JOURNAL OF SPORTS SCIENCES
https://doi.org/10.1080/02640414.2020.1804807

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SPORTS MEDICINE AND BIOMECHANICS

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Joint work is not shifted proximally after a long run in rearfoot strike runners

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ABSTRACT
Distal-to-proximal redistribution of joint work occurs following exhaustive running in recreational but not competitive runners but the influence of a *submaximal* run on joint work is unknown. The purpose of this study was to assess if a long submaximal run produces a distal-to-proximal redistribution of positive joint work in well-trained runners. Thirteen rearfoot striking male runners (weekly distance: 72.6 ± 21.2 km) completed five running trials while three-dimensional kinematic and ground reaction force data were collected before and after a long submaximal treadmill run (19 ± 6 km). Joint kinetics were calculated from these data and percent contributions of joint work relative to total lower limb joint work were computed. Moderate reductions in absolute negative ankle work ($p = 0.045$, Cohen's $d = 0.31$), peak plantarflexor torque ($p = 0.004$, $d = 0.34$) and, peak negative ankle power ($p = 0.005$, $d = 0.32$) were observed following the long run. Positive ankle, knee and hip joint work were unchanged ($p < 0.05$) following the long run. These findings suggest no proximal shift in positive joint work in well-trained runners after a prolonged run. Runner population, running pace, distance, and relative intensity should be considered when examining changes in joint work following prolonged running.

ARTICLE HISTORY
Accepted 24 July 2020

KEYWORDS
Kinetics; running; biomechanics; submaximal; lower extremity

Introduction

Lower limb joint kinetics during running are studied to understand locomotor strategies in response to various environmental or physiological conditions. Since running training consists of a series of prolonged runs of different intensities within a training cycle, biomechanists and physiologists have studied the influence of these prolonged runs of varying intensities on joint mechanics. However, the effects of prolonged running on joint kinetics yield mixed findings due to differences in run distance or duration, run intensity, and running experience or training level (Benson & O'Connor, 2015; Hashish et al., 2016; Paquette & Melcher, 2017; Willson et al., 2015). For example, altered joint kinetics following exhaustive runs include decreased peak plantarflexor torques (Benson & O'Connor, 2015; Hashish et al., 2016) and increased knee and hip angular abduction impulses (Willson et al., 2015). However, a long submaximal run (operationally defined as 25% of total weekly running volume) does not alter peak plantarflexor and knee extensors torques, ankle and knee joint stiffness (Melcher et al., 2017) nor does it change peak knee and hip abduction torques, and knee and hip abduction impulses (i.e., frontal plane joint kinetics) (Paquette & Melcher, 2017) in well-trained male runners.

Recently, Sanno et al. (Sanno et al., 2018) reported that prolonged running near maximal effort shifts the distribution of sagittal plane lower extremity positive joint work proximally in recreational but not competitive runners. Since the triceps surae muscle-tendon complex is critical to energy storage and return during locomotion (Alexander, 2002; Biewener & Roberts, 2000), the authors also speculated that shifting positive joint work from the triceps surae towards hip extensors could be detrimental to running economy (Sanno et al., 2018), a determinant of distance running performance (Saunders et al., 2004). The authors suggested that lesser plantarflexor fatigue due to greater muscular capacity in the competitive compared to the recreational group could explain the distal-to-proximal shift in joint work in recreational runners only. In addition, this proximal shift in joint kinetics from the ankle towards the hip is often referred to age-related plasticity of gait (DeVita & Hortobagyi, 2000), a hallmark of ageing brought about by reductions in plantarflexor capacity to produce torque and positive mechanical power during locomotion. Further, less-trained runners exhibit lower plantarflexor strength and tendon-aponeurosis stiffness than well-trained runners (Arampatzis et al., 2006), functional reductions that are also observable in older compared to younger runners (Karamanidis & Arampatzis, 2005). Thus, this distal-to-proximal shift in joint kinetics may potentially be a compensatory locomotion strategy used by individuals with lower physical capacity of the plantarflexors (e.g., less-trained runners or elderly).

It is important to note that Sanno et al. (Sanno et al., 2018) did not control for foot strike pattern. Strike pattern should be considered in such investigations because differences in joint kinetics exist between foot strike patterns (Kuhman et al., 2016; Paquette & Melcher, 2017; M. Paquette et al., 2013; Stearne et al., 2014; Williams et al., 2012), and non-rearfoot strike runners tend to either adopt a more posterior foot strike (i.e., centre of pressure is more posterior under the foot at initial contact) (Jewell et al., 2017) or a rearfoot strike (Larson et al., 2011) at the end of a prolonged exhaustive run. Further, Sanno et al. (Sanno et al., 2018) studied the effects of a near-maximal effort exhaustive run on joint kinetics. However, optimal

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endurance training adaptations occur from polarized training (i.e., ~80-90% submaximal or easy running volume and ~10-20% of higher intensity running volume) (Seiler, 2010) and volume of easy or submaximal running is a strong predictor of World-class distance running performance (Casado et al., 2019). Thus, studying the distal-to-proximal shift in positive joint work in well-trained runners following a long submaximal run would help further understand if more training can combat this gait alteration as a result of prolonged running. The purpose of this study is to examine if long submaximal run leads to a distal-to-proximal redistribution of positive joint work in well-trained rearfoot strike (RFS) runners. We hypothesized that a long submaximal run would not lead to a distal-to-proximal shift in positive lower limb joint work in well-trained RFS runners. Findings from this study will help guide the design of future longitudinal research studies to address the influence of training exposures on gait alterations.

Methods

Participants

An a priori power analysis (G*Power 3.1.5) indicated that 12 participants were needed to obtain a Cohen's *d* effect size of 0.81 from previously reported knee flexion excursion before and after a run (Melcher et al., 2017)), power of 0.8, and α of 0.05. A total of 13 well-trained male runners volunteered for this study (Table 1). Exclusion criteria included current injury or having suffered a lower limb injury within the past 6 months. Participants had to have been running at least 45 km per week for the past three months, be habitual RFS runners, and have completed at least one long run (i.e., 20–25% of weekly running volume) per week in the past three months. Written consent approved by the Institutional Review board for Human Participants Research was obtained from each participant during an initial screening visit.

Experimental protocol

Three-dimensional (3D) kinematic and ground reaction force (GRF) data were collected using a 9-camera motion capture system (240 Hz, Qualisys AB, Götenburg, Sweden) and a force platform (1200 Hz, BP600900, AMTI, Watertown, MA, USA), respectively. The force platform was embedded in the laboratory floor in the middle of a 25 m runway. Two photo-cells (63501 IR, Lafayette Instruments Inc., IN, USA) placed 3 m apart at shoulder height in the middle of the runway that started and stopped an electronic timer (54035 A, Lafayette Instruments Inc., IN, USA) were used to monitor running speed during testing.

Table 1. Participant characteristics.

	Mean ± SD
Age (years)	32.1 ± 9.7
Mass (kg)	73.6 ± 11.9
Height (m)	1.8 ± 0.1
BMI (kg·m^{-2})	22.8 ± 3.0
Weekly Running Volume (km·week^{-1})	72.6 ± 21.2
Experimental Run Distance (km)	18.2 ± 5.3
Experimental Run Time (minutes)	90.6 ± 21.5

Notes: BMI: body mass index.

Participants were required to attend two separate testing sessions. During the initial visit, participants completed a survey regarding their training details and body mass and height were recorded. Reflective spherical markers were placed on the lower limb of each participant (see details in procedures below) to track lower limb motion during the screening running tests. Participants then completed five successful over-ground running trials at their preferred long run pace to determine habitual foot strike pattern using the strike index (SI) method (Cavanagh & Lafortune, 1980). Successful trials were characterized by contact of the right foot naturally with the force plate at the appropriate speed. Participants with a confirmed RFS pattern (i.e., SI of 33% or less) were asked to attend the second testing session the next day.

The second testing session involved measuring gait during over-ground running trials performed before and after a prolonged submaximal treadmill run. This session began with a five-minute warm-up run on the testing treadmill (C962i, PRECOR, USA) at their self-selected long run pace. Following the warm-up, reflective markers were placed on the pelvis and right leg in agreement with a previously published marker set convention (McClay & Manal, 1999). Thermoplastic shells with at least three non-collinear reflective markers were secured to neoprene wraps around the pelvis, right thigh, and right shank. One shell was secured with adhesive tape to the heel of the right shoe to track segment motion during testing. A one-second static calibration trial was then recorded to define joint centres, segment lengths, segment coordinate systems. Prior to marker application, the location of anatomical markers was marked on the skin with black permanent ink to ensure quick and accurate anatomical marker replacement for the post-run motion capture trials. Further, the ink markings helped speed up marker placement time following the long run to minimize recovery time and maximize the influence of the long run on running joint kinetics. Elapsed time between the end of the long run and the start of the running trials ranged between two to three minutes, and over-ground testing procedures were completed within 6 to 7 minutes after the end of the long run as six to eight trials were required to obtain five successful trials. Pre and post-run testing consisted of five over-ground running trials over the 25 m runway while three-dimensional kinematics and ground reaction force (GRF) data were collected. The over-ground running trials were performed at the participants' preferred long run speed ± 5% using their habitual RFS pattern. The long run was performed on the treadmill at the runners' self-selected long run pace which was constant for the whole run of a distance equalling 25% of the runners' average weekly volume within the past three months (Daniels, 2013). Running testing and the long run were performed in the participants' personal running shoes to maximize external validity. No participant wore minimal or highly cushioned shoes.

Data analyses

All dependent variables were computed within Visual3D software (C-Motion, Inc., MD, USA). Interpolation of kinematic data was accomplished using a least-squares fit of a third-order polynomial with three data point fitting and a maximum allowable gap of 10 frames. GRF and kinematic data were low-pass filtered at 40 and 8 Hz, respectively. A right-hand rule with a Cardan rotational sequence (x-y-z) was used for the 3D angular computations where x represents the medial-lateral axis, y represents the anterior-posterior axis, and z represents the longitudinal axis. The ankle, knee, and hip joint angular kinematic and kinetic variables were expressed in the shank, thigh, and pelvis coordinate systems, respectively. A 20 N vertical GRF threshold was used to define heel strike and toe-off. Joint variables of interest between these events included peak torques, peak negative and positive angular powers, negative and positive angular work at the ankle, knee, and hip. Newtonian inverse dynamics were used to calculate net internal joint torques normalized to body mass ($Nm{\cdot}kg^{-1}$). Joint power was calculated as the dot product of joint torques and angular velocities ($W{\cdot}kg^{-1}$). *Absolute* positive and negative joint work was computed as the respective integral of the positive and negative area under the joint power curve for ankle, knee, and hip joints using the trapezoidal rule ($J{\cdot}kg^{-1}$). Further, *relative* individual joint work was computed as the percent contribution of joint work relative to total lower limb joint work. Ankle, knee and hip joint extension excursions during the stance phase were also calculated to provide explanatory kinematic factors for joint kinetic findings.

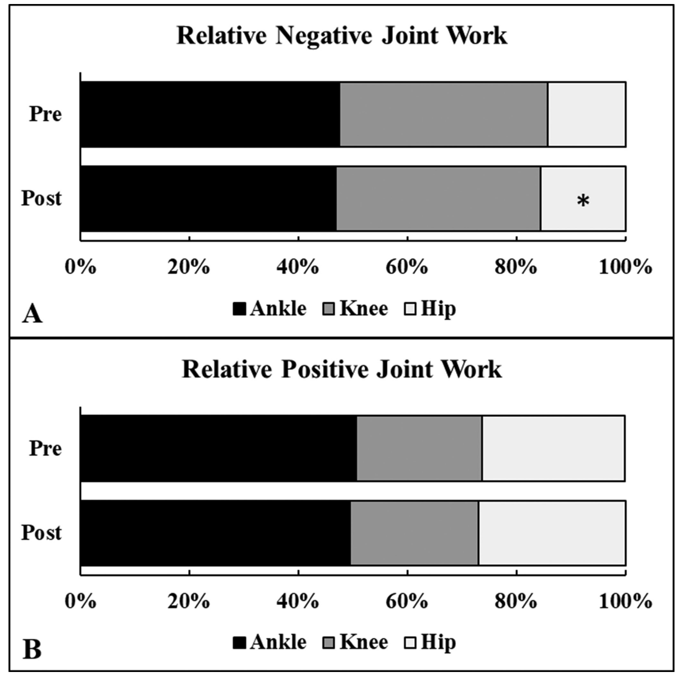

Figure 1. Relative negative (A) and positive (B) joint work contributions (%) to total lower limb joint negative and positive work. Pre: pre-run; Post: post-run. *: different than Pre ($p < 0.05$).

Statistical Analyses

Lower extremity joint kinetics before and after the prolonged run were compared using paired-samples t-tests (22.0 SPSS; IBM Inc., Chicago, IL, USA) to assess any differences. Normality of biomechanical data was examined with a Kolmogorov-Smirnov test, and a Mann-Whitney non-parametric test was used to compare group differences if data were non-uniformly distributed. All statistical tests used an alpha level of $p < 0.05$. Cohen's d effect size was calculated to assess magnitude of mean differences before and after the long run (i.e., small: $d< 0.2$; moderate: $0.2 \le d \ge 0.8$; large: $d> 0.8$).

Results

All data were normally distributed ($p > 0.05$) and therefore, the statistical results from the paired t-tests are reported below.

Joint work

Relative positive ankle ($p = 0.35$; $d = 0.17$), knee ($p = 0.73$; $d = 0.06$), and hip ($p = 0.53$; $d = 0.09$) work were unchanged following the long run (Figure 1A). A moderate reduction in absolute negative ankle work was observed while absolute positive ankle work was unchanged following the long run (Table 2). Absolute positive and negative knee and hip joint work remained unchanged following the long run (Table 2). Relative negative hip work was moderately increased following the run ($p = 0.040$; $d = 0.32$; Figure 1B). Relative negative ankle ($p = 0.29$; $d = 0.12$) and knee ($p = 0.48$; $d = 0.10$) work were also unchanged following the long run (Figure 1B).

Peak torques and powers

Moderate reductions in peak plantarflexor torque and peak negative ankle power were observed following the long run (Table 2). All other peak joint torques and peak positive and negative joint powers remained unchanged following the long run (Table 2).

Kinematic variables

Ankle plantarflexion excursion was unchanged after (35.6 ± 5.2°; $p = 0.53$; $d = 0.09$) compared to before (36.1 ± 5.0°) the run. Knee extension excursion was also unchanged after (24.6 ± 3.2°; $p = 0.91$; $d = 0.03$) compared to before (24.7 ± 3.0°) the run. Hip extension excursion was also unchanged after (36.4 ± 7.2°; $p = 0.40$; $d = 0.25$) compared to before (37.9 ± 4.0°) the run. Finally, strike index also remained unchanged after (14.6 ± 5.8%; $p = 0.57$; $d = 0.09$) compared to before (15.3 ± 6.3%) the run.

Discussion

The purpose of this study was to examine if a long submaximal run leads to a distal-to-proximal redistribution of positive joint work in well-trained RFS runners. Our primary hypothesis was that no changes would be observed in lower extremity positive joint work following a prolonged run in well-trained RFS runners. Indeed, no changes in positive joint work were found at either the ankle, knee, or hip before compared with after the prolonged run in these well-trained RFS male runners. However, despite not being statistically significant ($p = 0.12$), a moderate ($d = 0.32$) reduction in absolute ankle positive work was observed following the prolonged run. Despite a moderate reduction in peak plantarflexor torque, ankle joint excursion was unchanged following the run which likely contributes to the moderate non-significant reduction in positive ankle work. Regardless, the unchanged hip positive work suggests no

Table 2. Lower extremity joint kinetics pre- (PRE) and post-prolonged (POST) run (mean±SD).

	PRE	POST	p	*d*	CI
Peak Torques (Nm·kg^{-1})					
Ankle Plantarflexor [a]	−2.84 ± 0.47	−2.68 ± 0.47	**0.004**	0.34	[−0.26, −0.06]
Knee Extensor	2.72 ± 0.51	2.60 ± 0.44	0.20	0.25	[−0.07, 0.30]
Hip Extensor	−1.76 ± 0.61	−1.76 ± 0.63	0.98	0.00	[−0.12, 0.12]
Peak Negative Powers (W·kg^{-1})					
Ankle Joint [a]	−8.40 ± 2.02	−7.75 ± 2.08	**0.005**	0.32	[−1.06, −0.23]
Knee Joint	−13.52 ± 2.60	−12.84 ± 0.69	0.16	0.28	[−1.68, 0.31]
Hip Joint	−3.30 ± 1.89	−3.37 ± 2.11	0.73	0.04	[−0.41, 0.57]
Peak Positive Powers (W·kg^{-1})					
Ankle Joint	10.2 ± 2.81	9.69 ± 2.79	0.23	0.18	[−0.37, 1.39]
Knee Joint	4.40 ± 1.15	4.40 ± 1.08	0.99	0.00	[−0.52, 0.52]
Hip Joint	4.26 ± 1.94	4.47 ± 2.28	0.57	0.10	[−1.04, 0.60]
Positive Work (J·kg^{-1})					
Ankle Joint	0.64 ± 0.12	0.59 ± 0.13	0.12	0.33	[−0.10, 0.01]
Knee Joint	0.28 ± 0.09	0.28 ± 0.07	0.83	0.05	[−0.03, 0.04]
Hip Joint	0.35 ± 0.16	0.34 ± 0.14	0.72	0.05	[−0.04, 0.05]
Negative Work (J·kg^{-1})					
Ankle Joint [a]	0.57 ± 0.11	0.54 ± 0.10	**0.045**	0.31	[−0.06, −0.00]
Knee Joint	0.72 ± 0.16	0.67 ± 0.13	0.11	0.29	[−0.10, 0.01]
Hip Joint	0.22 ± 0.07	0.23 ± 0.08	0.31	0.17	[−0.01, 0.04]

Notes: [a]: $p < 0.05$ (bolded); CI: 95% Confidence Intervals of mean difference.

evident distal-to-proximal shift following a prolonged submaximal run in well-trained RFS male runners. The slight reduction in ankle positive work is similar to the small decrease in ankle positive work reported by Sanno et al. (Sanno et al., 2018) in competitive runners following a near-maximal 10 km run (i.e., sub 37:30 minute 10 km personal bests). The near-maximal effort 10 km run used in Sanno et al. (Sanno et al., 2018) did, however, lead to large reductions in ankle positive work and increases in hip positive work. Therefore, taken together these findings suggest that running experience and/or level of exertion may influence the effect magnitude of prolonged running on the distal-to-proximal shift in positive joint work. When considering differences between the results and design of this current study and Sanno et al. (Sanno et al., 2018), several delineations in runner population and experimental protocol such as differences in strike pattern, run intensity, and population can be made.

Foot strike pattern was not reported in Sanno et al. (Sanno et al., 2018) whereas the current study included only rearfoot strike runners. Different strike patterns within the population might have explained the distal-to-proximal shift in positive work throughout the run observed by Sanno et al. (Sanno et al., 2018). For example, if some of the recreational runners began the run with a more anterior strike pattern (i.e., towards mid or forefoot striking) and finished the run with a less anterior or more posterior strike pattern (i.e., towards rearfoot striking), then the reduction in ankle positive work observed at the end of the exhaustive run might have been the result of the posterior shift in the centre of pressure at foot strike. It is important to note that the total duration of a prolonged run (e.g., marathon (Hanley et al., 2019; Larson et al., 2011); 800 m and 1500 m races (Hanley et al., 2019; Hayes & Caplan, 2012; M. R. Paquette et al., 2017)); 15 minute intense run to volitional exhaustion (Jewell et al., 2017) may affect whether non-rearfoot runners change their foot strike pattern. Rearfoot runners, however, maintain their foot strike pattern throughout both shorter and longer prolonged runs (e.g., (Hanley et al., 2019; Hayes & Caplan, 2012; Larson et al., 2011; M.R. Paquette et al., 2017)). Given the likelihood that non-rearfoot runners across abilities and competitive levels may change to a rearfoot pattern by the end of a prolonged run, including only rearfoot strike runners ensured that the current study fully isolated the influence of the prolonged run on joint kinetics because rearfoot strike runners have not been observed to change foot strike during a prolonged run. Indeed, the smaller negative ankle work, peak plantarflexor torque and peak negative power observed after the run in the current study occurred in the absence of a change in strike index, which was ~15% before and after the run confirming a rearfoot strike pattern. Since dorsiflexor fatigue leads to greater ankle joint compliance during experimental pendulum impacts of the heel and enhanced force attenuation capacity (Duquette & Andrews, 2010), the observed increase in negative work and peak power absorption in the current study might be the result of muscular fatigue due to the long submaximal run. However, we did not measure muscular fatigue in this study and future studies will be necessary to confirm our interpretation.

Further, the running protocol in Sanno et al. (Sanno et al., 2018) included a 10 km run at a “near-maximal” effort at a speed equivalent to a 10 km run time 5% slower than their season best 10 km. However, in the current study, runners were instructed to complete the long run at their usual “easy”, or submaximal, running speed for a distance equivalent to 25% of the weekly mileage of each participant (~18.2 km). Additionally, participants in the current study completed on average ~73 km per week during training. Weekly running volume was not reported in Sanno et al. (Sanno et al., 2018) and although it is difficult to categorize their runners with respect to training level based on volume, it is likely that these competitive runners (i.e., sub 37:30 minute for 10 km personal best) were well-trained. Taken together, results of Sanno et al. (Sanno et al., 2018) and our current findings appear to suggest that competitive (who are arguably well-trained) and well-trained runners might be able to prevent or reduce the magnitude of a distal-to-proximal shift in sagittal plane joint kinetics from both prolonged exhaustive and submaximal runs. It is difficult, however, to conclude that the lack of observed distal-to-proximal shift in positive joint work was the result of additional training in well-trained runners due to the cross-sectional design of the current study. Thus, training interventions to assess the direct influence of more compared to less training over a period of time on the response of joint kinetics from a prolonged run are needed. Finally, in the current study we did not measure the response of recreational or less-trained runners to a prolonged submaximal run and therefore, it is difficult to make any claims regarding this population.

It is well-documented that oxygen uptake increases over the time-course of long-distance running (Candau et al., 1998; Kyröläinen et al., 2000), and this has been speculated to be the result of altered kinematics that increase metabolic costs (Derrick et al., 2002). In addition, morphological characteristics of distal and proximal musculo-tendinous complexes contribute to increased metabolic costs. Specifically, ankle plantarflexors (i.e., triceps surae) can more efficiently generate force due to slower shortening velocities (Fenn, 1931) as a result of an efficient stretch-shortening cycle of their series elastic elements (Lichtwark et al., 2007). Hip extensors on the other hand lack these long and compliant series elastic elements which reduces their ability to generate force efficiently (Ker et al., 1988). Further, it has been postulated that localized fatigue at the triceps surae during distance running may be a contributor to these altered kinematics and proximal shift in positive joint work towards the hip (Sanno et al., 2018). Well-trained distance runners exhibit greater plantarflexor muscle strength than less-trained runners (Arampatzis et al., 2006) and thus, greater plantarflexor capacity could potentially attenuate any run-induced reductions in ankle joint positive work in the competitive runners from Sanno et al. (Sanno et al., 2018) and the well-trained runners in this current study. These previous findings regarding ankle joint work agree with the present findings and suggest that training status may incur adaptations in the plantarflexor musculature that might contribute to prevent the proximal shift observed in less-trained runners over the course of a submaximal long run. Thus, the greater relative intensity of the recreational runners in the previous study (Sanno et al., 2018) may explain why those runners experienced the distal-to-proximal shift but the competitive runners in their study (Sanno et al., 2018) and the well-trained runners in the present study did not. That is, the self-selected pace of the well-trained runners in the current study was not metabolically or mechanically demanding enough on the plantarflexors relative to their capacity to elicit the proximal shift in positive joint work at this submaximal intensity. However, the competitive runner group in Sanno et al. (Sanno et al., 2018) ran at a pace of a similar "near-maximal" relative intensity as the recreational runners in their study (albeit at a faster speed of ~4.4 $m{\cdot}s^{-1}$) without experiencing this redistribution of positive joint work. Therefore, it may be that running pace, distance, and relative intensity must be considered when examining the causes of a proximal shift in positive joint work in prolonged running.

A limitation of the current work is the discontinuous assessments of joint kinetics following the prolonged treadmill run. Due to instrument limitations (i.e., no instrumented treadmill), there was a two to four-minute gap immediately following the long run to ready the participants for the post-run tests. Thus, this rest period might have alleviated the effects of the prolonged submaximal run on joint kinetics. Recent preliminary findings suggest that changes in joint kinematics persist up to four minutes following a submaximal treadmill run (Gruber et al., 2019). However, the length of the run in that study was much shorter (3.9 ± 1.6 km) than in the current study (18.2 ± 5.3 km) and the effects of a prolonged run likely persist for a longer time following longer runs. In addition, our findings are similar to the results of Sanno et al. (Sanno et al., 2018) in their competitive runner group suggesting the time gap might not have an influence on findings. Thus, the short time period between the end of the run and the beginning of the testing likely did not influence our findings but future studies on this methodological question are needed.

Conclusions

The results from this study show that well-trained RFS runners do not exhibit a proximal shift in lower extremity positive joint work following a long submaximal run. Taken together with previous findings, running experience and/or level of exertion may influence the effect magnitude of prolonged running on the distal-to-proximal shift in positive joint work. Therefore, runner population, running pace, distance, and relative intensity must be considered when examining the causes of a distal-to-proximal shift in positive joint work following prolonged running. More research into the effects of training level, running pace and duration, and foot strike pattern is necessary to further understand changes in joint work following prolonged running.

Acknowledgments

The authors would like to thank all volunteers for participating in the study. No funding was received for this study.

Disclosure statement

No potential conflict of interest was reported by the authors.

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