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Original research

Repeated sprints alter mechanical work done by hip and knee, but not ankle, sagittal moments

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ABSTRACT

Objectives: To quantify the changes in work done by lower limb joint moments during maximal speed running following a sports-specific repeated running protocol.
Design: Observational with repeated-measures.
Methods: Recreational athletes (n = 18 (9 females), aged = 26.2 ± 6.2 years) performed 12 maximal 30-m sprints on a non-motorised treadmill. Three-dimensional kinematics and ground reaction forces were subsequently recorded during a 10-m maximal overground sprint before and immediately after the repeated running protocol, from which we calculated work done by sagittal plane hip, knee, and ankle moments. Relative work (J/kg) was reported as a percentage of positive and negative work done by the sum of joint moments.
Results: Following the repeated running protocol, maximal sprint speed decreased by 19% and was accompanied by reductions in total positive (−1.47 J/kg) and negative (−0.92 J/kg) work, in addition to work done by hip (−0.43 to −0.82 J/kg) and knee (−0.28 J/kg) moments during swing. Compared to before the repeated running protocol, less relative work was done by hip (−9%) and knee (−3%) extension moments during swing. Reductions in work done by hip and knee joint moments during swing were significantly correlated with reductions in maximum running speed (r = 0.61–0.89, p < 0.05).
Conclusions: A sports-specific repeated running protocol resulted in reductions in mechanical work done by sagittal plane hip and knee joint moments during maximal overground sprinting. Interventions focused on maintaining positive work done by the hip flexors/extensors and negative work done by knee flexors/extensors during the swing phase of running may help prevent reductions in speed following repeated sprinting.

Practical implications

- Work done by lower limb joint moments is redistributed following repeated sprints, suggesting a change in joint-specific contribution to movement.
- Work done by ankle plantarflexors showed no association with running speed decrements.
- Maintaining work done by hip and knee joint moments during swing phase of running has potential to attenuate decrements in maximal running speed following repeated sprints.

1. Introduction

Field and court sports typically require repeated bouts of high intensity running (i.e. sprinting).[1,2] Kinematic and kinetic alterations following repeated sprinting discriminate player performance level[3,4] and potentially relate to risk of musculoskeletal injury.[5] Although physiological responses to repeated sprinting are well studied,[6–8] body mechanics have received less attention and are often simplified to a point-mass model.[5,8,9] Point-mass models have revealed phase fluctuations of kinetic and gravita-

Abbreviations: A1, negative work done by the ankle plantarflexors during early stance; A2, positive work done by the ankle platarflexors during late stance; CI, confidence interval; H1, positive work done by the hip extensors during early stance; H2, negative work done by the hip flexors during late stance; H3, positive work done by the hip flexors during early swing; H4, positive work done by the hip extensors during early swing; K1, negative work done by the knee extensors during early stance; K2, positive work done by the knee extensors during mid/late stance; K3, negative work done by the knee extensors during early swing; K4, negative work done by the knee flexors during late swing; MD, mean difference.

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tional potential energies, but do not resolve the mechanical work done by muscles. Alternatively, joint work quantifies the change in mechanical energy produced by the net moments acting about each joint[10] and is used as a surrogate of mechanical energy produced by muscle.[11] Quantifying work done by joint moments may reveal the biomechanics underpinning reductions in running speed following repeated sprints.

The work done by lower limb joint moments varies non-linearly with increased running speed.[12–14] Studies have investigated the effects of repeated sprints on ground reaction forces, leg stiffness, and spatiotemporal parameters (e.g. stride length, frequency).[5,8,9] Edouard et al.[15] reported decreased gluteus maximus and vastus lateralis myoelectric activity during late swing but not stance phase of running following 12 repeated 6-s sprints. Previous studies also suggested that work produced by hip and knee moments during swing are the main mechanisms for increasing running speed.[12,16,17] It remains unclear how mechanical work performed by lower limb joint moments is altered following repeated sprints.

In this study we determined the effects of a sports-specific repeated running protocol on the (1) absolute and relative changes in work done by sagittal moments about the hip, knee, and ankle, and (2) relationship between changes in mechanical work and changes in running speed. We hypothesised that mechanical work done by lower limb joint moments would decline following the repeated running protocol, particularly at the hip. We also hypothesised the reduction in sprint speed following the repeated running protocol would be correlated with changes in work done by the hip moments.

2. Methods

Eighteen recreationally active individuals (9 females and 9 males; aged = 26.2 ± 6.2 years; stature = 1.73 ± 0.08 m; mass = 70.5 ± 9.4 kg) participated. Participants were engaged in moderate to vigorous exercise at least three times per week. Exclusion criteria included: medical or self-reported contraindications to performing strenuous exercise; lower limb musculoskeletal injury in the last six months; illness within the last week; and any clinically diagnosed neuromuscular disorder. Participants attended a single laboratory session where they were asked to perform a sports-specific repeated running protocol wearing standardised minimal cushioning footwear (Dunlop Volley, Pacific Brands, Australia). Participants were asked to refrain from strenuous lower limb exercise and alcohol consumption for 24 h prior to testing. Caffeine consumption was not restricted to avoid impairing participant running performance.[18] Ethical approval was obtained from the institutional Human Research Ethics Committee. Participants were informed of the procedures and provided their written informed consent, consistent with the Declaration of Helsinki.[19]

Participants were familiarised with the non-motorised treadmill, equipped with reflective markers, and then performed a warm-up consisting of 10 bilateral and 20 unilateral bodyweight squats, 5 squat jumps, one 30-m sprint (on the treadmill), one overground 10-m sprint and one side-step cut to each side. Participants performed two maximal 10-m overground straight sprints and four side-step cuts (two to both left and right sides) to establish baseline values. Subsequently, they performed 12 maximal 30-m sprints on a non-motorised treadmill (Woodway Curve 3.0, WOODWAY USA, Waukesha, USA). After each 30-m treadmill sprint, participants performed one maximal 10-m overground sprint, followed by two side-step cuts (one to each side) (Fig. 1A). All overground tasks began from an upright stationary bipedal stance. Participants performed 10–15 seconds of slow jogging between overground tasks. Each treadmill sprint was separated by approximately 60 s. This protocol was designed based on previous studies,[7,20] though modified to a non-motorised treadmill given the space limits in our laboratory. All spatiotemporal parameters and mechanical work estimations were taken from overground trials to ensure treadmill familiarisation did not affect the assessment of running mechanics.

Participants were equipped with a full-body marker set consisting of 33 retroreflective markers (14 mm diameter) and eight marker clusters (3–4 markers each). Three-dimensional marker positions were obtained using a 12-camera motion analysis system (Vicon, Oxford, UK) sampling at 200 Hz and capture volume of ~2 m × 5 m × 2 m (width, length, height). Ground reaction forces were recorded using three ground-embedded force plates (Advanced Mechanical Technology, MASS, USA) sampling at 2000 Hz. Force plates were positioned 5.5–8.2 m from the starting position for overground sprints and cuts, and participants were asked to accelerate until they passed the last force plate (10 m). A static trial was recorded with the participant in a standardised standing position and used to define joint centres and scale a generic musculoskeletal model.[21] The limb for analysis was randomly selected prior to the baseline sprints and cuts, and analysed again following the repeated running protocol.

Marker coordinates were labelled and gap filled using Vicon Nexus (version 2.7). The MOtoNMS (version 2.2) toolbox[22] was used to process marker and force plate data in MATLAB (R2018b, The MathWorks) for subsequent use in OpenSim (version 3.3).[23] Marker trajectories were low-pass filtered using a 2nd order, dual-pass, zero-lag Butterworth filter with a cut-off frequency of 10 Hz. Ground reaction forces were unfiltered.[24] Gait cycles were visually inspected to identify ground contact and toe-off events based on foot marker positions and vertical ground reaction forces. Maximal running speed was determined by averaging maximal horizontal speed (m/s) of three sacral markers across the gait cycle. Stride length (m) was calculated as the horizontal displacement between two consecutive toe-offs determined by the marker placed atop the first metatarsal. Stride frequency (Hz) was calculated as the inverse of stride time.

For each participant, a generic full-body model[21] was linearly scaled to match individual anthropometry based on marker positions and regression-estimated joint centres.[21] The model consisted of torso (including head), arms, pelvis, and lower limbs, as well as hip, knee, and ankle joints with three, one, and one degrees of freedom, respectively. The scaled model was then used to determine sagittal plane joint kinematics and moments using inverse kinematics and inverse dynamics, respectively. Joint moments were normalised to body mass (Nm/kg). Normalised joint powers (W/kg) were calculated for the hip, knee, and ankle as the dot product between normalised joint moments and joint angular velocities (rad/s). Individual power bursts at each joint were identified based on the direction of the net moment (i.e. flexion or extension), direction of angular velocity (i.e. flexing or extending), and sign of power (i.e. + or −). Four bursts were observed for the hip (H1-4), four for the knee (K1-4), and two for the ankle (A1-2) (Fig. 1B).[25] Work done by the net hip, knee, and ankle joint moments were calculated using trapezoidal numerical integration of joint power-time series (J/kg). Total positive and negative limb work were calculated as the sum of positive and negative work done at the hip, knee, and ankle across the gait cycle. Relative work associated with each power burst was expressed as a percentage of total positive or negative limb work.

Data were inspected for normality using Shapiro–Wilk tests. The effect of the repeated running protocol (post versus pre) on absolute and relative work metrics were assessed using univariate analyses of variance or Mann–Whitney tests, as appropriate. All spatiotemporal parameters showed no deviation from normality and therefore were compared using paired t-tests. Given the trend observed in trial-to-trial variation was captured in a post-pre comparison (Supplementary Figs. 1–4) and our sample was not appropriately powered for 12 comparisons, only baseline (pre)

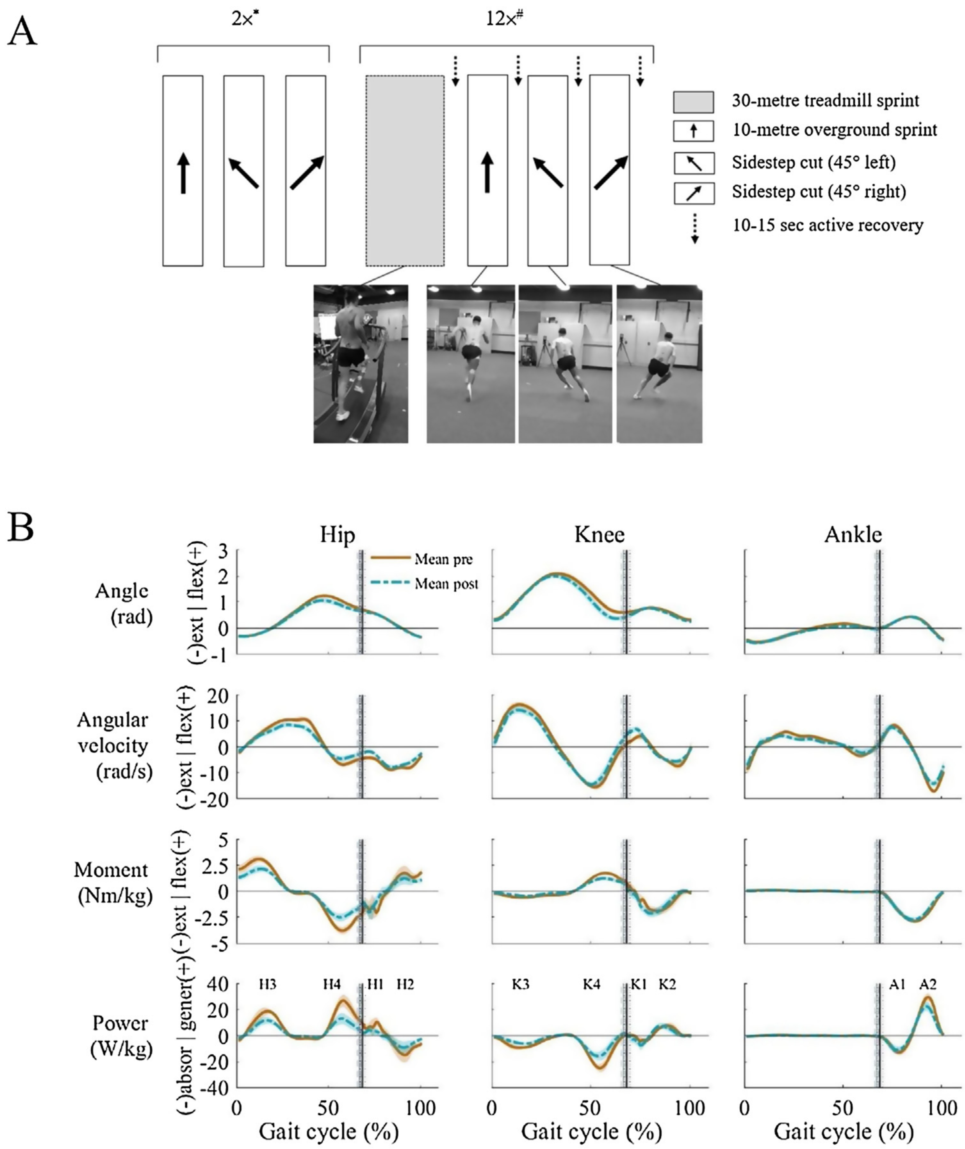

Fig. 1. (A) Schematic representation of the sports-specific repeated running protocol (12 × 30-m maximal sprints). (B) Ensemble averages (n = 18) of hip, knee, and ankle angle angular velocities, moments, and powers for a gait cycle pre (solid brown) and post (dashed blue) the protocol. Shaded regions indicate 95% confidence intervals and vertical lines denote foot contact pre (solid black) and post (dashed grey) the protocol. Gait cycles are defined from toe-off to toe-off and all data were normalised to the gait cycle. absor = absorption; ext = extension (extending for angular velocity); flex = flexion (flexing for angular velocity); gener = generation. Individual power bursts are labelled (H1-4, K1-4, and A1-2). See text for full description of power bursts. * trials used as pre measurement. # last overground sprint used as post measurement.

and 12th (post) overground sprints were directly compared. One pre- and one post-trial were used for each participant. Mean differences (MD) were calculated as the average of the differences between post- and pre-trials for each individual and reported with 95% confidence intervals (95% CI). Effect sizes were calculated as partial eta squared (η_p^2) for normally distributed variables[26] and as eta squared (η^2) for non-normally distributed variables.[27] Effect sizes for the spatiotemporal parameters were calculated as Cohen's dz as recommended for paired samples.[26] Cohen's dz can be interpreted as small (dz = 0.2), medium (dz = 0.5), large (dz = 0.8), and very large (dz = 1.2).[28] However these thresholds should be interpreted with caution.[28] The relationship between change in maximal running speed and change in work done during each power burst was assessed using the Pearson product-moment correlation coefficient (r). The association between variables was classified as small (r = 0.1), medium (r = 0.3), or large (r = 0.50).[29] Statistical analyses were performed using Statistical Package for the Social Sciences (SPSS), version 25.0 (IBM, New York, USA). Significance was accepted for $p < 0.05$.

3. Results

The sports-specific repeated running protocol resulted in significant decreases in maximal speed (MD −19%, 95%CI −15 to −24%, $p < 0.001$, dz = −2.01) and step frequency (MD −18%, 95%CI −13 to −23%, $p < 0.001$, dz = −2.17) during the 10-m overground sprints. Further, early changes in maximal running speed were observed starting from the first repeated sprint (MD −5.9%, 95%CI −4.3 to −7.5%, $p < 0.001$, dz = 1.56) (Supplementary Fig. 5).The repeated running protocol also resulted in significant increases in contact time, both absolute (MD 27%, 95%CI 20–33%, $p < 0.001$, dz = 1.95) and normalised to stride time (MD 1.6%, 95%CI 0.14–3.1%, $p = 0.034$, dz = 0.55). No significant differences were found for step length (MD −2%, 95%CI −4 to 7%, $p = 0.890$, dz = −0.16).

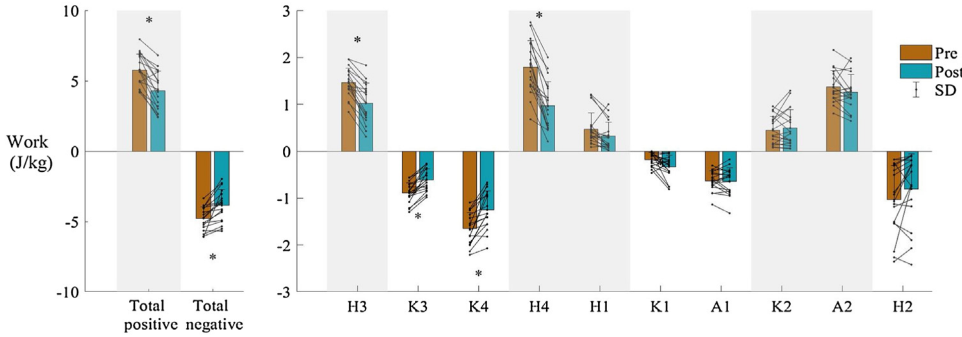

Fig. 2. Work done by sagittal plane total (left) and hip, knee, and ankle (right) moments pre (brown) and post (blue) sports-specific repeated running protocol. Shaded variables represent positive work and unshaded represent negative work. Data are presented as mean and standard deviation. Black lines are individual data (n = 18). *indicates significant differences between pre and post values (p < 0.05). H3-4 = work done by hip moments during swing; H1-2 = work done by hip moments during stance, K3-4 = work done by knee moments during swing; K1-2 = work done by knee moments during stance; A1-2 = work done by ankle moments during stance. See text for full description of power bursts.

Ensemble averages for hip, knee, and ankle external biomechanics are displayed in Fig. 1B. Relative to baseline, total positive (MD −1.47 J/kg, 95%CI −2.33 to −0.06, p = 0.002, $\eta_p^2 = 0.258$) and negative (MD -0.92 J/kg, 95%CI −1.59 to −0.25, p = 0.002, $\eta_p^2 = 0.258$) work decreased significantly following the repeated running protocol (Fig. 2, left). Relative to baseline, positive work done by the hip flexion joint moment during early swing (H3, MD −0.43 J/kg, 95%CI −0.69 to −0.18, p = 0.001, $\eta_p^2 = 0.266$) and positive work done by the hip extension joint moment during late swing (H4, MD −0.82 J/kg, 95%CI −1.19 to −0.46, p < 0.001, $\eta_p^2 = 0.381$) were significantly reduced following the repeated running protocol (Fig. 2, right). Relative to baseline, negative work done by the knee extension joint moment during early swing (K3, MD −0.28 J/kg, 95%CI −0.43 to −0.13, p = 0.02, $\eta^2 = 0.262$) and negative work done by the knee flexion joint moment during late swing (K4, MD −0.40 J/kg, 95%CI −0.65 to −0.15, p = 0.003, $\eta_p^2 = 0.234$) were significantly reduced following the repeated running protocol. In contrast, work done by the knee extension moment during early (K1, MD 0.15 J/kg, 95%CI 0.02 to 0.29, p = 0.71, $\eta^2 = 0.090$) and late (K2, MD 0.04 J/kg, 95%CI −0.19 to 0.28, p = 1.00, $\eta^2 < 0.001$) stance did not change relative to baseline (Fig. 2, right). No significant changes in work done by the ankle plantarflexors moment were observed during early (A1, MD −0.01 J/kg, 95%CI −0.18 to 0.16, p = 0.874, $\eta_p^2 = 0.001$) or late (A2, MD −0.11 J/kg, 95%CI −0.36 to 0.14, p = 0.374, $\eta_p^2 = 0.023$) stance.

Relative to baseline, the contribution of positive work done by the hip extension moment during late swing to total positive work decreased following the repeated running protocol (H4, MD −9.10%, 95%CI −13.36 to −4.85%, p < 0.001, $\eta_p^2 = 0.381$) and was accompanied by an increase in the contribution of positive work done by the ankle plantarflexion moment during late stance (A2, MD 6.43%, 95%CI 2.02–10.84%, p = 0.374, $\eta_p^2 = 0.023$) (Fig. 3, shaded region). Relative to baseline, the contribution of negative work done by the knee extension moment during early swing to total negative work was significantly reduced following the repeated running protocol (K3, MD −3.08%, 95%CI −5.43 to −0.73%, p = 0.025, $\eta^2 = 0.140$) and was accompanied by an increased contribution from the negative work done by the knee extension moment during early stance (K1, MD 5.37%, 95%CI 1.83–8.91%, p = 0.009, $\eta^2 = 0.187$). (Fig. 3, unshaded region).

The reduction in running speed relative to baseline following the repeated running protocol was significantly correlated with change in positive work done by the hip flexion (H3: r = 0.77, p < 0.001) and extension (H4: r = 0.61, p = 0.007) moments during swing and with the change in negative work done by the knee extension (K3: r = 0.89, p < 0.001) and flexion (K4: r = 0.79, p = 0.007) moments during swing (Supplementary Fig. 6).

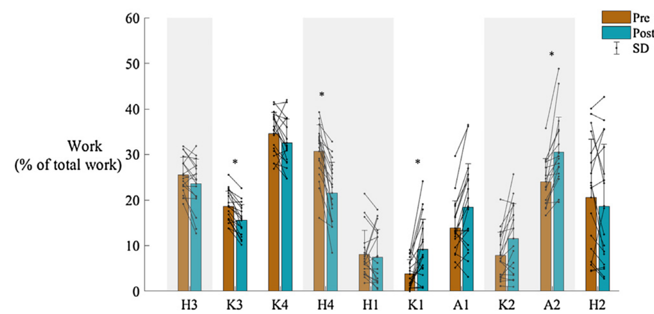

Fig. 3. Work done by sagittal plane hip, knee, and ankle joint moments pre (brown) and post (blue) sports-specific repeated running protocol expressed as a percentage of either total positive or negative work. Shaded variables represent positive work and unshaded represent negative work. Data are presented as mean and standard deviation. Black lines represent individual participant data (n = 18). *indicates significant differences between pre and post values (p < 0.05). H3 = hip flexion during initial swing, H4 = hip extension during late swing, H3-4 = work done by hip moments during swing; H1-2 = work done by hip moments during stance, K3-4 = work done by knee moments during swing; K1-2 = work done by knee moments during stance; A1-2 = work done by ankle moments during stance. See text for full description of power bursts.

4. Discussion

Consistent with our hypothesis, the repeated running protocol resulted in reductions in total positive (generation) and negative (absorption) work compared to baseline, mainly due to reductions in positive and negative work done by the hip and knee joint moments during the swing phase of running. Relative to baseline, the decrease in contribution from the positive work done by the hip extension moment to total positive work at the end of swing was accompanied by an increase in the relative work done by the ankle plantarflexion moment at the end of stance. Reductions in running speed following the repeated running protocol were significantly correlated with reductions in work done by the hip and knee moments during swing, corroborating our second hypothesis. Although causality cannot be inferred from our analysis, these findings suggest reduced work by the hip and knee moments during swing could be one of the mechanisms leading to reductions in performance following repeated running.

Total positive and negative work done by the lower limb joint moments decreased by 26% and 19%, respectively, following the repeated running protocol. The reduction in total work was explained by the decrease in positive work done by the hip flexor (H3) and extensor (H4) moments, and the decrease in negative work done by the knee extensor (K3) and flexor (K4) moments, during the swing phase. The large reduction (~50%) in energy generation (i.e. positive work) from the hip extensors (H4) following the repeated running protocol is consistent with previously observed decreases in gluteus maximus activation.[15] Further, the reductions in work done by the hip extensors and knee flexors at the end of swing suggest reduced mechanical work done by the hamstrings, since these muscles are primary contributors to both hip extension and knee flexion moments.[16] The reduced involvement of the biarticular knee flexor muscles is further supported by the observed decrease in biceps femoris activity following repeated sprint exercise.[30] In contrast, the work done by the ankle plantarflexors (A1 and A2) during stance was preserved following the repeated running protocol. Collectively, the abovementioned findings suggest work done by hip and knee spanning muscles declines following a repeated running protocol, similar to what has been observed when comparing different steady-state running speeds.[11,14,16] However, as previously suggested,[30] it remains unclear whether the observed changes relate to differences in running speed or neuromuscular fatigue.

Relative to baseline, decreases in total positive and negative lower limb joint work following the sports-specific repeated running protocol were accompanied by redistribution of work done by the joint moments. The contribution of the work done by the hip extension moment to total positive work decreased by ∼10% (30% (pre) to 20% (post)), whereas the contribution from ankle plantarflexors during push-off (A2) increased by ∼8% (25% (pre) to 33% (post)). Similar reductions in hip contribution to total positive work have also been reported when individuals run at slower steady-state speeds.[14] Our results indicate that muscles contributing to hip extension during late swing may experience the greatest reduction in work done following a repeated running protocol, and the ankle plantarflexors may compensate by producing a greater proportion of total positive work. In order to minimise the deleterious effects of repeated sprints on running mechanics, efforts should focus on maintaining work done by the hip extensors during late swing.

We observed large correlations between decline in maximal sprint speed and decrease in positive work done by the hip flexor/extensor moments during swing ($r = 0.61-0.77$), and negative work done by the knee extensor/flexor moments during swing ($r = 0.79-0.89$) (Supplementary Fig. 6). Our findings suggest that reductions in step frequency following repeated sprints may be regulated by changes in work done by hip and knee spanning muscles during the swing phase of running.[16] The reductions in step frequency (18%) and speed (19%) observed in the present study were larger than those previously reported (11–14% and 13–17%, respectively),[11,30] possibly reflecting differences in experimental design between studies (i.e. length of the protocol or tasks involved). Although previously discussed,[8,11,30] our results show for the first time, experimentally, a possible link between changes in segment mechanics during swing and spatiotemporal variables following repeated sprint exercise.

The study of joint mechanics[31] has successfully informed physical training,[32] suggesting the potential for similar approach to improve repeated sprint performance. However, optimal methods to improve knee and hip muscle function in the swing phase of running remain unclear. Short-term resistance training interventions (5–8 weeks) involving isolated exercises targeting knee[33,34] or hip[35] flexor strength, or more complex multi-joint movements[36,37] (e.g. squat, deadlift, plyometrics) showed significant improvements in sprint acceleration[35–36] or repeated sprint performance.[33,34] Studies assessing joint mechanics during repeated sprints before and after resistance training interventions are required to confirm whether maintaining work done by the hip and knee moments during swing is a mechanism by which resistance training benefits repeated sprint performance.

Several limitations of our research should be acknowledged. First, participants were asked to perform repeated 30-m sprints on a non-motorised treadmill due to space limitations in our laboratory. However, their running mechanics were assessed overground. We assessed the overground mechanics because the task is likely more familiar to participants and the results may be more relevant for field and court sports. Second, the number of tasks participants were required to perform and the short interval between tasks may have caused some pacing by participants, which was not directly assessed during the experiment. Nonetheless, this effect seems unlikely given that two researchers encouraged participants vigorously at all times and reductions in speed at the beginning of the protocol are within an acceptable range for (∼6%) for recreationally active individuals (Supplementary Fig. 1). Third, the effect of the repeated running protocol on running mechanics was evaluated by examining the work done by net joint moments, which does not reflect the work done by individual muscle-tendon units, neglects muscle co-contraction, and the mechanics of series elastic components and biarticular muscles.[38] Irrespective, our approach provides insight into the nature and extent of changes in running mechanics at the joint level. Future research exploring contributions of individual muscle-tendon units to changes in joint mechanics following a sports-specific repeated running protocol using computational modelling is recommended.[16] Fourth, our analysis was restricted to work done by joint moments in the sagittal plane thereby neglecting effects on mechanical work done in frontal and transverse planes. Further, maximal voluntary muscle activation and/or strength have likely decreased due to the running protocol,[7,34] but these parameters were not assessed, thus the observed changes in mechanical work cannot be directly associated with neuromuscular fatigue, commonly defined as a transient decrease in the muscle force production capacity.[39] Finally, this study evaluated the effect of a sport-specific repeated running protocol performed on a non-motorised treadmill,[1] thus caution should be taken when generalizing results to other sporting contexts or different sporting populations.

5. Conclusions

A sports-specific repeated running protocol resulted in an overall reduction in, and redistribution of, mechanical work done by sagittal plane hip and knee joint moments during maximal overground sprinting. Efforts to prevent the decline in maximum running speed following repeated sprints should focus on maintaining positive work done by the hip flexors/extensors and the negative work done by knee flexors/extensors during the swing phase of running.

Ethical approval

Ethical approval was obtained from the institutional Human Research Ethics Committee. Participants were informed of the procedures and provided their written informed consent, consistent with the Declaration of Helsinki.

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Declaration of interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jsams.2021.03.008.

References

1. Di Salvo V, Gregson W, Atkinson G et al. Analysis of high intensity activity in premier league soccer. *Int J Sports Med* 2009; 30(3):205–212.
2. Cunniffe B, Proctor W, Baker JS et al. An evaluation of the physiological demands of elite rugby union using Global Positioning System tracking software. *J Strength Cond Res* 2009; 23(4):1195–1203.
3. Impellizzeri FM, Rampinini E, Castagna C et al. Validity of a repeated-sprint test for football. *Int J Sports Med* 2008; 29(11):899–905.
4. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. *J Sports Sci* 2003; 21(7):519–528.
5. Lord C, Blazevich AJ, Drinkwater EJ et al. Greater loss of horizontal force after a repeated-sprint test in footballers with a previous hamstring injury. *J Sports Sci* 2019; 22(1):16–21.
6. Bishop DJ. Fatigue during intermittent-sprint exercise. *Clin Exp Pharmacol Physiol* 2012; 39(9):836–841.
7. Goodall S, Charlton K, Howatson G et al. Neuromuscular fatigability during repeated-sprint exercise in male athletes. *Med Sci Sports Exerc* 2015; 47(3):528–536.
8. Morin J-B, Samozino P, Edouard P et al. Effect of fatigue on force production and force application technique during repeated sprints. *J Biomech* 2011; 44(15):2719–2723.
9. Girard O, Brocherie F, Morin J-B et al. Running mechanics and leg muscle activity patterns during early and late acceleration phases of repeated treadmill sprints in male recreational athletes. *Eur J Appl Physiol* 2020; 120(12):2785–2796.
10. Robertson D, Caldwell G, Hamill J et al. *Research methods in biomechanics*, 2nd ed. Human Kinectics, 2014.
11. Farris DJ, Sawicki GS. The mechanics and energetics of human walking and running: a joint level perspective. *J R Soc Interface* 2012; 9(66):110–118.
12. Schache AG, Blanch PD, Dorn TW et al. Effect of running speed on lower limb joint kinetics. *Med Sci Sports Exerc* 2011; 43(7):1260–1271.
13. Nagahara R, Matsubayashi T, Matsuo A et al. Alteration of swing leg work and power during human accelerated Sprinting. *Biology Open* 2017; 6(5):633–641.
14. Schache AG, Brown NAT, Pandy MG. Modulation of work and power by the human lower-limb joints with increasing steady-state locomotion speed. *J Exp Biol* 2015; 218(15):2472–2481.
15. Edouard P, Mendiguchia J, Lahti J et al. Sprint acceleration mechanics in fatigue conditions: compensatory role of gluteal muscles in horizontal force production and potential protection of hamstring muscles. *Front Physiol* 2018; 9(1706):1–12.
16. Dorn TW, Schache AG, Pandy MG. Muscular strategy shift in human running: dependence of running speed on hip and ankle muscle performance. *J Exp Biol* 2012; 215(11):1944–1956.
17. Schache AG, Lai AKM, Brown NAT et al. Lower-limb joint mechanics during maximum acceleration sprinting. *J Exp Biol* 2019; 222(22), jeb209460.
18. Rogers PJ, Heatherley SV, Mullings EL et al. Faster but not smarter: effects of caffeine and caffeine withdrawal on alertness and performance. *Psychopharmacology (Berl)* 2013; 226(2):229–240.
19. [World Medical Association (AMM). Helsinki Declaration. Ethical principles for medical research involving human subjects]. *Assist Inferm Ric: AIR* 2001; 20(2):104–107.
20. Girard O, Micallef JP, Millet GP. Changes in spring-mass model characteristics during repeated running sprints. *Eur J Appl Physiol* 2011; 111(1):125–134.
21. Rajagopal A, Dembia CL, DeMers MS et al. Full-body musculoskeletal model for muscle-driven simulation of human gait. *IEEE Trans Biomed Eng* 2016; 63(10):2068–2079.
22. Mantoan A, Pizzolato C, Sartori M et al. MOtoNMS: a MATLAB toolbox to process motion data for neuromusculoskeletal modeling and simulation. *Source Code Biol Med* 2015; 10, 12-12.
23. Delp SL, Anderson FC, Arnold AS et al. OpenSim: open-source software to create and analyze dynamic simulations of movement. *IEEE Trans Biomed Eng* 2007; 54(11):1940–1950.
24. Edwards WB, Troy KL, Derrick TR. On the filtering of intersegmental loads during running. *Gait Posture* 2011; 34(3):435–438.
25. Winter DA. Energy generation and absorption at the ankle and knee during fast, natural, and slow cadences. *Clin Orthop Relat Res* 1983; 175:147–154.
26. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Front Physiol* 2013; 4, 863-863.
27. Tomczak M, Tomczak E. The need to report effect size estimates revisited. An overview of some recommended measures of effect size. *Trends Sport Sci* 2014; 1(21):19–25.
28. Sawilowsky SS. New effect size rules of thumb. *J Mod Appl Stat Methods* 2009; 8(2):26.
29. Cohen J. *Statistical power analysis for the behavioral sciences*, 2nd ed. Academic press, 1988.
30. Brocherie F, Millet GP, Girard O. Neuro-mechanical and metabolic adjustments to the repeated anaerobic sprint test in professional football players. *Eur J Appl Physiol* 2015; 115(5):891–903.
31. Lenton GK, Doyle TLA, Lloyd DG et al. Lower-limb joint work and power are modulated during load carriage based on load configuration and walking speed. *J Biomech* 2019; 83:174–180.
32. Wills JA, Saxby DJ, Glassbrook DJ et al. Load-carriage conditioning elicits task-specific physical and psychophysical improvements in males. *J Strength Cond Res* 2019; 33(9):2338–2343.
33. Delextrat A, Piquet J, Matthews MJ et al. Strength-endurance training reduces the hamstrings strength decline following simulated football competition in female players. *Front Physiol* 2018; 9:1059.
34. Small K, McNaughton L, Greig M et al. Effect of timing of eccentric hamstring strengthening exercises during soccer training: implications for muscle fatigability. *J Strength Cond Res* 2009; 23(4):1077–1083.
35. Deane RS, Chow JW, Tillman MD et al. Effects of hip flexor training on sprint, shuttle run, and vertical jump performance. *J Strength Cond Res* 2005; 19(3):615–621.
36. Blazevich AJ, Jenkins DG. Effect of the movement speed of resistance training exercises on sprint and strength performance in concurrently training elite junior sprinters. *J Sports Sci* 2002; 20(12):981–990.
37. Mendiguchia J, Martinez-Ruiz E, Morin JB et al. Effects of hamstring-emphasized neuromuscular training on strength and sprinting mechanics in football players. *Scand J Med Sci Sports* 2015; 25(6):e621–e629.
38. Sasaki K, Neptune RR, Kautz SA. The relationships between muscle, external, internal and joint mechanical work during normal walking. *J Exp Biol* 2009; 212(Pt 5):738–744.
39. Enoka RM, Duchateau J. Translating fatigue to human performance. *Med Sci Sports Exerc* 2016; 48(11):2228–2238.