

Review

Effects of fatigue on ground reaction forces-related variables: A systematic review in long-distance runners

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Abstract: Ground reaction forces (GRF) are a critical element acting on the joints of the lower limbs and the presence of fatigue may potentially modify running biomechanics. This systematic review aimed to assess and synthesize the current evidence on the effects of fatigue on GRF-related variables in long-distance runners. Following the PRISMA 2020 guidelines, four databases were consulted in September 2024 followed by a search of reference lists and expert suggestions. Eligibility criteria included healthy competitive or recreational long-distance runners, performing before and after an exercise-based fatigue-inducing protocol, and assessing GRF-related variables on a treadmill or overground using a force plate (the gold standard for kinetic performance analysis). 14 studies (345 participants, 193 females) were included. The studies investigated 27 different variables (with loading rate, active peak force and peak ankle plantarflexor). Most studies exhibited no effect of fatigue on GRF-related variables and there was considerable heterogeneity between studies (e.g., populations, interventions, testing). Risk of bias in the studies was moderate to high and certainty of evidence was judged as very low. Based on available data, there is no significant effect of fatigue on GRF during running, being uncertain to what extent they affect performance overall. Future research should focus on the ecological validity of the study, replicating the experiments during outdoor running.

Keywords: Biomechanics; kinetics; fatigue; Running

1. Introduction

Long-distance running is popular among individuals of all ages, ethnicities and economic backgrounds (Wells, Dickin, Popp, & Wang, 2020). People run for exercise and

health purposes, as well to train for long-distance races (like marathons or ultramarathons) or just for the sole pleasure of running (Morin & Samozino, 2018). Running requires the body to work as a



complex machine, with simultaneous functions to obtain a dynamic action (Napier, 2020). It implies complex adjustments in balance, muscle activity, limbs coordination, force production by the muscles and force transmission to the skeletal system by the tendons (Alexander, 1991). When running, this machinery organizes itself so quickly that it can allow a rate about 10,000 steps during one hour of jogging at 10 km/h, for example (Morin, 2018). This is the number of times the body supports large impact forces during very brief contacts, which requires the ability to deal with the management of forces/impacts, which can eventually lead to injuries (Morin, 2018).

Once gravity pulls us to earth, it applies a force on the ground that is met with an equal and opposite ground reaction force (GRF), mainly absorbed within the lower limbs (Napier, 2020). Thereby, it is thought GRF is a critical element acting on these joints and it may change the normal biomechanics and alter GRF-related variables like loading rate (the speed at which forces impact the body) (Bauer, Fuchs, Smith, & Snow, 2001; Crossley, Bennell, Wrigley, & Oakes, 1999), maximum vertical force (the highest recorded vertical force during landing) (Puddle & Maulder, 2013) and impact peak force (the local maximum in the vertical GRF that occurs at the initial stance) (Crowell, Milner, Hamill, & Davis, 2010). The three components of the GRF and the three angular moments in X (anterior-posterior), Y (vertical) and Z (mediolateral) axes during running ground contact phase (Vilas-Boas, 2016), can be measured using a force plate (the gold standard for kinetic performance analysis) (Richmond, Dames, Goble, & Fling, 2018; Silva, Moreira, & Rocha, 2017), that

allows to collect a large variety of high-quality data for analysis that are difficult to obtain via other means (Beckham, Suchomel, & Mizuguchi, 2014; Richmond et al., 2018; Silva et al., 2017).

Accordingly, the repetitive aspect of running contributes to injury, which produce a combined fatigue effect and ultimately inhibit the remodelling and repair process (Hreljac, Marshall, & Hume, 2000). These repetitive aspects require efficient movement patterns to prevent injury by absorbing the impact forces (Warren, 1984). Moreover, change in running patterns due to fatigue can partially explain the alteration in the running economy (energy expenditure that is usually expressed as the submaximal oxygen consumption at a given running speed) (Anderson, 1996), which is essential to enhance performance in long-distance runners (Barnes & Kilding, 2015; Millet, 2011; Millet et al., 2011). For instance, the presence of fatigue has been shown to modify running biomechanics after 40-minute of high intensity, loading rates increased (17%, moderate effect size), whereas a non-significant increase (9%, large effect size) occurred in impact peak force (Clansey, Hanlon, Wallace, & Lake, 2012). In addition, gait mechanics changed during a 3,200 m at maximum effort (Derrick, Dereu, & McLean, 2002), and a 30-minute exhaustion test, with increased acceleration magnitude of GRF observed in participants (Voloshin, Mizrahi, Verbitsky, & Isakov, 1998).

While previous systematic reviews have explored the impact of fatigue on various aspects of running (Apte et al., 2021; Darch, Chalmers, Wiltshire, Causby, & Arnold, 2022; Garrett et al., 2019; H. K. Kim, Mirjalili, & Fernandez, 2018; Napier, Cochrane,

Taunton, & Hunt, 2015; Winter, Gordon, & Watt, 2017; Zandbergen et al., 2023), none have exclusively focused on GRF-related variables in long-distance runners under fatigue-inducing protocols, both on treadmills and overground. Therefore, this systematic review aims to fill this gap in literature by assessing and synthesizing current evidence on the effects of fatigue on GRF-related variables (e.g., loading rate, impact peak force and maximum vertical force) in long-distance runners. This review will contribute to the ongoing research and discussion on running biomechanics and performance in long-distance runners. We hypothesized that GRF-related variables would increase following fatigue-inducing protocols, highlighting the importance of investigating these variables to understand fatigues' impact on running biomechanics and performance.

2. Materials and Methods

Study design and eligibility criteria - The protocol for the current systematic review was designed in accordance with the Preferred Reporting of Systematic Reviews and Meta-Analysis (PRISMA 2020) guidelines (Page et al., 2021), and was registered at Open Science Framework. We adopted the Participants, Intervention, Comparators, Outcomes and Study design (PICOS) approach that included healthy competitive or recreational long-distance runners (World Athletics, 2022) of any sex, age, competitive level, not injured upon the beginning of the study¹; exercise-based fatigue-inducing protocol (e.g., based on

running, shuttle running or strength training); GRF-related variables (e.g., loading rate and active peak force) during running (treadmill or overground), assessed pre- and post-fatigue with a force plate; and no study design restrictions. In addition, we included empirical studies published in peer-reviewed scientific journals, with no date or language limitations.

Information sources and search strategy

Searches were performed in five phases: beginning with automated searches performed in PubMed, Scopus and Web of Science (core collection) in early July 2022. Then, manual searches were conducted in the reference lists of included studies, snowballing citation tracking was performed in Web of Science. Lastly, the list of included articles and inclusion criteria were sent to five experts to suggest additional references, and searches for relevant errata or retractions were performed. On 26 September 2024, we conduct new searches in databases, respecting the specificities of each database, as conducted in the first search.

Regarding search strategy, Boolean operators were applied to the article title, abstract and/or keywords: ((runn*[Title/Abstract]) AND (fatigu*[Title/Abstract] OR exhausti*[Title/Abstract])) AND (kinetic* OR biomechanic* OR "ground reaction force*" OR impact* OR "vertical force*" OR "horizontal force*"). Data bases had some specificities, particularly: the search for title and abstract also included keywords in Scopus and the option "Topic" includes title, abstract, and keywords in Web of Science. No

¹Only long-distance runners that training or compete from 5,000 m onwards were selected for this study. Other types of participants (e.g. triathletes, cyclists and soccer players) were excluded. In the case of the triathletes, the running happens after substantial fatigue from swimming and cycling, so

their running patterns may not be comparable to those of long-distance runners.

filters were applied (for further details, see Supplementary Table 1).

2.3 Study selection, data collection, and data items process

Two authors (MS and JA) individually performed the eligibility assessment through title and abstract screening, and the full text was inspected whenever detailed information was needed. Disagreements were decided by a third author (FC). Reference lists from selected articles were also manually reviewed to detect possible additional relevant publications. Automated duplicates were removed using EndNote™ 20.3 (Clarivate™) and additional manual removal of duplicates was required. The authors (MS and FC) collected all data, and another author (JA) independently revised the process. We extracted data collection using a proprietary Excel spreadsheet and the WebPlotDigitizer v4.5 (Rohatgi, 2021) was used to extract data from graphics.

We sought to authors and publication date, country and continent; funding and conflicts of interest; experimental design; data collection procedures (e.g., treadmill or overground, fatigue protocol based on running, strength training or other); characteristics of interventions (e.g., exercise mode and intensity); and participant characteristics (i.e., sample size, age, sex, body height and weight, and competitive level which were reclassified according to the Participant Classification Framework (McKay et al., 2022). The studies investigated different GRF-related variables like loading rate, active peak force, peak hip and knee extension, and ankle plantarflexor.

Risk of bias assessment, synthesis methods and certainty of evidence - Risk of bias, which can classify individual studies as low, high and unclear risk was independently judged by two authors (JA and MS) using the Risk of Bias Assessment Tool for Nonrandomized Studies (RoBANS) assessing six domains: selection of participants, confounding variables, measurement of exposure, blinding of outcome assessments, incomplete outcome data, and selective outcome reporting. RoBANS includes criteria for judging the risk of bias for each domain (S. Y. Kim et al., 2013). FC reviewed the assessments to ensure the quality of the evaluations. Although originally designed for non-randomized studies, RoBANS tool is sufficiently open and flexible to also be applied to randomized trials.

Meta-analyses were planned, including subgroup and sensitivity analyses. However, the considerable heterogeneity between studies (e.g., populations, interventions and testing) precluded meta-analytical treatment of the data, and so only a narrative synthesis was provided. The planned analyses can be consulted in the registered protocol. The authors (MS and JA) used the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) method to assess the certainty of evidence which addresses five dimensions (risk of bias, inconsistency, indirectness, imprecision, and publications bias) that can downgrade studies when assessing the quality of evidence in clinical trials (Guyatt et al., 2011).

3. Results

Study selection - The initial search retrieved 6,967 results with the removal of

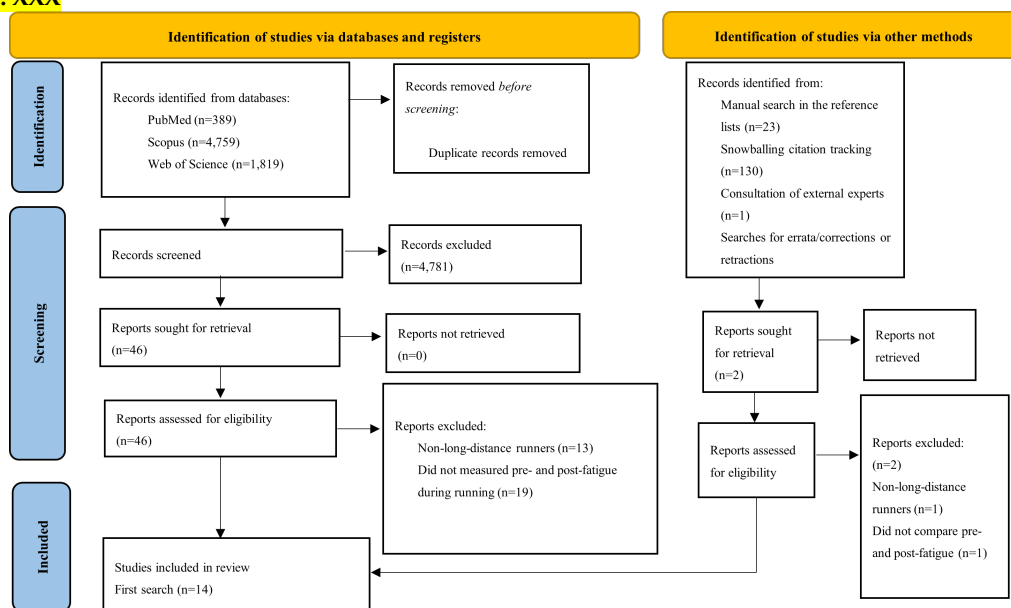
2,140 duplicates resulting in 4,827 records to be screened (of which 4,781 were excluded). Subsequently, 46 records were eligible for full-text analysis, 13 of which were excluded due to their focus on populations that were not long-distance runners (Crossley et al., 1999; Gao, Mei, Fekete, Baker, & Gu, 2020; Z. X. Gao et al., 2022; Girard, Brocherie, Morin, & Millet, 2017; Girard, Brocherie, Morin, Millet, & Hansen, 2020; Goncalves et al., 2021; Hart et al., 2009; Khassetarash, Vernillo, Krüger, Edwards, & Millet, 2022; Radzak & Stickley, 2020; Vial, Wilkie, Turner, Scanlan, & Blazevich, 2023; Wang et al., 2020; Willson, Loss, Willy, & Meardon, 2015; Zhang, Xia, Dai, Sun, & Fu, 2018).

19 studies did not measure pre- and post-fatigue during running (Chalitsios, Nikodelis, Konstantakos, & Kollias, 2021; Curi et al., 2024; Z. Gao et al., 2022; Giovanelli, Taboga, & Lazzer, 2017; Giovanelli et al., 2016; Hanley & Mohan, 2014; Hanley & Tucker, 2018; Jewell, Boyer, & Hamill, 2017; Li et al., 2022; Luo et al., 2019; Pachava & Paruthi, 2022; Patoz et al., 2023; Pohl, Mullineaux, Milner, Hamill, & Davis, 2008; Radzak, Putnam, Tamura, Hetzler, &

Stickley, 2017; Sanno, Epro, Brüggemann, & Willwacher, 2021; Sanno, Willwacher, Epro, & Brüggemann, 2018; Vernillo et al., 2020; Weir et al., 2019; Zakaria, El Badaoui, Lamraoui, & Khalil, 2016). Finally, 14 studies met our eligibility criteria (See Table 1). To note, one of the included records (Brown, Zifchock, Hillstrom, Song, & Tucker, 2016) used the same sample as another study included in our final sample (Brown, Zifchock, & Hillstrom, 2014). No additional eligible publication was identified from the references list of the selected studies or through snowballing citation tracking.

We contacted five experts and obtained three responses, with only one additional study being suggested, which had already been excluded during our screening. We found no retractions or errata for the included studies. Two studies had a pre-registered protocol (Jafarnejhadgero, Sorkhe, & Oliveira, 2019; Morin, Samozino, & Millet, 2011) that were considered for assessing risk of bias.

Figure 1. XXX



Study characteristics - The 14 selected studies included 345 participants (193 females) aged 18 to 65 years, who performed different fatigue protocols (see Table 1) overground and on the treadmill, with significantly varying distances (from 1.3 ± 0.2 to 153 ± 15 km). Weekly training mileages varied from 20 to 50 km (participants' characteristics can be found in Supplementary Table 2). Different comparisons were performed in ten of 14 studies. For instance, one study (Bazuelo-Ruiz, Durá-Gil, Palomares, Medina, & Llana-Belloch, 2018) analyzed men and women separately, another (Tam et al., 2017) analyzed both trained and well-trained runners, we selected both following our eligibility criteria. Forefoot, midfoot, and rearfoot strikes were analyzed in one study (Hashish, Samarawickrame, Baker, & Salem, 2016), for purposes of this review, we included all of them. The speeds of 10, 12, and 14 km/h were analyzed differently (Degache et al., 2013). Among these, the highest speed was chosen because it was close to the critical speed, which is the maximum sustainable speed without exhaustion over an extended period (Poole, Burnley, Vanhatalo, Rossiter, & Jones, 2016).

Supplementary Table 3 shows all comparisons presented in the studies, while Supplementary Table 4 provides the criteria for reclassifying participant levels according to the Participant Classification Framework (McKay et al., 2022). The 14 selected studies extracted GRF-related variables from the stance phase of each trial. GRF-related variables were reported by the authors in body weight (BW), body weight per second (BW/s), percent of body weight times second ($BW\% \times s$) and body weight times height (BW

$\times$ height). In addition, joint moments are measured in newton $\times$ meter per kilogram (Nm/kg), and impulses were converted in newton $\times$ second ($N \times s$). The terms and abbreviations of the variables constantly varied among the authors, so we decided to unify all the variables to the scientific terms (e.g., F_{peak} = impact peak force and F_{max} = maximum vertical force).

Risk of bias in individual studies - The Risk of bias in the studies was moderate to high. Figure 2 synthesizes the risk of bias assessments of RoBANS, and the full assessments can be found in Supplementary Table 5.

Results of individual studies - The selected studies investigate 27 different variables related to GRF (assessed using a force platform). GRF-related variables were analyzed 71 times individually, and the majority were not significant (see Table 2 for further details) (Bazuelo-Ruiz et al., 2018; Degache et al., 2013; Fischer, Storniolo, & Eyre-Tartaruga, 2015; Gerlach et al., 2005; Jafarnejhadgero et al., 2019; Morin et al., 2011; Tam et al., 2017). Ten variables (active peak force, impact peak force, loading rate, maximal vertical force, peak ankle plantarflexor, peak braking force, peak hip abductor moment, peak hip extensor moment, peak knee extensor moment and peak propulsive force) were analyzed more than once by different studies (Bazuelo-Ruiz et al., 2018; Degache et al., 2013; Fischer et al., 2015; Gerlach et al., 2005; Hashish et al., 2016; Jafarnejhadgero et al., 2019; Melaro, Gruber, & Paquette, 2021; Morin et al., 2011; Paquette & Melcher, 2017).

Table 1. Summary of the selected studies.

Authors, publication date & continent	Sample size & participant level (McKay et al., 2022)	Funding & conflicts of interest	Experimental design	Fatigue protocol	Data collection procedure	Running speed	GRF-related variables
Bazuelo-Ruiz, Durá-Gil, Palomares, Medina, and Llana-Belloch (2018) Spain, Europe	57 ♀ ♂ Tier 1 (Recreationally Active) & Tier 2 (Trained/Developmental) Performed two to three days a week with a weekly volume of 20 to 40 km	<i>Funding:</i> This research was funded by the Seventh European Framework Programme (FP7- SME- 2011-1) under grant agreement 285800 (RUNSAFER). <i>Conflicts of interest:</i> No competing interests	The participants were already familiar with the protocol because of a previous test they performed in the laboratory with the same protocol	(1) a running Course- Navette test,(Léger, Mercier, Gadoury, & Lambert, 1988) (2) running up and down a flight of stairs for 5 min, and (3) alternative jumps on a step (five sets of 1 min each with 30 resting seconds between the sets)	Overground. 15m long runway with force plate. Neutral running shoes	3.3 m/s (± 5%)	(BW): Active peak force, impact peak force, peak braking force and peak propulsive force (BW/s): Loading rate
Borgia, Dufek, Silvernail, and Radzak (2022) USA, America	30 ♀ ♂ Tier 2 (Trained/Developmental) Running a minimum of 4 runs and 29.93 miles per week.	<i>Funding:</i> This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. <i>Conflicts of interest:</i> N/A	Following warm-up and cool-down, participants performed the pre- and post-fatigue movement assessment. They were instructed to run the short course mapped out in the laboratory, allowing	Graded exercise test (GXT) and 5-minute cool-down	Overground. 10-m runway with force plates. Neutral laboratory shoes	Pre- fatigue: 3.5 m/s (± 5%) Post-fatigue: the Pace was not controlled but it was monitored based on heart rate and rate of perceived exertion	(BW): Maximal vertical force (Nm/Kg): Peak plantarflexor moment, peak knee extensor moment and peak hip extensor moment

			a dynamic start and avoiding acceleration and deceleration between trials				
Brown, Zifchock, and Hillstrom (2014)	20 ♀ <i>Tier 1 (Recreationally Active)</i>	<i>Funding:</i> Study 1, N/A Study 2, <i>no financial affiliation or funding</i>	Treadmill run to fatigue at a pace that approximated their 5 km race pace. This pace remained fixed for the duration of the run to fatigue	Fatiguing treadmill run (24.6 ± 7.0 min) at a self-selected pace.	Overground. 25-30m m runway with four force plate. Standard shoes.	3.35 m/s (± 10%)	(Nm/Kg): Peak ankle invertor, peak ankle plantarflexor, peak hip abductor and knee adductor and knee extensor Peak hip external rotator
Brown, Zifchock, Hillstrom, Song, and Tucker (2016) USA, America	Running a minimum of 15 miles (24km) per week for at least one year and were able to run at least one 9 min mile	<i>Conflicts of interest:</i> N/A					
Degache et al. (2013) Switzerland, Europe	8 ♂ <i>Tier 2 (Trained/Developmental)</i> Long-distance trail runners. Regional level	<i>Funding:</i> N/A <i>Conflicts of interest:</i> N/A	Before and immediately after the 5-hour hilly running, the participants ran for 1 minute with 1 minute interval rest on an instrumented	5 h run uphill/downhill simulating competitive conditions (37.5 ± 5.5 km) with 1730 ± 230 m of elevation	Instrumented treadmill. 1 minute run at 3 different speeds with 1 minute interval rest	10, 12 and 14 km/h	(BW): Maximal vertical force (BW/s): Loading rate

			treadmill at three different speeds (10, 12 and 14km/h)				
Fischer, Storniolo, and Eyré- Tartaruga (2015) Brazil, America	11 ♀ ♂ <i>Tier 2</i> <i>(Trained/Developmental)</i> Running at least 30 km per week during the previous 6 months and have participated in 5 km and/or 10 km races within the past year	<i>Funding:</i> This study was supported by a grant from the Federal University of Rio Grande do Sul Fund for the Incentive of Research, Porto Alegre, Brazil <i>Conflicts of interest:</i> N/A	Running was performed on an indoor track at the research laboratory. The participants ran 3 sets of 30 laps on the circuit at a constant speed before and after the fatigue protocol. The speeds were defined as self- selected or either faster or slower than self-selected	The fatigue protocol consisted of a vertical rebound jump series (60 s) of maximal countermovement jumps performed in a force plate	Overground. 28m on an indoor track with a force plate	Slower, 2.86 m/s ± 0.31 Self-selected, 3.23 m/s ± 0.35 Faster, 3.57 m/s ± 0.33	(BW): Impact peak force and maximal vertical force. (BW/s): Loading rate
Gerlach et al. (2005) USA, America	88 ♀ <i>Tier 2</i> <i>(Trained/Developmental)</i> Running a minimum of 20 miles (32 km) weekly. Most runners were competitive at the local and regional level, and a few subjects were national-caliber athletes	<i>Funding:</i> This research was supported in part by a Mark Diamond Research Grant <i>Conflicts of interest:</i> N/A	Participants performed a pre- and post-fatigue test where the VGRF were collected running at their approximate 5 km race pace. Then participants were fatigued using a	Exhaustive treadmill run: 3 min work intervals beginning at 2.2 m/s and a 1% gradient, with successive workloads 0.6 m/s faster until 4.5 m/s was reached, after which workloads increased by a	Treadmill with two force plates. Usual running shoes	2.7 to 4.5 m/s	(BW): Active peak force and impact peak force (BW/s): Loading rate

			modified discontinuous VO2max treadmill protocol	gradient of 2.5% until voluntary exhaustion			
Hashish, Samarawickrame, Baker, and Salem (2016) USA, America	21♀ ♂ <i>Tier 1</i> <i>(Recreationally Active)</i> Running between 15-40 km weekly	<i>Funding:</i> This study was partially funded by a Southern California CTSI pilot grant 12-2176-4124 <i>Conflicts of interest:</i> The authors have no personal or financial conflict interest that influenced this work	Participants performed 6 overground barefoot run trials in the laboratory at their self-selected speed in which the stance phase of the dominant limb should be entirely on a force plate located midway down this path. Immediately following the running trials, participants performed an exertion bout of running on an established, outdoor concrete surface running course. After finishing this	An overground barefoot run. Distance of 1.3 ± 0.2 km conducted at the participant's self- selected speed (2.7 ± 0.4 m/s)	Overground. Barefoot running in a path of 30m, the force plate was located approximately midway down this path	Self-selected speed	(BW/s): Loading rate (Nm): Peak ankle plantarflexor

			step, they repeated the test exercise described above				
Jafarnezhadgero, Sorkhe, and Oliveira (2019) Iran, Asia	22 ♀ <i>Tier 1 (Recreationally Active)</i> Running training volume of 2-3 times/week for 45 min or 10 km each workout. No participation in a systematic running training program for competitive performance	<i>Funding:</i> This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors <i>Conflicts of interest:</i> N/A	Participants performed 5 overground running trails (pre-fatigue) followed by a fatiguing treadmill running protocol (RPE between 13 and 17). Second overground run trials (5 trials) were conducted immediately after the fatiguing running task	Treadmill, set with no inclination. Participants started the protocol at 6 km/h, and the treadmill speed was increased 1 km/h every 2 min. Rate of perceived exertion was collected at the end of each stage through a 15-point Borg scale (Borg, 1998)	Overground. 18 m walkway containing two ground reaction force platforms in the middle of the walkway. Motion-control and neutral running shoes	3.3 m/s $\pm$ 2.5%	(BW): Impact peak force (BW/s): Loading rate (BW $\times$ height): Peak negative free moments
Jiang et al. (2021) China, Asia	16 ♂ <i>Tier 1</i> (Recreationally Active) Recreational runners who run a minimum of 20 km weekly	<i>Funding:</i> This study was sponsored by the Major Research plan of Zhejiang Province (2021C03130), Major Program of the National Social Science Foundation	Participants ran 10 min to familiarize themselves with the experimental procedures and warm up. After that, they performed 5 overground running trails using their	5 km on a motorized treadmill at their natural running pace. 2 min were given to runners to warm up on the treadmill, then ran at a natural running pace for 5 km	Overground runway track.	Self-selected speed (3.09 $\pm$ 0.16 m/s)	(BW): Impact peak force, active peak force, peak medial force, peak lateral force, peak propulsive force and peak braking force (BW/s): Loading rate

		of China (grant no. 19ZDA352), National Key R&D Program of China (2018YFF0300905), and K. C. Wong Magna Fund in Ningbo University.	dominant leg (pre- and post-fatigue)				(N × s): Vertical impulse, propulsive impulse, and braking impulse
		<i>Conflicts of interest:</i> The authors declare no conflict of interest					
Melaro, Gruber, and Paquette (2021) USA, America	13 ♂ <i>Tier 2</i> (<i>Trained/Developmental</i>) Running at least 45 km per week for the past three months	<i>Funding:</i> No funding was received for this study. <i>Conflicts of interest:</i> N/A	Testing session involved measuring gait during 5 overground running trials performed before and after a prolonged submaximal treadmill run	Long submaximal treadmill run (19 ± 6 km) at a self-select long run pace	Overground. 25 m runway with force plate in the middle. Personal running shoes	Preferred long run pace $\pm 5\%$	(Nm/kg): Peak ankle plantarflexor, peak hip extensor and peak knee extensor
Morin, Samozino, and Millet (2011) France, Europe	10 ♂ <i>Tier 3 (Highly Trained/National level)</i> Experienced ultra-endurance runners (they reported more than 15 years of training in running on average), and all of	<i>Funding:</i> No fund was received for this study from the National Institutes of Health, the Wellcome Trust, the Howard Hughes Medical Institute, or others	The 24TR started and participants ran at a freely chosen pace. Just before, every 2 h, and at the end of the 24TR, they ran at 10 km/h for 60 s on a	24 h run on a treadmill at a freely chosen pace (153 ± 15 km) at freely chosen pace	Just before, every 2 h, and at the end of the 24TR, participants ran at 10 km/h for 60 s on a	10 km/h	(BW): Maximal vertical force (BW/s): Loading rate

	them had completed at least one 24-h or 100 km race	<i>Conflicts of interest:</i> The authors declare no conflict of interest	treadmill dynamometer		treadmill dynamometer		
Paquette and Melcher (2017)	12 ♂ <i>Tier 2</i> <i>(Trained/Developmental)</i> Running an average of at least 50 km per week for the past 3 months, and completed at least 1 long run per week	<i>Funding:</i> Not reported <i>Conflicts of interest:</i> N/A	Participants performed 3 overground running trails at their preferred log run pace using the strike index before the fatigue protocol. Pre- and post-fatigue was collected overground. Begore running trials, they performed 5 min warm-up on the treadmill at their self-selected long run pace	Long run on a treadmill (19.1 ± 5.3 km) at a self-select long run pace	Overground. 3D force platform embedded in the laboratory floor at the midpoint of the 25-m runway. Usual running shoes	Preferred typical long run speed ± 5%	(BW/s): Loading rate (Nm/kg): Peak hip abduction moment and peak knee abduction moment (N × s): Hip abduction and knee abduction impulse
Tam et al. (2017)	22 ♂ <i>Tier 2</i> <i>(Trained/Developmental)</i> Running 10km between 45 and 60 min, and running a minimum of four times per week at the time of the	<i>Funding:</i> N/A <i>Conflicts of interest:</i> No potential conflict of interest was reported by the authors	6 overground running trials were performed in the biomechanics laboratory immediately before and after the	10 km run was performed at 42.0 ± 2.9 minutes in the well trained and at 51.2 ± 5.0 in the trained group. RPE at completion of the	Overground. 40m indoor synthetic running track with two force platforms. Barefoot and	4.4 m/s in the well-trained runners and 3.5 m/s in the trained group	(BW): Peak medio-lateral GRF and Maximal vertical force (BW/s): Loading rate

	study, with a longest routine run of 10 km		fatiguing treadmill run, with a maximum duration of two minutes between the end of the 10 km run and the post-fatigue biomechanical assessment trials	fatigue trial were 19.0 ± 1.1 and 19.5 ± 0.6 respectively- The speed was 2% faster than 10 km familiarization pace.	with the shoe in which they were currently completing the most training mileage		
Yu, Liang, Fekete, Baker, and Gu (2021) China, Asia	15 ♂ <i>Tier 0 (Sedentary)</i> Running less than two-three times a week and ran less than 10 km per trail	<i>Funding:</i> N/A <i>Conflicts of interest:</i> None to report	3 overground running trials at self-selected speed along a 20 m runway in the lab (with their dominant foot striking the force platform) before and after a treadmill run exhaustion	Participants start walking on a treadmill at a speed of 6 km/h. The speed of the treadmill increased by 1 km/h every 2 minutes. The participants graded 13 (somewhat hard) to 17 (very hard) on the Borg scale (Borg, 1998) or reached 90% of the maximum heart rate at a self-selected pace	Overground. 20 m runway with force platform. Usual running shoes	Self-selected speedg	(Nm/kg): Peak ankle, hip and peak knee moment

Values in the fatigue protocol are in mean and standard deviation. Participant Classification Framework (McKay et al., 2022). Running Course-Navette test (Léger et al., 1988). Borg scale of perceived exertion (Borg, 1998). Legend: GRF = ground reaction force; BW = body weight; BW/s = body weight per second; BW × height = body weight times height; Medio-lateral GRF = Medio-lateral ground reaction force; N/A = Information not available; Nm/Kg = newton meters per kilogram; N × s = newton x second. RPE = rate of perceived exertion; VGRF = Vertical ground reaction force.

Figure 2. XXX

	D1	D2	D3	D4	D5	D6	Sample size*
Bazuelo-Ruiz et al. (2018)	+	+	+	+	-	-	57
Brown et al. (2014) / Brown et al. (2016)	+	×	+	+	-	×	20
Borgia et al. (2022)	+	×	+	+	-	-	30
Degache et al. (2013)	+	+	+	+	-	-	8
Fischer et al. (2015)	+	+	+	+	-	-	11
Gerlach et al. (2005)	×	+	+	+	+	-	88
Hashish et al. (2016)	×	×	+	+	-	-	21
Jafarnejhadgero et al. (2019)	+	+	+	+	-	-	22
Melaro et al. (2021)	×	×	+	+	-	-	13
Jiang et al. (2021)	+	×	+	+	-	-	16
Morin et al. (2011)	+	+	+	+	×	×	10
Paquette and Melcher (2017)	×	+	+	+	-	-	12
Tam et al. (2017)	+	+	+	+	-	-	22
Yu et al. (2021)	+	+	+	+	-	-	15

D1: Selection of participants; D2: Confounding variables; D3: Measurements; D4: Blinding outcome; D5: Incomplete outcome data; D6: Selective outcome reporting.
Judgement: + Low; × High; - Unclear.

For instance, when comparing pre- and post-fatigue, the loading rate increased post-fatigue in three studies ($p < 0.05$ for forefoot and midfoot strikes, effect size 1.38 and 0.78, respectively (Hashish et al., 2016); $p < 0.05$ (Jafarnejhadgero et al., 2019); and $p < 0.05$, effect size 0.32 (Paquette & Melcher, 2017)). On the other hand, this variable decreased after fatigue in three other studies ($p < 0.05$, female (Bazuelo-Ruiz et al., 2018); $p < 0.05$ (Gerlach et al., 2005); and $p < 0.05$ rearfoot strikes, effect size 0.62 (Hashish et al., 2016)). Lastly, five studies reported no changes in loading rate post- fatigue (Bazuelo-Ruiz et al., 2018; Degache et al., 2013; Fischer et al., 2015; Morin et al., 2011; Tam et al., 2017).

Impact peak force was reduced in the fatigued state in three studies: Bazuelo-Ruiz et al. (2018) in females ($p < 0.05$), Fischer et al.

(2015) with an effect size of 0.40 ($p < 0.05$), and Gerlach et al. (2005) ($p < 0.05$). Conversely, Jafarnejhadgero et al. (2019) reported a significant increase ($p < 0.05$) when pronated runners wore neutral shoes, while Bazuelo-Ruiz et al. (2018) found no significant change in males ($p > 0.05$).

Maximal vertical force decreased ($p < 0.05$, effect size = 0.36) after a 24-hour treadmill run at 13 km/h (153 ± 15 km) (Morin et al., 2011), and in well-trained runners ($p < 0.05$) (Tam et al., 2017). However, other studies found no significant changes: Borgia, Dufek, Silvernail, and Radzak (2022) in young and older runners ($p > 0.05$); $p > 0.05$ Degache et al. (2013); $p > 0.05$, effect size 0.27 at 14 km/h (Fischer et al., 2015) and $p > 0.05$ in trained runners (Tam et al., 2017).

Active peak force showed no changes post-fatigue when analyzed in two studies, $p > 0.05$ (Bazuelo-Ruiz et al., 2018; Gerlach et al., 2005). Peak ankle plantarflexor moment showed reductions post-fatigue in two studies when analyzing rearfoot strike runners, $p < 0.05$, effect size 4.93 and 0.34, respectively. (Hashish et al., 2016; Melaro et al., 2021). However, one study showed no interactions in this variable between pre- and post-fatigue state when analyzing dominant lower limbs (Brown et al., 2014). Lastly, peak hip joint moment showed a moderation reduction, $p < 0.05$, effect size 1.24 (Yu, Liang, Fekete, Baker, & Gu, 2021). In addition, all other peak joint moments and impulses remained unchanged post-fatigue (see Table 2 for further details). Of note, the variance in the results may be explained (at least partially) by the high heterogeneity of fatigue protocols, participants' competitive level, nature of interventions, comparators and outcomes collected.

Synthesis of results - As established in the eligibility criteria, studies that analysed GRF-related variables pre- and post-fatigue performing exercise-based fatigue-inducing protocol would be group and/or subgroup analysis targets. We planned to do the analysis based on the GRF-related variables and the competitive level (e.g., Tier 1, 2 and 3). However, this was impossible due to considerable heterogeneity between studies (e.g., populations, interventions and testing). For instance, five studies were classified as Tier 1, but only three reported mean and standard deviation results for the variables (Bazuelo-Ruiz et al., 2018; Brown et al., 2014; Hashish et al., 2016). Furthermore, one of these studies (Brown et al., 2014) did not evaluate the same variables as the other

studies. Plus, one study did not report data in mean and standard deviation (Jafarnezhadgero et al., 2019). Meta-analysis would be performed if ≥ 3 studies are available. Combining the results of runners with different skill levels might lead to confounding effects (Apte et al., 2021).

Most of the studies did not properly report on their method of recruitment or used convenience sampling, like recruiting an entire team of runners (see Supplementary Table 5 for further details). This may limit the ability to generalize the results to a wider running population as shown in this review and supported by another review (Ceyssens, Vanelderen, Barton, Malliaras, & Dingenen, 2019).

Certainty of evidence - The certainty of evidence for each outcome could not strictly follow the GRADE approach since meta-analyses were not performed. However, a GRADE-based judgment showed that risk of bias in the studies was moderate to high; there was high heterogeneity of samples, interventions, outcomes, and specificity of evaluations (i.e., high inconsistency); statistical impact heterogeneity was not calculated as meta-analyses were not performed; likely reduced indirectness, as a result of the eligibility criteria; imprecision was not calculated, since it was not possible to perform a meta-analysis; and risk of publication bias (the same as described in the previous domain). Additionally, most studies were non-randomized and there was no demonstration of large magnitude effects, no establishment of dose-response relationships, and there was not always adequate control for confounding factors. As a result, we judged the certainty of the evidence to be very low.

Table 2. Results of GRF-related variables of the individual studies (values in mean and standard deviation).

Authors	GRF variables	Pre-fatigue	Post-fatigue	p- values
Bazuelo-Ruiz, Durá-Gil, Palomares, Medina, and Llana-Belloch (2018)	(BW) Active peak force Impact peak force ^a (BW/s) Loading rate ^a Peak braking force Peak propulsive force ^a	Male; Female 2.59 ± 0.22; 2.47 ± 0.19 1.91 ± 0.31; 1.95 ± 0.31 ^a 75.02 ± 17.48; 88.14 ± 25.82 ^a 0.36 ± 0.09; 0.38 ± 0.08 -0.26 ± 0.04 ^a ; -0.28 ± 0.04	Male; Female 2.61 ± 0.20; 2.46 ± 0.19 1.88 ± 0.32; 1.90 ± 0.31 ^a 74.26 ± 19.90; 83.97 ± 18.83 ^a 0.36 ± 0.09; 0.38 ± 0.07 -0.27 ± 0.05 ^a ; -0.28 ± 0.04	Male; Female > 0.05; > 0.05 > 0.05; < 0.05 > 0.05; < 0.05 > 0.05; > 0.05 < 0.05; > 0.05
Borgia, Dufek, Silvernail, and Radzak (2022)	(BW) Maximal vertical force (Nm/Kg) Peak plantarflexor moment Peak knee extensor moment Peak hip extensor moment	Young; Older 2.52 ± 0.16; 2.38 ± 0.21 -2.72 ± 0.31; -2.64 ± 0.35 2.43 ± 0.34; 2.20 ± 0.22 -2.49 ± 0.44; -2.54 ± 0.40	Young; Older 2.52 ± 0.17; 2.37 ± 0.23 -2.73 ± 0.33 -2.59 ± 0.38 2.40 ± 0.35 2.20 ± 0.34 -2.67 ± 0.58 -2.63 ± 0.50	Young and Older > 0.05 ^c > 0.05 ^c > 0.05 ^c > 0.05 ^c
Brown, Zifchock, and Hillstrom (2014)	(Nm/Kg) Peak ankle invertor moment Peak ankle plantarflexor moment Peak hip abductor moment Peak hip extensor moment Peak knee adductor moment Peak knee extensor moment	Dominant; non-dominant 0.3 ± 0.2; 0.2 ± 0.2 -2.8 ± 0.3; -2.7 ± 0.3 -2.2 ± 0.4; -2.2 ± 0.3 -1.7 ± 0.4; 1.7 ± 0.4 0.2 ± 0.1; 0.2 ± 0.1 -2.6 ± 0.5; -2.6 ± 0.3	Dominant; non-dominant 0.3 ± 0.2; 0.2 ± 0.2 -2.8 ± 0.3; 2.8 ± 0.3 -2.1 ± 0.4; -2.1 ± 0.3 -1.6 ± 0.4; 1.7 ± 0.4 0.2 ± 0.1; 0.2 ± 0.1 -2.5 ± 0.5; -2.6 ± 0.4	Dominant and non-dominant > 0.05 ^b > 0.05 ^b > 0.05 ^b > 0.05 ^b > 0.05 ^b > 0.05 ^b
Brown, Zifchock, Hillstrom, Song, and Tucker (2016)	Peak hip external rotator moment	-0.8 ± 0.24	-0.8 ± 0.23	> 0.05 ^b
Degache et al. (2013)	(BW/s) Loading rate (BW) Maximal vertical force	54.3 ± 8.3 2.42 ± 0.20	53.3 ± 7.6 2.40 ± 0.19	> 0.05 > 0.05
Fischer, Storniolo, and Eyré-Tartaruga (2015)	(BW) Impact peak force ^a Maximal vertical force	2.00 ± 0.50 ^a 2.49 ± 0.24	1.82 ± 0.37 ^a 2.42 ± 0.27	= 0.031 = 0.058



	(BW/s) Loading rate	60.4 ± 25.7	57.7 ± 21.1	= 0.38
Gerlach et al. (2005)	(BW) Active peak force Impact peak force ^a (BW/s) Loading rate ^a	2.46 ± 0.24 1.96 ± 0.34 ^a 128.3 ± 43.2 ^a	2.45 ± 0.23 1.83 ± 0.32 ^a 113.2 ± 38.7 ^a	= 0.18 = 0.0005 = 0.0005
Hashish, Samarawickrame, Baker, and Salem (2016)	(BW/s) Loading rate ^a (Nm) Peak ankle plantarflexor ^a	Forefoot; Midfoot; Rearfoot 56.7 ± 5.7 ^a ; 99.5 ± 31.1 ^a ; 187.3 ± 11.5 ^a 90 ± 23 ^a ; 89 ± 16 ^a ; 106 ± 32 ^a	Forefoot; Midfoot; Rearfoot 81.1 ± 8.4 ^a ; 114.3 ± 35.3 ^a ; 166.8 ± 14.4 ^a 72 ± 20 ^a ; 78 ± 13 ^a ; 93 ± 34 ^a	Forefoot; Midfoot; Rearfoot = 0.047; = 0.040; = 0.032 < 0.001; < 0.001; = 0.001
Jafarnezhadgero, Sorkhe, and Oliveira (2019)	(BW) Impact peak force ^a (BW/s) Loading rate ^a (BW × height) Peak negative free moments	N/A ^d N/A ^d N/A ^d	N/A ^d N/A ^d N/A ^d	< 0.05 < 0.05 > 0.05
Jiang et al. (2021)	(BW) Impact peak force Active peak force Peak medial force Peak lateral force Peak propulsive force Peak braking force (BW/s) Loading rate (N × s) Vertical impulse Propulsive impulse Braking impulse	1.65 ± 0.29 2.64 ± 0.15 -0.16 ± 0.05 0.07 ± 0.03 0.31 ± 0.03 -0.35 ± 0.03 61.81 ± 11.28 259.86 ± 0.55 16.10 ± 0.19 -13.77 ± 0.17	1.79 ± 0.26 2.56 ± 0.19 -0.14 ± 0.04 0.07 ± 0.03 0.27 ± 0.03 -0.38 ± 0.03 68.55 ± 18.75 259.50 ± 0.92 14.06 ± 0.08 -16.32 ± 0.14	N/A ^e N/A ^e N/A ^e N/A ^e N/A ^e N/A ^e N/A ^e N/A ^e N/A ^e N/A ^e
Melaro, Gruber, and Paquette (2021)	(Nm/Kg) Peak ankle plantarflexor ^a Peak hip extensor Peak knee extensor	-2.84 ± 0.47 ^a -1.76 ± 0.61 2.72 ± 0.51	-2.68 ± 0.47 ^a -1.76 ± 0.63 2.60 ± 0.44	= 0.004 = 0.98 = 0.20
Morin, Samozino, and Millet (2011)	(BW) Maximal vertical force ^a	2.24 ± 0.33 ^a	2.14 ± 0.25 ^a	= 0.011

	(BW/s) Loading rate	55.8 ± 59.2	59.2 ± 11.0	= 0.062
Paquette and Melcher (2017)	(N × s) Hip abduction impulse Knee abduction impulse (Nm/Kg) Peak hip abduction moment Peak knee abduction moment (BW/s) Loading rate ^a	-16.37 ± 3.46 -7.44 ± 3.21 -1.7 ± 0.2 -0.83 ± 0.26 96.6 ± 19.7 ^a	-15.62 ± 4.49 -7.44 ± 2.53 -1.7 ± 0.3 -0.83 ± 0.20 102.5 ± 24.0 ^a	= 0.31 = 0.34 = 0.89 = 0.90 = 0.04
Tam et al. (2017)	(BW) Peak medio-lateral GRF Maximal vertical force ^a (BW) (BW/s) Loading rate	Trained vs Well trained N/A ^d N/A ^d N/A ^d	Trained vs Well trained N/A ^d N/A ^d N/A ^d	Trained; Well- trained N/A ^d > 0.05 ^b ; = 0.03 > 0.05 ^b ; > 0.05 ^b
Yu, Liang, Fekete, Baker, and Gu (2021)	(Nm/Kg) Peak ankle moment Peak hip moment ^a Peak knee moment	0.09 ± 0.11 0.75 ± 0.18 ^a 0.23 ± 0.19	0.11 ± 0.12 0.56 ± 0.11 ^a 0.38 ± 0.34	> 0.05 ^b = 0.001 > 0.05 ^b

Notes: ^a Significant changes post-fatigue condition. ^b The authors did not report the exact *p*-value, then we assumed $p > 0.05$ because all results were insignificant. ^c No state of fatigue $\times$ age interaction was observed in the study of Borgia et al. (2022), then we assumed $p > 0.05$. ^d Two studies (Jafarnejadgero et al., 2019; Tam et al., 2017) reported data in plots from which we could not extract it. ^e The authors did not provide *p* value for the neutral shoes individually, which made it impossible for us to confirm whether there had been any changes in the variables. Upon requesting the data from the authors, we received only one response saying it was impossible to share the data with us. Legend: GRF = ground reaction force; BW = body weight; BW/s = body weight per second; BW $\times$ height = body weight times height; N/A = Information not available; Nm/Kg = newton meters per kilogram; N $\times$ s = newton $\times$ second

4. Discussion

This review aimed to assess and synthesize the current evidence on the effects of fatigue on GRF-related variables in long-distance runners. We hypothesized that GRF-related variables would increase following fatigue-inducing protocols. However, the overall findings indicated no discernible effect of fatigue on GRF during running. Diverse GRF-related variables were investigated in the included studies (e.g., loading rate, active peak force, and peak ankle plantarflexor). There was considerable heterogeneity regarding age, competitive level, distances covered, nature of interventions, comparators, specificity of the outcomes, and testing methods, which precluded the possibility of conducting a meta-analysis, as seen in a previous systematic review (Napier et al., 2015).

Changes in GRF-related variables due to fatigue have been observed in studies using various fatigue protocols, such as speed running (Nummela, Rusko, & Mero, 1994) and the 5 000 m self-paced run (Girard, Millet, Slawinski, Racinais, & Micallef, 2010). However, fatigue protocols should be “completely” exhaustive to reduce the critical influence of intersubject variability on fatigue responses (Nicol, Avela, & Komi, 2006), which was not confirmed in this review. When comparing pre- and post-fatigue, loading rate increased in three studies (Hashish et al., 2016; Jafarnezhadgero et al., 2019; Paquette & Melcher, 2017), including runners with forefoot and midfoot strike patterns. Such increases in loading rates have been previously linked with a greater risk of tibial stress fracture (Davis, Milner, & Hamill, 2004; Milner, Ferber,

Pollard, Hamill, & Davis, 2006). However, none of the included studies assessed injury occurrence, and so no links should be established between fatigue, GRF and injury risk based on the findings of our review. In contrast, loading rate decreased in studies analyzing rearfoot strikers (Gerlach et al., 2005; Hashish et al., 2016) and female runners (Bazuelo-Ruiz et al., 2018).

In five other studies, no significant changes in loading rate were observed (Bazuelo-Ruiz et al., 2018; Degache et al., 2013; Fischer et al., 2015; Morin et al., 2011; Tam et al., 2017). These varying results may be explained by differences in foot strike patterns, runner sex, competitive level, and study protocols. Notably, reductions in loading rate were more frequent in forefoot and midfoot strikers (Napier et al., 2015), which is attributed to the smoothing or absence of the vertical impact peak force (Napier et al., 2015). However, this phenomenon could not be conclusively confirmed in this review. Additionally, reductions in peak ankle plantarflexor moment post-fatigue were observed in two studies analyzing trained and well-trained runners (Hashish et al., 2016; Melaro et al., 2021). Several studies have reported decreases in peak ankle plantarflexor muscle strength after long-distance running (Ackermans et al., 2016; Girard, Millet, Micallef, & Racinais, 2012; Saldanha, Nordlund Ekblom, & Thorstensson, 2008), supporting the finding that well-trained long-distance runners exhibit greater plantarflexor muscle strength than less-trained runner (Arampatzis et al., 2006). This strength allows for better shock absorption at the ankle joints during running (Sanno et al., 2018).

We examined various GRF-related variables, such as active peak force, maximum vertical force, impact peak force, and peak braking force. No significant changes in these variables were observed in the post-fatigue state, consistent with recent findings (Darch et al., 2022). The heterogeneity in the studies including participant characteristics (such as experience level and familiarity with fatigue protocols) and protocol parameters (speed and duration), makes it difficult to compare biomechanical results. This issue has been highlighted in other reviews (Apte et al., 2021; H. K. Kim et al., 2018; Winter et al., 2017; Zandbergen et al., 2023). Future research should aim for more consistent study designs to determine whether one fatigue protocol has a greater impact on biomechanics than another. Similar to other recent reviews (Apte et al., 2021; Darch et al., 2022; Zandbergen et al., 2023), our study underscores the need for standardization in this area.

Furthermore, fatigue responses may differ between laboratory and outdoor running environments, as noted in the literature (Benson, Räisänen, Clermont, & Ferber, 2022). To improve ecological validity, future studies should prioritize outdoor running conditions to better simulate real-world scenarios. The GRADE assessments revealed a very low certainty of evidence, indicating that links between fatigue and GRF in long-distance runners are based on fragile evidence, and definitive conclusions should be avoided.

Strengths and Limitations

A key strength of this systematic review is its comprehensive synthesis of the available evidence on fatigue and GRF-

related variables in long-distance runners, providing valuable insights despite the high heterogeneity in study designs. However, the heterogeneity in participant characteristics, fatigue protocols, and outcome measures limited the ability to perform a meta-analysis and draw more definitive conclusions.

5. Practical Applications.

This review provides important insights for coaches and runners regarding fatigue management. Since most of the findings concern to rearfoot strike runners, who comprise 80-95% of distance runners (Napier, 2020), these findings should be applied primarily to this population. For instance, incorporating exercises that strengthen the ankle plantarflexors could help rearfoot strikers better absorb shock during running. This review found that fatigue responses can differ between male and female runners. Coaches working with female athletes should incorporate strength exercises and recovery strategies that specifically address the reduction in loading rate after long runs.

Our findings showed that competitive level may respond differently to fatigue. Training programs should be tailored to the runners' competitive level. Well-trained runners can handle higher training volumes with less impact on running biomechanics, while less trained runners may benefit from more frequent rest periods and focus on recovery strategies to minimize the impact of fatigue. Future research should also focus on younger runners (<23 years old), as fatigue responses may differ across age groups (Derrick et al., 2002; Dierks, Davis, & Hamill, 2010). The fatigue protocols used in the studies varied greatly, ranging from short

distances of 1.3 km to extreme distances of 153 km. Coaches should simulate fatigue conditions in training by adjusting workout intensity and duration.

Most studies were conducted in laboratory settings, which may limit the ecological validity of the findings. To enhance the applicability of future research, studies should prioritize replicating real-world conditions by conducting experiments in outdoor environments. Incorporating wearable technology to monitor fatigue-related changes in GRF during outdoor runs could provide more accurate and contextually relevant data. Such advances could bridge the gap between laboratory findings and real-world performance, offering a deeper understanding of how fatigue impacts running biomechanics in practical settings.

6. Conclusions

The results of this review exhibited no effect of fatigue on GRF-related variables. Risk of bias in the studies was moderate to high and certainty of evidence was judged as very low. Currently, based on data, there is no effect of fatigue on GRF during running, being uncertain and unclear to what extent they may affect performance overall. Further studies in this field are needed to clarify the potential effects of fatigue on GRF-related variables in long-distance runners.

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References

Ackermans, T. M. A., Epro, G., McCrum, C., Oberländer, K. D., Suhr, F., Drost, M. R.,

- ... Karamanidis, K. (2016). Aging and the effects of a half marathon on Achilles tendon force–elongation relationship. *European Journal of Applied Physiology*, 116(11-12), 2281-2292. doi:10.1007/s00421-016-3482-z
- Alexander, R. M. (1991). Energy-saving mechanisms in walking and running. *The Journal of Experimental Biology*, 160, 55-69. doi:10.1242/jeb.160.1.55
- Anderson, T. (1996). Biomechanics and running economy. *Sports Medicine*, 22(2), 76-89. doi:10.2165/00007256-199622020-00003
- Apte, S., Prigent, G., Stöggli, T., Martínez, A., Snyder, C., Gremeaux-Bader, V., & Aminian, K. (2021). Biomechanical Response of the Lower Extremity to Running-Induced Acute Fatigue: A Systematic Review. *Frontiers in Physiology*, 12. doi:10.3389/fphys.2021.646042
- Arampatzis, A., De Monte, G., Karamanidis, K., Morey-Klapsing, G., Stafilidis, S., & Brüggemann, G.-P. (2006). Influence of the muscle-tendon unit's mechanical and morphological properties on running economy. *Journal of Experimental Biology*, 209(17), 3345-3357. doi:10.1242/jeb.02340
- Barnes, K. R., & Kilding, A. E. (2015). Running economy: measurement, norms, and determining factors. *Sports Med Open*, 1(1), 8. doi:10.1186/s40798-015-0007-y
- Bauer, J., Fuchs, R., Smith, G., & Snow, C. (2001). Quantifying Force Magnitude and Loading Rate from Drop Landings That Induce Osteogenesis. *Journal of Applied Biomechanics*, 17, 142-152. doi:10.1123/jab.17.2.142
- Bazuelo-Ruiz, B., Durá-Gil, J. V., Palomares, N., Medina, E., & Llana-Belloch, S. (2018). Effect of fatigue and gender on kinematics and ground reaction forces variables in recreational runners. *PeerJ*, 6, 12. doi:10.7717/peerj.4489
- Beckham, G., Suchomel, T., & Mizuguchi, S. (2014). Force Plate Use in Performance Monitoring and Sport Science Testing. *New Studies in Athletics*, 29, 25-37.
- Benson, L. C., Räisänen, A. M., Clermont, C. A., & Ferber, R. (2022). Is This the Real Life, or Is This Just Laboratory? A Scoping Review of IMU-Based Running Gait Analysis. *Sensors*, 22(5), 1722.
- Borgia, B., Dufek, J. S., Silvernail, J. F., & Radzak, K. N. (2022). The effect of fatigue on running mechanics in older and younger

- runners. *Gait & Posture*, 97, 86-93. doi:10.1016/j.gaitpost.2022.07.249
- Brown, A. M., Zifchock, R. A., & Hillstrom, H. J. (2014). The effects of limb dominance and fatigue on running biomechanics. *Gait & Posture* 39(3), 915-919. doi:10.1016/j.gaitpost.2013.12.007
- Brown, A. M., Zifchock, R. A., Hillstrom, H. J., Song, J., & Tucker, C. A. (2016). The effects of fatigue on lower extremity kinematics, kinetics and joint coupling in symptomatic female runners with iliotibial band syndrome. *Clinical Biomechanics*, 39, 84-90. doi:10.1016/j.clinbiomech.2016.09.012
- Ceyssens, L., Vanelderden, R., Barton, C., Malliaras, P., & Dingenen, B. (2019). Biomechanical risk factors associated with running-related injuries: A systematic review. *Sports Medicine*, 49(7), 1095-1115. doi:10.1007/s40279-019-01110-z
- Chalitsios, C., Nikodelis, T., Konstantakos, V., & Kollias, I. (2021). Sensitivity of movement features to fatigue during an exhaustive treadmill run. *European Journal of Sport Science*. doi:10.1080/17461391.2021.1955015
- Clansey, A. C., Hanlon, M., Wallace, E. S., & Lake, M. J. (2012). Effects of fatigue on running mechanics associated with tibial stress fracture risk. *Medicine & Science in Sports & Exercise*, 44(10), 1917-1923. doi:10.1249/mss.0b013e318259480d
- Crossley, K., Bennell, K. L., Wrigley, T., & Oakes, B. W. (1999). Ground reaction forces, bone characteristics, and tibial stress fracture in male runners. *Medicine & Science in Sports & Exercise*, 31(8), 1088-1093. doi:10.1097/00005768-199908000-00002
- Crowell, P., Milner, C., Hamill, J., & Davis, I. (2010). Reducing Impact Loading During Running With the Use of Real-Time Visual Feedback. *The Journal of orthopaedic and sports physical therapy*, 40, 206-213. doi:10.2519/jospt.2010.3166
- Curi, G., Costa, F. D. D., Medeiros, V. S., Barbosa, V. D., Santos, T. R. T., & Dionisio, V. C. (2024). The effects of core muscle fatigue on lower limbs and trunk during single-leg drop landing: A comparison between recreational runners with and without dynamic knee valgus. *Knee*, 50, 96-106. doi:10.1016/j.knee.2024.07.017
- Darch, L., Chalmers, S., Wiltshire, J., Causby, R., & Arnold, J. (2022). Running-induced fatigue and impact loading in runners: A systematic review and meta-analysis. *J Sports Sci*, 40(13), 1512-1531. doi:10.1080/02640414.2022.2089803
- Davis, I. S., Milner, C. E., & Hamill, J. (2004). Does increased loading during running lead to tibial stress fractures? A prospective study. *Medicine and Science in Sports and Exercise*, 36.
- Degache, F., Guex, K., Fourchet, F., Morin, J.-B., Millet, G. P., Tomazin, K., & Millet, G. Y. (2013). Changes in running mechanics and spring-mass behaviour induced by a 5-hour hilly running bout. *J Sports Sci*, 31(3), 299-304. doi:10.1080/02640414.2012.729136
- Derrick, T. R., Dereu, D., & McLean, S. P. (2002). Impacts and kinematic adjustments during an exhaustive run. *Medicine & Science in Sports & Exercise*, 34(6), 998-1002. doi:10.1097/00005768-200206000-00015
- Dierks, T. A., Davis, I. S., & Hamill, J. (2010). The effects of running in an exerted state on lower extremity kinematics and joint timing. *Journal of Biomechanics*, 43(15), 2993-2998. doi:10.1016/j.jbiomech.2010.07.001
- Fischer, G., Storniolo, J. L., & Eyre-Tartaruga, L. A. (2015). Effects of fatigue on running mechanics: Spring-mass behavior in recreational runners after 60 seconds of countermovement jumps. *Journal of Applied Biomechanics*, 31(6), 445-451. doi:10.1123/jab.2014-0235
- Gao, Z., Mei, Q., Fekete, G., Baker, J. S., & Gu, Y. (2020). The effect of prolonged running on the symmetry of biomechanical variables of the lower limb joints. *Symmetry*, 12(5). doi:10.3390/SYM12050720
- Gao, Z., Zhao, L., Fekete, G., Katona, G., Baker, J. S., & Gu, Y. (2022). Continuous time series analysis on the effects of induced running fatigue on leg symmetry using kinematics and kinetic variables: Implications for knee joint injury during a countermovement jump. *Front Physiol*, 13, 877394. doi:10.3389/fphys.2022.877394
- Gao, Z. X., Fekete, G., Baker, J. S., Liang, M. J., Xuan, R. R., & Gu, Y. D. (2022). Effects of running fatigue on lower extremity symmetry among amateur runners: From a biomechanical perspective. *Frontiers in Physiology*, 13. doi:10.3389/fphys.2022.899818

- Garrett, J. M., Gunn, R., Eston, R. G., Jakeman, J., Burgess, D. J., & Norton, K. (2019). The effects of fatigue on the running profile of elite team sport athletes. A systematic review and meta-analysis. *Journal of Sports Medicine and Physical Fitness*, 59(8), 1328-1338. doi:10.23736/s0022-4707.19.09356-3
- Gerlach, K. E., White, S. C., Burton, H. W., Dorn, J. M., Leddy, J. J., & Horvath, P. J. (2005). Kinetic changes with fatigue and relationship to injury in female runners. *Medicine & Science in Sports & Exercise*, 37(4).
- Giovanelli, N., Taboga, P., & Lazzer, S. (2017). Changes in running mechanics during a 6-hour running race. *International Journal of Sports Physiology and Performance*, 12(5), 642-647. doi:10.1123/ijssp.2016-0135
- Giovanelli, N., Taboga, P., Rejc, E., Simunic, B., Antonutto, G., & Lazzer, S. (2016). Effects of an Uphill Marathon on Running Mechanics and Lower-Limb Muscle Fatigue. *International Journal of Sports Physiology and Performance*, 11(4), 522-529. doi:10.1123/ijssp.2014-0602
- Girard, O., Brocherie, F., Morin, J. B., & Millet, G. P. (2017). Lower limb mechanical asymmetry during repeated treadmill sprints. *Human Movement Science*, 52, 203-214. doi:10.1016/j.humov.2017.02.008
- Girard, O., Brocherie, F., Morin, J. B., Millet, G. P., & Hansen, C. (2020). Running mechanics and leg muscle activity patterns during early and late acceleration phases of repeated treadmill sprints in male recreational athletes. *Eur J Appl Physiol*, 120(12), 2785-2796. doi:10.1007/s00421-020-04500-8
- Girard, O., Millet, G., Slawinski, J., Racinais, S., & Micallef, J. P. (2010). Changes in leg-spring behavior during a 5000m self-paced run in differently trained athletes. *Science and Sports*, 25(2), 99-102. doi:10.1016/j.scispo.2009.10.001
- Girard, O., Millet, G. P., Micallef, J. P., & Racinais, S. (2012). Alteration in neuromuscular function after a 5 km running time trial. *European Journal of Applied Physiology*, 112(6), 2323-2330. doi:10.1007/s00421-011-2205-8
- Goncalves, B. A. M., Meinders, E., Saxby, D. J., Barrett, R., Bourne, M. N., & Diamond, L. E. (2021). Repeated sprints alter mechanical work done by hip and knee, but not ankle, sagittal moments. *Journal of Science and Medicine in Sport*, 24(9), 939-944. doi:10.1016/j.jsams.2021.03.008
- Guyatt, G., Oxman, A. D., Akl, E. A., Kunz, R., Vist, G., Brozek, J., . . . Debeer, H. (2011). GRADE guidelines: 1. Introduction—GRADE evidence profiles and summary of findings tables. *Journal of Clinical Epidemiology*, 64(4), 383-394. doi:10.1016/j.jclinepi.2010.04.026
- Hanley, B., & Mohan, A. K. (2014). Changes in gait during constant pace treadmill running. *Journal of Strength and Conditioning Research*, 28(5), 1219-1225. doi:10.1519/JSC.0b013e3182a38796
- Hanley, B., & Tucker, C. B. (2018). Gait variability and symmetry remain consistent during high-intensity 10,000 m treadmill running. *Journal of Biomechanics*, 79, 129-134. doi:10.1016/j.jbiomech.2018.08.008
- Hart, J. M., Kerrigan, D. C., Fritz, J. M., Saliba, E. N., Gansneder, B., & Ingersoll, C. D. (2009). Jogging gait kinetics following fatiguing lumbar paraspinal exercise. *Journal of Electromyography and Kinesiology*, 19(6), e458-e464. doi:10.1016/j.jelekin.2008.09.003
- Hashish, R., Samarawickrame, S. D., Baker, L., & Salem, G. J. (2016). The influence of a bout of exertion on novice barefoot running dynamics. *Journal of Sports Science and Medicine*, 15(2), 327-334.
- Hreljac, A., Marshall, R. N., & Hume, P. A. (2000). Evaluation of lower extremity overuse injury potential in runners. *Med Sci Sports Exerc*, 32(9), 1635-1641. doi:10.1097/00005768-200009000-00018
- Jafarnezhadgero, A. A., Sorkhe, E., & Oliveira, A. S. (2019). Motion-control shoes help maintaining low loading rate levels during fatiguing running in pronated female runners. *Gait and Posture*, 73, 65-70. doi:10.1016/j.gaitpost.2019.07.133
- Jewell, C., Boyer, K. A., & Hamill, J. (2017). Do footfall patterns in forefoot runners change over an exhaustive run? *J Sports Sci*, 35(1), 74-80. doi:10.1080/02640414.2016.1156726
- Khassetarash, A., Vernillo, G., Krüger, R. L., Edwards, W. B., & Millet, G. Y. (2022). Neuromuscular, biomechanical, and energetic adjustments following repeated bouts of downhill running. *J Sport Health Sci*, 11(3), 319-329. doi:10.1016/j.jshs.2021.06.001
- Kim, H. K., Mirjalili, S. A., & Fernandez, J. (2018). Gait kinetics, kinematics, spatiotemporal and foot plantar pressure alteration in

- response to long-distance running: Systematic review. *Human Movement Science*, 57, 342-356. doi:10.1016/j.humov.2017.09.012
- Kim, S. Y., Park, J. E., Lee, Y. J., Seo, H.-J., Sheen, S.-S., Hahn, S., . . . Son, H.-J. (2013). Testing a tool for assessing the risk of bias for nonrandomized studies showed moderate reliability and promising validity. *Journal of Clinical Epidemiology*, 66(4), 408-414. doi:<https://doi.org/10.1016/j.jclinepi.2012.09.016>
- Li, J., Song, Y., Xuan, R., Sun, D., Teo, E. C., Bíró, I., & Gu, Y. (2022). Effect of Long-Distance Running on Inter-segment Foot Kinematics and Ground Reaction Forces: A Preliminary Study. *Front Bioeng Biotechnol*, 10, 833774. doi:10.3389/fbioe.2022.833774
- Luo, Z., Zhang, X., Wang, J., Yang, Y., Xu, Y., & Fu, W. (2019). Changes in ground reaction forces, joint mechanics, and stiffness during treadmill running to fatigue. *Applied Sciences (Switzerland)*, 9(24). doi:10.3390/app9245493
- McKay, A. K. A., Stellingwerff, T., Smith, E. S., Martin, D. T., Mujika, I., Goosey-Tolfrey, V. L., . . . Burke, L. M. (2022). Defining training and performance caliber: A participant classification framework. *International Journal of Sports Physiology and Performance*, 17(2), 317-331. doi:10.1123/ijsp.2021-0451
- Melaro, J. A., Gruber, A. H., & Paquette, M. R. (2021). Joint work is not shifted proximally after a long run in rearfoot strike runners. *J Sports Sci*, 39(1), 78-83. doi:10.1080/02640414.2020.1804807
- Millet, G. Y. (2011). Can neuromuscular fatigue explain running strategies and performance in ultra-marathons? *Sports Medicine*, 41(6), 489-506. doi:10.2165/11588760-000000000-00000
- Millet, G. Y., Tomazin, K., Verges, S., Vincent, C., Bonnefoy, R., Boisson, R.-C., . . . Martin, V. (2011). Neuromuscular consequences of an extreme mountain ultra-marathon. *PLoS One*, 6(2), e17059. doi:10.1371/journal.pone.0017059
- Milner, C. E., Ferber, R., Pollard, C. D., Hamill, J., & Davis, I. S. (2006). Biomechanical factors associated with tibial stress fracture in female runners. *Med Sci Sports Exerc*, 38(2), 323-328. doi:10.1249/01.mss.0000183477.75808.92
- Morin, J.-B. (2018). A simple method for measuring lower limb stiffness during running. In J.-B. Morin & P. Samozino (Eds.), *Biomechanics of training and testing: Innovative concepts and simple field methods* (pp. 165-193). Nice: Springer.
- Morin, J.-B., & Samozino, P. (2018). *Biomechanics of training and testing: Innovative concepts and simple field methods* (Vol. 1). Nice: Springer.
- Morin, J.-B., Samozino, P., & Millet, G. Y. (2011). Changes in running kinematics, kinetics, and spring-mass behavior over a 24-h run. *Medicine & Science in Sports & Exercise*, 43(5), 829-836. doi:10.1249/MSS.0b013e3181fec518
- Napier, C. (2020). *Science of running: analyse your technique, prevent injury, revolutionize your training* (Vol. 1). London.
- Napier, C., Cochrane, C. K., Taunton, J. E., & Hunt, M. A. (2015). Gait modifications to change lower extremity gait biomechanics in runners: a systematic review. *British Journal of Sports Medicine*, 49(21), 1382-1388. doi:10.1136/bjsports-2014-094393
- Nicol, C., Avela, J., & Komi, P. V. (2006). The stretch-shortening cycle : a model to study naturally occurring neuromuscular fatigue. *Sports Medicine*, 36(11), 977-999. doi:10.2165/00007256-200636110-00004
- Nummela, A., Rusko, H., & Mero, A. (1994). EMG activities and ground reaction forces during fatigued and nonfatigued sprinting. *Medicine & Science in Sports & Exercise*, 26(5), 605-609.
- Pachava, S. R., & Paruthi, N. (2022). Acute effects of long distance running on gait parameters. *Series on Biomechanics*, 36(4), 46-53. doi:10.7546/SB.05.04.2022
- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., . . . Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *British Medical Journal*(71). doi:10.1136/bmj.n71
- Paquette, M. R., & Melcher, D. A. (2017). Impact of a long run on injury-related biomechanics with relation to weekly mileage in trained male runners. *Journal of Applied Biomechanics*, 33(3), 216-221. doi:10.1123/jab.2016-0170
- Patoz, A., Blokker, T., Pedrani, N., Spicher, R., Borrani, F., & Malatesta, D. (2023). Biomechanical adaptations during exhaustive runs at 90 to 120% of peak

- aerobic speed. *Sci Rep*, 13(1), 8236. doi:10.1038/s41598-023-35345-8
- Pohl, M. B., Mullineaux, D. R., Milner, C. E., Hamill, J., & Davis, I. S. (2008). Biomechanical predictors of retrospective tibial stress fractures in runners. *Journal of Biomechanics*, 41(6), 1160-1165. doi:<https://doi.org/10.1016/j.jbiomech.2008.02.001>
- Poole, D. C., Burnley, M., Vanhatalo, A., Rossiter, H. B., & Jones, A. M. (2016). Critical Power: An Important Fatigue Threshold in Exercise Physiology. *Medicine & Science in Sports & Exercise*, 48(11), 2320-2334. doi:10.1249/mss.0000000000000939
- Puddle, D. L., & Maulder, P. S. (2013). Ground reaction forces and loading rates associated with parkour and traditional drop landing techniques. *Journal of Sports Science and Medicine*, 12(1), 122-129.
- Radzak, K. N., Putnam, A. M., Tamura, K., Hetzler, R. K., & Stickley, C. D. (2017). Asymmetry between lower limbs during rested and fatigued state running gait in healthy individuals. *Gait Posture*, 51, 268-274. doi:10.1016/j.gaitpost.2016.11.005
- Radzak, K. N., & Stickley, C. D. (2020). Fatigue-Induced Hip-Abductor Weakness and Changes in Biomechanical Risk Factors for Running-Related Injuries. *J Athl Train*, 55(12), 1270-1276. doi:10.4085/1062-6050-531-19
- Richmond, S. B., Dames, K. D., Goble, D. J., & Fling, B. W. (2018). Leveling the playing field: Evaluation of a portable instrument for quantifying balance performance. *Journal of Biomechanics*, 75, 102-107. doi:10.1016/j.jbiomech.2018.05.008
- Rohatgi, A. (2021). WebPlotDigitizer v.4.5 (Version 4.5). Pacifica, California, USA. Retrieved from <https://automeris.io/WebPlotDigitizer>
- Saldanha, A., Nordlund Ekblom, M. M., & Thorstensson, A. (2008). Central fatigue affects plantar flexor strength after prolonged running. *Scandinavian Journal of Medicine & Science in Sports*, 18(3), 383-388. doi:<https://doi.org/10.1111/j.1600-0838.2007.00721.x>
- Sanno, M., Epro, G., Brüggemann, G. P., & Willwacher, S. (2021). Running into Fatigue: The Effects of Footwear on Kinematics, Kinetics, and Energetics. *Medicine and Science in Sports and Exercise*, 53(6), 1217-1227. doi:10.1249/MSS.0000000000002576
- Sanno, M., Willwacher, S., Epro, G., & Brüggemann, G. P. (2018). Positive work contribution shifts from distal to proximal joints during a prolonged run. *Medicine & Science in Sports & Exercise*, 50(12).
- Silva, M. G., Moreira, P. V. S., & Rocha, H. M. (2017). Development of a low cost force platform for biomechanical parameters analysis. *Research on Biomedical Engineering*, 33(3), 259-268. doi:10.1590/2446-4740.01217
- Tam, N., Coetzee, D. R., Ahmed, S., Lamberts, R. P., Albertus-Kajee, Y., & Tucker, R. (2017). Acute fatigue negatively affects risk factors for injury in trained but not well-trained habitually shod runners when running barefoot. *European Journal of Sport Science*, 17(9), 1220-1229. doi:10.1080/17461391.2017.1358767
- Vernillo, G., Aguiar, M., Savoldelli, A., Martinez, A., Giandolini, M., Horvais, N., ... Millet, G. Y. (2020). Regular changes in foot strike pattern during prolonged downhill running do not influence neuromuscular, energetics, or biomechanical parameters. *European Journal of Sport Science*, 20(4), 495-504. doi:10.1080/17461391.2019.1645212
- Vial, S., Wilkie, J. C., Turner, M., Scanlan, M., & Blazeovich, A. J. (2023). Does fatigue influence joint-specific work and ground force production during the first steps of maximal acceleration? *Scand J Med Sci Sports*, 33(6), 894-906. doi:10.1111/sms.14318
- Vilas-Boas, J. P. (2016). Biomecânica na avaliação do movimento desportivo e no fornecimento de feedback ao executante. In V.-B. J.P. (Ed.), *Biomecânica do Desporto* (Vol. 1.1, pp. 108-110). Lisboa: Instituto Português do Desporto e Juventude, I.P.
- Voloshin, A. S., Mizrahi, J., Verbitsky, O., & Isakov, E. (1998). Dynamic loading on the human musculoskeletal system effect of fatigue. *Clinical Biomechanics*, 13(7), 515-520. doi:10.1016/S0268-0033(98)00030-8
- Wang, I. L., Graham, R. B., Bourdon, E. J. P., Chen, Y. M., Gu, C. Y., & Wang, L. I. (2020). Biomechanical Analysis of Running Foot Strike in Shoes of Different Mass. *J Sports Sci Med*, 19(1), 130-137.
- Warren, B. L. (1984). Anatomical factors associated with predicting plantar fasciitis in long-distance runners. *Med Sci Sports Exerc*, 16(1), 60-63.

- Weir, G., Jewell, C., Wyatt, H., Trudeau, M. B., Rohr, E., Brüggemann, G. P., & Hamill, J. (2019). The influence of prolonged running and footwear on lower extremity biomechanics. *Footwear Science*, 11(1), 1-11. doi:10.1080/19424280.2018.1539127
- Wells, M. D., Dickin, D. C., Popp, J., & Wang, H. (2020). Effect of downhill running grade on lower extremity loading in female distance runners. *Sports Biomechanics*, 19(3), 333-341. doi:10.1080/14763141.2018.1510538
- Willson, J. D., Loss, J. R., Willy, R. W., & Meardon, S. A. (2015). Sex differences in running mechanics and patellofemoral joint kinetics following an exhaustive run. *J Biomech*, 48(15), 4155-4159. doi:10.1016/j.jbiomech.2015.10.021
- Winter, S., Gordon, S., & Watt, K. (2017). Effects of fatigue on kinematics and kinetics during overground running: A systematic review. *Journal of Sports Medicine and Physical Fitness*, 57(6), 887-899. doi:10.23736/S0022-4707.16.06339-8
- World Athletics. (2022). Our sport. *World Athletics*. Retrieved from <https://worldathletics.org/our-sport>
- Yu, P., Liang, M., Fekete, G., Baker, J. S., & Gu, Y. (2021). Effect of running-induced fatigue on lower limb mechanics in novice runners. *Technology and Health Care*, 29(2), 231-242. doi:10.3233/THC-202195
- Zakaria, F. A., El Badaoui, M., Lamraoui, M., & Khalil, M. (2016). Fatigue study of ultra-runners: Presentation of a new approach for the separation of GRF signals components. *Mechanical Systems and Signal Processing*, 75, 648-667. doi:10.1016/j.ymssp.2015.12.005
- Zandbergen, M. A., Marotta, L., Bulthuis, R., Buurke, J. H., Veltink, P. H., & Reenalda, J. (2023). Effects of level running-induced fatigue on running kinematics: A systematic review and meta-analysis. *Gait & Posture*, 99, 60-75. doi:<https://doi.org/10.1016/j.gaitpost.2022.09.089>
- Zhang, X. N., Xia, R., Dai, B. Y., Sun, X. L., & Fu, W. J. (2018). Effects of Exercise-Induced Fatigue on Lower Extremity Joint Mechanics, Stiffness, and Energy Absorption during Landings. *Journal of Sports Science and Medicine*, 17(4), 640-649.