

2023

## Does fatigue influence joint-specific work and ground force production during the first steps of maximal acceleration?

Shayne Vial

*Edith Cowan University, s.vial@ecu.edu.au*

Jodie C. Wilkie

*Edith Cowan University*

Mitchell Turner

*Edith Cowan University, mitchel.turner@ecu.edu.au*

Mark Scanlan

*Edith Cowan University, m.scanlan@ecu.edu.au*

Anthony J. Blazevich

*Edith Cowan University, a.blazevich@ecu.edu.au*

Follow this and additional works at: <https://ro.ecu.edu.au/ecuworks2022-2026>



Part of the [Sports Sciences Commons](#)

---

[10.1111/sms.14318](https://doi.org/10.1111/sms.14318)

Vial, S., Wilkie, J. C., Turner, M., Scanlan, M., & Blazevich, A. J. (2023). Does fatigue influence joint-specific work and ground force production during the first steps of maximal acceleration?. *Scandinavian Journal of Medicine & Science in Sports*. Advance online publication. <https://doi.org/10.1111/sms.14318>

This Journal Article is posted at Research Online.

<https://ro.ecu.edu.au/ecuworks2022-2026/1842>

# Does fatigue influence joint-specific work and ground force production during the first steps of maximal acceleration?

Shayne Vial<sup>1</sup>  | Jodie Cochrane Wilkie<sup>1,2</sup>  | Mitchell Turner<sup>3</sup>  | Mark Scanlan<sup>1</sup>  | Anthony J. Blazeovich<sup>1</sup> 

<sup>1</sup>Centre for Human Performance, School of Medical and Health Science, Edith Cowan University, Joondalup, Western Australia, Australia

<sup>2</sup>Physical Activity, Sport and Exercise Research Theme, Faculty of Health, Southern Cross University, Lismore, Queensland, Australia

<sup>3</sup>Centre for Precision Health, School of Medical and Health Science, Edith Cowan University, Joondalup, Western Australia, Australia

## Correspondence

Anthony J. Blazeovich, Centre for Human Performance, School of Medical and Health Science, Edith Cowan University, Joondalup, WA, Australia.

Email: [a.blazeovich@ecu.edu.au](mailto:a.blazeovich@ecu.edu.au)

During initial acceleration, the first steps of a maximal-effort (sprint) run often determine success or failure in the capture and evasion of an opponent, and is therefore a vital factor of success in many modern sports. However, accelerative events are commonly performed after having already run considerable distances, and the associated fatigue should impair muscle force production and thus reduce acceleration. Despite this, the effects of running-induced fatigue on our ability to accelerate as well as the running technique used to achieve it have received little attention. We recorded 3-D kinematics and ground reaction forces during the first three steps of the acceleration phase from a standing start before and after performing a high-speed, multi-directional, fatiguing run-walk protocol in well-trained running athletes who were habituated to accelerative sprinting. We found that the athletes were able to maintain their acceleration despite changing running technique, which was associated with use of a more upright posture, longer ground contact time, increased vertical ground reaction impulse, decreased hip flexion and extension velocities, and a shift in peak joint moments, power, and positive work from the hip to the knee joint; no changes were detected in ankle joint function. Thus, a compensatory increase in knee joint function alleviated the reduction in hip flexor-extensor capacity. These acute adaptations may indicate that the hip extensors (gluteal and hamstring muscle groups) were more susceptible to fatigue than the ankle and knee musculature, and may thus be a primary target for interventions promoting fatigue resistance.

## KEYWORDS

acceleration, biomechanics, fatigue, gait, sprint

## 1 | INTRODUCTION

The top running speed of an athlete is commonly considered to influence the capacity to capture or evade an opponent during a competition; however, even athletes with the highest running speed frequently fail in their

attempt to capture or evade an opponent, perhaps because top running speeds are seldom reached.<sup>1,2</sup> Alternatively, the ability to accelerate, including the ability to abruptly change direction, typically dictates whether an opponent is captured more so than the top speed.<sup>3-5</sup> Indeed, in team-sport athletes, the early identification of stimulus and,

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2023 The Authors. *Scandinavian Journal of Medicine & Science In Sports* published by John Wiley & Sons Ltd.

importantly, the initial movement reaction speed, are considered to be keys to overall success in situations where acceleration strongly influences the chase outcome.<sup>4,5</sup> Thus, the acceleration capacity (linear or non-linear) of an athlete, particularly within the first steps, could be more critical to success than top running speed. For example, athletes successfully capture or evade an opponent through rapid acceleration, regardless of whether changes of direction occur, without reaching maximum running speed.<sup>6–8</sup> Therefore, the capacity for skeletal muscles to produce the substantial forces required to accelerate the body during the early phase of sprinting will critically influence outcome success.

Athletes frequently shift between walking, jogging, and sprinting gaits during a competition or match.<sup>9–11</sup> As the competition progresses, for example in the latter stages of a quarter or half in team sports, fatigue may become prominent.<sup>12,13</sup> Yet, the demands of the game remain similar and athletes are still required to accelerate rapidly to catch or evade an opponent, requiring substantial physical exertion while fatigued.<sup>1,5,8,14,15</sup> As fatigue deepens, muscle force generation capacity becomes impaired and our maximum acceleration consequently decreases,<sup>16–20</sup> increasing the risk of failure to either catch an opponent or evade capture by another, which would be costly to athletes.

In sport, athletes shift between movement patterns such as rapidly accelerating to reach high running speeds, changing the direction of running (e.g., 45° turn from direction running), and jumping.<sup>2,9,21</sup> The ground reaction forces produced result from the joint forces and moments generated by muscles of the lower limb joints.<sup>22</sup> But because each muscle has a different function, morphology, location, and thus contraction force and/or velocity capacity,<sup>19,23</sup> muscles can fatigue to different magnitudes and at different rates.<sup>17,24</sup> Thus, fatigue-related torque degeneration may be muscle- or joint-dependent.<sup>24–26</sup> Therefore, to retain the same movement velocity as before fatigue, muscle force, work, and power production may be shifted from highly fatigued muscles to other, less fatigued muscles, which may then act across different joints. This would confer a change in movement pattern and joint-specific contribution to the task, although such changes may mitigate acceleration loss and thus provide the greatest chance of movement success, that is, acceleration.<sup>27,28</sup> At the distal ankle joint, the Achilles tendon performs much of the work; however, joint work is redistributed from the ankle to the larger, more proximal knee and hip joints during prolonged running. Unlike the ankle joint, these muscle groups perform work primarily through muscle contraction, and therefore tend to fatigue at a faster rate.<sup>29</sup> Speculatively, redistributing relative joint contributions may serve as an adaptation that either maintains

acceleration performance or decreases joint and soft tissue loading to reduce risk of injury. While the mechanism of joint work redistribution during fatigue in rapid, accelerative running is plausible, it remains untested.

Nonetheless, a better understanding of fatigue-induced technique alterations may allow for more specific hypotheses to be drawn and thus for future research to be designed. While acceleration mechanics are relatively well-understood, particularly in track sprinters,<sup>30</sup> we currently know relatively little about how humans move during fatigued accelerative running, and whether movement patterns are adapted as a result of such fatigue. The primary purpose of the current study was to describe the kinematic and kinetic patterns of the lower limbs in the first three steps of both non-fatigued and fatigued accelerated running (sprinting), and thus to assess the changes to within-limb distribution in response to fatiguing running exercise. Due to differences in center of mass (CoM) velocity between steps, a true comparison between limbs (i.e., dominant vs. non-dominant legs) was not possible. Therefore, we tested the hypothesis that reduced horizontal velocity and substantial, acute kinematic and kinetic adaptations would be observed with fatigue.

## 2 | METHODS

### 2.1 | Population and training history

Thirteen intermediate-level (semi-professional) male Association Football (Soccer) players (age: 19.1 ± 2.1 y, body mass: 72.5 ± 6.9 kg, height: 175.0 ± 7.7 cm) participated in this study. This cohort was chosen because they undertook regular training and participated in matches that include walking, slow jogging, and running at varying speeds. To ensure use of their own freely chosen running technique, inclusion criteria included the participants performing no previous formal running technique instruction or training. No subjects participated in formal strength training or other supplementary training (e.g., plyometrics) that might influence their running performance, technique, or response to fatiguing running exercise. All participants were free from injury for at least 6 months before testing, reported no residual impediments from previous injury, and wore their normal training attire, which included the same running shoes during testing and soccer boots to perform the fatiguing protocol. Only outfield players were accepted into the study as goalkeepers tend not to perform maximal sprinting during training or match play. The study was approved by Edith Cowan University of Human Ethics Committee, and players gave written consent prior to testing.

## 2.2 | Biomechanical measurements

Thirteen VICON (T20 series) motion capture cameras (Oxford Metrics Ltd., Oxford, UK) set at a frame rate of 250 Hz were positioned to capture the region from 0 to 5 m of the linear running acceleration trials. Ground reaction force data were simultaneously collected by five in-ground 600×900-mm triaxial force platforms positioned in a series (Kistler Quattro, Type9290AD, Victoria, Australia) sampling at 1000 Hz. Motion capture cameras were arranged around the in-ground force platforms over which the subjects performed their running acceleration trials. The subjects started behind the first force platform, and the finish line was located 20 m from the start to ensure that subjects did not decelerate through the data capture zone; that is, although only the first three steps were examined, the subjects were required to accelerate maximally over a longer distance, which might more likely lead to opponent capture or evasion.

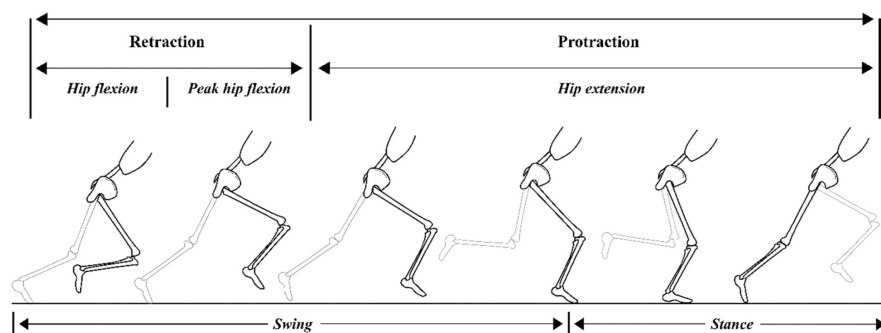
## 2.3 | Protocol

Upon arrival, height and body mass were recorded for each subject, and a custom cluster-based set of retroreflective markers were placed on anatomical landmarks for 3-dimensional motion capture (see Table S1). Subjects then completed a standardized, comprehensive warm-up (section 2 – Supporting Information) which included practice trials for single-leg vertical jumps (SLVJ) on each leg and acceleration run efforts performed at 50%, 75%, and 100% of maximal effort for the full 20-m distance (Figure S1) from a standing stationary start; the subjects started in a semi-crouched position with one foot in front of the other and the toes of the front foot on the start line; the hands did not touch the ground in this position.

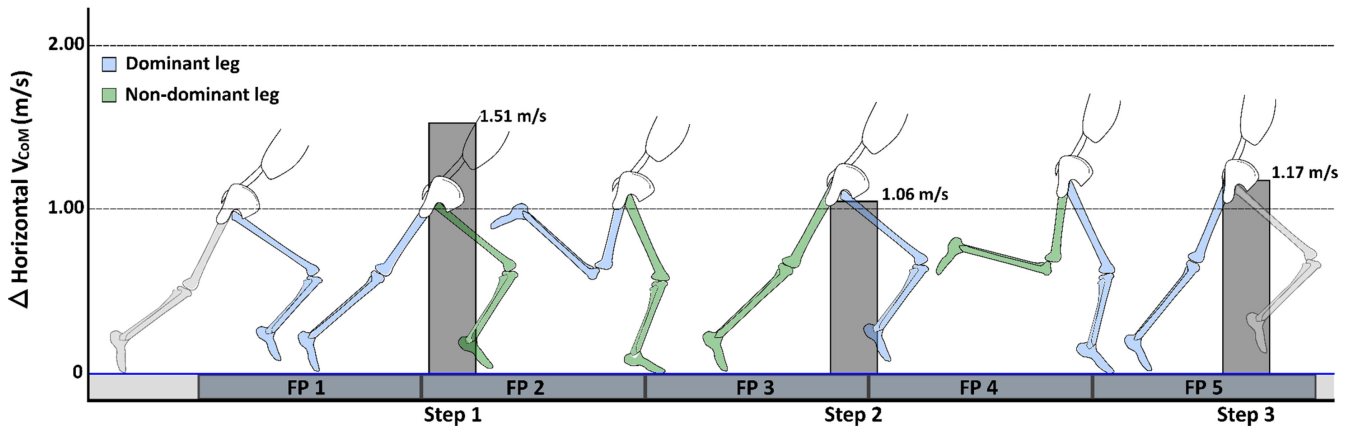
Once the warm-up and practice trials were completed, three SLVJs were performed on each leg to obtain jump

heights to determine dominant and non-dominant legs prior to and after the fatiguing protocol. The SLVJ test was used to define the “strongest” (dominant) and “weakest” (non-dominant) limbs as it encapsulates the ability to coordinate lower limb segments to rapidly produce force with minimal influence from the other leg. Therefore, the leg that produced greater jump height was selected as dominant. In some studies, researchers have designated the preferred kicking leg as dominant, which may not be the stronger of the two legs and thus may not accord with our definition. Subjects then performed a maximal effort 60-m sprint prior to and after the fatiguing protocol. The motion camera capture volume (8 × 3 m) was located 40 m from the starting point, subjects ran through the center of the capture volume while wearing the retroreflective markers, this allowed us to determine whole-body center of mass position and calculate the maximum horizontal velocity attained as they passed through the capture volume. This, together with SLVJ jump height, was used to assess the level of fatigue. Then, once in their standing start position, a countdown from 5 to 1 led into the first 20-m maximal acceleration trial (see Figures 1 and 2), and subjects repeated this twice to obtain the *pre-fatigue* measurements. Verbal encouragement was given to ensure the subjects accelerated maximally and did not decelerate through the data capture zone. Subjects were allowed exactly 60 s of rest between trials, which included walking back to the start line. This relatively short rest was used to minimize the recovery from fatigue in post-running (fatigued) trials but did not induce detectable running fatigue in the non-fatigued tests (see Section 3).

Once the first set of maximal acceleration trials was completed, the subjects jogged for 100 m at a comfortable pace to a grassed sports surface where markers placed on the surface demarcated a soccer-specific fatiguing exercise protocol (Ball-Sport Endurance and Sprint Test; BEAST 45) that would last 45 min (Ref. 34; see Figure S2). The fatigue protocol has been shown to be a valid and



**FIGURE 1** Representation of one step in accelerative sprint gait cycle. Leg retraction (forward rotation) begins as the foot leaves the ground and continues up until peak hip flexion. Leg protraction (backward rotation) commences as the hip extends and continues up until toe-off. For each step, data were obtained as the hip transitioned from flexion (i.e., late retraction) to extension through to toe-off (i.e., protraction phase).



**FIGURE 2** The first three steps of accelerated running from a standing start are overlaid on the horizontal center of mass velocity ( $V_{CoM}$ ). The vertical axis shows the change in  $V_{CoM}$  from Step 1 to Step 2 and Step 3; five force platforms (FP) positioned in a series. The greatest change in horizontal  $V_{CoM}$  was observed in Step 1, followed by Step 3, with Step 2 being the lowest. (Blue) DL: dominant leg; (Green) NDL: non-dominant leg. The step cycle was defined from the second half of the swing phase to toe-off.

reliable simulator of soccer match play with respect to the movement patterns (walking, running, jumping, backwards running), intensity (i.e., distance and speed), and fatigue levels observed during a match (see [Supporting Information](#)).<sup>31–34</sup> This protocol was familiar to the subjects, who were practiced in completing it without a notable pacing strategy and did not require further, extensive familiarization. The protocol requires all directions of movement that might be needed in the chase or evasion of an opponent and is also reflective of the movement patterns required in many team-based sports. Subjects were also verbally instructed to run as fast as possible during the sprint sections and to decelerate within the allocated areas. After performing the fatiguing exercise, subjects jogged at a comfortable pace (100 m) back to the laboratory, performed three SLVJs on each leg, and then performed a 50 m sprint trial prior to determine *post-fatigue* maximal running velocity. Once complete, subjects returned to the start line before a countdown from 5 to 1 led into the first of three 20 m maximal acceleration trials (*post-fatigue* test; *fatigued* trials) with 60 s of walk-back recovery between trials.

## 2.4 | Data analysis

All static and dynamic motion capture trials were digitized using VICON Nexus software (Oxford Metrics Ltd., Oxford, UK) and exported as C3D files to Visual 3D (C-Motion, Germantown, MD, USA). Ground reaction force and marker trajectory data were filtered using a fourth-order (zero lag), low-pass Butterworth filter with a 15-Hz cutoff frequency, as determined through residual analysis of marker trajectory data.<sup>35,36</sup> Together, subject height, body mass, and the static standing trial data were used

to create an individually scaled skeletal model that included the trunk, pelvis, thigh, shank, and foot segments in Visual 3D software using standard inertial parameters (segment mass<sup>37</sup>) and moments of inertia.<sup>38</sup> Dynamic calibration trials were collected to determine functional joint centers for the hip, knee, and ankle joints. For all trials, segmental angles were computed relative to the laboratory reference frame using the right-hand rule and were normalized to upright standing. Standard methods using Newton-Euler procedures were used to calculate joint moments and powers in Visual 3D. The timings of foot-strike and toe-off were determined using force platform data with a threshold value set at 20 N. Braking, propulsive, and vertical impulse (Ns) data were calculated and then normalized to body mass expressed in meters per second (m/s).

To obtain joint powers, the net joint moments were multiplied by joint angular velocities for the hip, knee, and ankle joints. Then, to calculate positive and negative mechanical work performed by the lower limbs, joint power data were individually integrated with respect to time using the trapezoid method. For each step, all positive work and all negative work values were summed to provide individual joint totals for each for positive and negative work. The average positive powers calculated for the hip, knee, and ankle joints were summed, and this value was described as total positive power output (equation 1), where  $P_{tot}^+$ ,  $P_{hip}^+$ ,  $P_{knee}^+$ ,  $P_{ankle}^+$  are total, hip, knee, and ankle joint average positive powers. Each joint's average positive power as a percentage of total average positive power was determined (equation 2), where  $J_{percent}$  is the percentage of an individual joint to the total work. The same equations were used to obtain total average negative power at each joint.

$$P_{\text{tot}}^+ = P_{\text{hip}}^+ + P_{\text{knee}}^+ + P_{\text{ankle}}^+ \quad (1)$$

and

$$J_{\text{percent}} = \left( \frac{P_j^+}{P_{\text{tot}}^+} \right) \times 100\% \quad (2)$$

Data from three non-fatigued and fatigued acceleration trials were averaged for each subject for the dominant and non-dominant limbs from the second half of retraction and entire protraction phases for the first, second, and third steps of the acceleration trial, respectively. Each step was defined from the second half of the retraction phase through to toe-off (Figure 1).

## 2.5 | Statistical analysis

Descriptive statistics are expressed as mean and standard deviation (SD). Paired *t*-tests with Bonferroni corrections were used to compare discrete kinematic, kinetic, and temporal variables between non-fatigued and fatigued conditions. The differences between non-fatigued and fatigued conditions were assessed through the effect size (ES) using Cohen's *d*, interpreted as follows: small difference  $\leq 0.38$ , medium difference  $0.38-0.67$ , large difference  $0.67-0.76$ , and very large difference  $\geq 0.76$ , and the alpha level was set at 0.05. All statistical analyses for discrete variables were performed using JAMOVI (Version 1.6, Sydney, Australia).

## 3 | RESULTS

Data from the second half of retraction to toe-off for the initial three steps of accelerated sprint running were compared between non-fatigued and fatigued conditions. The non-fatigued and fatigued within-limb comparisons included the dominant leg (DL; stronger) during the first and third steps and non-dominant leg (NDL; weaker) during the second step (Figure 2).

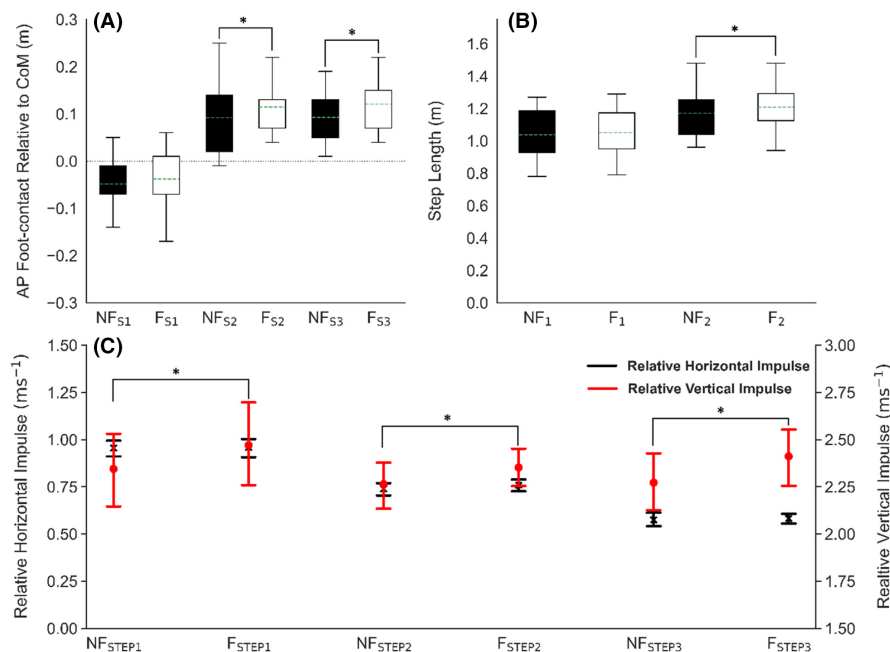
### 3.1 | Step-to-step comparisons: non-fatigued, accelerated running

The average horizontal center of mass (CoM) velocity increased by  $\sim 41\%$  ( $p < 0.001$ , ES = 4.15) from Step 1 (S1) to Step 2 (S2) (1.51–2.57 m/s) and then  $\sim 31\%$  ( $p < 0.001$ , ES = 1.89) from S2 to Step 3 (S3) (2.57–3.74 m/s), while vertical CoM velocity and displacement (i.e., from maximum to minimum heights) remained constant. Ground contact times decreased by  $\sim 9\%$  from S1 to S2 and  $\sim 5\%$  from S2 to S3 (Table 1). In S1, the foot landed 0.05 m behind the body's CoM, while foot contacts in S2 and S3 were both 0.09 m in front of the CoM (Figure 3). Horizontal foot velocity relative to CoM at ground contact increased with each successive step, i.e., increased forward foot speed relative to CoM (see Figure S3), while vertical velocity, i.e., downward foot speed, did not change. During the steps, relative horizontal impulse decreased by  $\sim 22\%$ , while relative vertical impulse remained relatively constant (Table 1).

**TABLE 1** Ground contact times, relative horizontal and vertical impulse across three steps during running acceleration trials before (Non-fatigued) and after (Fatigued) fatiguing running.

	Non-fatigued	Fatigued	Mean diff	95% CI (change)
	Mean $\pm$ SD	Mean $\pm$ SD		
<b>Step 1</b>				
Ground contact time (s)	0.20 $\pm$ 0.02	0.20 $\pm$ 0.01	–0.01	0.00, –0.01
Relative horizontal impulse (m·s <sup>–1</sup> )	0.96 $\pm$ 0.07	0.96 $\pm$ 0.08	–0.01	–0.02, 0.02
Relative vertical impulse (m·s <sup>–1</sup> )	2.34 $\pm$ 0.33*	2.47 $\pm$ 0.36*	–0.13	–0.06, –0.20
<b>Step 2</b>				
Ground contact time (s)	0.18 $\pm$ 0.02*	0.19 $\pm$ 0.01*	–0.01	–0.01, –0.01
Relative horizontal impulse (m·s <sup>–1</sup> )	0.74 $\pm$ 0.09	0.76 $\pm$ 0.09	–0.02	–0.03, 0.07
Relative vertical impulse (m·s <sup>–1</sup> )	2.26 $\pm$ 0.33*	2.35 $\pm$ 0.29*	–0.09	–0.02, –0.19
<b>Step 3</b>				
Ground contact time (s)	0.17 $\pm$ 0.01*	0.18 $\pm$ 0.01*	–0.01	–0.01, –0.01
Relative horizontal impulse (m·s <sup>–1</sup> )	0.58 $\pm$ 0.06	0.58 $\pm$ 0.05	–0.02	–0.04, –0.01
Relative vertical impulse (m·s <sup>–1</sup> )	2.27 $\pm$ 0.26*	2.41 $\pm$ 0.26*	–0.12	–0.05, –0.19

\*Statistical difference (*t*-test) between non-fatigued and fatigued trials ( $p < 0.05$ ).



**FIGURE 3** Non-fatigued and fatigued accelerated sprint running performance outcomes. After fatiguing exercise, the foot contacted the ground further in front of the CoM (A: S2,  $p = 0.026$ ; S3,  $p = 0.001$ ), step length increased (B: S2 only,  $p = 0.012$ , ES = 0.51) and relative vertical impulse increased across all steps (C:  $p = 0.021$ , ES = 0.45;  $p = 0.01$ , ES = 1.02;  $p = 0.009$ , ES = 1.04), respectively. NF, non-fatigued (black); F, fatigued (white); step number indicated in subscript. (A) anterior–posterior (AP) foot–ground contact distance relative to the horizontal position of CoM (meters); (B) step length (meters); (C) relative horizontal impulse ( $\text{m}\cdot\text{s}^{-1}$ ; primary axis) and relative vertical impulse ( $\text{m}\cdot\text{s}^{-1}$ ; secondary axis). \*Statistical difference ( $t$ -test) between non-fatigued and fatigued trials ( $p < 0.05$ ).

### 3.2 | Step-to-step kinematic, kinetic, and mechanical work comparisons: Non-fatigued, accelerated running

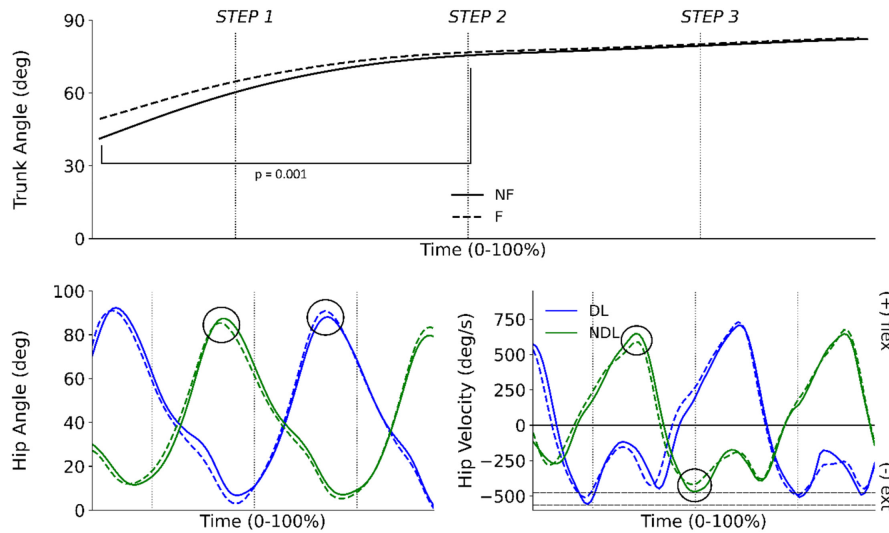
The sagittal trunk angle relative to the ground at ground contact increased in each successive step ( $\sim 58^\circ$  for S1,  $\sim 72^\circ$  for S2, and  $\sim 84^\circ$  for S3; see Figure 4). On average, peak hip flexion angle tended to decrease slightly with each successive step while peak knee extension angle remained constant for S1 and S3 but decreased slightly (greater flexion) between S1 and S2 (see Figure 5). No differences were observed in ankle joint kinematics between steps.

Peak hip extension moment significantly increased from S1 to S2 ( $p = 0.001$ ; ES = 1.64), but no changes were detected between S2 and S3 (Figure 5). Peak knee extension moment and power were similar from S1 to S2 but significantly increased from S2 to S3 ( $p = 0.004$ ; ES = 0.92). Small increases in peak plantarflexion moment and power were observed with each successive step but did not reach statistical significance. Positive work was greatest at the ankle joint for S3 (38.6%), while similar contributions were made by the hip (S1: 33.9%; S2: 37.3%) and ankle (S1: 35.1%; S2: 36%) joints in S1 and S2. The hip work contribution in S3 (35.3%) was the next greatest, while the knee contributed least to all steps, with this difference being most marked in, and not different between, S2 and

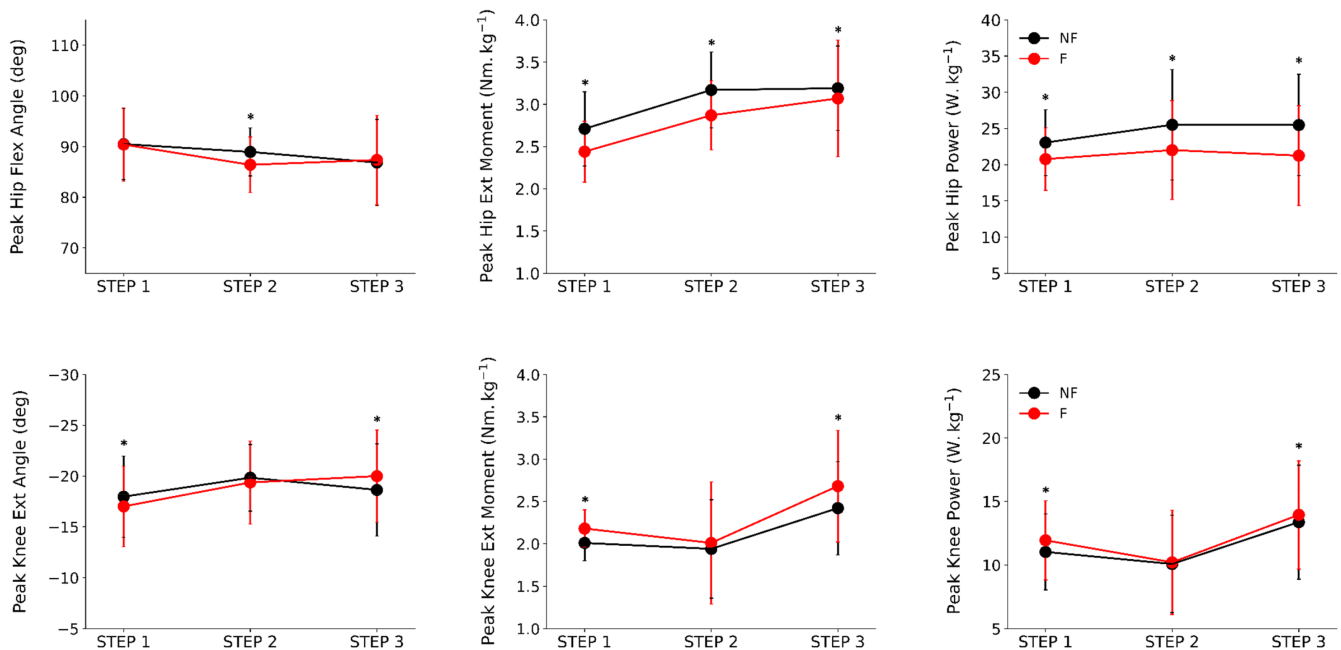
S3 (S1: 30.9%; S2: 26.7%; S3: 26.1%). Total positive work performed was similar for S1 (2.78 J/kg) and S2 (2.62 J/kg) but increased by 48% from S2 to S3 (to 5.10 J/kg;  $p = 0.01$ ; ES = 0.89) (Figure 6).

### 3.3 | Step-to-step variable comparison between non-fatigued and fatigued accelerated running

Fatiguing exercise did not detectably alter either CoM horizontal velocity or vertical CoM displacement in any step. However, while ground contact times did not significantly change for S1,  $\sim 6\%$  increases were detected in S2 ( $p = 0.008$ , ES = 0.53) and S3 ( $p = 0.004$ , ES = 0.66) (with no significant difference between S2 and S3—see Table 1). During S1, the horizontal position of the foot relative to the CoM at ground contact was unchanged by fatigue, but the foot landed further in front of the CoM in S2 (20%,  $p = 0.026$ , ES = 0.44) and S3 (23%,  $p = 0.001$ , ES = 0.66) compared to the non-fatigued condition. Horizontal foot velocity was also unchanged in S1 but tended to increase in S2 (26%) and S3 (15%) with fatigue, although statistical significance was not reached ( $p = 0.07$  and  $p = 0.06$ , respectively). Vertical foot velocity and relative horizontal impulse remained unchanged, but vertical impulse

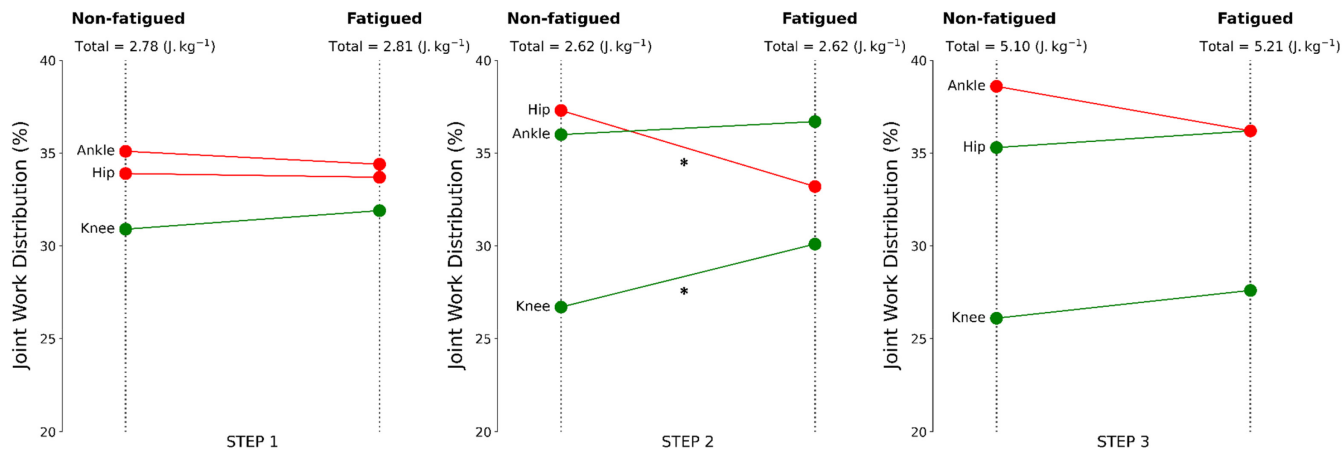


**FIGURE 4** Trunk and hip kinematics during non-fatigued and fatigued acceleration trials. Vertical dotted lines represent foot-strikes for steps 1, 2, and 3, respectively. After fatiguing exercise, larger trunk angle relative to the ground was observed, that is, a more upright posture during S1 and S2 ( $p = 0.001$ ,  $ES = 0.75$ ) (top); simultaneous decreases were detected in peak hip flexion angle ( $p = 0.03$ ,  $ES = 0.38$ ) and hip extension velocity ( $p = 0.02$ ,  $ES = 0.44$ ) for S2, while S1 ( $p = 0.06$ ) and S3 ( $p = 0.10$ ) hip extension velocity was maintained (bottom right). Top: sagittal plane angle of the trunk relative to the ground (degrees) in non-fatigued (solid line) and fatigued (dashed line) conditions; bottom left: sagittal hip angle (degrees) for dominant leg (DL, blue) and non-dominant leg (NDL, green) in non-fatigued (solid line) and fatigued (dashed line) conditions from early protraction to toe-off for all three steps; middle right: sagittal hip velocity (deg/s) for DL (blue) and NDL (green) in non-fatigued (solid line) and fatigued (dashed line) conditions from early protraction to toe-off for all three steps.



**FIGURE 5** Peak hip and knee joint angles, moments, and positive power during non-fatigued and fatigued acceleration trials. After fatiguing exercise, peak hip extension moments (S1  $p = 0.04$ ,  $ES = 0.54$ ; S2  $p = 0.03$ ,  $ES = 0.49$ ; S3  $p = 0.05$ ,  $ES = 0.19$ ) and positive power slightly decreased across all steps (S1  $p = 0.04$ ,  $ES = 0.24$ ; S2  $p = 0.03$ ,  $ES = 0.12$ ; S3  $p = 0.05$ ,  $ES = 0.30$ ); peak knee extension moments and positive power increased for S1 ( $p = 0.04$ ,  $ES = 0.79$ ) and S3 ( $p = 0.03$ ,  $ES = 0.43$ ). Top left: peak hip flexion angle (degrees); top middle: peak hip extension moment (Nm/kg); top right: peak positive hip joint power (W/kg); bottom left: peak knee extension angle (degrees); bottom middle: peak knee extension moment (Nm/kg); bottom right: peak positive knee power (W/kg) during non-fatigued (black) and fatigued (red) conditions. \*Statistical difference ( $t$ -test) between non-fatigued and fatigued trials ( $p < 0.05$ ).





**FIGURE 6** Joint work distribution of lower limb joints expressed as a percentage of total positive work across each step during non-fatigued and fatigued acceleration trials. For S2, positive hip joint work ( $p = 0.02$ ,  $ES = 39$ ) performed decreased while positive knee joint work ( $p = 0.042$ ,  $ES = 0.42$ ) increased (center); no significant differences were observed for S1 (left) and S3 (right). Green line represents an increase from non-fatigued to fatigued conditions, while red line indicates a decrease. Total positive joint work (J/kg) performed for each step is provided above each condition. \*Statistical difference ( $t$ -test) between non-fatigued and fatigued trials ( $p < 0.05$ ).

(Figure 3) significantly increased ~4%–6% after fatigue across all steps ( $p = 0.021$ ,  $ES = 0.45$ ;  $p = 0.01$ ,  $ES = 1.02$ ;  $p = 0.009$ ,  $ES = 1.04$ ), respectively.

### 3.4 | Kinematic, kinetic, and mechanical work comparison between non-fatigued and fatigued accelerated running

Sagittal trunk angle relative to the horizontal significantly increased at the initiation of acceleration ~15% ( $7.2^\circ$ ), ~10% ( $4.1^\circ$ ) at foot-ground contact during S1 and ~5% ( $2.0^\circ$ ) in S2 with fatigue ( $p = 0.001$ ,  $ES = 0.75$ ) but was not different in S3 (Figure 4). The peak hip flexion angle also remained unchanged in S1 and S3 but decreased ~3% for S2 ( $p = 0.05$ ,  $ES = 0.38$ ). Peak knee extension angle prior to foot-ground contact, that is, the phase between early protraction and foot-ground contact, decreased for S1 (5%) but increased for S3 (7%) (Figure 5). Additionally, kinematics about the ankle joint did not change statistically in any step after fatigue.

Peak hip extension moments (S1: 12%, S2: 9%, S3: 4%) and power (S1: 10%, S2: 12%, S3: 17%) significantly decreased with fatigue, while knee moments and power significantly increased in S1 (~7%) and S3 (~4%) without change in S2 (Figure 5), and peak plantarflexion moment increased only in S1 (8%). The distribution of positive work performed did not significantly change during S1 and S3; however, the hip extensor contribution significantly decreased (~4%) while knee extension contribution increased (~4%) during S2. The total positive work performed did not change with fatigue; however, proportionally more work was performed in S1 (2.82J/kg) than S2

(2.62J/kg), and more positive work was performed in S3 (5.21J/kg) than S2 (Figure 6).

### 3.5 | SLVJ and maximum sprint running tests

Paired  $t$ -tests identified significant differences in jump height ( $p < 0.001$ ) between DL and NDL in the non-fatigued condition, with DL producing ~1.6 cm greater jump height and ~8% greater relative vertical impulse than NDL. Jump height significantly decreased between non-fatigued and fatigued conditions for DL ( $p < 0.001$ ,  $ES = 2.26$ ) and NDL ( $p < 0.001$ ,  $ES = 1.47$ ), and no statistical differences were observed between DL and NDL ( $p < 0.069$ ). The average maximum horizontal velocity of the center of mass (CoM) during the non-fatigued condition was 8.59 m/s and decreased 0.33 m/s after completing the fatiguing protocol.

## 4 | DISCUSSION

### 4.1 | Overview

Contrary to the tested hypotheses, acceleration did not decrease within the first three steps after the completion of fatiguing running exercise despite significant decreases in one-leg jump height being induced by the exercise and this same exercise previously leading to significant reductions in maximum running speed. After performing fatiguing exercise, a more upright posture was adopted, slightly longer step lengths were used with the foot contacting the ground

further in front of the CoM, longer ground contact times evolved, and greater relative vertical impulse was produced while relative horizontal impulse was maintained. In combination with differences in posture and step characteristics, hip flexion and extension velocity, and hip extension power and moments decreased but peak knee moments, power, and positive joint work increased, while ankle joint kinetics did not detectably change with fatigue. Although these acute adaptations may speculatively help to maintain horizontal velocity, it may also indicate that the hip extensors (i.e., gluteal and hamstring muscle groups) were more susceptible to fatigue than those spanning the ankle and knee joints, and therefore contributed to a lesser extent during fatigued accelerated sprinting. Therefore, a strategy appears to have been adopted that incorporated longer ground contact times, a more upright posture, and greater peak knee moments and positive work production, which was sufficient to maintain the rate of acceleration during the first steps of acceleration after running-induced fatigue as before the fatiguing exercise.

The ability to retain acceleration observed after fatiguing exercise might have been gained through our cohort of athletes regularly performing repeated acceleration efforts, particularly under fatigued conditions, in both training and match situations. Nonetheless, reductions in both single leg vertical jump height and maximum sprint running velocity indicate that subjects experienced performance-related fatigue. Team-sport athletes rarely run uninterrupted for long distances and seldom reach maximal sprinting speed, and therefore accelerated sprints are one of the most frequently completed high-speed running tasks in training and matches.<sup>39</sup> This experience might speculatively have resulted in them developing, that is, learning, to alter their movement patterns so as to maintain acceleration in the face of fatigue. This hypothesis requires more explicit scrutiny in future studies.

## 4.2 | Non-fatigued accelerated sprint performance and technique

Forward leaning posture and leg motion following a downward and backward path (relative to CoM) led to primarily forward and upward ground reaction forces being applied back to the body. Forward lean and relative horizontal impulse was greatest during the first step and decreased with each successive step, respectively. As momentum (mass $\times$ velocity) increases,<sup>40</sup> net force (horizontal direction) should decrease with the increase in velocity. This effect was observed in the present study, with ground contact times and horizontal foot velocity (i.e., forward foot velocity relative to CoM) decreasing as

posture became more upright and resulted in the first step having the greatest relative horizontal impulse, which decreased with each successive step. Although whole-body velocity increased at each step, vertical impulse was relatively unchanged across steps, likely due to greater vertical force production and shorter ground contact times. Although relative horizontal impulse decreased with each step, overall acceleration mechanics for steps 1 (dominant leg; DL), 2 (non-dominant leg; NDL), and 3 (DL again) remained similar. Equal relative positive work was performed at the hip and ankle joints in S1 and S2, while a slightly greater relative ankle joint contribution was observed in S3 (Figure 6). As such, we speculate that there was relatively equal contribution from the larger proximal hip extensors (i.e., gluteal and hamstring muscles) and distal elastic powered ankle joint (i.e., Achilles' tendon, gastrocnemii, and soleus muscles) for propulsion during all steps. In agreement with previous work, maximum sprinting acceleration in non-fatigued conditions appears to largely depend on the work performed by the hip and ankle joints.<sup>41</sup>

The individual limb contribution to total positive joint work was slightly greater in S1 than S2; however, a 48% increase was observed from S2 to S3. That is, the positive joint work performed in S3 was almost double that of S2, but horizontal velocity continued to increase. Intuitively, the positive joint work performed should reflect increases in whole-body velocity. For example, the relative joint work done may be expected to increase simultaneously with horizontal velocity. Yet, horizontal velocity increased despite a lack of increase in total positive joint work done in S2. One explanation might be provided by the differences in posture between steps; a more forward leaning posture was adopted in S1 and S2 than S3, allowing the gravitational force to do work on the body to assist horizontal acceleration. Once the foot contacted the ground, a more forward position of the body's center of mass over the support leg caused gravity to have a greater effect on the forward rotation of the body about the foot. Nevertheless, horizontal CoM velocity reached  $\sim 1.51$  m/s for S1, increased by 1.06–2.57 m/s for S2, and increased 1.17–3.74 m/s for S3; hence, acceleration was lowest in S2 (see Figure 2). The main findings of interest during non-fatigued accelerated sprinting included a non-linear decrease in acceleration with each step, with the third step producing nearly double the positive joint work of the previous steps. The change in horizontal velocity was greatest for step 1 (1.51 m/s), decreased  $\sim 30\%$  to step 2 (1.06 m/s), and then increased slightly to step 3 (1.17 m/s). These data, in combination with positive joint work done and jump test results (i.e., SLVJ jump height), indicate that the non-dominant leg was indeed the weaker limb.

### 4.3 | Non-fatigued and fatigued accelerated sprint performance and technique comparison

Unlike top speed sprinting, which requires large vertical forces to be produced in a very short foot-ground contact time of  $\sim 0.1$  s,<sup>42</sup> accelerated sprinting requires a magnitude of vertical impulse that is sufficient to project the body into the next step with adequate time to reposition the leg toward the front of the body.<sup>43</sup> We observed that ground contact times during S1 were unaltered after fatiguing exercise compared to non-fatigued running but were increased in S2 and S3. Meanwhile, relative horizontal impulse remained unchanged, and instead, significant increases in relative vertical impulse were observed across all steps. No changes in relative horizontal impulse were found after fatiguing exercise, which might be attributed to small changes in the duration and magnitude of force applied to the ground. A compensatory strategy for maintaining impulse in the face of fatigue may involve slightly lengthening the time the foot is in contact with the ground while slightly decreasing the magnitude of ground force application, which could be detrimental for performance when attempting to evade or capture an opponent. In addition, hip flexion and extension velocities decreased in the fatigued running condition with simultaneous decreases in hip extension moments and powers across all steps (i.e., dominant and non-dominant legs). Hunter et al.<sup>43</sup> hypothesized that vertical impulse may be smaller during initial acceleration in individuals who are able to reposition their limbs more quickly in preparation for the next step. However, we observed a significant increase in vertical impulse after fatiguing exercise and, according to Hunter et al.'s<sup>43</sup> premise, the capacity to reposition the lower limbs (i.e., reduced hip flexion/extension velocity) in preparation for the next step may have been diminished due to fatigue. With an increase in vertical impulse, one might expect a simultaneous increase in vertical CoM displacement, while the mean difference between conditions showed an increasing trend, this did not reach statistical significance; however, we instead observed a significant increase in the projection angle (i.e., a more upright posture—see Figure 4). Given the above, we speculate that in order to overcome the slowing of hip flexion and extension, the use of a more upright posture allowed more time to reposition the lower limbs for the following step, and therefore orientated the body in a better position to generate vertical impulse. That is, producing downward force is far easier if the body is more upright, and therefore vertical force production increased because of the change in posture.

In combination with greater vertical force production, we also observed a shift in joint contribution, including

a decrease in hip joint contribution and simultaneous increase in peak knee joint moments, power, and positive work done in particular, after fatiguing exercise. However, slightly different strategies were used for dominant and non-dominant limbs. Greater peak knee extension moments and power were observed in S1 and S3 (i.e., dominant leg), but similar positive work was performed in the non-fatigued condition. While peak knee joint moments and power were similar for S2 (i.e., non-dominant leg) to the non-fatigued condition, positive hip joint work decreased while positive knee work increased. The longer ground contact times and greater vertical force production might have resulted from increased peak knee extension moments (dominant leg) and positive knee joint work performed (non-dominant leg). In prolonged, middle-distance speed running,<sup>44</sup> a proximal shift from the ankle to the knee joint was observed with fatigue. Instead, we observed a relative reduction in positive joint work at the hip and increase at the knee joint. While the present results and those of Willer et al.<sup>44</sup> tend to reveal similar outcomes (i.e., a shift to knee joint work production), the point of difference is the proximo-distal direction of the shift. The relative shift from the hip extensors, which contribute significantly to horizontal force production in sprinting acceleration, indicates that fatigue might manifest differently in slower, continuous running than multi-directional higher intensity exercise. An alternative explanation is that fatigue simply manifests differently between sprinting and jogging. Incorporating the use of periods of acceleration and sprinting in our fatiguing protocol, which requires significant hip work and power production, might influence this capacity in a subsequent test of acceleration, whereas continual jogging may evoke greater distal muscle fatigue that is then detected during a subsequent jogging test. Irrespective of the mechanism or site of fatigue, our cohort of athletes adapted their movement pattern to negate acceleration loss.

While one hypothesis may be that our cohort have a learned ability to shift muscle force production from more fatigued to less fatigued muscles to maintain acceleration, an alternative explanation, or additional benefit, is that the hip-to-knee muscle force redistribution may serve a fatigued-induced muscle injury protective purpose, particularly for the injury prone hamstring muscles. Hamstring muscle injuries are highly prevalent in modern sports and are the most prevalent injury in running-based sports such as Association Football (soccer).<sup>13,45</sup> Although injuries are problematic for modern athletes, injury in early humans would have had severe consequences, so the adoption of injury reduction practices or preserving acceleration ability to evade predators while fatigued would have been important for survival. A shift from hip extensor (hamstring) to knee extensor

(quadriceps) work and power production may provide a useful injury minimization purpose, especially since hip flexion angles are acute, and thus places the hamstring muscles at long length, when the body has a significant forward lean during accelerative running. This hypothesis is worthy of explicit examination in future studies.

#### 4.4 | Summary

In the non-fatigue trials, the first steps of accelerated sprinting appear to mostly depend upon hip and ankle work and power contributions. Our primary findings included a non-linear decrease in acceleration, with step 2 (i.e., non-dominant leg) having the lowest horizontal velocity. Secondly, similar positive work was done during the first (DL) and second (NDL) steps, while work in the third step (DL) was nearly double that of S1 and S2. These data, in combination with jump test results (i.e., SLVJ jump height), indicate that the non-dominant leg is indeed the weaker leg. With fatigue, we observed a more upright posture, longer ground contact times, increased vertical impulse, and a shift in peak moments, power, and positive work done from the hip to the knee joint. We theorize that this shift is either a direct cause or a result of reduced hip flexion and extension velocity to reposition the lower limbs in preparation for the next step. Similar to previous research in slower, more economical running, we observed that running-induced fatigue led to a compensatory increase in knee joint work.<sup>44</sup> However, unlike those previous findings, fatigue promoted a shift from the larger, powerful hip extensors rather than elastic powered ankle propulsion to muscle-dominant knee power production. Thus, maximal acceleration, contrary to slower-speed running, does not seem to be compromised by a loss of ankle work or power while in a fatigued state. As an alternative, we suggest that fatigue induced through the combination of slow, moderate, and high speed multi-directional movements used in the present study may have induced a marked hip extensor fatigue (i.e., gluteal and hamstring muscle groups) with a compensatory increase in knee peak moments, power, and positive work (i.e., by quadriceps muscles); the degree of hip extensor fatigue evoked by the running protocol requires quantification in future experiments. Regardless, this adaptation may be used as a strategy to maintain acceleration or reduce the risk of injuring muscles (e.g., hamstrings) that may be more susceptible to fatigue. Nevertheless, the results provide insight into the mechanics that hunter-gather people may have also used when undertaking similar accelerating activities, particularly when fatigued.

#### 4.5 | Limitations

A noteworthy limitation was that testing was conducted in an indoor laboratory on a synthetic athletics track while the fatiguing protocol was completed outdoors on a grassed sports field. Additionally, since subjects wore their normal running shoes for testing in the laboratory and soccer boots during the fatiguing protocol, the transition between footwear may have impacted their running technique. Future research should investigate accelerative running mechanics on grassed and dirt surfaces, which may be more comparable to the surfaces used in hunter-gatherer societies. It should also be noted that joint moments, powers, and work were calculated using the inverse dynamics method, which determines the net moment acting across a joint. Using this method may lead to the under- or overestimation of force produced about a joint and does not account for the effects of muscle co-contractions and two-joint muscles, for example, and thus the results should be interpreted accordingly.

#### 4.6 | Perspectives

The combination of walking, jogging, change of direction, and sprinting led to a reduction in hip extensor contribution during accelerative sprinting, leading to an increase in knee extension and power and a decrease in hip joint contribution. This shift in joint contribution may be due to a more upright posture and may lessen hamstring load, which are particularly prone to injury during sprinting.<sup>46</sup> However, maximal acceleration was maintained by shifting to muscle-dominant knee power. These findings suggest that minimizing hip flexor/extensor load may reduce the risk of hamstring injuries during acceleration, and increasing knee extensor contribution may help prevent fatigue from impeding performance.

#### AUTHOR CONTRIBUTIONS

Shayne Vial, Jodie Cochrane Wilkie, and Anthony J. Blazeovich designed research; Shayne Vial, Mark Scanlan, and Mitchell Turner performed research; Shayne Vial and Anthony J. Blazeovich analyzed data; and Shayne Vial, Jodie Cochrane Wilkie, Mark Scanlan, Mitchell Turner, and Anthony J. Blazeovich wrote the paper.

#### FUNDING INFORMATION

No financial support was provided for this study.

#### CONFLICT OF INTEREST

The authors declare no conflict of interest.

## DATA AVAILABILITY STATEMENT

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

## ORCID

Shayne Vial  <https://orcid.org/0000-0002-9235-8979>

Jodie Cochrane Wilkie  <https://orcid.org/0000-0003-1234-9579>

Mitchell Turner  <https://orcid.org/0000-0001-6406-1273>

Mark Scanlan  <https://orcid.org/0000-0002-1462-0855>

Anthony J. Blazevich  <https://orcid.org/0000-0003-1664-1614>

## REFERENCES

- Malone S, Owen A, Mendes B, Hughes B, Collins K, Gabbett TJ. High-speed running and sprinting as an injury risk factor in soccer: can well-developed physical qualities reduce the risk? *J Sci Med Sport*. 2018;21(3):257-262. doi:10.1016/j.jsams.2017.05.016
- Varley MC, Fairweather IH, Aughey RJ. Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. *J Sports Sci*. 2012;30(2):121-127. doi:10.1080/02640414.2011.627941
- Brughelli M, Cronin J, Levin G, Chaouachi A. Understanding change of direction ability in sport. *Sports Med*. 2008;38:1045-1063. doi:10.2165/00007256-200838120-00007
- Dalen T, Jørgen I, Gertjan E, Geir Havard H, Ulrik W. Player load, acceleration, and deceleration during forty-five competitive matches of elite soccer. *J Strength Cond Res*. 2016;30(2):351-359. doi:10.1519/JSC.0000000000001063
- Harper DJ, Carling C, Kiely J. High-intensity acceleration and deceleration demands in elite team sports competitive match play: a systematic review and meta-analysis of observational studies. *Sports Med*. 2019;49:1923-1947. doi:10.1007/s40279-019-01170-1
- Gabbett TJ. Science of rugby league football: a review. *J Sports Sci*. 2005;23(9):961-976. doi:10.1080/02640410400023381
- Nagahara R, Morin JB, Koido M. Impairment of Sprint mechanical properties in an actual soccer match: a pilot study. *Int J Sports Physiol Perform*. 2016;11(7):893-898. doi:10.1123/ijsp.2015-0567
- Varley MC, Aughey RJ. Acceleration profiles in elite Australian soccer. *Int J Sports Med*. 2013;34(1):34-39. doi:10.1055/s-0032-1316315
- Brewer C, Dawson B, Heasman J, Stewart G, Cormack S. Movement pattern comparisons in elite (AFL) and sub-elite (WAFL) Australian football games using GPS. *J Sci Med Sport*. 2010;13(6):618-623. doi:10.1016/j.jsams.2010.01.005
- Gabbett TJ. GPS analysis of elite women's field hockey training and competition. *J Strength Cond Res*. 2010;25(5):1321-1324. doi:10.1519/JSC.0b013e3181ceebbb
- Johnston RJ, Watsford ML, Pine MJ, Spurr RW, Murphy AJ, Pruy EC. The validity and reliability of 5-Hz global positioning system units to measure team sport movement demands. *J Strength Cond Res*. 2012;26(3):758-765. doi:10.1519/JSC.0b013e318225f161
- Ekstrand J. Epidemiology of football injuries. *Sci Sports*. 2008;23(2):73-77. doi:10.1016/j.scispo.2007.10.012
- Woods C, Hawkins RD, Maltby S, Hulse M, Thomas A. The football association medical research Programme: an audit of injuries in professional football-analysis of hamstring injuries. *Br J Sports Med*. 2004;38:36-41. doi:10.1136/bjism.2002.002352
- Gabbett TJ. Influence of training and match intensity on injuries in rugby league. *J Sports Sci*. 2004;22(5):409-417. doi:10.1080/02640410310001641638
- Mohr M, Krstrup P, Nybo L, Nielsen JJ, Bangsbo J. Muscle temperature and sprint performance during soccer matches – beneficial effect of re-warm-up at half-time. *Scand J Med Sci Sports*. 2004;14(3):156-162. doi:10.1111/j.1600-0838.2004.00349.x
- Ciacci S, Merni F, Bartolomei S, Di Michele R. Sprint start kinematics during competition in elite and world-class male and female sprinters. *J Sports Sci*. 2017;35(13):1270-1278. doi:10.1080/02640414.2016.1221519
- Hautier CA, Arzac LM, Deghdegh K, Souquet J, Belli A, Lacour JR. Influence of fatigue on EMG/force ratio and cocontraction in cycling. *Med Sci Sports Exerc*. 2000;32(4):839-843. doi:10.1097/00005768-200004000-00017
- Nagahara R, Matsubayashi T, Matsuo A, Zushi K. Kinematics of transition during human accelerated sprinting. *Biol Open*. 2014;3:689-699. doi:10.1242/bio.20148284
- Pinniger GJ, Steele JR, Groeller H. Does fatigue induced by repeated dynamic efforts affect hamstring muscle function? *Med Sci Sports Exerc*. 2000;32(3):647-653. doi:10.1097/00005768-200003000-00015
- Small K, McNaughton LR, Greig M, Lohkamp M, Lovell R. Soccer fatigue, sprinting and hamstring injury risk. *Int J Sports Med*. 2009;30(8):573-578. doi:10.1055/s-0029-1202822
- Perl J. A neural network approach to movement pattern analysis. *Hum Mov Sci*. 2004;23(5):605-620. doi:10.1016/j.humov.2004.10.010
- Cavagna GA, Komarek L, Mazzoleni S. The mechanics of sprint running. *J Physiol*. 1971;217:709-721. doi:10.1113/jphysiol.1971.sp009595
- Barry BK, Enoka RM. The neurobiology of muscle fatigue: 15 years later. *Integr Comp Biol*. 2007;47(4):465-473. doi:10.1093/icb/icm047
- Lord C, Maayah F, Blazevich AJ. Change in knee flexor torque after fatiguing exercise identifies previous hamstring injury in football players. *Scand J Med Sci Sports*. 2018;28(3):1235-1243. doi:10.1111/sms.13007
- Dutto DJ, Smith GA. Changes in spring-mass characteristics during treadmill running to exhaustion. *Med Sci Sports Exerc*. 2002;34(8):1324-1331. doi:10.1097/00005768-200208000-00014
- Jones DA. Changes in the force-velocity relationship of fatigued muscle: implications for power production and possible causes. *J Physiol*. 2010;588(16):2977-2986. doi:10.1113/jphysiol.2010.190934
- Gates DH, Dingwell JB. The effects of muscle fatigue and movement height on movement stability and variability. *Exp Brain Res*. 2011;209:525-536. doi:10.1007/s00221-011-2580-8
- Hiemstra LA, Lo IKY, Fowler PJ. Effect of fatigue on knee proprioception: implications for dynamic stabilization. *J Orthop Sports Phys Ther*. 2001;31(10):598-605. doi:10.2519/jospt.2001.31.10.598
- Sanno M, Willwacher S, Epro G, Brüggemann GP. Positive work contribution shifts from distal to proximal joints during

- a prolonged run. *Med Sci Sports Exerc.* 2018;50(12):2507-2517. doi:10.1249/MSS.0000000000001707
30. Bezodis NE, Willwacher S, Salo AIT. The biomechanics of the track and field Sprint start: a narrative review. *Sports Med.* 2019;49(9):1345-1364. doi:10.1007/s40279-019-01138-1
  31. Delextrat A, Piquet J, Matthews MJ, Cohen DD. Strength-endurance training reduces the hamstrings strength decline following simulated football competition in female players. *Front Physiol.* 2018;9:1059. doi:10.3389/fphys.2018.01059
  32. Matthews MJ, Heron K, Todd S, et al. Strength and endurance training reduces the loss of eccentric hamstring torque observed after soccer specific fatigue. *Phys Ther Sport.* 2017;25:39-46. doi:10.1016/j.ptsp.2017.01.006
  33. Williams J, Abt G, Kilding AE. Effects of creatine monohydrate supplementation on simulated soccer performance. *Int J Sports Physiol Perform.* 2014;9(3):503-510. doi:10.1123/IJSP.2013-0407
  34. Williams JD, Abt G, Kilding AE. Ball-sport endurance and sprint test (BEAST90): validity and reliability of a 90-minute soccer performance test. *J Strength Cond Res.* 2010;24(12):3209-3218. doi:10.1519/JSC.0b013e3181bac356
  35. Kristianslund E, Krosshaug T, van den Bogert AJ. Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention. *J Biomech.* 2012;45(4):666-671. doi:10.1016/j.jbiomech.2011.12.011
  36. van den Bogert A, de Koning JJ. On optimal filtering for inverse dynamics analysis. In *Proceedings of the IXth biennial conference of the Canadian society for biomechanics.* 1996;214-215.
  37. Hanavan EP. A mathematical model of the human body. *AMRL-TR-64-102. AMRL TR.* 1964;1-149.
  38. Winter DA. *Biomechanics and Motor Control of Human Movement.* 4th ed. WILEY; 2009.
  39. Andrzejewski M, Chmura P, Konefal M, Kowalczyk E, Chmura J. Match outcome and sprinting activities in match play by elite German soccer players. *J Sports Med Phys Fitness.* 2018;58(6):785-792. doi:10.23736/S0022-4707.17.07352-2
  40. Cavagna GA, Saibene FP, Margaria R. Mechanical work in running. *J Appl Physiol.* 1964;19(2):249-256. doi:10.1152/jappl.1964.19.2.249
  41. Schache AG, Lai AKM, Brown NAT, Crossley KM, Pandy MG. Lower-limb joint mechanics during maximum acceleration sprinting. *J Exp Biol.* 2019;222(Pt22):jeb209460. doi:10.1242/jeb.209460
  42. Clark KP, Ryan LJ, Weyand PG. A general relationship links gait mechanics and running ground reaction forces. *J Exp Biol.* 2017;220(2):247-258. doi:10.1242/jeb.138057
  43. Hunter JP, Marshall RN, McNair PJ. Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *J Appl Biomech.* 2005;21(1):31-43. doi:10.1123/jab.21.1.31
  44. Willer J, Allen S, Burden R, Folland J. Neuromechanics of middle-distance running fatigue: a key role of the plantar flexors? *Med Sci Sports Exerc.* 2021;53(10):2119-2130. doi:10.1249/MSS.0000000000002695
  45. Ekstrand J, Hägglund M, Waldén M. Injury incidence and injury patterns in professional football: the UEFA injury study. *Br J Sports Med.* 2011;45(7):553-558. doi:10.1136/bjsm.2009.060582
  46. Liu H, Garrett WE, Moorman CT, Yu B. Injury rate, mechanism, and risk factors of hamstring strain injuries in sports: a review of the literature. *J Sport Health Sci.* 2012;1:92-101. doi:10.1016/j.jshs.2012.07.003

## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Vial S, Wilkie JC, Turner M, Scanlan M, Blazevich AJ. Does fatigue influence joint-specific work and ground force production during the first steps of maximal acceleration? *Scand J Med Sci Sports.* 2023;00:1-13. doi:10.1111/sms.14318