Received: 13 July 2022 | Revised: 11 December 2022 | Accepted: 3 February 2023

DOI: 10.1111/sms.14331

ORIGINAL ARTICLE

WILEY

Changes in running biomechanics during the 2017 IAAF world championships men's 1500 m final

Brian Hanley[1] | **Athanassios Bissas**[2] | **Stéphane Merlino**[3] | **Geoffrey T. Burns**[4]

[1]Carnegie School of Sport, Leeds Beckett University, Leeds, UK

[2]School of Sport and Exercise, University of Gloucestershire, Gloucester, UK

[3]International Relations and Development Department, World Athletics, Monte Carlo, Monaco

[4]School of Kinesiology, University of Michigan, Ann Arbor, Michigan, USA

Correspondence
Geoffrey Burns, School of Kinesiology, University of Michigan, 830 N University Ave, Ann Arbor, MI 48109, USA.
Email: gtburns@umich.edu

Abstract

The aim of this study was to analyze key kinematic, spatiotemporal, and global mechanical characteristics in world-class middle-distance racing. Eight men were recorded halfway along the home straight on the second, third, and final laps in the 2017 IAAF World Championship 1500 m final. Video data (150 Hz) from three high-definition camcorders were digitized to calculate relevant variables, subsequently analyzed in relation to running speed and finishing position. Better-placed finishers had greater hip extension at initial contact and through late stance, greater knee excursion throughout stance, and longer overstriding distances. Step length did not change with faster speeds as runners relied on increasing step frequency, but the highest-finishing athletes had longer contact phases and greater fluctuations in speed through the step cycle, which were related to higher normalized peak horizontal forces. The best athletes also had lower leg stiffnesses and vertical stiffnesses. The extended contact phase and greater compression could allow for more sustained force production, enabling better acceleration and maintenance of sprinting speed, indicating a trade-off between aerobic energetic efficiency and anaerobic power capacity. Coaches should note that these factors, as well as the best athletes' greater overstriding distances, show that elite 1500 m runners might prioritize a technique that favors running speed over economy.

KEYWORDS

elite-standard athletes, endurance, performance, speed, track and field

1 | INTRODUCTION

"...the miler is a strange beast, half sprinter, half distance runner."[1]

The dynamic interplay of speed and strength uniquely characterizes middle-distance racing and elevates the 1500 m to a perpetual blue riband status at the Olympic Games and World Athletics Championships. Whereas the aerobic system contributes approximately 80% of energy requirements, the remaining anaerobic contribution is critical to performance and most heavily exercised during the final lap.[2] Indeed, the predominant pacing profile of male 1500 m championship runners is to gradually increase speed from 300 m until the finish,[3] with world-class men achieving speeds of 26–28 km/h in the final stages. This tactical progression presents the enigmatic phenomenon that defines the event: athletes tend to be most tired when they must run their fastest. At running speeds above 20 km/h, increases in step frequency are more pronounced than increases in step length[4]; however, as faster runners are just as likely to run with lower rather than higher step frequencies,[4] it is important to analyze the role of these variables relative to race finishing position as well as to changes in speed.

The mechanical features of runners who successfully navigate this event are similar to those of high-standard long-distance runners. Lower vertical oscillation, less horizontal velocity decrement during stance, and a lower duty factor (the ratio of contact time to total stride time) have been linked to greater performance capacities in both middle- and long-distance specialists.[5] These features have been linked to running economy, suggesting that their contribution to middle- and long-distance performance is due to their beneficial effects on locomotor and aerobic efficiency.[5] In middle-distance runners, spring-mass characteristics[6] discriminate between runners of differing abilities, with greater leg and vertical stiffnesses, lower duty factors, and steeper impact angles distinguishing elite from highly trained runners.[7] However, the demands of successful middle-distance racing are not satisfied by efficient running characteristics alone; the need to modulate and sustain speeds across a spectrum of paces and to execute fast sprint finishes are essential.[8] Given the complexity of the event's dynamics, the kinematic, spatiotemporal, and global mechanical characteristics that facilitate superior 1500 m racing are unclear. The aim of this study was to analyze key kinematic, spatiotemporal, and global mechanical characteristics in world-class middle-distance racing across different running speeds and to assess how those characteristics differed with respect to the finishing position of the racers.

2 | METHODS AND METHODS

2.1 | Participants

Data were collected as part of the London 2017 World Championships Biomechanics Project, and the use of those data (including athlete identities) was approved by the IAAF (now renamed World Athletics), who control the data, and locally through the institution's research ethics procedures (application no. 52410). Participants' dates of birth and personal best (PB) times were obtained from World Athletics,[9] whereas their statures and masses were obtained from Matthews[10] and online sources (en.wikipedia.com/wiki and en.asiangames2018.id/sport/athletics). Eight men (age: 27 ± 4 years; stature: 1.81 ± 0.05 m; mass: 65 ± 3 kg) were analyzed approximately halfway along the home straight on the second, third, and fourth laps of the men's 1500 m final (~650 m, 1050 m, and 1450 m of total race distance). The other four finalists could not be analyzed because they were obscured by other competitors on at least one lap. Athletes' finishing times were obtained from the World Athletics website.[11]

2.2 | Data collection

Three stationary Sony PXW-FS7 digital cameras (Sony) recording at 150 Hz (shutter speed: 1/1250 s; ISO: 1600; FHD: 1920 × 1080 px) were used to record the athletes as they ran through the calibrated middle section of the home straight (47.0–55.5 m from the start line used for the 100 m event). The cameras were placed in three locations along the home straight, and angled at approximately 45°, 100°, and 135° to the plane of motion, respectively. A rigid cuboid calibration frame (length: 3.044 m, width: 3.044 m, height: 3.044 m) was positioned twice over discrete predefined areas on the track to ensure an accurate definition of a volume within which the athletes ran. Markings on the frame produced 24 non-coplanar control points per individual calibrated volume (48 points in total) and facilitated the construction of a global coordinate system.

2.3 | Data analysis

All videos were manually digitized by a single experienced operator using SIMI Motion version 9.2.2 (Simi Reality Motion Systems GmbH). An event synchronization technique using four gait events (right initial contact, right toe-off, left initial contact and left toe-off) was applied to synchronize the two-dimensional coordinates from each camera. Digitizing started at least 15 frames before the first analyzed gait event and completed at least 15 frames after the last analyzed gait event to provide padding during filtering.[12] Each file was first digitized frame-by-frame and, upon completion, adjustments were made using the points-over-frame method,[13] where each point was tracked through the entire sequence with the aid of the trajectory-tracking function in SIMI Motion. The direct linear transformation (DLT) algorithm[14] was used to reconstruct the three-dimensional coordinates from each camera's x- and y-image coordinates. Sixteen segment endpoints and the head were digitized for each participant and de Leva's body segment parameter models[15] used to obtain data for the CM and for various body segments. Occasionally, dropout occurred where joint positions were not visible, and estimations were made by the operator. The 3D still image measurement tool in SIMI Motion was used to assist this process as it allowed for the prediction of a joint position in any frame, provided it was identified in the other two cameras. A recursive second-order, low-pass Butterworth digital filter (zero phase-lag) was employed, where the cut-off frequencies were calculated using residual analysis,[16] ranging between 10.7 and 22.6 Hz.

To measure reliability of the digitizing process on the speed and spatiotemporal data, repeated digitizing of one running sequence (a single digitized gait cycle from one lap of one runner) was performed with an intervening period of 48 h. Three statistical methods for assessing reliability were used: 95% limits of agreement (LOA), coefficient of variation (CV), and intraclass correlation coefficient (ICC).[17] The data for each tested variable were assessed for heteroscedasticity by plotting the standard deviations (SD) against the individual means of the two trials.[17] If the data exhibited heteroscedasticity, a logarithmic transformation of the data ($\log_e$) was performed.[18] The LOA (bias ± random error), CV, and ICC (3, 1) values for CM horizontal speed were −0.004 ± 0.034 m/s, ±0.29%, and 0.98, respectively; for the CM horizontal coordinates −0.001 ± 0.001 m, ±0.02% and 1.00, respectively; and for both right and left foot horizontal coordinates 0.001 ± 0.001 m, ±0.01%, and 1.00, respectively. The results relating to the most important spatiotemporal variables therefore showed minimal systematic and random errors, and confirmed the high reliability of the digitizing process.

The spatiotemporal and joint angular variables analyzed are described in Table 1. When summed, the foot ahead, foot behind, flight distance, and foot movement distances equal step length. Joint angular data were averaged between left and right sides and have been presented at specific events of the gait cycle, as defined below:

- Initial contact – the first instant during stance where the athlete's foot visibly contacted the ground.
- Midstance – the instant during stance where the athlete's foot center of mass was directly below the CM (i.e., in the anteroposterior direction).
- Toe-off: the last instant during stance before the foot visibly left the ground.

Measures of spring-mass behavior were estimated using the method presented by Morin et al.[19] Briefly, this approximates the vertical ground reaction force (GRF) time series as a sinusoid and uses the contact and flight times of the runner to estimate peak GRFs, vertical displacement during stance (Δy), leg compression (ΔL), vertical stiffness (k_{vert}), leg stiffness (k_{leg}), and impact angle (α) (Figure 1B). Contact times were adjusted by a factor of 0.93 to account for deviations from global spring-mass behavior in the final stages of propulsion and thus more accurately model the runners' spring-mass dynamics.[20] The stance velocities and peak horizontal forces were estimated using the method of Burns and Zernicke.[21]

2.4 | Statistical analysis

For each measurement variable, the effects of speed and final finishing position were assessed with an individual multiple linear regression model, where speed and final finishing position were each treated as independent continuous predictors. Although finishing position as a variable is ordinal in nature, it was treated as an interval-scaled variable here, assuming monotonic increases between subsequent positions. Type I error was controlled at $p < 0.05$, and all *p*-values from the analysis were adjusted for multiple comparisons using Benjamini–Hochberg's false discovery rate correction.[22] All statistical analyses were conducted using R (v4.0.2, R Foundation for Statistical Computing).

3 | RESULTS

The mean (±1 SD) PB (min:s) for the eight athletes analyzed was 3:30.93 (±2.96) and their mean finishing time was 3:35.82 (±1.63). Five athletes ran their fastest during lap 4, two on lap 3, and one on lap 2. As such, the individual data in Figures 2 and 4 are presented with respect to running speed, irrespective of lap sequence, but the lap number for each data point is indicated within the respective circle.

In terms of joint kinematic variables (Figures 2 and 3), faster running speeds were associated with more extended elbows at contact (Table 2). Better finishing positions were associated with longer foot ahead and foot behind distances, as well as greater overstriding distances. At initial contact, the hip flexed more in better-placed finishers, and their knees had a greater range of motion from initial contact to midstance. Better-placed finishers also had greater hip extension and knee extension from midstance to toe-off during the unloading phase (Table 2).

Regarding spatiotemporal variables, faster running speeds were associated with shorter contact times and concomitantly greater step frequencies (Figure 4). Faster running was also associated with higher relative contact velocity, less vertical compression, and greater vertical stiffness (Table 3). Better finishing positions were associated with longer contact times and greater fluctuations in speed during the step cycle. In terms of estimated GRF variables, better finishing positions were associated with higher normalized peak horizontal forces. Better finishing positions

TABLE 1 Variables analyzed in the study and their description.

Variable name	Description
Running speed (km/h)	The mean CM horizontal speed during a complete gait cycle
Step length (m)	The distance between successive foot contacts from a specific event on the gait cycle on a particular foot (e.g., toe-off) to the equivalent event on the other foot
Step frequency (Hz)	Calculated by dividing horizontal speed by step length
Contact time (s)	The time duration from initial contact to toe-off
Flight time (s)	The time duration from toe-off of one foot to initial contact of the opposite foot
Swing time (s)	The time duration from toe-off on one foot to initial contact on the same foot
Duty factor	The proportion of stride time (contact time plus swing time) when the foot is in contact with the ground
Flight distance (m)	The distance the CM traveled during flight (from the instant of toe-off on a particular foot to the instant of initial contact on the other foot)
Foot ahead distance (m)	The horizontal distance from the foot center of mass to the CM at initial contact
Foot behind distance (m)	The horizontal distance from the foot center of mass to the CM toe-off
Foot movement distance (m)	The distance the foot center of mass moved from its horizontal position at initial contact to toe-off
Overstriding distance (m)	The distance between the horizontal coordinate of the contact leg knee and the ipsilateral ankle, where larger distances indicated that the ankle landed farther in front of the knee
Stance velocity (m/s)	The mean CM horizontal velocity during the stance phase (from initial contact to toe-off)
Relative contact velocity (%)	The velocity during stance relative to the mean CM horizontal speed during a complete gait cycle
Impact angle (α) (°)	The vertical angle between the foot's contact position and the CM at initial contact
Leg compression (ΔL) (m)	The shortening of the effective lower limb (relative to its standing length) as the CM pendularly rotates over the foot during stance, mostly achieved through knee flexion
Vertical displacement (Δy) (m)	The maximum vertical displacement of the CM during stance, partly caused by leg compression
Hip angle (°)	The sagittal plane angle between the trunk and thigh segments (180° in the anatomical standing position). Angles above 180° indicate hyperextension.
Knee angle (°)	The sagittal plane angle between the thigh and lower leg segments (180° in the anatomical standing position)
Ankle angle (°)	The sagittal plane angle between the lower leg and foot segments, calculated in a clockwise direction (110° in the anatomical standing position)
Shoulder angle (°)	The sagittal plane angle between the trunk and upper arm (0° in the anatomical standing position; negative values for the shoulder therefore indicate a hyperextended position)
Elbow angle (°)	The sagittal plane angle between the upper arm and forearm (180° in the anatomical standing position)

were associated with shallower impact angles, greater leg compression, and lower leg and vertical stiffnesses (Table 3).

4 | DISCUSSION

The aim of this study was to analyze key kinematic, spatiotemporal, and global mechanical characteristics in world-class middle-distance racing across different running speeds and in relation to finishing position. Typically, individuals increase both step length and frequency to run faster, and the magnitude of increase in step length is more substantial.[23] Here, at faster running speeds, step length did not change, but frequency substantially increased instead. This could be indicative of a shift in mechanical strategy for the runners in the upper

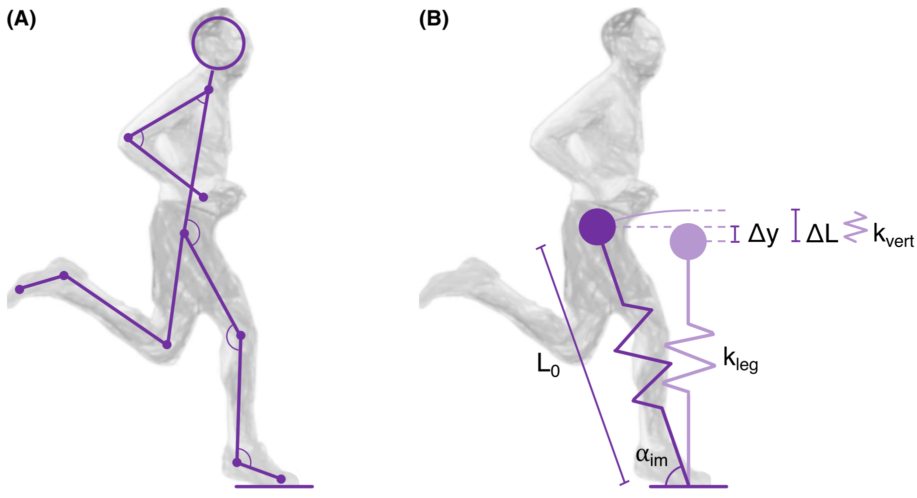

FIGURE 1 Visual representations of the mechanical analyses: (A) kinematic joint angles; and (B) global spring-mass characteristics.

domains of their maximal anaerobic speed capacities. Runners achieve faster speeds by increasing step length at lower speeds, but shift to increasing step frequency to achieve their fastest speeds.[24] In both elite and highly trained middle-distance runners, Burns et al.[7] observed a predominantly linear relationship with speed between both step length and step frequency across submaximal running speeds. However, at the fastest observed speeds in each group (23–25 km/h in the elite and 21–23 km/h in the sub-elite), there was a distinct nonlinear shift, with a similar plateau in step length and a sharp increase in step frequency.[7] As middle-distance runners race in the anaerobic speed domain with the finish necessarily being a maximal sprint,[8] the mechanical strategies exhibited here indicate that elite middle-distance runners compete at speeds above this mechanical shift.

Whereas the spatiotemporal observations suggest some differences related to finishing position, the global characteristics were more discriminatory. The top two finishers, as well as their compatriot and former Olympic and World Champion, had longer ground contacts for a given speed with higher duty factors and lower step frequencies. These characteristics produced lower estimated vertical forces and higher estimated horizontal forces. As such, they had more compliant spring mechanics, with greater leg and vertical compression and, correspondingly, lower leg and vertical stiffnesses. This finding is distinct from the previous observations of Burns et al.,[7] who observed higher leg and vertical stiffnesses in elite middle-distance runners across a range of speeds. In the present study, most of the world-class athletes did exhibit those relatively homogenous, stiffer spring characteristics observed by Burns et al.[7] (i.e., k_{leg} values ~11.5 kN/m). However, the differing patterns in the top two individuals and the former Olympic Champion could highlight a unique, discriminating attribute of world-class middle-distance racers: extended ground contacts and "softer" spring characteristics that allow for greater horizontal propulsive force development. Although this style might not be the most energetically economical running technique for distance runners,[25] it could allow for greater sprint performance and higher anaerobic speed capacity, a necessary ingredient for championship 1500 m sprint finishes. This extended contact phase and greater compression could allow for greater muscular force development,[26] facilitating better acceleration when needed and maintenance of top speed.[27] This again indicates a trade-off between aerobic energetic efficiency and anaerobic power capacity. Similarly, the top finishers also had the longest foot ahead distances and overstriding distances (see Table 1 for definitions), which could be detrimental to running economy but conducive to longer step lengths and greater top speeds. Although running coaches have recommended short foot ahead distances at initial contact (e.g., Anderson[28]), world-class male sprinters moving at 10 m/s have foot ahead distances of approximately 0.38 m long,[29] only slightly more than the values found in this group of top middle-distance athletes running 7.0–7.5 m/s. In an event where submaximal efficiency is less deterministic than in long-distance analogues, 1500 m athletes could thus gain an advantage in a championship setting by having a technique that favors speed over economy.

The higher placing athletes had greater knee flexion and extension during the loading and unloading phases of stance, respectively. They also exhibited greater hip extension during unloading in late stance. Previous research on kinematic measures and their relationship to performance in distance runners have been somewhat inconclusive and not particularly discriminating.[5] For example, in a study on national-standard middle-distance runners where the men ran overground in a laboratory setting at a target pace (mean speed: ~26 km/h), Trowell et al.[30] also observed

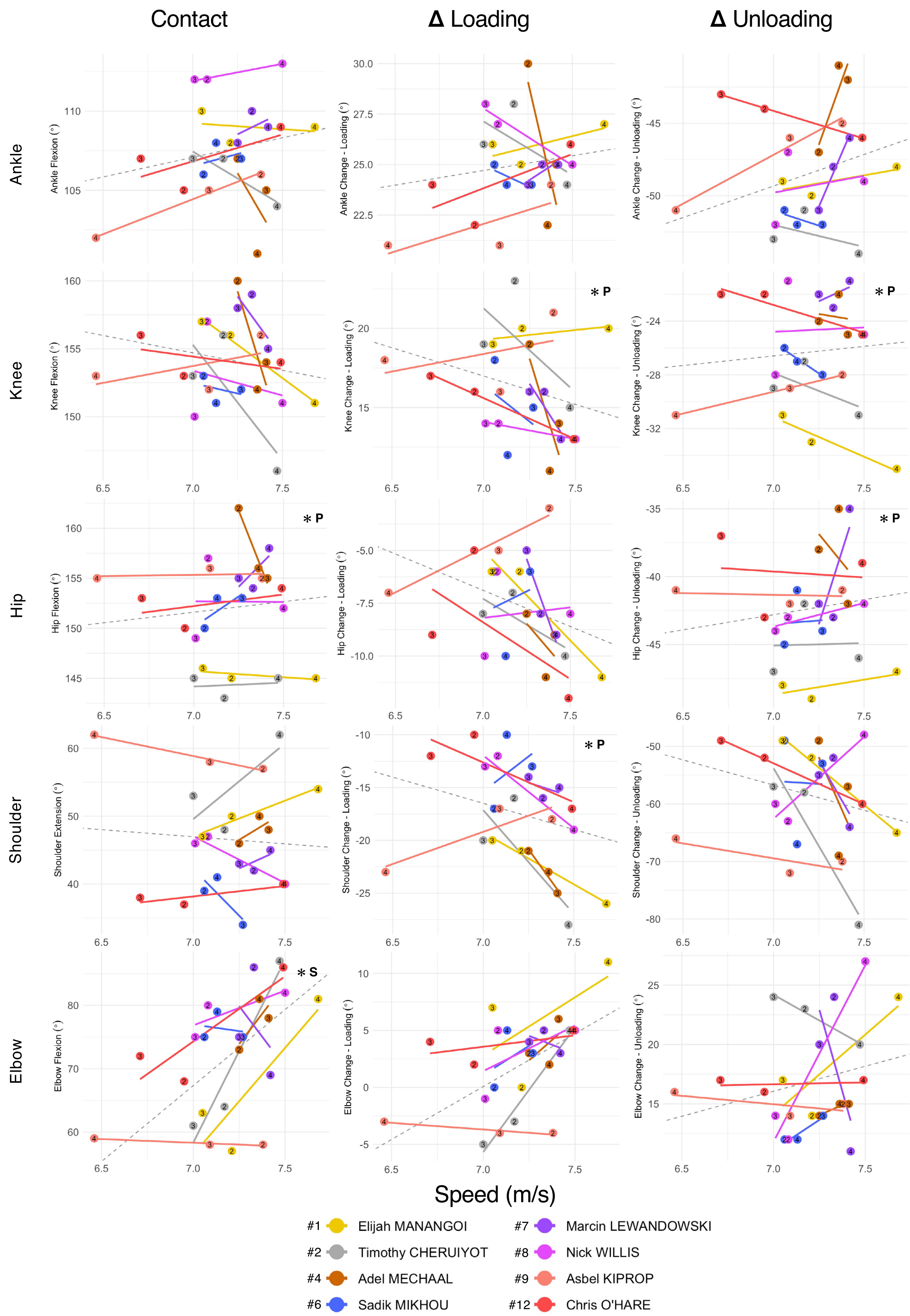

FIGURE 2 Kinematic characteristics within racers across speeds. Individuals and their own trends are color-coded (see legend at bottom). Results are provided for the individual values at initial contact (left column) as well as the within-individual changes from initial contact to midstance (middle column) and from midstance to terminal stance (right column). The colored lines indicate the within-individual trends across speeds, and the dashed line indicates the collective trend across speeds. The individual data points are labeled for their lap numbers within individuals. Significant relations with speed (S) and/or final finishing position (P) are marked where significant with respect to $p < 0.05$ (*).

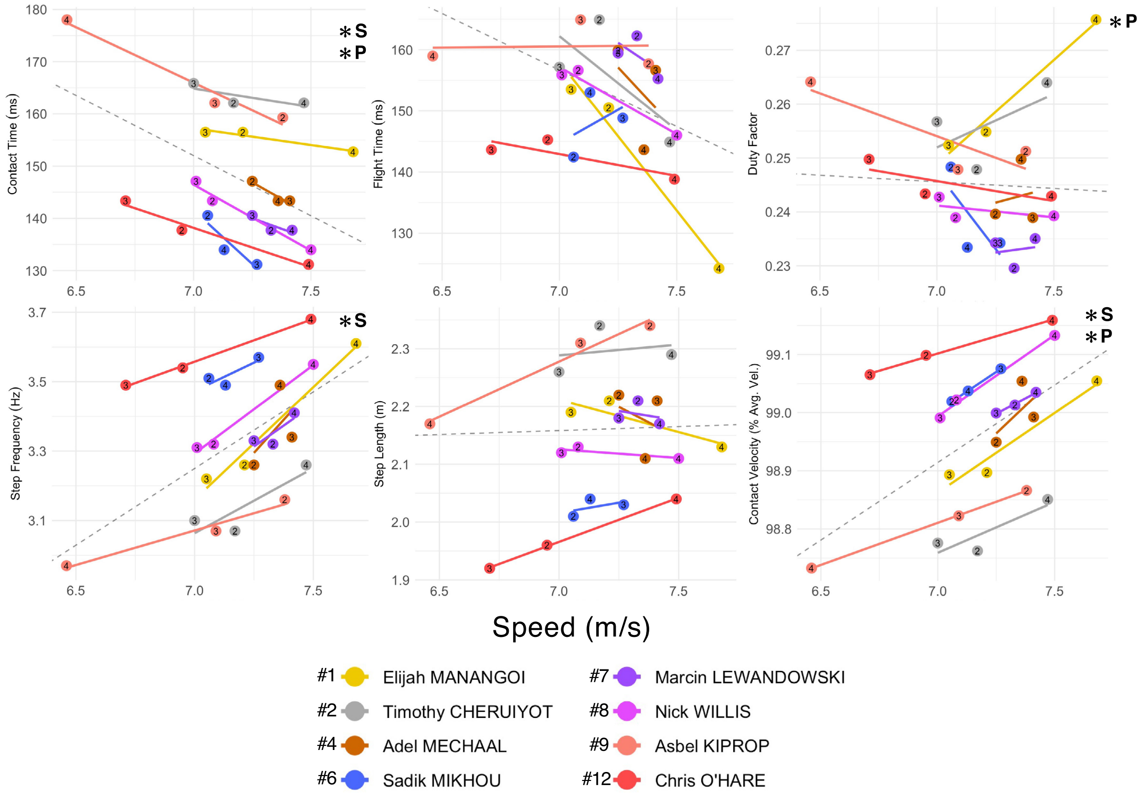

FIGURE 3 Spatiotemporal characteristics within racers across speeds. Individuals and their own trends are color-coded (see legend at bottom). The colored lines indicate the within-individual trends across speeds, and the dashed line indicates the collective trend across speeds. The individual data points are labeled for their lap numbers within individuals. Significant relations with speed (S) and/or final finishing position (P) are marked where significant with respect to $p < 0.05$ (*).

that the best 1500 m runners exhibited greater knee flexion during stance. By contrast, both Leskinen et al.,[31] whose analysis included data from the 2005 IAAF World Championships men's 1500 m final, and Folland et al.,[5] who analyzed runners during a controlled, incremental treadmill test, postulated that less flexion was related to a greater lower limb stiffness, which could be more efficient in recycling energy through the step cycle. Trowell et al.[30] suggested that greater flexion and more compliance in the limb allowed for a more favorable force-length-velocity relationship in the muscles and facilitated a greater vertical impulse. In this study, the performance relationship was driven primarily by the top two finishers, who were able to increase speed on the final lap much more than their rivals. Perhaps both sets of conclusions from these previous investigations are therefore true in the context of a championship 1500 m race: greater knee flexion might be less energetically efficient, but also affords a greater capacity to generate force and higher speeds.

Among the upper limb joints, the only measures that consistently changed with speed during the race were the elbow angles, with wider angles at initial contact appearing as the athletes ran faster and more movement arose during the loading phase. The other upper limb measures bore no consistent relationships with speed as the patterns within each athlete were highly individualized. Interestingly, arm carriage was cited as a key mechanical point of intervention by one of the athletes' coaches,[32] who postulated that an athlete's propensity to extend their elbows in a race's closing stages was a sign of "tying up" and fatiguing, and thus that maintenance of arm position is a developmental aim during fast running.

Whether the characteristics described above are inherent in the athletes or developed is an open question. Most elite 1500 m runners employ some common attributes of training: endurance running, threshold running, anaerobic intervals, hill repetitions, plyometric drills, and strength training.[33] The global attributes of all athletes in this cohort, as well as those related to speed and those that separated performers, might respond to these training interventions. Plyometric drills immediately before running enhanced both leg stiffness and running economy in recreational athletes,[34] and improved running economy and time trial performance as a training intervention in trained distance runners.[35] Similarly, resistance training increased tendon stiffness[36] and improved running economy and time-to-exhaustion in runners.[37] Those elements could help develop the global mechanical characteristics

TABLE 2 Kinematic characteristics during stance.

	Mean (SE)	Speed (SE)	Place (SE)
Hip			
Contact (°)	152 (1)	2.1 (3.8)	0.8 (0.3)*
Loading (Δ°)	−8 (1)	−3.4 (1.9)	−0.0 (0.1)
Unloading (Δ°)	−42 (1)	2.2 (2.9)	0.1 (0.2)*
Knee			
Contact (°)	154 (1)	−2.6 (2.8)	0.1 (0.2)
Loading (Δ°)	16 (1)	−3.6 (2.4)	−0.5 (0.2)*
Unloading (Δ°)	−26 (1)	1.4 (2.9)	0.7 (0.2)*
Ankle			
Contact (°)	108 (1)	2.5 (2.5)	0.2 (0.2)
Loading (Δ°)	25 (1)	1.5 (1.9)	−0.2 (0.1)
Unloading (Δ°)	−49 (1)	4.4 (2.9)	0.5 (0.2)
Shoulder			
Contact (°)	−47 (2)	2.1 (6.4)	0.9 (0.5)
Loading (Δ°)	−17 (1)	−5.0 (3.5)	0.8 (0.3)*
Unloading (Δ°)	−59 (2)	−8.7 (7.7)	0.1 (0.6)
Elbow			
Contact (°)	72 (2)	24.0 (6.9)*	0.9 (0.5)
Loading (Δ°)	2 (1)	9.3 (3.0)	0.1 (0.2)
Unloading (Δ°)	17 (1)	4.2 (4.0)	−0.2 (0.3)

Note: Coefficients for speed indicate changes per m/s (e.g., Δ° per m/s) during the loading (initial contact to midstance) and unloading phases (midstance to toe-off). Coefficients for finishing place indicate changes per final race position, with a positive coefficient indicating a relation with a worse finishing position.

*Coefficient significant at $p < 0.05$.

of elite middle-distance runners, for example, higher leg stiffnesses, steeper impact angles, and greater vertical forces,[7] but how the mechanical characteristics that separate the top performers here within an elite cohort are developed might be related to propulsive horizontal force generation. The gold and silver medalists and the former Olympic Champion frequently use a less traditional technique for middle-distance training: resisted running.[38] They employ long repetitions in excess of 1000 m dragging a tire tied to the waist over undulating terrain or with a waist-worn harness attached to a braking bicycle behind.[38] Hill training is commonly employed by many middle- and long-distance runners, but the resistance imposed on the runner by the incline is considerably smaller than with weighted sleds.[39] The use of level-ground resisted running could thus serve to uniquely augment the ability of middle-distance runners to generate horizontal propulsive forces, essential to elevating maximal sprinting speed.

This investigation provided novel insight into the mechanical characteristics that underpin elite 1500 m racing, and further revealed some key attributes that differentiated medalists from finalists. First were the distinct spring-mass characteristics of the better placing runners; previous studies of elite 1500 m runners have shown them to have distinct spring-mass characteristics, namely higher leg and vertical stiffnesses with more upright impact angles, relative to sub-elite 1500 m runners,[7] but here the better finishing runners within the elite cohort demonstrated less stiff spring mechanics. The reasons underpinning the differences in spring characteristics are likely different between the cohorts. The sub-elite runners in Burns et al.[7] might have had more compliant spring mechanics because of characteristics of their musculotendinous structures, their neuromuscular coordination patterns, or even more inefficient loading and unloading progressions. The higher placing runners here who had more compliant spring mechanics were likely not differentiated on these aspects, but rather their compliant systems were a manifestation of their ability to generate higher propulsive forces, enabling greater speeds during the final kick. As such, the means to develop these characteristics are twofold: first, developing the characteristics that lead to stiffer apparent mechanics that are characteristic of more efficient and more elite runners; and second, developing the capacity to generate substantial propulsive forces for the finishing stages, characteristic of runners who can elevate speed in the closing stages of races. The techniques to train these characteristics include strength training, hill work, and resisted sprinting. The developments within athletes of horizontal force production in sprinting can be monitored by coaches in the field using resisted sprints and velocity recordings from photocells, laser, or radar devices.[40]

The second important observation for coaches was that the athletes exhibited relatively constant step lengths throughout the race, modulating their speeds largely through changes in step frequency. This study demonstrates that elite 1500 m racing is contested primarily at speeds where runners no longer increase step length. This serves as a mechanical monitoring framework for speed, with two domains: the step length domain and the step frequency domain. In the former, runners increase both step length and step frequency as they run faster and, in the latter, step frequency only. Profiling step length / step frequency versus speed within runners could serve as an informative tool for coaches of elite athletes. Moreover, how the threshold of those domains change in relation to performance is an informative adaptive metric, as the elite middle-distance runners in Burns et al.[7] exhibited this shift at higher speeds relative to the sub-elite runners. Measurement of step length, frequency, and duty factor in training is highly accessible with the advent of wearable technology solutions, enabling this sort of profiling to be readily implemented in the field.

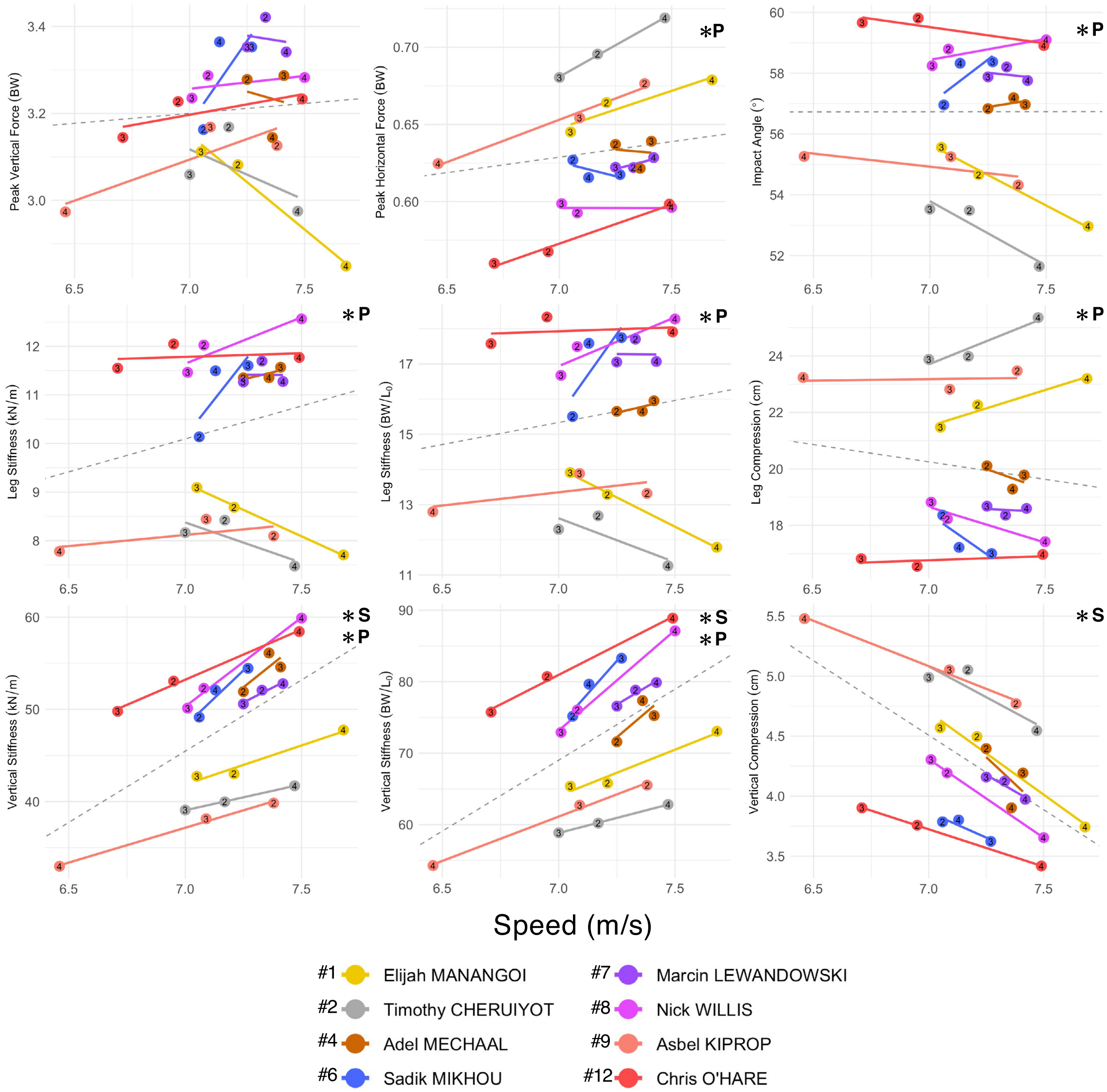

FIGURE 4 Spring-mass characteristics within racers across speeds. Individuals and their own trends are color-coded (see legend at bottom). Relative stiffnesses are provided as BW/L_0. The colored lines indicate the within-individual trends across speeds, and the dashed line indicates the collective trend across speeds. The individual data points are labeled for their lap numbers within individuals. Significant relations with speed (S) and/or final finishing position (P) are marked where significant with respect to $p < 0.05$ (*).

The main strength of this study was that the use of in-stadium cameras allowed for the analysis of the world's best male middle-distance runners and meant highly ecological findings. However, some compromise is made in sensitivity against laboratory analysis, which could be an additional explanation for the lack of discriminatory kinematic variables. Additionally, because of this capture method, single gait cycles only were captured for each athlete per lap. Ideally, future efforts would capture multiple steps to improve the precision of the estimates and inform intra-individual variances. Furthermore, the global characteristics (e.g., the spring-mass variables) were estimated using temporal measurements rather than direct kinetic measurement. This method has demonstrated good agreement with kinetic measurement among outcome measures, but it prevents a high-resolution analysis of force characteristics and waveforms.[19] The horizontal force estimations were made via the method of Burns and Zernicke,[21] which similarly uses the runners' temporal patterns to estimate braking and propulsive forces assuming spring-mass dynamics. The method performs well in spring-mass models across a range of speeds, but is less precise in runners observed at lower speeds. Its utility here is less in the exact magnitudes of the forces per se, but more in their relative magnitudes, that is, demonstrating that particular runners sustain and generate more horizontal forces at given speeds given their temporal dynamics and anthropometric characteristics. Finally, the exceptionality of the athletes and the unique circumstances under

TABLE 3 Spring-mass and estimated kinetic characteristics.

	Mean (SE)	Speed (SE)	Place (SE)
Step length (m)	2.16 (0.02)	0.01 (0.09)	−0.02 (0.01)
Step frequency (Hz)	3.34 (0.03)	0.44 (0.14)*	0.02 (0.01)
Foot ahead (m)	0.35 (0.01)	−0.019 (0.031)	−0.006 (0.002)*
Foot behind (m)	0.59 (0.01)	0.006 (0.035)	−0.008 (0.003)*
Overstriding distance (m)	0.043 (0.003)	−0.001 (0.014)	−0.003 (0.001)*
Contact time (s)	0.147 (0.022)	−0.023 (0.087)*	−0.002 (0.007)*
Flight time (s)	0.153 (0.017)	−0.018 (0.007)	0.001 (0.005)
Duty factor	0.245 (0.002)	−0.002 (0.008)	−0.002 (0.001)*
Relative contact velocity (%)	0.990 (0.000)	0.003 (0.001)*	0.001 (0.001)*
Peak vertical force (BW)	3.21 (0.02)	0.05 (0.10)	0.02 (0.01)
Peak horizontal force (BW)	0.63 (0.01)	0.02 (0.02)	−0.01 (0.01)*
α (°)	56.7 (0.4)	0.01 (1.4)	0.5 (0.1)*
ΔL (cm)	0.20 (0.005)	−0.012 (0.020)	−0.005 (0.002)*
Δy (cm)	0.043 (0.001)	−0.012 (0.004)*	−0.001 (0.001)
k_{leg} (kN/m)	10.4 (0.3)	1.4 (1.2)	0.3 (0.1)*
k_{vert} (kN/m)	48.5 (1.2)	15.4 (4.8)*	1.1 (0.4)*

Note: Coefficients for speed indicate changes per m/s (e.g., N/m per m/s). Coefficients for finishing place indicate changes per final race position, with a positive coefficient indicating a relation with a worse (higher) finishing position. Contact and flight times have been adjusted by a factor of 0.93.

*Coefficient significant at $p < 0.05$.

which they were observed–a global championship final–necessarily begs a small sample. As such, caution should be taken with outright generalization, and the findings should be interpreted as ecological observation that provides new insight into this class of athletes and their success-related characteristics along with opportunity for future, broader investigation.

5 | PERSPECTIVE

This was the first study to analyze the biomechanics of elite male 1500 m runners during a World Championship final over multiple laps. Within this group, the runners exhibited mechanical characteristics that were related to both their speeds within the race and their overall finishing position, showing an important difference in running mechanics. The highest finishers had longer contact times, greater fluctuations in speed through the step cycle, shallower impact angles, and lower leg stiffnesses, which were important in being able to produce higher propulsive forces during the sprint finish. We have provided unique ecological evidence that these elite runners were differentiated from each other by mechanical features, and that the differences, especially those of global mechanical behavior, explained their performance. Coaches should note that certain aspects of global running style featuring lower duty factors and higher leg stiffness might be beneficial to some determinants of performance, such as better running economy, but those aspects of a style featuring higher duty factors and lower leg stiffnesses might be beneficial to other determinants, such as greater horizontal force production. The former might be important for athletes to develop to realize a fast sprint finish, which is a necessary ingredient for championship middle-distance racing success.

CONFLICT OF INTEREST STATEMENT

The data collection and initial data analysis were supported by funding provided by the IAAF as part of a wider development/education project; however, the nature of the data is purely descriptive and not associated with any governing body, commercial sector, or product. No funding was provided for the writing of this manuscript. The results of the present study do not constitute endorsement by the IAAF/World Athletics.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Brian Hanley https://orcid.org/0000-0001-7940-1904
Athanassios Bissas https://orcid.org/0000-0002-7858-9623
Geoffrey T. Burns https://orcid.org/0000-0001-5225-588X

REFERENCES

1. Moore K. Where have all our milers gone? *Sports Illus*. 1986;65:63-64.
2. Fukuba Y, Whipp BJ. A metabolic limit on the ability to make up for lost time in endurance events. *J Appl Physiol*. 1999;87:853-861.
3. Hettinga FJ, Edwards AM, Hanley B. The science behind competition and winning in athletics: using world-level competition data to explore pacing and tactics. *Front Sports Act Living*. 2019;1:11.
4. van Oeveren BT, de Ruiter CJ, Beek PJ, van Dieën JH. The biomechanics of running and running styles: a synthesis. *Sports Biomech*. 2021;1-39. doi:10.1080/14763141.2021.1873411. Online ahead of print.
5. Folland JP, Allen SJ, Black MI, Handsaker JC, Forrester SE. Running technique is an important component of running economy and performance. *Med Sci Sports Exerc*. 2017;49:1412-1423.
6. McMahon TA, Cheng GC. The mechanics of running: how does stiffness couple with speed? *J Biomech*. 1990;23:65-78.
7. Burns GT, Gonzalez R, Zendler JM, Zernicke RF. Bouncing behavior of sub-four minute milers. *Sci Rep*. 2021;11:1-15.
8. Sandford GN, Kilding AE, Ross A, Laursen PB. Maximal sprint speed and the anaerobic speed reserve domain: the untapped tools that differentiate the World's best male 800 m runners. *Sports Med*. 2019;49:843-852.
9. World Athletics. Start list: 1500 metres men – final. https://media.aws.iaaf.org/competitiondocuments/pdf/5151/AT-1500-M-f----.SL2.pdf. Accessed January 3, 2022.
10. Matthews P. *Athletics 2017: the International Track and Field Annual*. SportsBooks Ltd.; 2017.
11. World Athletics. Results: 1500 metres men – final. https://media.aws.iaaf.org/competitiondocuments/pdf/5151/AT-1500-M-f----.RS6.pdf. Accessed January 3, 2022.
12. Smith G. Padding point extrapolation techniques for the Butterworth digital filter. *J Biomech*. 1989;22:967-971.
13. Bahamonde RE, Stevens RR. Comparison of two methods of manual digitization on accuracy and time of completion. *Proceedings of the XXIV International Symposium on Biomechanics in Sports*. University of Salzburg; 2006:650-653.
14. Abdel-Aziz YI, Karara HM, Hauck M. Direct linear transformation from comparator coordinates into object space coordinates in close-range photogrammetry. *Photogramm Eng Remote Sensing*. 2015;81:103-107.
15. de Leva P. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *J Biomech*. 1996;29:1223-1230.
16. Winter DA. *Biomechanics and Motor Control of Human Movement*. John Wiley & Sons; 2009:70-74.
17. Atkinson G, Nevill AM. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Med*. 1998;26:217-238.
18. Bland JM, Altman D. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet*. 1986;327:307-310.
19. Morin JB, Dalleau G, Kyröläinen H, Jeannin T, Belli A. A simple method for measuring stiffness during running. *J Appl Biomech*. 2005;21:167-180.
20. Burns GT, Gonzalez R, Zernicke RF. Improving spring–mass parameter estimation in running using nonlinear regression methods. *J Exp Biol*. 2021;224:jeb232850.
21. Burns GT, Zernicke RF. A simple computational method to estimate stance velocity in running. *J Exp Biol*. 2021;224:jeb242787.
22. Benjamini Y, Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *J R Stat Soc, B: Stat Methodol*. 1995;57:289-300.
23. Cavanagh PR, Kram R. Stride length in distance running: velocity, body dimensions, and added mass effects. *Med Sci Sports Exerc*. 1989;21:467-479.
24. Weyand PG, Sternlight DB, Bellizzi MJ, Wright S. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Phys*. 2000;89:1991-1999.
25. Chang YH, Kram R. Metabolic cost of generating horizontal forces during human running. *J Appl Phys*. 1999;86:1657-1662.
26. Weyand PG, Sandell RF, Prime DN, Bundle MW. The biological limits to running speed are imposed from the ground up. *J Appl Phys*. 2010;108:950-961.
27. Morin JB, Edouard P, Samozino P. Technical ability of force application as a determinant factor of sprint performance. *Med Sci Sports Exerc*. 2011;43:1680-1688.
28. Anderson O. *Running Form: how to Run faster and Prevent Injury*. Human Kinetics; 2018.
29. Bissas A, Walker J, Paradisis GP, et al. Asymmetry in sprinting: an insight into sub-10 and sub-11 s men and women sprinters. *Scand J Med Sci Sports*. 2022;2:69-82.
30. Trowell D, Phillips E, Saunders P, Bonacci J. The relationship between performance and biomechanics in middle-distance runners. *Sports Biomech*. 2021;20:974-984.
31. Leskinen A, Häkkinen K, Virmavirta M, Isolehto J, Kyröläinen H. Comparison of running kinematics between elite and national-standard 1500-m runners. *Sports Biomech*. 2009;8:1-9.
32. FloTrack. Warhurst on the tools that the greats have [Video]. https://www.flotrack.org/video/5161764-warhurst-on-the-tools-that-the-greats-have. Accessed January 10, 2022.
33. Casado A, Hanley B, Santos-Concejero J, Ruiz-Pérez LM. World-class long-distance running performances are best predicted by volume of easy runs and deliberate practice of short-interval and tempo runs. *J Strength Cond Res*. 2021;35:2525-2531.
34. Wei C, Yu L, Duncan B, Renfree A. A plyometric warm-up protocol improves running economy in recreational endurance athletes. *Front Physiol*. 2020;11:197.
35. Spurrs RW, Murphy AJ, Watsford ML. The effect of plyometric training on distance running performance. *Eur J Appl Physiol*. 2003;89:1-7.
36. Kubo K, Kanehisa H, Ito M, Fukunaga T. Effects of isometric training on the elasticity of human tendon structures in vivo. *J Appl Physiol*. 2001;91:26-32.
37. Støren Ø, Helgerud J, Støa EM, Hoff J. Maximal strength training improves running economy in distance runners. *Med Sci Sports Exerc*. 2008;40:1089-1094.
38. Gault J. The secrets of the world's best 1500-meter training group: How Elijah Manangoi, Timothy Cheruiyot, & coach Bernard Ouma turned Rongai Athletics Club into a powerhouse. https://www.letsrun.com/news/2018/08/secrets-worlds-best-1500-meter-training-group-elijah-manangoi-timot

hy-cheruiyot-coach-bernard-ouma-turned-rongai-athletics-club-powerhouse/. Accessed January 10, 2022.
39. Delaney JA, McKay BA, Radcliffe J, et al. Uphill sprinting load- and force-velocity profiling: assessment and potential applications. *J Sports Sci*. 2021;40:281-287.
40. Samozino P, Rabita G, Dorel S, et al. A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running. *Scand J Med Sci Sports*. 2016;26:648-658.

How to cite this article: Hanley B, Bissas A, Merlino S, Burns GT. Changes in running biomechanics during the 2017 IAAF world championships men's 1500 m final. *Scand J Med Sci Sports*. 2023;00:1-12. doi:10.1111/sms.14331