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The relationship between performance and biomechanics in middle-distance runners

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ABSTRACT

The present study aimed to identify movement patterns most related to running performance among highly trained middle-distance runners. Eleven male runners performed overground running trials on an indoor running track, and three-dimensional analyses techniques were used to measure running kinematics and kinetics. Performance was measured as season and personal best time over 1500 m. The average velocity during the running trials was 7.2 ± 0.3 m/s. The average season and personal best 1500 m race times were 3:49.7 ± 0:05.8 and 3:46.0 ± 0:08.3 minutes, respectively. Regression analysis revealed that a smaller range of sagittal-plane hip motion during swing, less thorax flexion at toe-off and a smaller ankle plantarflexion angle at contact accounted for 95.7% ($p < 0.001$) of the variation in season best running performance. Less sagittal-plane hip motion during swing and a smaller ankle plantarflexion angle at contact also explained 79% of the variance in personal best time. Slower middle-distance runners make initial ground contact with a more plantarflexed ankle and greater forward lean of the trunk. We recommend that coaches and runners pay attention to ankle, shank and thorax angles during technical development and training to identify opportunities to optimise middle-distance running mechanics and performance.

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Introduction

In track and field, competitive races range from 60 m to the 10,000 m and cover any distance in between. The 400 m race and shorter events are classed as 'sprints' and events beyond 3000 m are classified as 'distance' races. Running events that cover distances between these two disciplines (i.e. >400 m and ≤3000 m) are classified as 'middle-distance' events. The most common middle-distance events featured on athletic programs are the 800 m, 1500 m and 3000 m, and middle-distance races can take 2–10 min for trained runners to complete. Success in competitive running is dependent on many factors including the environment, anthropometry, training, physiology and biomechanics of the athlete (Saunders, Pyne, Telford, & Hawley, 2004). These factors have been extensively researched in sprinters and long-distance runners (Mero, Komi, & Gregor, 1992; Saunders

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et al., 2004; Williams & Cavanagh, 1987); however, knowledge of the determinants of middle-distance racing success is limited. In particular, very little is understood about the relationship between middle-distance running mechanics and performance.

It is thought that experienced runners develop a running technique that is specific to their race discipline through self-optimisation (Williams & Cavanagh, 1987). Sprinters adopt a running technique that maximises speed with little attention given to mechanical efficiency, while long-distance runners must maintain submaximal speeds for extended periods of time through the adoption of an economical running technique (Bushnell & Hunter, 2007; Williams & Cavanagh, 1987). Middle-distance racing requires a unique combination of speed and efficiency (Brandon, 1995); accordingly, the running technique of these athletes manifests as a hybrid of sprint and long-distance running mechanics (Cunningham, Hunter, Seeley, & Feland, 2013). For example, Cunningham et al. (2013) compared female sprinters, middle- and long-distance runners during treadmill running. At each matched speed, long-distance runners had the shortest stride length, longest ground contact time, greatest centre of mass separation (i.e. horizontal displacement between the landing toe and centre of mass during ground contact time) and greatest knee flexion range during stance. Sprinters were most dissimilar to long-distance runners, while middle-distance runners were in the middle of a continuum for each of the variables examined.

A number of studies (Cunningham et al., 2013; Hayes & Caplan, 2012; Kyröläinen, Avela, & Komi, 2005; Skof & Stuhec, 2004) have described middle-distance running biomechanics, but only two studies (Folland, Allen, Black, Handsaker, & Forrester, 2017; Leskinen, Häkkinen, Virmavirta, Isolehto, & Kyröläinen, 2009) have examined these in relation to performance. Folland et al. (2017) analysed both mid- and long-distance runners together, and found four variables that accounted for 30.5% of the variability in performance. Faster runners had a significantly smaller shank angle at touchdown (explained 10% of the variance), smaller peak braking velocity of the pelvis during ground contact (9.9%), a lower duty-factor (i.e. percentage of the total gait cycle which one foot is on the ground; 6.4%), and a more upright trunk across the gait cycle (4.2%). An important limitation of this research is that the criterion used for performance (10 km time) was calculated using each participants' season best time over 12 months in races ranging from 1500 m to the marathon. However, a runner who is superior at their preferred race distance may not necessarily convert to a superior 10 km runner because of differences in the physiological and biomechanical demands between middle- and long-distance events (Brandon, 1995). The authors then compared biomechanical data collected during treadmill running at 2.8 to 3.3 m/s, which is not representative of 10 km race pace for trained runners. The fastest participants in this study ran 10 km in less than 30 min, which would equate to an average overground running speed of 5.7 m/s. Kinematics were also collected during treadmill running, and there are known dissimilarities between overground and treadmill running (Nigg, De Boer, & Fisher, 1995).

Leskinen at al. (2009) are the only researchers to have described middle-distance running biomechanics exclusively and in relation to performance. They analysed video footage of national-standard and elite middle-distance athletes during a 1500 m competitive race. The largest effect sizes (standardised mean difference (SMD)) revealed that faster middle-distance runners had: (i) a slower knee extension velocity during terminal stance (SMD = −2.6); (ii) a shorter duration of knee flexion during stance (SMD = −2.23); (iii) a faster peak knee flexion velocity during swing (SMD = +1.6); and, (iv) a faster hip flexion velocity between touchdown and contralateral touchdown (SMD = +1.6). Based on their findings the authors proposed that faster runners optimise power generation at toe-off, which facilitates a faster recovery leg during swing. Consequently, faster runners had a smaller centre of mass separation at touchdown and thus, a smaller duration and range of knee flexion during stance.

While Leskinen et al. (2009) provide foundational evidence for the relationship between middle-distance running mechanics and performance, there are a number of important limitations to their study. First, this study relied on the digitisation of two-dimensional video footage. While this may be an effective approach to analysing athletes during competition, this method is susceptible to manual digitisation errors and occlusion of body segments (Richards, 2008). For example, the view of the foot was obstructed by a small edge on the running track so foot strike patterns and ankle kinematics could not be determined. Failure to identify ground contact and toe-off events limits the accurate identification of stance and flight phases; consequently, readers should retain caution when interpreting results. This study also analysed just one stride cycle for the left side of the body, which is significantly less than current recommendations. Literature suggests that an individual's running technique should include inspection of at least four stances and swing phases to achieve performance stability and an accurate representation of movement variability (James, Herman, Dufek, & Bates, 2007).

To further understand the relationship between running technique and performance, there is a clear need for additional high-quality research studies examining middle-distance runners of different standards. Therefore, the purpose of this study is to identify the kinematics and kinetics most related to performance among a highly trained cohort of middle-distance runners. It was hypothesised that trunk and ankle plantarflexion angles at contact, and a smaller range of knee flexion during stance, will be the variables most related to running performance. This study aims to address the limitations of past research by analysing a series of overground running trials at race pace using contemporary three-dimensional analyses methods.

Methods

Eleven male runners (age: 22.3 ± 5.1 years; body mass: 67.7 ± 6.1 kg; height: 181.8 ± 5.4 cm) participated in this study. All participants were national-level athletes in the 1500 m. Study procedures were approved by the Deakin University and Australian Institute of Sport (AIS) Human Research Ethics Committees and all athletes provided written informed consent.

Each athlete's season best and personal best race times over 1500 m were located from the Athletics Australia results archive (Athletics Australia, 2016). The Australian track and field season is five months long; for this reason season best times were defined as the fastest time an athlete had run within a five month timeframe of the testing session. Without a direct training intervention, there is no evidence to suggest that running mechanics would change over this time in experienced runners (Lake & Cavanagh, 1996). Personal best times were defined as the fastest time an athlete had run following their testing session, irrespective of the elapsed time.

Biomechanical data were collected during overground running on a 110 m indoor synthetic running track. Kinematic data were collected using a 20-camera Vicon motion analysis system (Oxford Metrics Ltd., Oxford, UK) sampling at 250 Hz. Kinetic data were simultaneously captured using eight in-ground 900 × 600 mm Kistler force plates (Kistler, Amherst, NY, USA) sampling at 1000 Hz. Participants completed three successful trials at a speed representative of their 1500 m race pace. Running speed was monitored by two sets of timing gates positioned at each end of the 20 m capture space. Trials were deemed successful if they were within 2.5% of the target velocity, and there were four clear foot strikes on the force plates for each trial (i.e. 12 foot contacts in total). Plug-in Gait's FullBody Model (Vicon Motion Systems Ltd, 2010) was used to calculate three-dimensional kinematic and kinetic data. Biomechanical data were processed using Vicon Nexus Software (Oxford Metrics Ltd., Oxford, UK). Following a residual analysis, marker trajectories and ground reaction forces (GRFs) were filtered using a Woltring Filtering Routine with a predicted mean squared error value of 10 mm^2. Contact and toe-off gait events were identified using a 10 Newton threshold of the vertical GRF (O'Connor, Thorpe, O'Malley, & Vaughan, 2007). A large number of biomechanical variables were exported to lessen the chance that important variables were excluded from the analysis (Williams & Cavanagh, 1987). Vicon ProCalc 1.1 (Oxford Metrics Ltd., Oxford, UK) was used to export a range of stride parameters, vertical oscillation measures, GRFs, and discrete sagittal-plane angular kinematics, angular velocities and joint moments for each side of the body. The sagittal angle of the shank at contact and toe-off was also included in this analysis based on past research findings (Williams & Cavanagh, 1987).

All statistical analyses were performed using SPSS (IBM Corporation, Armonk, NY, USA) and JMP (SAS Institute Inc., Cary, NC, USA). Each variable was averaged across trials for each participant. Paired sample t-tests and SMD's were used to compare kinematic and kinetic data between the left and right sides. There were non-significant ($p< 0.050$) and small effects (SMD < 0.37) for all variables examined (Hopkins, 2002). Thus, gait symmetry was assumed and the dominant limb was selected for all subsequent analyses (Coren, 1993). Descriptive statistics were calculated and variables were checked for speed-interactions using Pearson's correlation coefficients.

A series of diagnostic tests were used to examine suitability for regression analyses. No outliers were present in the data, and data met the assumptions of normality, linearity and homoscedasticity (Field, 2009). However, multicollinearity was high between some variables so Partial Least Squares Regression (PLS-R) was used for preliminary analysis. PLS-R is highly appropriate when the relative number of explanatory variables to individual cases is large, multicollinearity is high, and dimension reduction is required (Abdi, 2010; Barker & Rayens, 2003). It was deemed suitable for eliminating variables in the prelude to multiple linear regression, similar to the methodology used in the pioneering research by Williams and Cavanagh (1987). The predicted residual error sum of squares (PRESS) and van der Voet T2 statistics were calculated to determine the optimum number of latent variables to retain. Cross-validation occurred using the leave-one-out method. Variables that did not positively contribute to the model were removed following interpretation of coefficients and the Variable Importance on the Projection (VIP) statistic (i.e. < 10) (SAS Institute Inc., n.d.). Seven variables were retained and entered into a multiple linear regression model to calculate the overall R^2 and error value, and also to determine the significance of individual coefficients. Significance was set at $p < 0.050$.

Results

Overground running trials were completed at an average velocity of 7.2 ± 0.3 m/s (6.7 to 7.8 m/s). The average season best 1500 m time was 3:49.7 ± 0:05.8 min (3:41.6 to 4:00.9 min). The average personal best 1500 m time was 3:46.0 ± 0:08.3 min (3:31.1 to 4:00.9 min). There were no significant correlations between biomechanical variables and trial velocity.

Table 1 presents summary statistics for a number of biomechanical variables that demonstrated significant relationships or trends towards 1500 m season best times. Following the PLS-R for dimension reduction, seven biomechanical variables were retained for further analysis (Figure 1). Runners with faster 1500 m season best race times showed a smaller range of sagittal-plane hip motion during swing (range: 92.4° to 103.9°); less thorax flexion at toe-off (range: −2.6° to 10.0°); a smaller range of sagittal-plane knee motion during swing (range: 118.8° to 148.4°); a larger peak vertical GRF (range: 249.1% to 372.7% of bodyweight); a smaller knee flexion angle at initial swing (range: 4.4° to 27.5°); a larger range of vertical oscillation during stance (range: 4.2° to 5.4°); and a smaller ankle plantarflexion angle at contact (range: −17.1° to 2.2°). From these seven variables, the hip flexion/extension angle range of motion during swing, the thorax flexion/extension angle at toe-off and the ankle plantar/dorsiflexion angle at contact could explain 95.7% of the variance in season best race performance (Adjusted R^2 = 0.94; $p < 0.001$). All three variables added significantly ($p < 0.050$) to the prediction of race time and, and the root mean square error (RMSE) was 00:01.2 min(Table 2).

When personal best race time replaced season best race time as the dependent variable, two variables were retained to give an R^2 of 0.79 (Adjusted R^2= 0.73; p = 0.032). These were the hip flexion/extension angle range of motion during swing and the ankle plantar/dorsiflexion angle at contact. Both variables added significantly ($p <$ 0.050) to the prediction and the RMSE was 0:03.4 min (Table 2). If the thorax angle at toe-off was forcibly entered into the regression model, then these three variables produced an R^2 of 0.86 (Adjusted R^2 = 0.80; $p < 0.005$). However, the thorax angle at toe-off was not significant; therefore, this variable was removed.

Table 1. Descriptive statistics for biomechanical variables of interest and relationship with 1500 m performance.

	Mean ± SD	R^2	p	Faster runners
Peak knee flexion angle during stance (°)	48.6 ± 7.0	0.35	0.055	↑ Flexion
Knee flexion angle at toe-off (°)	13.7 ± 7.5	0.30	0.080	↑ Flexion
Sagittal range of hip motion during swing (°)	97.6 ± 3.8	0.60	0.005	↓ ROM
Knee flexion angle at initial swing (°)	12.3 ± 7.6	0.39	0.041	↑ Flexion
Sagittal range of knee motion during swing (°)	136.3 ± 8.0	0.46	0.022	↓ ROM
Thorax flexion angle at contact (°)	8.4 ± 3.5	0.34	0.058	↓ Flexion
Thorax flexion angle at toe-off (°)	3.7 ± 3.8	0.50	0.015	↓ Flexion
Ankle plantarflexion angle at contact (°)	-5.1 ± 5.1	0.34	0.077	↓ Flexion
Global foot angle at contact (°)	-88.3 ± 4.4	0.26	0.110	↓ Flexion
Peak knee angular velocity during swing (°/s)	1000.3 ± 122.8	0.44	0.026	↓ Speed
Centre of mass vertical oscillation during stance (cm)	4.7 ± 0.4	0.47	0.019	Larger
Shank sagittal angle at contact (°)	-1.8 ± 3.7	0.35	0.056	Straighter
Peak vertical GRF (% of bodyweight)	327.3 ± 34.2	0.41	0.035	↑ Force
Centre of mass separation (% of leg length)	0.4 ± 0.0	0.23	0.134	Smaller

R^2 coefficient of determination; *SD* standard deviation; *GRF* ground reaction force; *ROM* range of motion

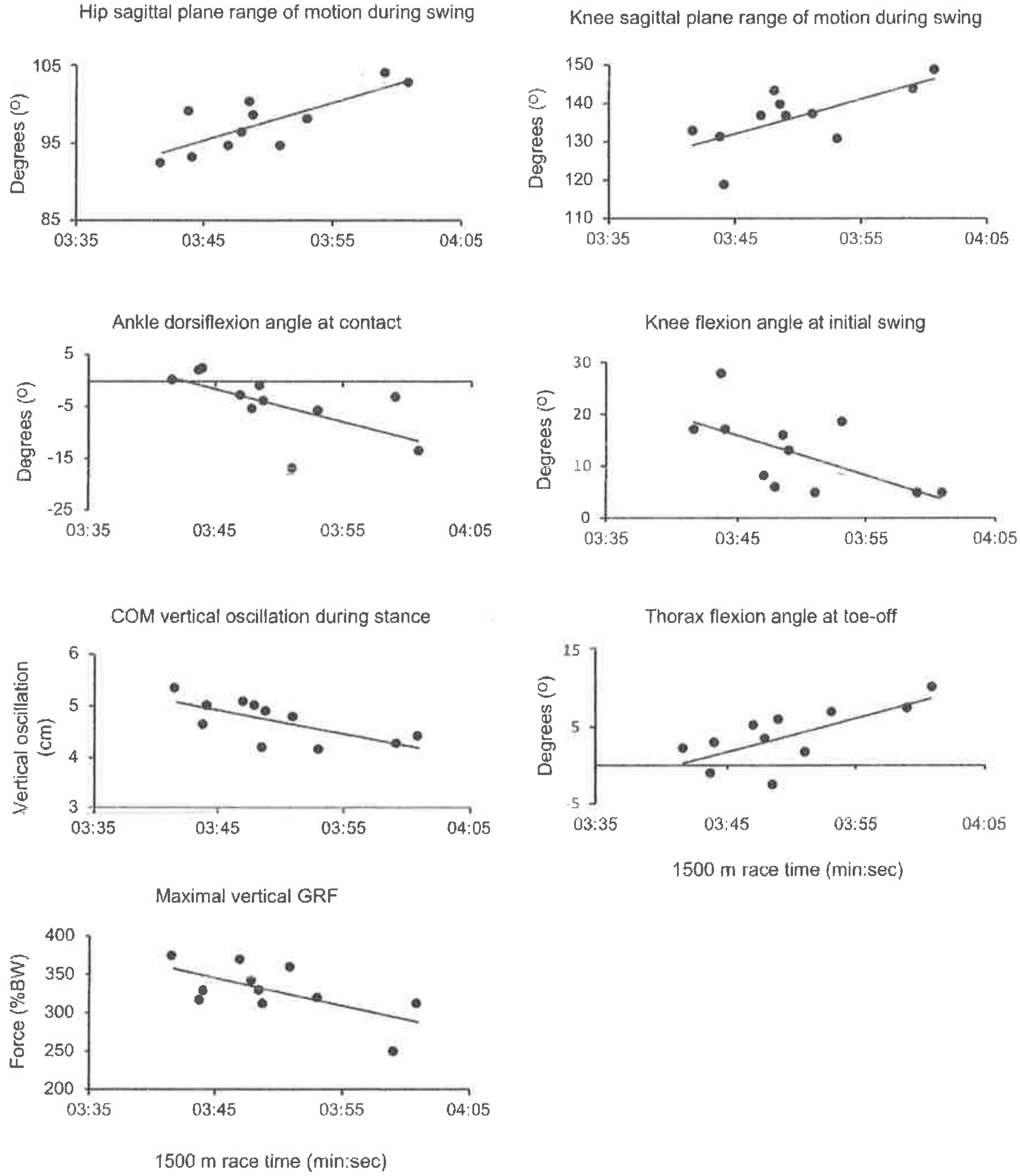

Figure 1. Individual scatterplots with regression lines displaying the relationship between biomechanical variables and race time for the seven variables retained following the partial least squares regression. *COM* centre of mass; *%BW* force as percentage of body weight.

Table 2. Summary of the multiple regression analyses between 1500 m season best or personal best times and biomechanical variables.

	Season best time			Personal best time		
Variable	*B*	SE_B	*β*	*B*	SE_B	*β*
(Constant)	126.88*	13.98		101.49*	33.59	
Hip sagittal-plane range (swing)	1.02*	0.15	0.67	1.26*	0.35	0.65
Thorax flexion angle (toe-off)	0.45*	0.17	0.26			
Ankle plantarflexion angle (contact)	−0.36*	0.09	−0.35	−0.62*	0.23	−0.48

B unstandardised regression coefficient; SE_B Standard error of the coefficient; *β* standardised coefficient; * $p < 0.050$.

Discussion and implications

To the best of our knowledge, this is the first study to use three-dimensional analyses techniques to investigate the relationship between middle-distance running mechanics and performance during overground running at race pace. The results of this study show that runners with faster 1500 m season best race times had a smaller range of sagittal-plane hip motion during swing, less thorax flexion at toe-off, and a smaller ankle plantarflexion angle at contact. These three variables could account for 95.7% of the variation in season best race time. This is consistent with Folland et al. (2017) who found the shank angle at touchdown and trunk extension angle combine to explain variability in 10 km performance among mid- and long-distance runners. When the present analysis was replicated with personal best times as the dependent variable, the same variables could account for a large portion of the variation in race time. This provides support that these variables have an important role in determining 1500 m race time and the level of performance a runner may achieve in the future. In addition, greater knee flexion at initial swing, a smaller total range of sagittal-plane knee motion during swing, slower peak knee flexion velocity during swing, larger vertical oscillation of the centre of mass during stance, and a larger peak vertical GRF were also significantly associated with better race performance. As a consequence of these findings, the initial hypothesis can be accepted, with the exception that faster runners had a tendency to flex their knee more during the stance phase of running.

The larger ankle plantarflexion angle (relative angle between the shank and the foot) demonstrated by slower runners at ground contact occurred because slower runners landed with their foot further ahead of their knee, increasing the angle of the shank relative to vertical. In comparison, faster runners displayed less ankle plantarflexion and a slightly larger vertical GRF because their centre of mass and leg axis were more vertically aligned at ground contact. Faster runners also displayed less thorax flexion at toe-off and were typically more upright at touchdown. This supports existing evidence (Folland et al., 2017; Preece, Mason, & Bramah, 2016) that trained distance runners have less thorax inclination at different running speeds compared to recreational runners. The range of thorax inclination that Preece et al. (2016) reported were similar to the findings in the present study (i.e. recreational: 6.5 ± 5.5°; elite: 3.5 ± 3.5°). Preece et al. (2016) determined that a 3–4° increase in trunk inclination shifts the centre of mass anteriorly by 2–3 cm. They suggest this could increase the metabolic cost of running because the back extensors and gluteus maximus are required to control larger thorax flexion-extension moments, and that excessive trunk inclination could also lead to compensatory changes in foot placement at ground contact. The researchers proposed that recreational runners may overstride to maintain a similar horizontal distance between their centre of mass and centre of pressure. This could explain why slower runners in the current study had a more extended leg and plantarflexed ankle at ground contact. This also provides an explanation for the absence of a significant relationship between centre of mass separation and performance in this study because this measure is dependent on the vertical projection of the centre of mass on the floor, which is easily manipulated through flexion or extension of the trunk. Future research should use a more robust measure to establish overstriding, such as the horizontal displacement between the calcaneus and centre of the pelvis at ground contact.

Overstriding most commonly occurs with ankle dorsiflexion, and is associated with many unfavourable performance characteristics, such as increasing braking forces and the work required for forward propulsion (Anderson, 1996; Heiderscheit, Chumanov, Michalski, Wille, & Ryan, 2011). In the current study, all athletes were mid- or fore-foot runners who landed with a neutral or plantarflexed ankle. Overstriding with a plantarflexed ankle has not previously been investigated; however, it is conceivable that this technique would impose similar consequences as overstriding with a dorsiflexed ankle. Excessive plantarflexion at the ankle may result in uncontrolled dorsiflexion during loading because the length of the Achilles tendon moment arm is longer at contact, while the downward force of the body mass is applied more posterior to the fulcrum of the ankle. A plantarflexed ankle at contact may also require active muscle contractions from the soleus and gastrocnemius, and limit the passive storage of energy by the Achilles tendon. This could expose athletes to unnecessary tensile loads and predispose them to overuse injuries (Scholz, Bobbert, Van Soest, Clark, & van Heerden, 2008).

Faster runners appear to have a smaller range of sagittal-plane knee flexion during swing; however, they appear to have a more flexed knee throughout the stance phase which is not in agreement with the initial hypothesis. The results of this study show that faster middle-distance runners make ground contact with a more flexed knee and vertical shank, then flex their knee more during weight acceptance resulting in greater vertical oscillation and peak vertical GRFs, before terminating stance with a more flexed knee. This conflicts existing evidence that faster middle-distance runners display less knee flexion (Folland et al., 2017; Leskinen et al., 2009) and vertical oscillation (Folland et al., 2017) during stance. Smaller ranges of joint motion during stance are believed to indicate greater musculotendinous stiffness and the return of positive work from the stretch-shortening cycle (Folland et al., 2017). The current findings do not support the theory that faster middle-distance runners have greater lower-limb musculotendinous stiffness (Folland et al., 2017; Leskinen et al., 2009). One possible explanation for this is that faster runners have more compliant tendons that lengthen further during stance and allow the contractile muscles to operate at more favourable force-length-velocity relationships (Fletcher, Esau, & MacIntosh, 2010). For example, the quadriceps femoris develops progressively larger torques up to 60^{0} of knee flexion (Hahn, Olvermann, Richtberg, Seiberl, & Schwirtz, 2011). If force-length-velocity relationships are enhanced by greater knee flexion then a more flexed knee during stance may facilitate larger vertical GRFs. In the absence of changes in ground contact time, this may enhance vertical impulse and a change in momentum. The greater knee flexion observed at toe-off would also assist in reducing the legs' moment of inertia by positioning the centre of gravity of the whole leg closer to the hip joint, thus lowering the energy required to produce hip flexion during the swing phase (Burke & Brush, 1979).

When running at steady state speeds below 7 m/s, the primary strategy for increasing running velocity is to increase stride length by pushing on the ground harder (Dorn, Schache, & Pandy, 2012). When steady state running speeds exceed 7 m/s, there is a strategic shift, and higher speeds are achieved by increasing stride frequency. This is achieved by increasing the magnitude of work and net power performed by the hip flexors and extensors to rapidly accelerate the leg during swing. Faster middle-distance runners had a smaller range of sagittal-plane knee and hip motion during swing and extended their leg less during swing while generating larger GRFs. Collectively, the findings of this study suggest that slower runners undergo this strategic shift towards sprinting mechanics at slower speeds than faster middle-distance runners. When running at the same speed, slower runners appear to emphasise larger ranges of motion at the hip and knee joints during swing, while faster runners focus on generating larger propulsive forces. Better runners may have a higher speed reserve due to this delayed shift in their running technique that assists them in achieving faster top speeds.

The present findings, along with past research (Folland et al., 2017; Preece et al., 2016), suggest that trunk flexion may play an important role in regulating foot placement at contact. By landing with their foot closer to their centre of mass at ground contact, faster runners may be able to optimise plantarflexor power output to generate larger vertical support forces and achieve faster running speeds. Thus, to facilitate better performance, it is recommended that coaches pay attention to foot, shank and trunk angles during technical development and training. It appears that coaches could reduce overstriding by limiting trunk flexion. Future research should examine the effects of a technical training intervention using these recommendations to determine whether they can facilitate an improvement in performance.

Results of the present study should be made with careful consideration of the trained sample. The current study examined highly trained 1500 m runners who were eligible to compete at a national level. Future research on this topic could aim to include a larger and more representative sample group to enable broader generalisations. While our sample of 11 highly trained runners may appear small, middle-distance running is a unique racing discipline and biomechanists will rarely have access to runners of varying abilities at any given time in the one place (Leskinen et al., 2009). It is also important to acknowledge that the variables selected for the multiple regression analyses were chosen based on their performance in the PLS-R, and as a consequence, some variables may have been eliminated if they correlated highly with another chosen variable. The PLS-R identified a representative set of variables, but these may not necessarily be the only set of explanatory variables. Finally, it must be recognised that running technique can vary due to many individual factors, including anthropometry. However, the physical characteristics of athletes competing in the same discipline are often similar and there is still a need for a general model of middle-distance running to help identify any modifiable biomechanical determinants related to performance (Skof & Stuhec, 2004).

Conclusions

The results of this study demonstrate that less thorax flexion at toe-off and a smaller ankle plantarflexion angle at ground contact could account for a large variation in middle-distance running performance. The collective findings suggest that faster middle-distance runners extend their leg less throughout the running gait cycle and optimise foot placement closer to the centre of mass at ground contact, which facilitates greater vertical oscillation and peak vertical GRFs.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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