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Review Article

Influence of Fatigue on the Modification of Biomechanical Parameters in Endurance Running: A Systematic Review

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ABSTRACT

International Journal of Exercise Science 17(1): 1377-1391, 2024. Fatigue accumulated during the practice of endurance running can be understood as the decrease in sports performance caused by physical exertion. Since fatigue can manifest itself in multiple ways, its influence is difficult to understand, and many authors propose different studies with the aim of obtaining firm conclusions. Thus, the aim of this systematic review was to analyze the effect of fatigue on the modification of biomechanical parameters to mitigate adverse effects and optimize positive adaptations to training. A systematic review was carried out using scientific research papers from specific sport science databases in advanced search dated 02/2023. This systematic review was performed using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Eligibility criteria were established according to the PICO (Participants, Intervention, Comparison, Outcome) strategy. The PEDro scale was used to evaluate the methodological quality of the publications. Twelve papers were analyzed, with a median PEDro score of 8.0, including 375 participants. The main results show that fatigue affects biomechanical parameters in endurance running, especially untrained athletes. Fatigue affects the biomechanical parameters of running and consequently triggers a decrease in sports performance. There is controversy among authors on the modification of some biomechanical parameters. The proposal of new measurement sensors can be a success to monitor the evolution of fatigue. The dominant mechanism for the perception of fatigue is neuromuscular fatigue. There are differences between trained and untrained runners.

KEY WORDS: Biomechanics, performance, runners, sensors

INTRODUCTION

The popularity of running as a sport has increased worldwide, due to the numerous benefits it offers, its accessibility, and its role in promoting fitness and preventing chronic diseases (4). Nevertheless, further analysis would require consideration of additional factors, such as fatigue and the associated kinematic alterations, as these factors may influence the metabolic cost of running at a constant submaximal speed (13). Regarding performance, it can be argued that fatigue accumulates during running and that this is the cause of the decrease in performance that is observed (15). Furthermore, it could also increase risk factors and develop injuries (27).

Therefore, maintaining movement patterns over time can be a significant challenge (4). The influence of fatigue on biomechanical parameters has been widely studied, with a particular focus on stride frequency and stride length, ground contact time, vertical oscillation, and leg spring stiffness (7). Being evident that an understanding of the influence of acute running-induced fatigue on body homeostasis would allow for the mitigation of adverse effects and the optimization of positive adaptations to training (27).

Currently, and according to Apte et al. (1), there is a significant gap in the literature caused by the lack of field studies with continuous measurement during outdoor running activities. This is most likely due to the complexity of such measurement due to the multitude of states and forms that fatigue can take and explains why it remains scarce despite the proliferation of portable measurement systems and motion analysis algorithms in sports science (1). Inertial measurement units (IMUs) have now helped coaches and athletes alike to record biomechanical parameters (23, 24) in the field, while previous methods of analysis have required well-equipped research laboratories (22). For example, stability of running stride biomechanical parameters during half-marathon race have been analyzed (26). Also, Enoka and Duchateau (8) state that direct measurement is difficult given that fatigue depends on interactions between performance and perceived fatigability, and the latter is fully subjective and depends solely and exclusively on the athlete. It is often investigated by measuring their simultaneous effects on cardiovascular, neuromuscular and psychological states through sensor-based approaches and self-reported questionnaire scores (30). Other approaches include blood tests for lactate and performance monitoring in functional tests such as Counter-Movement Jump (CMJ) and maximal voluntary contraction (2). Regarding the influence of fatigue on autonomic cardiac control, this can be estimated through heart rate dynamics such as Heart Rate Variability (HRV) and Complexity of Rate Variability (CRV) (14).

Analyzing the existing scientific studies detailed in this systematic review, it is easy to state that in some cases there is great controversy about the effects of fatigue on running biomechanics because of the numerous inter- and inter-personal variables that lead to unsound conclusions. In fact, tier classifications (fair, tourist, regional, national, international) based on the sex and level of the athlete are proposed as this is fundamental in the field of sport science and endurance performance (25). Even relevant studies have approached the definition of the calibre of training and performance by considering the training volume and performance metrics to classify a participant (19). For example, recreationally active athletes do not identify with a specific sport nor are they competitive, while trained athletes do (19). Thus, the main purpose of the present systematic review is to analyze the effect of fatigue on the modification of biomechanical parameters in endurance running in trained athletes. The specific purpose is to provide information on the value of measuring running metrics that could be used to detect fatigue during endurance running.

According to the current state of knowledge, it was previously hypothesized that the detection and understanding of the influence of fatigue on the modification of biomechanical parameters of running could allow an improvement in athletic performance.

METHODS

Since the aim of this study was to examine the effects of fatigue on biomechanical parameters in endurance running, a systematic literature review was performed following the preferred reporting items for systematic reviews and meta-analysis (PRISMA-P) 2015 guidelines (20). For this purpose, systematic protocols for data collection were applied to determine objective and valid conclusions to answer the following research question: How does fatigue influence the modification of biomechanical parameters in endurance running?

This study is a systematic review that synthesizes the available evidence on the topic. It follows the guidelines by Sánchez-Meca (29) and uses explicit methods to locate, select and evaluate the current research published on the subject. The review covers both quantitative and qualitative aspects of primary studies and aims to summarize the existing information. The methods are objective and clear. In addition, the application of strategies has been carried out with the aim of reducing biases that allow the integration, analysis, and synthesis of the most important studies on the topic in question (17). In this case, how fatigue influences the modification of biomechanical parameters in endurance running.

Eligibility criteria

The eligibility criteria were established according to the PICO (participants, intervention, comparison, outcome) strategy (20).

Only research with a minimum distance of 10 km were taken into consideration to ensure the application of the endurance factor and those that addressed the study considering the fatigue factor as a relevant variable and biomechanical parameters as the main topic to be addressed.

All those researches whose interventions are biomechanical parameters, fatigue and endurance running and that focused on the relationship between them were analyzed: influence on the modification of biomechanical parameters in endurance running in addition to the perception of fatigue or the proposal of new sensors to measure biomechanical parameters or fatigue.

All studies with fatigue comparators, biomechanical parameters and endurance races were included regardless of the form of comparison that these exposes and being able to refer to fatigue only as a form of perception or visible and measurable evidence and biomechanical parameters only as visible and measurable evidence, both without compliance with a specific form of data collection.

The papers selected for this review mainly focused on professional or trained athletes. However, some studies also compared trained and untrained athletes, as they provided relevant information on the changes of biomechanical parameters due to fatigue. The data collection methods varied among the studies: some measured the parameters before and after the race, some during the entire race continuously, and some at intervals of a few kilometres.

The variables analyzed in the papers included in this systematic review, which are of greater relevance, are as follows: detection of modifications in running mechanics and their relationship with fatigue, differences between data collection during the course of the races in stride frequency, stride length, contact time and vertical oscillation and differences between trained and untrained runners.

Next, all the papers whose results were aimed at analyzing the influence of fatigue in endurance running were carefully studied, as well as those that presented information on new sensors for measuring fatigue, since this information is relevant for future research on the subject.

It has been tried to make a review as updated as possible due to the large amount of research found, considering as valid the papers published from the year 2000 to the present year 2023. In addition, only research in the English language was included due to its great relevance to the subject in question, and only scientific research papers were taken into consideration, valuing the notable reliability that they contribute to the subject in question.

Finally, those research that did not meet the inclusion criteria were excluded. The main reasons for exclusion were: not being related to the subject, not being a scientific study, not having the full text available, presenting distances of less than 10 km, and not addressing the study taking into consideration the fatigue variable or publications prior to the year 2000.

Search procedure

Data and information sources: For the search of the papers of the present systematic review, the following databases were accessed: SPORTDiscus with Full Text, MEDLINE, Complementary Index, Academic Search Index, Academic Search Complete, Directory of Open Access Journals, Supplemental Index, OpenDissertations, OAIster, Dialnet Plus, British Library EThOS, TDX, ERIC, Dialnet. All the publications selected in the detailed search engines are meticulously referenced.

Search Strategy: The most relevant words for the search of the publications were considered to be: "running", "kinematic", "mechanic", "fatigue", "marathon", "ultramarathon", "change", "biomechanical parameters", "half marathon" and "fatigue" all of them delimited in their appearance to the sections "Abstract, summary", connected between them with the Boolean operator "AND" and found through the advanced search of specific sport science databases. Based on the above and as mentioned above, four search phases have been elaborated, which are complementary to each other to obtain the selected publications: "running" AND "kinematic" AND "fatigue" AND "change"; "mechanics" AND "running" AND "marathon" AND "marathon"; "mechanics" AND "running" AND "ultramarathon" AND "ultramarathon"; "biomechanical parameters" AND "half marathon" AND "fatigue".

Methodological Quality: The PEDro scale, based on the Delphi list and developed by Verhagen and collaborators (31) and last modified on June 21, 1999, was used to evaluate the publications. In the search process using the aforementioned strategy, a total of 275 publications were found.

The process for obtaining them consisted of four searches using key words such as Abstract, summary in all of them.

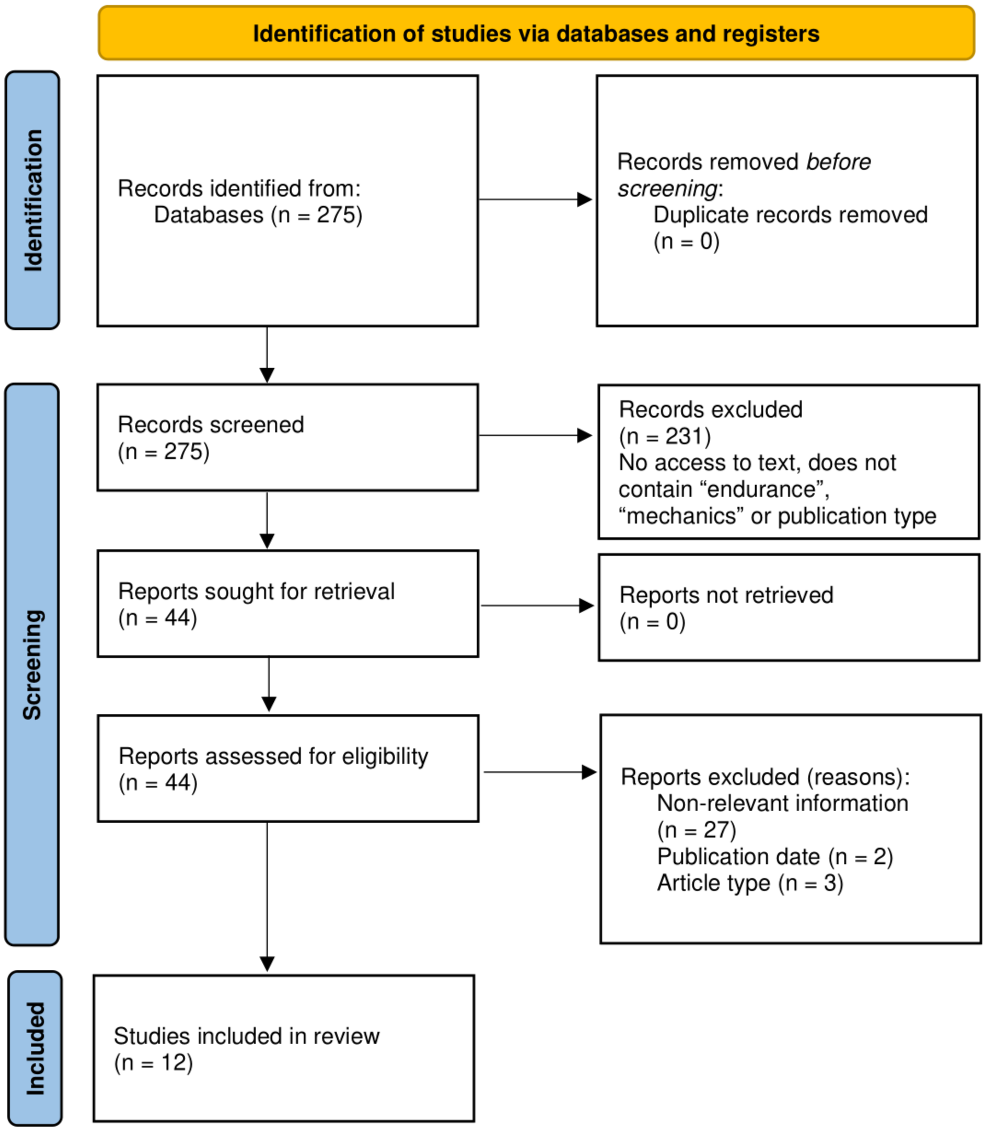

Figure 1. Literature search flow chart. *n* number of studies.

In the first search using the words "running" AND "kinematic" AND "fatigue" AND "change" a total of 215 publications were obtained. During the second search using the words "mechanics" AND "running" AND "marathon" a total of 48 publications were obtained. In the third search "biomechanical parameters" AND "half marathon" AND "fatigue" a total of 9 publications were obtained. Finally in the fourth search using the words "mechanics" AND "running" AND "ultramarathon" a total of 3 publications were obtained. After applying the following exclusion criteria: no access to the text, not contain endurance, mechanics, kinetics, or type of publication, 231 publications were discarded. The remaining 44 were carefully reviewed by an exhaustive reading and 32 were discarded after applying the following eligibility criteria: non-relevant information, date of publication and type of publication. As a result, 12 publications were finally selected.

The search process for the selection of publications for the present systematic review can be seen below (Table 1). Figure 1 shows the flowchart which highlights in detail: the search phases carried out, the exclusion criteria, the eligibility criteria and the number of publications selected. Finally, Table 2 details the characteristics of the selected publications.

Table 1. Search Selection Process.

Database	Keywords	Number of publications	Selected papers
SPORTDiscus with Full Text, MEDLINE, Complementary Index, Academic Search Index, Academic Search Complete, Directory of Open Access Journals, Supplemental Index, OpenDissertations, OAIster, Dialnet Plus, British Library EThOS, TDX, ERIC, Dialnet	Abstract: "running" AND "kinematic" AND "fatigue" AND "change"	215	5
	Abstract: "mechanics" AND "running" AND "marathon"	48	5
	Abstract: "biomechanical parameters" AND "half marathon" AND "fatigue"	9	1
	Abstract: "mechanics" AND "running" AND "ultramarathon"	3	1
	Total	**275**	**12**

Table 2. Characteristics of the publications selected.

Reference	Participants	Intervention	Comparison	Outcomes
(Chan-Roper et al., 2012) (3)	n=179	Kinematic changes km 8 and km 40.	Km 8 vs km 40.	Kinematic differences km 8 vs km 40.
(Chen et al., 2022) (4)	n=15 13 males 2 females. Non-professionals.	Coordination and loading rate differences.	Parameters km 2 to km 20.	Segment coordination differences, not loading rate.
(Degache et al., 2016) (6)	n=24 16 experienced runners 8 non-experienced runners.	Mechanical running and mass-spring effects.	Running and mass-spring mechanics km 0 vs km 148.7 vs 30 min later km 330.	Modifications of running and spring-mass parameters.
(Giandolini et al., 2016) (10)	n=23 13 males 10 females. Experienced.	Consequences ultra-marathon mountain 110 km.	Parameters before vs. after ultra-marathon.	Evolution of parameters before vs. after ultra-marathon.
(Giovanelli et al., 2016) (11)	n=25 Males (18 finishing).	Effects of mechanical parameters and neuromuscular fatigue.	Evolution of parameters before vs. after marathon.	Mechanical running changes caused by fatigue.
(Kyrolainen et al., 2000) (16)	n=7 1 female 6 males. Experienced athletes.	Characteristics running economy.	Parameters before vs. during vs. after marathon.	Increased physiological load may be due to several mechanisms.
(Matta et al., 2020) (18)	n=16 4 females 12 males. Experienced athletes.	If slow onset affects performance, running kinematics, fatigue perception.	Evolution of parameters before vs. after marathon.	Slow onset affects perceived exertion and fatigue but not performance.
(Morin et al., 2011) (21)	n=34 18. Experienced athletes are included.	Fatigue affectation in mechanical running and mass-spring ultra-marathon mountain.	Evolution of parameters days before vs. 3h after ultra-marathon.	Running and mass-spring mechanical modification.
(Prigent et al., 2022) (27)	n=13 11 males 2 females. Non-experienced athletes.	Measuring response: biomechanical, physiological, and psychological parameters of acute half marathon fatigue.	Evolution of parameters during half marathon.	Alteration of biomechanical, physiological, and psychological parameters.
(Reenalda et al., 2016) (28)	n=5 Experienced athletes.	Introduce magnetic inertial measurement units. Observe mechanical running changes.	Parameters evolution during marathon.	Possible 3D kinematic analysis using magnetic inertial sensors. Running mechanical changes.
(Willwacher et al., 2020) (32)	n=24 13 non-professionals 11 professionals	Describe fatigue effects on running kinematics.	Evolution parameters 10 km race.	Kinematic deviations of joints in frontal and transverse planes without fatigue. Fatigue may affect hip adduction and foot eversion.

(Zakaria et al., 2016) (33)	n=10 Trained athletes.	New indicators and parameters.	Parameter evolution during 24h.	Troubleshoot problems. Introduces new indicators and parameters.

RESULTS

Table 3 presents the list of the most recent studies of the present systematic review analyzing the influence of fatigue on the modification of biomechanical parameters in endurance running.

Table 3. Characteristics of the publications selected.

Study	PEDro's Scale Score	Sample	Participants	Intervention and comparison	Instrumentation and measurements	Results
(Chan-Roper et al., 2012) (3)	8	179	Trained runners.	Evaluate kinematic changes marathon km 8 vs km 40. Compare potential changes between fast vs slow runners.	Two high-speed cameras installed on tripods 10 m from the right side of the race. A third camera installed at a height of 1 m recording frontal images of the runners.	Differences between km 8 and km 40: increased stride, contact time length, maximum hip, and knee flexion during swing, decreased running speed, stride frequency, maximum knee flexion during stance and hip extension during swing. Fast runners exhibited more constant maximal knee flexion during stance than slow runners.
(Chen et al., 2022) (4)	6	15	Recreational runners. 13 males and 2 females.	Coordination and charge rate differences from km 2 to km 20 every 2 km.	A treadmill with two computer-controlled force platforms. A motion capture system with 10 cameras and 28 markers for motion capture. Kinematic data were recorded for 10 seconds every 2 km from km 2.	Significant variables due to mileage were found in body segment coordination, but not in loading rate.
(Degache et al., 2016) (6)	8	24	16 trained runners and 8 control runners.	Investigate the running mechanics and spring-mass behaviour of experienced runners during the world´s most demanding ultra-marathon.	Pressure sensor placed on the ground. 2 photocells placed at 5m distance to measure speed. Measurements were taken before, during and after the race.	There were modifications in the running pattern and behaviour of the spring mass mainly during the first half to minimize pain at each step of the eccentric phase and the changes were not superior to those measured in shorter ultra-marathons.

(Giandolini et al., 2016) (10)	8	23	23 runners. 13 males and 10 females.	To investigate the consequences of a 110 km ultra-marathon and running kinematics to determine if these changes are related to neuromuscular fatigue.	Treadmill, uniaxial accelerometer, LabChart 7, reflector markers, camera located 1.5 m from the treadmill and Shapiro-Wilk, Fisher, T-Student, Wilcoxon, ANOVA normality tests.	Regardless of the running parameters characteristic of each subject, after the race runners make changes in running kinetics. Whether these changes are due to fatigue and whether they are conscious, or unconscious remains to be investigated.
(Giovanelli et al., 2016) (11)	8	25 Included are 18 finished.	25 runners of which 18 finishers are included for data analysis.	To investigate the effects of an uphill marathon on running mechanics and neuromuscular fatigue in lower extremity muscles.	Body mass and VO_{2max} were evaluated one week before. Day before and immediately after the race, MMP was assessed with a CMJ using the Bosco test 17. TMG before and after (2-4 min) the race using a protocol described by Simunic. 4 digital cameras placed perpendicularly to the race during km 3, 14, 30 and post. After the race the runners ran at a constant self-selected speed for video analysis. Running speed was measured by 2 photocells placed before and after the videotaping area.	Changes in running mechanics and neuromuscular fatigue were observed. Thus, lower extremity muscle strength is important in determining performance.
(Kyrolainen et al., 2000) (16)	8	7	7 runners. 1 females and 6 males. Experienced athletes.	Investigate the interactions between running economy and mechanics during and after a marathon.	Monitoring of pulse rate and expired respiratory gas. Blood and blood lactate samples. Video analysis.	There were results on running economy and mechanics after the marathon and the results show that the weakening of running economy cannot be explained through changes in running mechanics and it is possible that the increase in psychological load is due to severe mechanisms such as fat utilization, increased thermoregulatory demands, energy substrates and possible muscle damage.

(Matta et al., 2020) (18)	8	16	16 trained runners. 4 females and 12 males.	To investigate whether a slow running start affects performance, kinematic changes in running, perception of effort and fatigue.	ROF scale, RPE, TQR, 5-point Likert, motivation questionnaire, CMJ, Galbraith, Hopker, Jobson and Passfield tests, three time trials of 3600, 2400 and 1200 m, stopwatches, body mass measurement, INCOTERM mercury thermometer, MT-242 thermo-hygrometer, GM8908 LCD anemometer, Speedway R220 RAIN RFID chip, Hero 4 digital camera, GoPro in the direction of travel recording a 12m section, 5-step analysis with Kinovea software and data analysis with SPSS.	The decrease in initial speed minimizes perceived exertion and fatigue but does not necessarily affect performance. Kinematic changes do not seem to be affected by running pace.
(Morin et al., 2011) (21)	7	34 18 are included.	34 volunteers. 22 are accepted to finish the ultra marathon and only the data of the 18 who finished were analyzed.	Observe changes in stride mechanics and spring mass due to fatigue. Measurements were taken one or two days before the race and three hours after reaching the finish line.	Measurements were performed on a pressure gateway (GAITRirteGold, CIRSystems), computer. The stride speed was measured by photocells. Mechanical data were sampled. Calculation method proposed by Morin et al. (2005). MUM was evaluated by effect size and Cohen's coefficient.	A reduction in vertical oscillation of the mass-spring system was observed. These changes could be due to less impact to reduce pain during running.
(Prigent et al., 2022) (27)	8	13	13 participants. 11 males and 2 females.	The influence of fatigue on biomechanics and physiological parameters based on running progression. Continuous measurement	GNSS-IMU-ECG sensor, Polar Pro Strap electrodes, IMU sensor, Android smartphone, Fieldwiz and Physilog 5 wearable sensors.	Little perceived fatigue influences biomechanical parameters. Dynamics and heart rate are altered at higher levels of fatigue.

(Reenalda et al., 2016) (28)	7	5	5 experienced runners. Due to technical problems, data from only 3 were analyzed.	To present a measurement setup based on inertial magnetic measurement units to perform a 3D kinematic analysis of the running technique continuously.	8 IMMU and Garmin Forerunner 210 GPS each runner. Xsens software, MATLAB R2013a. Repeated measures ANOVA.	A 3D kinematic analysis of the running technique can be performed using magnetic inertial sensors. Changes in running mechanics were observed during the marathon.
(Willwacher et al., 2020) (32)	8	24	24 male runners.	To observe how lower extremity running kinematics is altered in the non-sagittal plane in a 10 km run and its relationship to fatigue. Continuous measurement throughout the race.	13 MX-F40 cameras, 4 3D force transducers, Treadmetrix treadmill, 78 reflective markers, digital Butterworth filter.	Deviations in running kinematics are observed with and without fatigue.
(Zakaria et al., 2016) (33)	8	10	10 experienced runners.	Propose new indicators and parameters for the measurement of running to obtain data for fatigue analysis. Continuous measurement.	Treadmill equipped with accelerometers, GRF and vertical GRF analysis.	Presentation of new indicators and parameters.

Note. ANOVA: Analysis of variance; VO_{2max}: Maximum oxygen uptake; MMP: Maximal mechanical power of limbs; TMG: Temporal tensiomyographic; ROF: Ratings of fatigue; RPE: Ratings of perceived exertion; TQR: Total quality recovery scale; CMJ: Countermovement jump; MUM: Mountain ultra-marathon race; GNSS: Global navigation satellite system; IMU: Inertial measurement unit; ECG: Electrocardiogram; IMMU: Inertial magnetic measurement units; GPS: Global Positioning System; GRF: Ground Reaction Force.

DISCUSSION

Throughout the present systematic review, an analysis of the influence of fatigue on the biomechanical parameters of running has been carried out based on the previous hypothesis that the detection and understanding of the influence of fatigue on these parameters could allow an improvement in sports performance and a reduction in the risk factors for running-related injuries.

Regarding spatiotemporal factors and stride frequency, this ranges from around 2.90 steps/s in trained runners during 6-h ultramarathon races (18). Referring to the affectation of fatigue on this factor there is controversy among authors, while some claim that due to fatigue this is reduced (3, 28), Giandolini et al. (10) observed increases of ~2.7%, Morin et al. (21) increases of 5% and other authors (6, 33) support this hypothesis with similar results. Furthermore, Reenalda et al. (28) complement the hypothesis that increasing stride frequency could be an adaptive strategy to decrease or minimize the impact on the body. In contrast, Morin et al. (21) state that they did not observe variations in stride frequency and this result is also supported by other authors such as Matta et al. (18) who did not observe changes in the study conducted during a 6-hour ultra marathon highlighting that running kinematic changes do not seem to be affected by pacing manipulation.

Concerning stride length, many authors (3, 18, 28) show that stride length decreases. According to Matta et al. (18) this oscillates around 1.30 m at the beginning of the race and 1.10 m in fatigue state and according to Chan-Roper et al. (3) around 2.04 m at 8 km run and 1.41 m at kilometre 40. In addition, Matta et al. (18) detected that the greatest decrease in stride length occurs during approximately the first hour from the beginning of the race, analyzing in their study a decrease of -13%. In contrast, after 5 hours of running, this only decreased by 5.1% (11) and after 40 km this did not decrease (18). Also, Reenalda et al. (28) explain that because of the decrease in stride length observed a decrease in running speed.

In terms of vertical oscillation, Matta et al. (18) exposed that this decreases mostly during the first half hour of running analyzing a value of -34% and after 4:30 hours only an attenuation of -29%. According to Morin et al. (21) this reduction may be due to a decrease in the strength capacity of the main muscles of the lower extremities. The values of this factor in trained runners, can oscillate around 0.075 s at a running start and to 0.045 s in fatigue states (18).

Relative to contact time, numerous authors (3, 18, 27) highlight that it increases in the presence of fatigue. Matta et al. (18) analyzed that this increase occurs mostly during the beginning of the race indicating that in their study they detected an increase of +7% in the first hour and only an increase of +7.1% after 4:30h of running (18). In trained athletes this value can range from around 0.260 s at the beginning of a run to 0.300 s in a fatigued state (18). Chan-Roper et al. (3) complements that this may be related to the fact that the biceps femoris and rectus femoris are the first to fatigue during long distance running. This muscle fatigue results in reduced muscle stiffness or leg stiffness (3, 9, 12) which in turn results in attenuation of ground reaction forces and consequently increased contact time (3).

Focussing attention on neuromuscular fatigue, it seems to be the dominant mechanism influencing fatigue perception during the initial part of the run, suggesting a correlation between perceived fatigue and neuromuscular impairments (27) which are known to be the underlying mechanism responsible for the alteration of running technique (27). Subsequently, feedback from the fatiguing cardiorespiratory system appears which could also increase the perception of effort and finally, the cardiac cost which has a high tolerance to fatigue (27). In this situation, additional motor units are needed to produce the same overall neuromuscular efficiency, resulting in higher physiological/metabolic costs (27) and triggering inefficient running performance.

A more in-depth analysis of the differences between trained and untrained runners, trained runners always adopted better running technique. Untrained runners showed a greater change in heart rate dynamics throughout the run than trained runners. Trained runners better perceive their physiological limits and present a higher sensitivity of perceived fatigue (27) so trained runners can become dynamically optimize their running biomechanics in response to their physiological state (5).

Concerning the introduction of new sensors for fatigue measurement through changes in stride frequency and other indicators, it can be a success to monitor fatigue evolution because the presented results demonstrated the effectiveness of the proposed features for the characterization of running related to ultra-endurance performance (33).

In conclusion, it is important to highlight that fatigue affects multiple biomechanical parameters of running in endurance running. The main differences between trained and untrained runners are that fatigue affects less in trained runners compared to untrained runners. Untrained runners show a greater change in heart rate dynamics throughout running than trained runners. Trained runners have better running technique, more capacity and better resources to detect and manage fatigue states than untrained runners. Finally, the introduction of new sensors may be successful in monitoring the evolution of fatigue by observing biomechanical changes during endurance races.

REFERENCES

1. Apte S, Prigent G, Stöggl T, Martínez A, Snyder C, Gremeaux-Bader V, Aminian K. Biomechanical response of the lower extremity to running-induced acute fatigue: a systematic review. Front Physiol 12: 646042, 2021.

2. Bourdon PC, Cardinale M, Murray A, Gastin P, Kellmann M, Varley MC, Gabbett TJ, Coutts AJ, Burgess DJ, Gregson W. Monitoring athlete training loads: consensus statement. Int J Sports Physiol Perform 12(s2): S2-170, 2017.

3. Chan-Roper M, Hunter I, Myrer JW, Eggett DL, Seeley MK. Kinematic changes during a marathon for fast and slow runners. J Sport Sci Med 11(1): 77, 2012.

4. Chen TL, Wong DW, Wang Y, Tan Q, Lam W, Zhang M. Changes in segment coordination variability and the impacts of the lower limb across running mileages in half marathons: Implications for running injuries. J Sport Health Sci 11(1): 67-74, 2022.

5. De Ruiter CJ, Verdijk PW, Werker W, Zuidema MJ, de Haan A. Stride frequency in relation to oxygen consumption in experienced and novice runners. Eur J Sport Sci 14(3): 251-258, 2014.

6. Degache F, Morin J, Oehen L, Guex K, Giardini G, Schena F, Millet GY, Millet GP. Running mechanics during the world's most challenging mountain ultramarathon. Int J Sports Physiol Perform 11(5): 608-614, 2016.

7. Derrick TR, Dereu D, McLean SP. Impacts and kinematic adjustments during an exhaustive run. Med Sci Sports Exerc 34(6): 998-1002, 2002.

8. Enoka RM, Duchateau J. Translating fatigue to human performance. Med Sci Sports Exerc 48(11): 2228, 2016.

9. Fourchet F, Girard O, Kelly L, Horobeanu C, Millet GP. Changes in leg spring behaviour, plantar loading and foot mobility magnitude induced by an exhaustive treadmill run in adolescent middle-distance runners. J Sci Med Sport 18(2): 199-203, 2015.

10. Giandolini M, Gimenez P, Temesi J, Arnal PJ, Martin V, Rupp T, Morin J, Samozino P, Millet GY. Effect of the fatigue induced by a 110-km ultramarathon on tibial impact acceleration and lower leg kinematics. PLoS One 11(3): e0151687, 2016.

11. Giovanelli N, Taboga P, Rejc E, Simunic B, Antonutto G, Lazzer S. Effects of an uphill marathon on running mechanics and lower-limb muscle fatigue. Int J Sports Physiol Perform 11(4): 522-529, 2016.

12. Hayes PR, Caplan N. Leg stiffness decreases during a run to exhaustion at the speed at O 2max. Eur J Sport Sci 14(6): 556-562, 2014.

13. Hunter I, Smith GA. Preferred and optimal stride frequency, stiffness and economy: changes with fatigue during a 1-h high-intensity run. Eur J Appl Physiol 100: 653-661, 2007.

14. Jayasekera S, Hensel E, Robinson R. Feasibility assessment of wearable respiratory monitors for ambulatory inhalation topography. Int J Environ Res Public Health 18(6): 2990, 2021.

15. Knicker AJ, Renshaw I, Oldham AR, Cairns SP. Interactive processes link the multiple symptoms of fatigue in sport competition. Sports Med 41: 307-328, 2011.

16. Kyröläinen H, Pullinen T, Candau R, Avela J, Huttunen P, Komi PV. Effects of marathon running on running economy and kinematics. Eur J Appl Physiol 82: 297-304, 2000.

17. Last JM. A dictionary of epidemiology, edited by John M. Last, Robert A. Spasoff, and Susan G. Harris. Am J Epidemiol 154(4): 389, 2001.

18. Matta GG, Bossi AH, Millet GY, Lima P, Lima JPd, Hopker JG. Influence of a slow-start on overall performance and running kinematics during 6-h ultramarathon races. Eur J Sport Sci 20(3): 347-356, 2020.

19. McKay AK, Stellingwerff T, Smith ES, Martin DT, Mujika I, Goosey-Tolfrey VL, Sheppard J, Burke LM. Defining training and performance caliber: a participant classification framework. Int J Sports Physiol Perform 17(2): 317-331, 2021.

20. Moher D, Shamseer L, Clarke M, Ghersi D, Liberati A, Petticrew M, Shekelle P, Stewart LA, Prisma-P Group. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Syst Rev 4: 1-9, 2015.

21. Morin JB, Tomazin K, Edouard P, Millet GY. Changes in running mechanics and spring–mass behavior induced by a mountain ultra-marathon race. J Biomech 44(6): 1104-1107, 2011.

22. Norris M, Anderson R, Kenny IC. Method analysis of accelerometers and gyroscopes in running gait: A systematic review. Proc Inst Mech Eng Pt P J 228(1): 3-15, 2014.

23. Olaya-Cuartero J, Cejuela R. Influence of biomechanical parameters on performance in elite triathletes along 29 weeks of training. Appl Sci 11(3): 1050, 2021.

24. Olaya-Cuartero J, Plaza-Morales D, Jimenez-Olmedo JM, Lipinska P. Sensor analysis for the assessment of biomechanical parameters in endurance runners: a systematic review. J Phys Educ Sport 23(9): 2385-2393, 2023.

25. Olaya-Cuartero J, Pueo B, Penichet-Tomas A, Jimenez-Olmedo JM. Classification of Male Athletes Based on Critical Power. Int J Sports Med, 2024.

26. Olaya-Cuartero J, Pueo B, Villalon-Gasch L, Jimenez-Olmedo JM. Stability of Running Stride Biomechanical Parameters during Half-Marathon Race. Appl Sci 14(11): 4807, 2024.

27. Prigent G, Apte S, Paraschiv-Ionescu A, Besson C, Gremeaux V, Aminian K. Concurrent evolution of biomechanical and physiological parameters with running-induced acute fatigue. Front Physiol 13: 74, 2022.

28. Reenalda J, Maartens E, Homan L, Buurke JJ. Continuous three dimensional analysis of running mechanics during a marathon by means of inertial magnetic measurement units to objectify changes in running mechanics. J Biomech 49(14): 3362-3367, 2016.

29. Sánchez Meca J. Cómo realizar una revisión sistemática y un meta-análisis. Aula abierta 53(2): 169-179, 2010.

30. Thorpe RT, Atkinson G, Drust B, Gregson W. Monitoring fatigue status in elite team-sport athletes: implications for practice. Int J Sports Physiol Perform 12(s2): S2-34, 2017.

31. Verhagen AP, De Vet HC, De Bie RA, Kessels AG, Boers M, Bouter LM, Knipschild PG. The Delphi list: a criteria list for quality assessment of randomized clinical trials for conducting systematic reviews developed by Delphi consensus. J Clin Epidemiol 51(12): 1235-1241, 1998.

32. Willwacher S, Sanno M, Brüggemann G. Fatigue matters: An intense 10 km run alters frontal and transverse plane joint kinematics in competitive and recreational adult runners. Gait Posture 76: 277-283, 2020.

33. Zakaria FA, El Badaoui M, Lamraoui M, Khalil M. Fatigue study of ultra-runners: Presentation of a new approach for the separation of GRF signals components. Mech Syst Signal Process 75: 648-667, 2016.