles [e.g., High/Med vs. Low/Med], others displayed more velocity-oriented profiles [e.g., Med/Slow vs. Low/Slow], Figure 4). Since F_0 and V_0 are strong determinants of Acc and MSS, respectively, it could have been expected to observe more force-oriented profile in player with greater Acc and velocity-oriented in players with high MSS. However, since the F–V profile is actually a ratio between force and velocity, small changes in one of the variables can have large impact on their ratio, which may explain some on the non-expected results. Additionally, the F–V profile presented larger trial-to-trial variations (9%) than V_0 (<2%), which might add some variability in the between-player comparisons. Finally, these data suggest that absolute force and velocity have a likely greater impact on actual sprinting performance rather than their ratio. Further studies examining the influence of different F–V profiles in players matched for similar absolute force and velocity are still requited to clarify the importance of the F–V profile in this population.

Practical applications

Present results show that variations in the ability to apply mechanical horizontal force can explain some of the individual differences in performance with respect to acceleration and MSS. Therefore, practitioners may individualise speed-related training contents based on players' mechanical characteristics and on field requirements. More specifically, players needing to especially improve their acceleration might need to put a greater emphasis on developing maximal horizontal force production capacity, which may be achieved with horizontally oriented resistance exercises (e.g., 2–5 series of 1–5 repetitions at maximal intensity, including hip extension wall drills, sled-walking (50–60% of body mass), sled-towing (30% of body mass), (unilateral) horizontal jumps (5% of body mass), lunges, hip thrust and (unilateral) Romanian deadlift (Los Arcos et al., 2014; Meylan et al., 2014)). For further details on horizontally oriented resistance exercises prescription, the reader is referred to coaching articles (e.g., (Contreras, Cronin, & Schoenfeld, 2011; Randell et al., 2010)).

Conclusions

Present results in highly trained young soccer players suggest that speed is likely a general quality, but that variations (both time and magnitude) in the ability to apply mechanical horizontal force, among other factors, can explain some of the individual differences in performance with respect to acceleration and MSS. The promising aspect of the present modelling approach (Samozino, Morin, et al. 2013) is that it allows a more detailed profiling of the players than when using simple sprinting times only, that is, defining what are the mechanical properties linked to the observed performance. Present results suggest therefore the need for individualising training contents based on players' mechanical characteristics and on field requirements (Di Salvo et al., 2010; Mendez-Villanueva, Buchheit, Simpson, Peltola, & Bourdon, 2011; Varley & Aughey, 2013). While maximal speed training may be beneficial for both acceleration and MSS, players willing to improve their acceleration might need to put a greater emphasis on developing maximal horizontal force production capacity, which may be achieved with horizontally oriented resistance exercises (Los Arcos et al., 2014; Meylan et al., 2014; Randell et al., 2010). More longitudinal studies are nevertheless required to verify the efficacy of these recommendations.

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References

Brughelli, M., Cronin, J., Levin, G., & Chaouachi, A. (2008). Understanding change of direction ability in sport: A review of resistance training studies. *Sports Medicine*, *38*, 1045–1063.

Buchheit, M. (2012). Repeated-sprint performance in team sport players: Associations with measures of aerobic fitness, metabolic control and locomotor function. *International Journal of Sports Medicine*, *33*, 230–239.

Buchheit, M., & Mendez-Villanueva, A. (2013). Reliability and stability of anthropometric and performance measures in highly-trained young soccer players: Effect of age and maturation. *Journal of Sports Sciences*, *31*, 1332–1343.

Buchheit, M., Mendez-Villanueva, A., Delhomel, G., Brughelli, M., & Ahmaidi, S. (2010). Improving repeated sprint ability in young elite soccer players: Repeated shuttle sprints vs. explosive strength training. *Journal of Strength and Conditioning Research*, *24*, 2715–2722.

Clarke, D., & Clarke, H. (1970). *Research processes in physical education, recreation and health*. Engelwood Cliffs, NJ: Prentice-Hall.

Contreras, B., Cronin, J., & Schoenfeld, B. (2011). Barbell hip thrust. *Strength and Conditioning Journal*, *33*, 58–61.

Cronin, J., & Sleivert, G. (2005). Challenges in understanding the influence of maximal power training on improving athletic performance. *Sports Medicine*, *35*, 213–234.

Di Salvo, V., Baron, R., González-Haro, C., Gormasz, C., Pigozzi, F., & Bachl, N. (2010). Sprinting analysis of elite soccer players during European Champions League and UEFA Cup matches. *Journal of Sports Sciences*, *28*, 1489–1494.

Dorn, T. W., Schache, A. G., & Pandy, M. G. (2012). Muscular strategy shift in human running: Dependence of running speed on hip and ankle muscle performance. *Journal of Experimental Biology*, *215*, 1944–1956.

Faude, O., Koch, T., & Meyer, T. (2012). Straight sprinting is the most frequent action in goal situations in professional football. *Journal of Sports Sciences*, *30*, 625–631.

Harris, N. K., Cronin, J. B., Hopkins, W. G., & Hansen, K. T. (2008). Relationship between sprint times and the strength/power outputs of a machine squat jump. *Journal of Strength and Conditioning Research*, *22*, 691–698.

Haugen, T. A., Tonnessen, E., & Seiler, S. (2013). Anaerobic performance testing of professional soccer players 1995–2010. *International Journal of Sports Physiology and Performance*, *8*, 148–156.

Hoff, J. (2005). Training and testing physical capacities for elite soccer players. *Journal of Sports Sciences*, *23*, 573–582.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine & Science in Sports & Exercise*, *41*, 3–13.

Hunter, J. P., Marshall, R. N., & McNair, P. J. (2005). Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *Journal of Applied Biomechanics*, *21*, 31–43.

Little, T., & Williams, A. G. (2005). Specificity of acceleration, maximum speed, and agility in professional soccer players. *The Journal of Strength & Conditioning Research*, *19*, 76–78.

Los Arcos, A., Yanci, J., Mendiguchia, J., Salinero, J. J., Brughelli, M., & Castagna, C. (2014). Short-term training effects of vertically and horizontally oriented exercises on neuromuscular performance in professional soccer players. *International Journal of Sports Physiology and Performance*, *9*, 480–488.

Mendez-Villanueva, A., Buchheit, M., Kuitunen, S., Douglas, A., Peltola, E., & Bourdon, P. (2011). Age-related differences in acceleration, maximum running speed, and repeated-sprint performance in young soccer players. *Journal of Sports Sciences*, *29*, 477–484.

Mendez-Villanueva, A., Buchheit, M., Simpson, B., Peltola, E., & Bourdon, P. (2011). Does on-field sprinting performance in young soccer players depend on how fast they can run or how fast they do run? *Journal of Strength and Conditioning Research*, *25*, 2634–2638.

Mendez-Villanueva, A., Buchheit, M., Simpson, B. M., & Bourdon, P. C. (2013). Match play intensity distribution in youth soccer. *International Journal of Sports Medicine*, *34*, 101–110.

Mendiguchia, J., Samozino, P., Martinez-Ruiz, E., Brughelli, M., Schmikli, S., Morin, J. B., & Mendez-Villanueva, A. (2014). Progression of mechanical properties during on-field sprint running after returning to sports from a hamstring muscle injury in soccer players. *International Journal of Sports Medicine*, *35*, 690–695.

Meylan, C. M., Cronin, J. B., Oliver, J. L., Hopkins, W. G., & Contreras, B. (2014). The effect of maturation on adaptations to strength training and detraining in 11-15-year-olds. *Scandinavian Journal of Medicine & Science in Sports*, *24*, e156–164.

Morin, J.-B., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P., & Lacour, J.-R. (2012). Mechanical determinants of 100-m sprint running performance. *European Journal of Applied Physiology*, *112*, 3921–3930.

Morin, J.-B., Edouard, P., & Samozino, P. (2011). Technical ability of force application as a determinant factor of sprint performance. *Medicine & Science in Sports & Exercise*, *43*, 1680–1688.

Nummela, A., Keränen, T., & Mikkelsson, L. O. (2007). Factors related to top running speed and economy. *International Journal of Sports Medicine*, *28*, 655–661.

Randell, A. D., Cronin, J. B., Keogh, J. W. L., & Gill, N. (2010). Transference of strength and power adaptation to sports performance—horizontal and vertical force production. *Strength and Conditioning Journal*, *32*, 100–106.

Samozino, P., Edouard, P., Sangnier, S., Brughelli, M., Gimenez, P., & Morin, J. B. (2013). Force-velocity profile: Imbalance determination and effect on lower limb ballistic performance. *International Journal of Sports Medicine*, *35*, 505–510.

Samozino, P., Morin, J. B., Dorel, S., Slawinski, J., Peyrot, N., Saez de Villarreal, E., & Rabita, G. (2013, August 2–9). *A simple method for measuring power, force and velocity properties of sprint running*. International Society of Biomechanics Congress, Natal.

Samozino, P., Rejc, E., Di Prampero, P. E., Belli, A., & Morin, J.-B. (2012). Optimal force-velocity profile in ballistic movements–altius: Citius or fortius? *Medicine & Science in Sports & Exercise*, *44*, 313–322.

Sleivert, G., & Taingahue, M. (2004). The relationship between maximal jump-squat power and sprint acceleration in athletes. *European Journal of Applied Physiology*, *91*, 46–52.

Varley, M. C., & Aughey, R. J. (2013). Acceleration profiles in elite Australian soccer. *International Journal of Sports Medicine*, *34*, 34–39.

Vescovi, J. D., & McGuigan, M. R. (2008). Relationships between sprinting, agility, and jump ability in female athletes. *Journal of Sports Sciences*, *26*, 97–107.

Weyand, P. G., & Davis, J. A. (2005). Running performance has a structural basis. *Journal of Experimental Biology*, *208*, 2625–2631.

Weyand, P. G., Sandell, R. F., Prime, D. N., & Bundle, M. W. (2010). The biological limits to running speed are imposed from the ground up. *Journal of Applied Physiology*, *108*, 950–961.

Weyand, P. G., Sternlight, D. B., Bellizzi, M. J., & Wright, S. 2000. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *Journal of Applied Physiology*, *89*, 1991–1999.