Effects of Fatigue on Running Mechanics Associated with Tibial Stress Fracture Risk

ADAM C. CLANSEY[1], MICHAEL HANLON[1], ERIC S. WALLACE[1], and MARK J. LAKE[2]

[1]Sport and Exercise Sciences Research Institute, University of Ulster, Newtownabbey, Co Antrim, Northern Ireland, UNITED KINGDOM; and [2]Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool, England, UNITED KINGDOM

ABSTRACT

CLANSEY, A. C., M. HANLON, E. S. WALLACE, and M. J. LAKE. Effects of Fatigue on Running Mechanics Associated with Tibial Stress Fracture Risk. *Med. Sci. Sports Exerc.*, Vol. 44, No. 10, pp. 1917–1923, 2012. **Purpose**: The purpose of this study was to investigate the acute effects of progressive fatigue on the parameters of running mechanics previously associated with tibial stress fracture risk. **Methods**: Twenty-one trained male distance runners performed three sets (Pre, Mid, and Post) of six overground running trials at 4.5 $m \cdot s^{-1}$ (±5%). Kinematic and kinetic data were collected during each trial using a 12-camera motion capture system, force platform, and head and leg accelerometers. Between tests, each runner ran on a treadmill for 20 min at their corresponding lactate threshold (LT) speed. Perceived exertion levels (RPE) were recorded at the third and last minute of each treadmill run. **Results**: RPE scores increased from 11.8 ± 1.3 to 14.4 ± 1.5 at the end of the first LT run and then further to 17.4 ± 1.6 by the end of the second LT run. Peak rearfoot eversion, peak axial head acceleration, peak free moment and vertical force loading rates were shown to increase ($P < 0.05$) with moderate–large effect sizes during the progression from Pre to Post tests, although vertical impact peak and peak axial tibial acceleration were not significantly affected by the high-intensity running bouts. **Conclusion**: Previously identified risk factors for impact-related injuries (such as tibial stress fracture) are modified with fatigue. Because fatigue is associated with a reduced tolerance for impact, these findings lend support to the importance of those measures to identify individuals at risk of injury from lower limb impact loading during running. **Key Words:** HIGH INTENSITY, KINEMATICS, KINETICS, OVERUSE INJURY POTENTIAL, RUNNERS

The tibia has been reported as the most common site for stress fracture injuries in running populations, accounting for between 35% and 49% of all stress fractures acquired (18,21,22,34). The cause of tibial stress fracture (TSF) development is linked to accumulation of mechanical forces transmitted to the bone, which exceed the repairing and remodeling process of the bone structure over time (23). Rehabilitation from such injuries is a lengthy process, with Harrast and Colonno (23) suggesting that runners sustaining a grade 4 stress fracture should undertake 6 wk in a cast followed by 6 wk of non–impact-based activities. Because of the severity and high frequency of TSF among runners, several researchers have investigated mechanical factors that could be linked with increased risk of TSF development.

Prospective evidence has shown that runners who developed a TSF along with other overuse injuries had significantly greater peak axial tibial accelerations (PTAs), vertical impact peak (IP), vertical average loading rates (VALRs), and vertical instantaneous loading rates (VILRs) compared with runners who did not (10,11). In addition, retrospective reports have identified links to certain key stance phase mechanical variables, specifically increased peak rearfoot eversion (RFEV), peak hip adduction (HADD), knee stiffness, and peak free moment (FM) with runners who had previously sustained a TSF (33,34,38). Although these key mechanical variables linked with greater TSF risk have been identified, it is acknowledged that the etiology of overuse injuries is multifactorial (25).

Research has suggested that differences in gender may be a possible contributor to increased TSF risk (27); however, Bennell et al. (4) reported no such gender differences. Similarly, contrasting reports are also evident in the bone structure characteristics (3,9,21). Despite these risk factors showing some support for increased TSF risk, Hreljac and Ferber (26) recognize the importance of training errors (such as sudden increases in mileage, resulting in greater fatigue and stress levels) being the major attributer of overuse injury risk in runners.

Several reports have shown that when runners run in a fatigued state, their bodies are exposed to greater mechanical forces (15,36,43,44). However, because of the complex nature of fatigue on running gait, reports on its effects on mechanical variables associated with TSF are limited and inconclusive within the literature. Increased PTAs have been reported in recreational runners during fatiguing running (15,36,43,44), whereas no such increases were seen in trained

Address for Correspondence: Adam C. Clansey, M.Sc., Sport and Exercise Sciences Research Institute, University of Ulster, Jordanstown, Shore Rd, Co Antrim BT37 0QB, Northern Ireland, United Kingdom; E-mail: clansey-a@email.ulster.ac.uk.
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runners (1,32). Significant increases in RFEV (15–17,36) along with increased HADD (17) have also been reported in fatigued runners. Conversely, a recent report showed no changes in kinematics within fatigued runners (1). A study that examined the effects of running fatigue on vertical loading rates reported a significant decrease in these rates in fatigued female runners (19). They claimed the possible reasons for the decreased loading rates were related to changes in joint landing and stance kinematics, causing a reduction in the effective mass of the system. In support, Derrick (14) reported that the influence of effective mass on impact loads was related to alterations in joint kinematics on landing and system stiffness characteristics. Furthermore, Coventry et al. (8) suggested that joint kinematics at initial contact (IC) and alterations in peak joint flexion ranges were linked to the modulation of loading and impact shock during landing, whereas Keller et al. (28) have linked increased stride lengths with higher impact loading rates in running. From research evidence, it seems there are important mechanical mechanisms at IC and during stance that influence variables associated with TSF risk.

Continuous running at lactate threshold (LT) speed has been shown to impair the stretch-shortening cycle and eccentric function of the musculoskeletal system (13,41). Consequently, authors suggested that running at this intensity for a prolonged period would inevitably result in a level of peripheral fatigue of the musculoskeletal system (41). In the few studies that have adopted high-intensity threshold running as a fatigue protocol, results showed that runners became less tolerant to impact accelerations within 15 to 20 min of running (36,43,44). Authors suggested that the increase observed in impact accelerations may be a result of runners being less capable of handling impacts as run duration increases, with evidence of runners also showing greater peak accelerations at the head (15,32). However, these observations have only examined one risk factor related to TSF (impact accelerations) during a single high-intensity running bout. Given the high training workloads that trained distance runners perform at, there is a requirement for research to assess the timing of progressive fatigue effects across high-intensity LT running. The purpose of this study was to examine the acute effects of progressive fatigue in trained distance runners on running mechanics associated with TSF risk. Landing and stance phase kinematic variables were also included in this analysis to enhance the interpretation of fatigue effects on these TSF variables. It was hypothesized that the variables previously associated with TSF risk would significantly increase when runners became progressively fatigued across two levels. It was also hypothesized that with increased fatigue levels, runners would demonstrate greater levels of shock at the head along with increased changes observed in joint kinematics at IC and midstance phases.

METHODS

Twenty-one highly trained, rearfoot striking male distance runners (age, 36.2 ± 12.5 yr; mass, 75.4 ± 11.5 kg; height, 1.80 ± 0.8 m; LT speed at 3.5-mM blood lactate concentration, 13.8 ± 2.1 $km \cdot h^{-1}$) volunteered as participants. All subjects were free from musculoskeletal injury and signed a written informed consent form as approved by the University Ethics Review Board. Subjects were training at an average of 72 ± 34 $km \cdot wk^{-1}$ and competing in distances ranging from 5 km up to marathon. All subjects wore their own running shoes and were asked to wear tight-fitting Lycra clothing during testing. Two weeks before fatigue testing, all subjects performed a standardized incremental treadmill (T170 DE; HP Cosmed, United Kingdom) onset of blood lactate accumulation running test (1% gradient) to identify subject's LT speed at 3.5-mM blood lactate concentration (46). This speed was used to standardize the intensity of each subject's treadmill running fatiguing protocol.

Two mounted biaxial (16 g, sensitivity range of ± 400 $mV \cdot g^{-1}$, frequency response of 5–6 kHz) accelerometers (Noraxon, Scottsdale, AZ) were attached to the surface of each participant's distal anteromedial aspect of the tibia and anterior aspect of the forehead. At the site of attachment, the skin was shaved using a sterile razor. A water-repellent adhesive tape (Kinesiology tape; Vivomed, United Kingdom) was then used to stretch the skin and fasten the accelerometers. The placement of the tibia accelerometer was set at approximately 0.10 m above the ankle joint center. In addition, the head accelerometer was secured tightly by an elasticated head band. Acceleration data were sampled at 1500 Hz. A full-body six-degree-of-freedom retroreflective marker set (7) was collected at 200 Hz using a 12-motion capture system (Oqus 3; Qualisys, Sweden). The marker set defined the anatomical coordinate system and inertial parameters of both left and right lower extremities, pelvis, and torso segments. The markers were directly attached onto the shoes and on top of the clothing and skin. The makers were placed over the first and fifth metatarsal heads, heels, medial and lateral malleoli, medial and lateral femoral condyles, both greater trochanters, anterior superior iliac spines, iliac crests, T8, sternum, C7, xiphoid process, and both acromions. Additional four-marker clusters attached to thermoplastic plates were used to track both shank and thigh segments. With all markers attached, a 1-s static calibration trial was collected. In this trial, subjects stood in an anatomical position with feet approximately shoulder width apart, knees fully extended, hips neutral, and trunk vertically upright. This static anatomical position defined joint angles as 0°. Hip joint centers were determined using the functional method approach as described by Begon et al. (2). During the dynamic trials, the anatomical markers for medial and lateral malleoli, medial and lateral femoral condyles, and greater trochanters were all removed. A force platform (type 9287CA; Kistler Instruments Limited, Switzerland) sampling at 1000 Hz was synchronized with motion and acceleration data.

All subjects were asked to refrain from running 24 h before the fatigue testing. Subjects performed three gait analysis tests (Pre, Mid, and Post) before and after two 20-min fatiguing treadmill runs at the LT for each runner (Fig. 1). The tests consisted of six acceptable overground running trials at 4.5 $m \cdot s^{-1}$ (± 5%) along a 15-m runway. Velocity was determined using two pairs of photoelectric gates (TC-PhotoGate; Brower Timing System, United Kingdom) in the filming volume 2 m apart. Subjects performed a standard 5-min warm-up jog along with familiarization trials to ensure a consistent running velocity could be maintained. Trials were discarded if subjects targeted the force plate. Once subjects completed the Pre-gait analysis test, they ran on a treadmill (1% gradient) at their LT speed (previously determined) for 20 min. After completion of this running bout, they immediately (within a 1-min period) performed the Mid-gait analysis test, followed by a further 20-min LT treadmill run before completing the final Post-gait analysis test. All markers remained in place during the whole testing session; this was to reduce the periods between treadmill running and gait analysis tests. RPE values on a scale of 1–20 were taken at the 3rd (start) and 20th (end) minute of each treadmill running bout as a physiologically valid tool for subjectively prescribing exercise intensity and fatigued state (42). Once subjects completed the LT running, they were instructed to immediately perform overground running trials.

All marker trajectories were tracked and labeled in Qualisys Track Manager (Qualisys, Gothenburg, Sweden), after which, all data were processed in Visual 3D (C-Motion, Germantown, MD). On the basis of a residual analysis (45), motion and force data were filtered using a fourth-order low-pass Butterworth filter at 12 and 80 Hz, respectively. Head and tibial accelerations were also filtered at 30 and 60 Hz on the basis of a residual analysis. Segment masses were based on Dempster data (12) and defined by frustra of cones for the center of mass and moments of inertia. All joint angles with a Cardan rotation sequence of *X, Y, Z* were resolved about the joint coordinate system and were referenced to the proximal segment (22). Vertical ground reaction force variables of IP, VILR, and VALR were determined. Both loading rates were calculated between 20% and 80% of the period from IC to IP (34). PTA and peak head accelerations (PHA) were determined as the maximum positive acceleration that occurred during stance phase. The key stance mechanical variables of interest were HADD, RFEV, and adduction FM (38). Knee sagittal plane joint stiffness (KSTIF) were calculated as the change in joint moment divided by the change in joint angle (18). The change in moment and angle was taken from IC to maximum flexion during stance. Step length was taken as the horizontal displacement of the right foot at IC to the next left foot IC. Knee excursion joint range of motion (KEXC) was defined from IC to IP during early stance (35). Sagittal plane joint kinematics at IC and midstance were calculated to determine initial conditions. Midstance was defined as the lowest position of the center of mass during the stance phase. Positive sagittal plane joint angles were defined in the flexion/dorsiflexion direction, whereas extension/plantarflexion were negative.

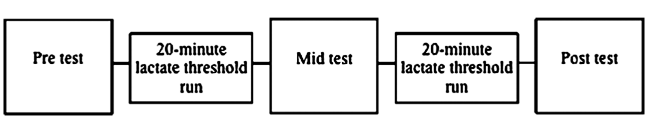

FIGURE 1—Protocol testing design.

DATA ANALYSIS AND STATISTICS

A repeated-measures ANOVA (SPSS version 17.0.0; SPSS Inc., Chicago, IL) was used to assess the significance of run duration (three time levels: Pre, Mid, and Post) on each kinetic and kinematic variable. When a main effect for run duration was noted, *post hoc* pairwise comparisons were used to determine between which time intervals the significant changes occurred. The magnitude of differences between Pre and Post tests for variables linked with TSF were also represented using Cohen *d* effect sizes (6) interpreted as small, 0.2–0.49; medium, 0.5–0.79; and large, 0.8+. An alpha level of $P < 0.05$ was used throughout.

RESULTS

During the first 20-min LT running bout, subject RPE scores increased significantly ($P < 0.001$) from 11.8 ± 1.3 to 14.4 ± 1.5. RPE showed a further significant increase ($P < 0.001$) to 17.4 ± 1.5 by the end of the second LT run. Of the stance phase variables (Table 1), both VALR and VILR were shown to significantly increase ($P = 0.001$, $P = 0.004$) from Pre to Post test conditions, respectively. The *post hoc* results showed that after the second 20-min LT run, both VALR and VILR increased ($P = 0.001$, $P = 0.005$) from Mid to Post tests. Although IP did show an increase with a large effect size with fatigue, no significant change was reported ($P = 0.096$). Similarly, KEXC tended to decrease with fatigue, but no significant differences were reported ($P = 0.098$). PHA, RFEV, and FM showed significant increases ($P = 0.001$, $P = 0.036$, $P = 0.004$) after completing the 20-min running bouts. PHA showed a significant change ($P < 0.001$) from Mid to Post test conditions, whereas FM increased ($P = 0.032$) after the first 20-min run. Step length and PTA showed no significant differences throughout each test condition.

Temporal kinematic variables at IC (Table 2 and Fig. 2) showed increases ($P < 0.001$) in trunk extension from Pre to Post tests and then again Mid to Post test conditions ($P < 0.001$). Both hip and ankle also became significantly ($P = 0.046$, $P = 0.018$) more extended and plantar flexed after the two 20-min runs. The *post hoc* reports showed a hip extension increase ($P = 0.038$) from Pre to Mid tests, whereas ankle plantarflexion increased ($P = 0.046$) from Mid to Post test conditions.

At midstance (Table 3 and Fig. 2), the trunk showed a similar trend to IC, with runners becoming progressively extended after each 20-min running bout ($P = 0.010$, $P = 0.006$). An increase in hip extension ($P = 0.029$) along with increased ankle plantarflexion ($P = 0.032$) after 40 min of running was also evident. However, despite most observed

TABLE 1. Mean (SD) during Pre, Mid, and Post test conditions; main effect *P* values; and effect sizes for step length and stance phase variables.

Variable	Pre	Mid	Post	*P*	Effect Size
VALR ($BW \cdot s^{-1}$)	107.90 (25.29)	113.87 (31.56)	130.53 (39.60)^{a,b}	0.001	0.70
VILR ($BW \cdot s^{-1}$)	148.75 (39.13)	162.56 (44.88)	181.73 (54.73)^{a,b}	0.004	0.71
IP (BW)	2.21 (0.28)	2.32 (0.22)	2.41 (0.13)	0.096	0.98
Step length (m)	1.70 (0.05)	1.68 (0.09)	1.69 (0.06)	0.698	0.18
PHA (*g*)	1.04 (0.31)	1.17 (0.35)	1.30 (0.34)^{a,b}	0.001	0.80
PTA (*g*)	11.30 (2.15)	11.13 (2.13)	11.79 (1.77)	0.226	0.25
KEXC (°)	10.13 (2.64)	9.33 (2.06)	8.52 (1.91)	0.098	0.71
KSTIF ($N \cdot m \cdot kg^{-1}$)	0.12 (0.02)	0.13 (0.02)^{c}	0.13 (0.02)	0.174	0.50
FM	12.05 (2.39)	13.09 (2.40)^{c}	13.88 (2.60)^{b}	0.004	0.73
HADD (°)	12.72 (1.40)	12.94 (1.09)	13.24 (1.19)	0.702	0.40
RFEV (°)	16.78 (1.34)	19.11 (2.28)	20.68 (1.95)^{b}	0.036	2.37

Effect size represents Cohen *d* value between the Pre and Post test values.
[a] Significant difference ($P < 0.05$) between the Pre and Mid test conditions.
[b] Significant difference ($P < 0.05$) between the Mid and Post test conditions.
[c] Significant difference ($P < 0.05$) between the Pre and Post test conditions.
BW, body weight.

joint adaptations, runners were able to maintain consistent knee flexion ranges at IC and midstance in each test condition.

DISCUSSION

This study aimed to investigate the acute effects of progressive fatigue on running mechanics associated with TSF risk. On the basis of the RPE results, the prescribed fatigue protocol consisting of two 20-min LT runs appeared to be successful at inducing progressive levels of fatigue within subjects (22% and 21% increases in RPE across bouts 1 and 2, respectively). Both instantaneous and average vertical loading rates were shown to significantly increase (VILR 18.1%, VALR 17.3%, both with moderate effect sizes) after 40 min of high-intensity running, whereas a nonsignificant increase (9% with a large effect size) occurred in IP. Such increases in loading rates have been previously linked with a greater risk of TSF (11,34). In support of the hypothesis, the increases seen in impact kinetics suggest runners who perform repeated runs at high intensity over a period without adequate recovery could place themselves at a greater risk of injury. One study supporting the present findings showed an increase in loading rates during running, with localized fatigue administered to the ankle dorsiflexors (5). However, in contrast, Gerlach et al. (19) reported a decrease in loading rates after runners completed an incremental exhaustive run. The inconsistent findings may be attributed to the type and level of fatigue induced by the studies. For example, the exhaustive incremental fatigue protocol of Gerlach et al. (19) may not have exhibited enough neuromuscular fatigue, as Abt et al. (1) suggested that participants may terminate the test because of cardiovascular limitations before neuromuscular fatigue is accumulated.

Previous studies identified that continuous LT running around 20–35 min caused peripheral fatigue by impairing the stretch-shortening cycle and eccentric control of the lower limbs (31,41). This impairment in muscle functioning has led to the suggestion that the present study's fatigue protocol may have forced the lower limbs to a situation where runners become less tolerant to impact. In support, Nicol et al. (37) also identified this loss of tolerance to impact in runners who completed a marathon run. The progressive increases seen in loading rate magnitudes with greater levels of fatigue indicate that runner's ability to cushion impact becomes diminished. Given that most distance runners compete and train at subthreshold continuous workloads (e.g., tempo runs and 10-km races), it appears that the present results may be more representative than the previous studies of the typical fatigue effects experienced by such runners.

TABLE 2. Mean (SD) IC characteristics for Pre, Mid, and Post test conditions and main effect *P* values.

Variable	Pre	Mid	Post	*P*
Trunk angle at IC (°)	3.60 (2.43)	−0.53 (3.30)^{a}	−3.06 (3.39)^{b,c}	<0.001
Hip angle at IC (°)	43.04 (2.61)	40.30 (2.86)^{a}	39.03 (2.80)^{c}	0.046
Knee angle at IC (°)	14.96 (2.86)	16.09 (2.90)	16.11 (2.78)	0.324
Ankle angle at IC (°)	−1.01 (1.90)	−2.14 (1.94)	−3.51 (2.00)^{b,c}	0.018

Positive values indicate flexion/dorsiflexion direction. Negative values indicate extension/plantarflexion direction.
[a] Significant difference ($P < 0.05$) between the Pre and Mid test conditions.
[b] Significant difference ($P < 0.05$) between the Mid and Post test conditions.
[c] Significant difference ($P < 0.05$) between the Pre and Post test conditions.

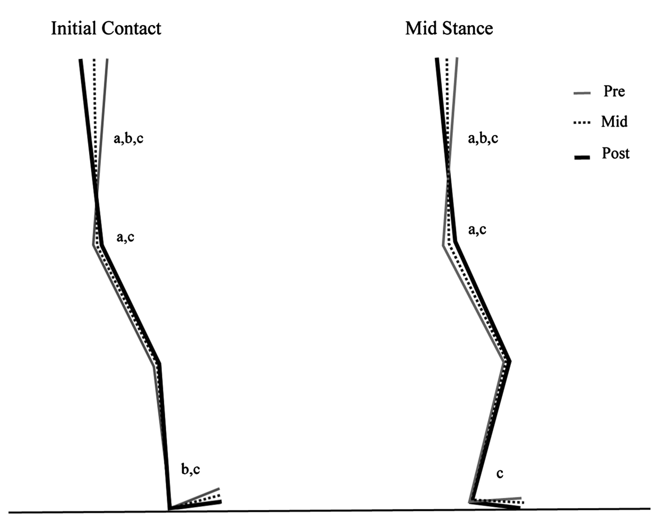

FIGURE 2—Mean stick figure representation at IC and midstance phases (diagram is for illustration purposes only). Superscripts indicate significant differences ($P < 0.05$) between the [a] Pre and Mid test conditions, [b] Mid and Post test conditions, and [c] Pre and Post test conditions.

TABLE 3. Mean (SD) midstance characteristic for Pre, Mid, and Post test conditions and main effect *P* values.

Variable	Pre	Mid	Post	*P*
Trunk angle at MS (°)	−2.44 (10.55)	−6.22 (10.81)[a]	−9.54 (11.64)[b,c]	<0.001
Hip angle at MS (°)	33.10 (9.20)	30.75 (9.87)[a]	28.38 (8.96)[c]	0.006
Knee angle at MS (°)	41.17 (4.26)	40.49 (4.3)	40.27 (5.28)	0.158
Ankle angle at MS (°)	8.31 (3.91)	6.79 (5.11)	5.64 (6.05)[c]	0.034

Positive values indicate flexion/dorsiflexion direction. Negative values indicate extension/plantarflexion direction.
[a] Significant difference ($P < 0.05$) between the Pre and Mid test conditions.
[b] Significant difference ($P < 0.05$) between the Mid and Post test conditions.
[c] Significant difference ($P < 0.05$) between the Pre and Post test conditions.
MS, midstance.

Although HADD did not support the hypothesis, FM and RFEV displayed significant increases in response to fatigue, with a large effect size seen for RFEV. Such trends in HADD and RFEV with fatigue were also evident in the study of Dierks et al. (16). In support, other reports showed increases in RFEV with fatigue (15,17). Despite no changes observed in HADD, we suspect that changes in RFEV may be related to greater fatigue induced in the distal muscle groups, causing a reduction in muscular functionality, with Christina et al. (5) reporting increases in RFEV when they administered localized fatigue to the distal muscle groups. In addition, the lack of change seen in HADD could be attributed to the trained status of the present runners having effective hip adductor stabilizers, thus preventing excessive HADD (31). The increased FM with fatigue may be linked to the increased RFEV, because previous research has shown this relation to be significant (24). The fatigue levels that the runners experienced may have induced both central and peripheral fatigue, causing changes in the body's ability to effectively maintain consistent movement patterns (15,36). Again, these findings suggest a potential for greater accumulation of microdamage during the latter stages of prolonged duration runs and possible inadequate periods of recovery between repeated running bouts.

The PTA values reported in this study were in agreement with Lafortune et al. (30) who also showed similar ranges of 7.52*g* to 12.16*g* for 4.5 $m{\cdot}s^{-1}$ over ground running trials. The present study showed runners were able to maintain PTA values after both bouts of 20 min of running despite increasing fatigue developments. In support, similar results were observed in fatigued trained runners (1,32). However, conflicting results showed significant increases in PTA with running fatigue (15,36,43,44). The inconsistencies in findings may be related to not only the level of fatigue induced by the studies but also the training status of the runners. This is supported by Mercer et al. (32) who refer to the complexity of fatigue, which inevitably produces different mechanical responses depending on the level, type, and experience level of subjects. Like Mercer et al. (32) and Abt et al. (1), all subjects in this study were trained distance runners, whereas the contrasting studies recruited nonathletic populations. It could be suggested that experienced runners may have more effective coping strategies when in a fatigued state than untrained counterparts because they are more accustomed to induced levels of fatigue (40). However, despite PTA remaining consistent, it seemed runners became less effective at attenuating accelerations at the head in an increased fatigued state. The nonsignificant increase (12.5%) seen in PHA after 20 min of running is in agreement with previous reports that displayed a similar average run duration time of 14.5 min (1,15,32). After a further 20 min of running (total of 40 min running), the increase in head accelerations became statistically significant (25%) and displayed a large effect size. Apart from the body's ability to use passive structures (tissue and bone) in attenuating impact shock (29), it appears that the active mechanisms of altered joint mechanics due to muscular fatigue may be primarily responsible for not only the increases seen in loading rates but also increases seen in PHA (39,43,44).

It has been recognized that impact shock and forces are greatly affected by joint mechanics at IC and during the stance phase of running (14). There are many mechanical variables that influence the changes seen in impact forces, head accelerations, and maintenance in acceleration at the tibia. In this study, it could be suggested that the increases seen in loading rates and tendency for an increased IP force (with fatigue) could be the result of the ankle becoming more plantar flexed at IC, alongside small increases in KSTIF and a 16% reduction in KEXC during early stance. A simulation study has identified that these observed knee and ankle mechanical changes, i.e., stiffer lower extremity joints and flatter foot landing, produce increased loading rate (20). Conversely, the increases in trunk and hip extension at IC and midstance could be partially responsible for the lack of change in PTA with fatigue, with the increased extension leading to a greater effective mass at IC (14). This increased extension observed in the proximal segments may be related to the runner's inability to maintain postural control of the heavier proximal segments while in a fatigued state (31).

The subjects in this study were able to maintain consistent knee flexion angles at IC, and this could also explain the reason for no significant changes in PTA (14). Although several studies have reported runners who exhibited higher PTA have gone on to develop overuse injuries, Derrick et al. (15) indicate that these high accelerations are less of a potential injury risk compared with high impact forces. They claim that a reduction in effective mass of the system through greater knee flexion at IC could result in higher leg accelerations but consequently lower impact forces. However, further investigation is required not only to identify the key mechanical variables that could be primarily responsible for contributing to increased overuse injury risk, but also to understand the relation between these variables.

When considering the timeline of fatigue effects, the results indicate that a greater number of variables ($n = 11$) showed significant fatigue-related changes after 40 min than after just 20 min ($n = 5$). The *post hoc* results indicate that these differences do not relate to a greater effect of fatigue over the latter 20-min running bout, because a similar number of variables ($n = 6$) showed significant changes from Mid to Post tests. It seemed that the variables demonstrating a significant change after 40 min showed a consistent trend of change across both running bouts, with the changes only reaching statistical significance after 40 min in most of these variables.

In conclusion, modifications to previously identified risk factors for impact-related injuries such as TSF are evident with increasing levels of fatigue. The reduced ability to cushion impact loading rates with fatigue may be attributed to the possible impairment of musculoskeletal functioning in controlling the lower limbs to a situation for less tolerance to impact. An association with a reduced tolerance for impact while in a fatigued state provides support to the importance of identifying these measures in individuals who are at risk of injury from impact loading during running. The observed mechanical responses to progressive fatigue also provide further insight into the biomechanical coping strategies adopted by trained distance runners in racing or training scenarios.

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There are no conflicts of interest with the present study findings.

The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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