

Original Research

Analysis of tibial and head accelerations in recreational runners classified by their functional response to fatigue

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Abstract: Running offers numerous benefits but is also linked to a high incidence of injuries, with fatigue being a factor contributing to biomechanical changes in runners. Despite the identification of multiple injury factors, their mechanisms remain poorly understood motivating the development of new clustering methods based on biomechanical risk factors (BRFs) responses. This study aimed to analyse impact acceleration differences between subgroups of recreational runners identified through clustering based on their response to fatigue. Thirty-nine male recreational runners performed a 30-min treadmill protocol at 80 % of their maximal aerobic speed (MAS). Impact accelerations, spatiotemporal variables, heart rate (HR), and rate of perceived exertion (RPE) were measured pre- and post-fatigue. Functional groups (FGs) were identified using K-means based on changes in tibial peak accelerations, and differences associated with fatigue and FGs were analysed. Fatigue increased HR ($p < 0.01$), RPE ($p < 0.01$), head magnitude ($p = 0.037$) and tibial loading rate ($p = 0.014$). Three FGs were identified, differing significantly in impact attenuation, with FG3 showing reduced values after the fatigue protocol ($p = 0.042$) compared to FG1 and FG2. These variations in attenuation observed in FG3 suggest distinct biomechanical responses to fatigue between groups. The identification of distinct FGs highlights the importance of considering individual biomechanical profiles when analysing fatigue-related running mechanics and designing training strategies.

Keywords: Biomechanical risk factors; cluster analysis; injury prevention; machine learning.



1. Introduction

According to the latest barometer of the Spanish Sports Council (CSD), approximately 19 % of the Spanish population identified running as their main physical activity (CSD, 2022). This discipline has been recognised as an effective strategy for reducing all-cause mortality, weight and improving cardiovascular and cardiorespiratory fitness (Oja et al., 2024). Despite these advantages, running is associated with a high risk of overuse injuries (Raghunandan et al., 2021). Normally, close to 50 % of runners experience running-related injuries (RRI) annually, predominantly affecting the lower limbs (Raghunandan et al., 2021). Risk factors for these injuries are typically classified as intrinsic or extrinsic (Raghunandan et al., 2021). Nonetheless, the lack of consensus on injury definitions, inconsistencies in methodologies, and insufficient evidence quality limits the conclusions regarding injury risk factors (Peterson et al., 2022; van Poppel et al., 2021). As a result, the identification of BRFs emerged as an alternative method for the improvement of technical, training, and feedback systems interventions by targeting populations at risk (Willwacher et al., 2022). However, the current prospective evidence relating BRFs with RRI risk is largely dependent on the population and injuries being studied (Ceyssens et al., 2019). Therefore, new injury models have emerged emphasising the importance of identifying FGs of runners who respond to certain interventions in a similar manner, with the aim of

individualising training and rehabilitative practices (Langley, 2023). In this regard, clustering is an unsupervised learning method that groups similar data points to reveal hidden patterns (Rivadulla et al., 2024). Unlike traditional analysis, it leverages multiple variables simultaneously to characterize running profiles more accurately (Carter et al., 2022). One particularly relevant variable for identifying functional responses is fatigue, as it significantly alters biomechanical parameters during running, particularly among recreational athletes (Olaya-Cuartero & Villalon, 2024). It has been associated with increasing the injury risk due to its effects on kinematics (Riazati et al., 2020) and impact acceleration (Encarnación-Martínez et al., 2022). Notably, fatigue can amplify the propagation of impact forces through the body by up to 50 %, potentially contributing to the development of spinal injuries and degenerative changes in joints and articular cartilage (Mizrahi et al., 2000). Therefore, the primary objective of this study was to examine how recreational runners respond to fatigue in terms of impact acceleration during running and to determine whether these responses can be used to classify individuals into distinct FGs. We hypothesised that distinct FGs would emerge based on individual responses to the fatigue protocol, with some groups exhibiting more pronounced alterations in impact acceleration. Additionally, we hypothesised that fatigue would induce significant changes in physiological (HR), perceptual

(RPE), and biomechanical variables, particularly peak tibial acceleration.

2. Material and Methods

Subjects – Sample size was previously calculated with the G-power software (version 3.1.9.7, Düsseldorf, Germany). A priori analysis indicated that a repeated-measures ANOVA would require a minimum of 39 participants to detect a significant within-between interaction with a large effect size (ES) (Encarnación-Martínez et al., 2025). ES was assessed using Cohen's eta partial (≥ 0.01 = small, 0.06 = moderate, > 0.14 = large) (Cohen, 1988). Accordingly, the final sample consisted of 39 recreational male runners (Table 1).

Table 1. Descriptive data (mean $\pm$ standard deviation (SD)) of the sample (n = 39)

Variable	mean $\pm$ SD
Age (years)	29.60 $\pm$ 10.70
Height (m)	1.70 $\pm$ 0.10
Body mass (kg)	73.30 $\pm$ 8.60
Body mass index (BMI) (kg/m ²)	24 $\pm$ 2.60
Weekly distance (km/week)	38.40 $\pm$ 17.90
MAS (km/h)	16.60 $\pm$ 1.80

Data showed as mean $\pm$ SD. MAS: Maximal aerobic speed.

All participants fulfilled the inclusion criteria: age must be at least 18 years old, level should be recreational (2-3 days of weekly training), no injuries in the previous 6 months and not undergoing medical treatments that could affect their physical

capacities. Participants that did not meet the inclusion criteria were excluded. All participants were informed of the protocol and study design, and an informed written consent to participate was obtained. They were also aware of the risks of participating in the study and they had the option to revoke consent at any time during the study. Finally, this study complies with the Helsinki Declaration (World Medical Association, 2008) and has been approved by the Ethics Committee of the correspondent University (registration number: 2588640).

Design and Methodology – Once the study sample was recruited, participants attended the laboratory on two sessions, with a minimum of 48-hour rest between them (Encarnación-Martínez et al., 2025). During the first session, participants signed the informed consent and confidentiality agreements, image consent form, and completed the Physical Activity Readiness Questionnaire (PAR-Q). Personal, sports, and anthropometric data were collected, including body mass (Tanita BIA Technology, Amsterdam, The Netherlands) and height (Asimed Barys Plus, Sibel, S.A.U, Barcelona). Foot type was assessed by the same examiner using the Foot Posture Index (FPI) (Redmond et al., 2006) and was included to provide a structural characterization of the sample. Intra-observer reliability was assessed using Cronbach's alpha ($\alpha = 0.927$) and Intra-Class Correlation Coefficient (ICC = 0.927, 95 % CI = 0.790 - 0.974) was assessed using an ICC (3,1) model based on two-way mixed-effects

approach, with absolute agreement definition and singles measure estimates, with both demonstrating values above 0.8, ensuring data quality (Encarnación-Martínez et al., 2025). Additionally, the MAS was determined at least 48 hours before the laboratory test by a maximal effort 5-min running field test on a 400 m track (Berthon et al., 1997) to determine individual speeds for the subjects at the treadmill test (García-Pérez et al., 2014). In the second session, participants performed a 30-min test at 80 % of the individual MAS (Encarnación-Martínez et al., 2025). After the measurement of pre-post fatigue data, different FGs were identified using the unsupervised clustering algorithm K-means based on specific BRFs (Willwacher et al., 2022), and comparisons were made between FGs (Mai et al., 2022). Participants used their habitual footwear in both sessions to reduce the influence of unfamiliar footwear on biomechanical running response (Nigg et al., 2015). Before starting the warm-up, runners were equipped with the acceleration system, which consisted of three wireless sensors (Xsens DOT; Movella, USA). Both accelerometers on the tibia were placed on the distal part of the leg (Lucas-Cuevas et al., 2016) aligned with the longitudinal axis of the bone, while the head accelerometer was attached to the frontal bone (Izquierdo-Renau et al., 2021) (Figure 1). Accelerometers were attached to the skin with adhesive tape (tesa SE- A Beiersdorf Company) and secured with a neoprene-type bandage covering them (Encarnación-Martínez et al., 2018). This fixation was adjusted to ensure

participant comfort while maintaining sensor stability (Derrick et al., 2002). Additionally, the 6-20 RPE scale (Borg, 1982) was explained to the participants to ensure an adequate understanding of its use. Following instrumentation, a 10-min warm-up on the treadmill (h/p/cosmos pulsar® 3p, h/p/cosmos, Nußdorf, Germany) based on speed increments was conducted (Encarnación-Martínez et al., 2025). As mentioned, the main test consisted of 30-min of continuous running at 80 % of each participant's individual MAS (Encarnación-Martínez et al., 2024), with the treadmill set to a 1 % incline to approximate the energetic cost of outdoor running (Jones & Doust, 1996). Two consecutive 20-s recordings were obtained at each time point (pre- and post-fatigue), capturing more than 50 complete gait cycles per condition for each participant (Encarnación-Martínez et al., 2025). In addition, the RPE was assessed at the beginning (pre) and at the end (post) of the running protocol.

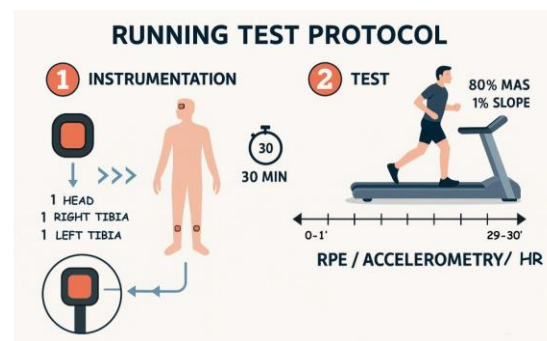


Figure 1. Running test protocol conducted in session 2 of the study. RPE: Rate of Perceived Exertion, HR: Heart Rate.

Data and statistical analysis – Time domain parameters from the tibia and head accelerometers were analysed using a custom routine performed with the MATLAB program (MathWorks, Inc., Natick, MA, USA). Time-domain acceleration signal was filtered using a second-order low-pass Butterworth filter with a cutoff frequency of 50 Hz. The selection of an appropriate filter is critical for accurately capturing impact acceleration signals (Sheerin et al., 2018). Accordingly, a power spectral analysis was conducted to identify the optimal cut-off frequency revealing that most of the signal energy associated with impact accelerations was concentrated below 50 Hz. This filter selection was further supported by previous studies employing similar sensor configurations (Catalá-Vilaplana et al., 2023; Lucas-Cuevas et al., 2015). Stride frequency (Hz), defined as the time between two consecutive leg impact peaks, and stride length (m), were calculated as spatiotemporal variables (Mercer et al., 2002). As variables related with impact acceleration, tibia and head loading rate (g/s) (slope from ground contact to peak acceleration), tibia and head peak acceleration (g) (maximal amplitude of the signal), tibia and head magnitude (g) (difference between the positive and the negative peak, and impact attenuation (%) (reduction in impact acceleration from the tibia to the head) were derived from the acceleration signal (Lucas-Cuevas et al., 2015). Concerning FGs, participants were divided based on changes (results after the

fatigue protocol - results before the fatigue protocol) in BRFs (Willwacher et al., 2022): peak acceleration in the tibia in the time domain analysis. To achieve this, participants were categorised using the unsupervised K-means algorithm with MATLAB software (version R2022b) (Encarnación-Martínez et al., 2025). Prior to grouping, the silhouette method determined the best number of clusters (Rousseeuw, 1987) to feed into the K-means algorithm. The statistical analysis of the data was performed using SPSS v28 (IBM Corp., Armonk, NY). Normality of the data was checked using the Shapiro-Wilk test ($n < 50$). To observe the relationship between FPI and FGs a chi-square test was conducted (Encarnación-Martínez et al., 2025). To analyse the effects of fatigue (intra-subject factor) and grouping in the FGs according to the BRFs (inter-subject factor) on each of the dependent variables (a) Acceleration impacts, (b) Spatiotemporal variables, (c) RPE, (d) HR, a repeated measures analysis of variance (ANOVA) was performed, adjusting significance levels in pairwise comparison using Bonferroni correction ($p \leq 0.05$). Moreover, differences based on FGs were measured using a one-way ANOVA, with significance levels in pairwise comparisons adjusted using Bonferroni correction ($p \leq 0.05$). The assumption of sphericity was assessed using Mauchly's test, and when this assumption was violated, the Huynh–Feldt correction was applied. While multiple dependent variables were analysed, no global adjustment across different outcomes was performed, as they represent distinct

physiological and mechanical domains. However, to minimize Type I error inflation, Bonferroni corrections were strictly applied for all pairwise post-hoc comparisons. Finally, the ES was calculated using partial eta squared (Cohen, 1988) interpreted as: 0.01 = small, 0.06 = moderate, > 0.14 = large. The magnitude of the changes found were expressed using the difference in means and 95 % confidence intervals. The level of significance was set at $p \leq 0.05$.

3. Results

By using the silhouette method, three FGs were identified with FG1 ($n = 18$), FG2 ($n = 8$) and FG3 ($n = 10$) based on variations in BRFs, specifically focusing on tibia peak acceleration. Due to injury ($n = 1$) and errors in the acceleration measurements ($n = 2$), the final sample consisted of thirty-six recreational runners. According to anthropometric and training variables, no significant differences ($p > 0.05$) were observed between FGs (Table 2).

Table 2. Descriptive data (mean $\pm$ standard deviation (SD)) of the functional groups.

Arthrometric variables	FG1 (n = 18)	FG2 (n = 8)	FG3 (n = 10)
Age (years)	30 $\pm$ 11	31 $\pm$ 10	29 $\pm$ 7
Height (m)	1.74 $\pm$ 0.04	1.74 $\pm$ 0.07	1.74 $\pm$ 0.05
Body mass (kg)	72.36 $\pm$ 9.76	72.71 $\pm$ 5.81	75.91 $\pm$ 9.18
Body mass index (BMI) (kg/m ²)	23.90 $\pm$ 2.87	24.02 $\pm$ 2.48	24.89 $\pm$ 2.01
MAS (km/h)	16.51 $\pm$ 1.95	16.29 $\pm$ 1.06	16.32 $\pm$ 1.59
Weekly distance (km/week)	40.61 $\pm$ 16.35	40.63 $\pm$ 19.72	33 $\pm$ 19.61

MAS = Maximal aerobic speed

The FPI conducted by the examiners noted that 61.11 % of the final sample had normal feet, 36.11 % were pronators, and only one participant (2.78 %) had a supinated foot. When analysing the relationship between FGs and FPI, no significant differences were found ($p > 0.05$) (Table 3).

Table 3. Descriptive data (mean $\pm$ SD) of the Foot Posture Index (FPI)

FPI	FG1	FG2	FG3
Normal (n = 22)	55.6 %	50 %	80 %
Pronated (n = 13)	44.4 %	50%	10 %
Supinated (n = 1)	0 %	0 %	10 %

FPI= Foot posture index, FG = Functional group

The 30-min instrumented test showed increases in HR ($p < 0.01$, ES = 0.512; mean diff. = 21.70 bpm, 95 % CI = 14 to 29.3 bpm), and RPE across the total sample ($p < 0.01$, ES = 0.744; mean diff. = 5.9, 95 % CI = 4.60 to 7.10), with the post condition being higher compared to pre-condition (Table 4). However, no differences between FGs were found in HR ($p = 0.447$) and RPE ($p = 0.068$).

Table 4. Descriptive (mean $\pm$ SD) data of the HR and RPE.

		FG1	FG2	FG3
HR (bpm)	PRE	148 $\pm$ 23*	156 $\pm$ 9*	153 $\pm$ 24*
	POST	171 $\pm$ 17	170 $\pm$ 11	180 $\pm$ 11
RPE	PRE	10 $\pm$ 3*	9 $\pm$ 3*	10 $\pm$ 2*
	POST	15 $\pm$ 3	14 $\pm$ 2	17 $\pm$ 2

Results showed as mean $\pm$ SD. HR = Heart rate, RPE = Rating of perceived exertion, PRE = Pre fatigue condition (min 0-1); POST = post-fatigue condition (min 29-30); FG = Functional group. * Differences between pre and post condition ($p < 0.05$).

Results did not show significant differences ($p > 0.05$) in spatiotemporal variables (Table 5). Regarding FGs, the results did not show

significant differences ($p > 0.05$) between groups.

Table 5. Descriptive data (mean $\pm$ SD) of the spatiotemporal parameters.

		FG1	FG2	FG3
Stride Length (m)	PRE	2.61 $\pm$ 0.36	2.62 $\pm$ 0.14	2.55 $\pm$ 0.18
	POST	2.60 $\pm$ 0.38	2.61 $\pm$ 0.12	2.53 $\pm$ 0.21
Stride Frequency (Hz)	PRE	1.41 $\pm$ 0.07	1.40 $\pm$ 0.06	1.42 $\pm$ 0.07
	POST	1.41 $\pm$ 0.05	1.40 $\pm$ 0.06	1.43 $\pm$ 0.06
Step length (m)	PRE	1.30 $\pm$ 0.18	1.30 $\pm$ 0.07	1.25 $\pm$ 0.09
	POST	1.30 $\pm$ 0.20	1.31 $\pm$ 0.05	1.25 $\pm$ 0.10

Results showed as mean $\pm$ SD. FG = Functional group. PRE = Pre fatigue condition (min 0-1'); POST = post-fatigue condition (min 29-30').

Impact acceleration variables showed a significant effect related to fatigue in the overall analysis of the sample (Table 6). Specifically, the head magnitude ($p = 0.037$, $ES = 0.141$; mean diff. = 0.518 g, 95 % CI = 0.033 to 1.004 g), and head loading rate during impact ($p = 0.014$, $ES = 0.192$; mean diff. = 6.363 g, 95 % CI = 1.404 to 11.302 g) showed a significant increase after the running protocol. Additionally, a significant difference was observed between FGs in the impact attenuation. In this regard, the attenuation measured in the left tibia was significantly lower at the FG3 ($p = 0.042$, $ES = 0.197$; mean diff. = 6.643 %, 95 % CI = 0.977 to 12.309 %) compared to FG1, and FG2 ($p = 0.042$, $ES = 0.197$; mean diff. = 7.725 %, 95 % CI = 0.466 to 14.983 %) after the fatigue protocol.

		FG1	FG2	FG3
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R Time Tibial Peak (ms)	PRE	15.57 ± 5.21	14.10 ± 4.29	21.52 ± 17.93
	POST	14.80 ± 4.37	13.69 ± 3.55	19.07 ± 11.55
L Time Tibial Peak (ms)	PRE	15.19 ± 5.74	12.14 ± 6.47	14.37 ± 6.72
	POST	16.79 ± 12.49	11.31 ± 6.72	13.30 ± 7.46
R Tibial peak (g)	PRE	8.45 ± 1.92	9.04 ± 2.20	6.90 ± 1.76
	POST	8.90 ± 1.81	8.93 ± 2.45	7.73 ± 2.70
L Tibial peak (g)	PRE	7.59 ± 1.66	7.68 ± 1.42	6.61 ± 1.38
	POST	7.60 ± 2	7.84 ± 1.39	7.08 ± 1.75
R Head peak (g)	PRE	2.63 ± 0.49	2.58 ± 0.34	2.56 ± 0.23
	POST	2.61 ± 0.50	2.57 ± 0.23	2.56 ± 0.29
L Head peak (g)	PRE	2.50 ± 0.27	2.44 ± 0.21	2.42 ± 0.24
	POST	2.46 ± 0.32	2.44 ± 0.23	2.44 ± 0.37
R Tibial Magnitude (g)	PRE	8.14 ± 2.13	8.98 ± 2.16	6.61 ± 1.93
	POST	8.67 ± 1.89	8.99 ± 2.75	7.62 ± 2.86
L Tibial Magnitude (g)	PRE	7.36 ± 1.85	7.32 ± 1.34	6.29 ± 1.56
	POST	7.49 ± 2.15	7.47 ± 1.67	6.93 ± 1.89
R Head Magnitude (g)	PRE	2.85 ± 0.59	2.87 ± 0.48	2.70 ± 0.26
	POST	2.78 ± 0.64	2.88 ± 0.42	2.74 ± 0.27
L Head Magnitude (g)*	PRE	2.66 ± 0.32	2.68 ± 0.31	2.55 ± 0.18
	POST	2.61 ± 0.38	2.73 ± 0.34	2.59 ± 0.30
R Attenuation (%)	PRE	68.08 ± 6.26	70.55 ± 5-66	61.28 ± 9.02
	POST	70.4 ± 5.09	70.10 ± 6.23	63.92 ± 10.45
L Attenuation (%) †	PRE	66.31 ± 4.81	67.71 ± 5.53	† 62.42 ± 7.62
	POST	66.23 ± 6.71	68.27 ± 5.82	† 63.93 ± 8.64
R Tibial Loading Rate (g/s)	PRE	249.72 ± 118.85	285.87 ± 237.02	161.85 ± 70.72
	POST	232.77 ± 73.66	337.95 ± 279.01	185.54 ± 100.15
L Tibial Loading Rate (g/s)	PRE	192.85 ± 70.56	234.59 ± 176.41	141.96 ± 61.09
	POST	199.43 ± 82.53	179.98 ± 69.01	164.67 ± 79.09
R Head Loading Rate (g/s)	PRE	34.10 ± 13.31	34.24 ± 8.36	33.32 ± 8.29
	POST	33.96 ± 9.66	36.04 ± 8.74	33.21 ± 9.17
L Head Loading Rate (g/s) *	PRE	66.01 ± 17.35	60.80 ± 14.45	60.04 ± 16.85
	POST	66.20 ± 17.02	67.21 ± 18.10	66.65 ± 18.77

Results showed as mean ± SD. FG: Functional Group. PRE: Pre fatigue condition (min 0-1'); POST: post-fatigue condition (min 29-30'). L: left, R: Right. *Differences between pre and post condition ($p < 0.05$). †Differences between FG.

Table 6. Descriptive data (mean ± SD) of time domain variables.

4. Discussion

The main objective of this study was to explore the fatigue-induced responses to BRFs related to impact acceleration, and whether these responses could differentiate FGs of runners by using unsupervised algorithms. The hypothesis suggested that fatigue would induce significant modifications in perceptual, physiological and impact acceleration variables, especially those related to the tibia and head peak accelerations. In this sense, results showed that fatigue led to significant alterations in perceptual and physiological aspects, as well as in impact acceleration variables, and further identified three FGs of runners exhibiting distinct impact attenuation responses following the running protocol. Despite the identification of three FGs, no significant differences were observed ($p > 0.05$) between the anthropometric characteristics and foot type across FGs. These results are in line with those presented by Rivadulla et al. (2024), who identified FGs based on the running technique, but also did not find differences in the anthropometric parameters. In contrast, Trudeau et al. (2015) identified two FGs of runners based on their plantar loading patterns, and participants in one group were notably older than those in the other. These differences may be explained by the present age variability in running population (Rivadulla et al., 2024), which could modify the grouping outcomes. In relation to foot posture, the results showed no significant correlation ($p > 0.05$) between the FPI and the FGs. Most participants

presented a normal foot posture, followed by pronated and supinated foot types. The extreme categories (highly pronated and highly supinated) were not observed in the sample. These results suggest that the foot type appears to be irrelevant among the FGs identified in our study. Regarding physiological parameters, our findings indicate that HR values exhibited a substantial increase across FGs ($p < 0.05$) (Table 4). This rise in HR to levels approaching 180 bpm indicates a high level of exertion, consistent with findings from previous studies (Mercer et al. 2003), wherein a fatigue-inducing protocol resulted in mean post-fatigue HR values of 178 ± 10 beats/min. Similarly, RPE values were markedly elevated ($p < 0.01$) after the fatigue protocol (Table 4). Given that a value of 17 was recorded on the scale following the test. This suggests that the protocol intensity was sufficient to elicit significant perceptual sensations, thereby facilitating the achievement of fatigue states (Encarnación-Martínez et al., 2023). The findings align with previous studies (Lucas-Cuevas et al., 2015), in which a comparable test (30-min at 80 % of MAS) produced post-test values of 17.60 ± 0.50 . As reported in previous studies (Langley, 2023; Rivadulla et al., 2024), physiological and perceptual parameters remained constant across their respective runner's FGs. The homogeneity of the sample may explain the absence of differences in physiological and perceptual responses among FGs. For example, if the study sample was based on ethnicity, some differences could have appeared, as Weston

et al. (1999) demonstrated in their study, African runners exhibited greater fatigue resistance compared to Caucasian. Nonetheless, when comparing RPE across running-performance level runners, the results are quite similar (Hoenig et al., 2019), suggesting that subjective values have lower variability in different populations under fatigue conditions. Spatiotemporal variables have been considered as potential risk factors correlated with the incidence of injuries (Ceyssens et al., 2019); nonetheless, the actual evidence is derived from a limited number of studies, thereby emphasising the necessity for more extensive high-quality prospective investigations to validate their association with injury, ultimately facilitating more rigorous clinical guidelines (Ceyssens et al., 2019). Results showed no statistically significant variances ($p > 0.05$) in the spatiotemporal variables assessed (stride and step length, alongside stride frequency) between the pre-fatigue and post-fatigue conditions (Table 5). Overall, these parameters remained stable, with stride length showing the largest, though non-significant, change after fatigue (Table 5). These findings align with those presented in various studies (Encarnación-Martínez et al., 2022; Lucas-Cuevas et al., 2015), which similarly reported no significant fluctuations in parameters such as stride frequency and stride length under similar treadmill conditions. Conversely, other investigations (Brahms et al., 2022) demonstrated alterations in stride length and stride time following protocols where intensity was calibrated based on performance in the 5-km

test. In contrast, research examining the effects of prolonged time trials, such as marathons, has indicated notable changes in spatiotemporal variables, particularly stride length (Meyer et al., 2021). When comparing FGs, spatiotemporal variables did not differ between groups ($p > 0.05$). These results could also be attributed to sample homogeneity. As Gómez-Molina et al. (2017) investigated, trained runners have higher step rate and shorter step length values compared to untrained runners in a graded exercise test. This suggests that spatiotemporal parameters could not differ across FGs with similar running levels under fatigue conditions. Regarding the effects of acceleration, significant alterations in the magnitude of tibial acceleration were observed post-fatigue onset, with this metric exhibiting heightened values during the post-test condition. These results are consistent with the findings of García-Pérez et al. (2014), who identified a significant increase in the magnitude during treadmill running under fatigued conditions. Nevertheless, studies such as Lucas-Cuevas et al. (2017) did not observe significant changes in this variable following a fatigue protocol. The results indicate that the head loading rate exhibited a significant increase of 4.40 % following fatigue. This finding may be interpreted considering the role of loading rate as a key variable associated with the propagation of shock waves through the musculoskeletal system during locomotor activities (Lucas-Cuevas et al., 2017). Rapidly applied repetitive loads have been shown to be more associated with joint degeneration

(Davis et al., 2004). Therefore, the observed increase in head ratio following fatigue could reflect an altered ability to dissipate impact forces, potentially increasing the mechanical burden on the musculoskeletal system and contributing to injury risk over time. Regarding impact attenuation, not significant alterations ($p > 0.05$) between pre- and post-fatigue conditions were observed. This observation aligns with prior research (Reenalda et al., 2019), which also documented no changes following a 20-min track and field protocol. Nonetheless, the effect of contextual and experimental frameworks is apparent due to investigations such as that conducted by Catalá-Vilaplana et al. (2023), who identified significant disparities when contrasting various surfaces, including the ground and the treadmill. Likewise, García-Pérez et al. (2014) reported no alterations in attenuation following the implementation of a similar fatigue protocol. These inconsistencies among studies may be explained by methodological differences, including accelerometer placement, the specific fatigue protocol, and sample characteristics, which may also affect the observed outcomes (Mercer et al., 2003). Although our research did not reveal discrepancies among FGs concerning anthropometric measurements, foot type, spatiotemporal characteristics, physiological attributes, and perceptual metrics, variations in impact acceleration were evident between the FGs. Impact attenuation manifested significant differences among the FGs. Specifically, FG3 exhibited a diminished attenuation ($63.17 \pm$

8.13) when compared to FG1 (66.27 ± 5.76) and FG2 (67.99 ± 5.67). A reduction in attenuation heightens the susceptibility to spinal injuries as well as degeneration of cartilage and joints (Mizrahi et al., 2000). This phenomenon may be attributed to the fatigue-state that led to the inadequacy or impairment of the musculoskeletal system and anatomical structures to effectively mitigate impacts travelling through the body (Hamill et al., 1995). It is important when measuring impact attenuation, also consider stride length (Mercer et al., 2003). Since stride length was stable after the fatigue protocol and across FGs, it could suggest that runners prefer to maintain their most economical pattern in favour of the metabolic cost, while neglecting more its attenuation (Mercer et al., 2003), and therefore increasing the tissue deformation as more energy propagates up the body, imposing a greater burden on proximal structures (Kiernan et al., 2025) in the FG3. The magnitude of these differences, reflected by moderate-to-large ES (0.197), indicates that the observed changes are not only statistically significant but also biomechanically meaningful. From a mechanical perspective, such alterations in impact attenuation may lead to increased transmission of shock waves through the musculoskeletal system, thereby elevating cumulative loading on proximal structures and potentially contributing to the development of running overuse injuries. The results of this study aligned with those presented by Langley (2023), who identify two FGs of response to rearfoot kinematics after a 5 km protocol using the same K-means

algorithm. The combination of both studies may suggest that fatigue alters both, kinematic and impact variables on an individual basis, which may affect the injury risk of those FGs which had a less homogeneous response at the fatigue state, reinforcing the fact that FGs with different responses may require special training adaptations (Langley, 2023).

5. Practical Applications

The identification of FGs based on individual biomechanical responses to fatigue provides relevant insights for coaches, athletes, and sports scientists aiming to enhance performance and potentially reduce the injury risk in recreational runners. Specifically, the results highlight that not all runners respond homogeneously to fatigue-induced stress, with FG3 displaying reduced impact attenuation capabilities post-fatigue. This subgroup may be more vulnerable to overuse injuries, particularly those affecting the spine and lower extremity joints, due to insufficient mechanical attenuation from impacts while running. From a practical standpoint, coaches and practitioners can leverage these findings to design individualised training programs. Runners demonstrating greater fatigue-induced alterations in impact attenuation, like those in FG3, may benefit from targeted interventions such as strength and neuromuscular training aimed at enhancing lower limb stiffness and impact absorption. Despite its contributions, the study has several limitations that may affect the

generalizability of its findings. First, the use of treadmill running as a controlled testing environment may not fully replicate the biomechanical demands of overground running, where surface variability and environmental factors play a significant role. Secondly, the reliance on the K-means algorithm—an approach that is sensitive to the initial placement of centroids—may influence the formation of clusters. Furthermore, the unequal sample sizes among the identified groups may affect the statistical robustness of the comparisons. In this context, FGs were derived from fatigue-induced changes in acceleration variables, which may introduce some degree of statistical dependency in subsequent between-group comparisons. Additionally, the absence of foot strike pattern analysis and the inclusion of only male runners limit the understanding of its potential influence on impact-related variables, particularly given the known differences in the biomechanical parameters between rearfoot and forefoot strikers, and sexes. Future research should aim to validate these findings in overground running conditions and across diverse populations, including different genders, skill levels, and habitual foot strike patterns. Moreover, longitudinal studies are recommended to investigate whether specific FGs profiles are predictive of future running-related injuries.

6. Conclusions

In conclusion, this study provides valuable insights into the BRFs, and

acceleration impacts associated with running, particularly under fatigue conditions. The findings suggest that fatigue significantly alters perceptual, physiological, and impact acceleration variables, revealing distinct responses among different functional groups of runners. Notably, variations in impact attenuation capabilities were observed, indicating that FG3 exhibited reduced attenuation during running under fatigued conditions. This mechanical response suggests that impacts may propagate more through the body in this group, potentially increasing the mechanical demand on proximal structures. Finally, the identification of specific FGs of runners and their responses to fatigue, allows for more targeted strategies to reduce running-related injury risk and improve runner performance and injury prevention.

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Soriano, P. (2025). Fatigue Effects on Angular Kinematics in Recreational Runners Grouped by Functional Response. The overlapping methodological aspects reflect the standardised protocol employed across the research project. However, the objectives, analyses, and results presented here are distinct and explore different aspects of fatigue-related biomechanical responses. This acknowledgment aims to ensure transparency and proper scholarly attribution.

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References

- Berthon, P., Fellmann, N., Bedu, M., Beaune, B., Dabonneville, M., Coudert, J., & Chamoux, A. (1997). A 5-min running field test as a measurement of maximal aerobic velocity.
- Brahms, C. M., Zhao, Y., Gerhard, D., & Barden, J. M. (2022). Long-range correlations and stride pattern variability in recreational and elite distance runners during a prolonged run. *Gait and Posture*, 92, 487–492. <https://doi.org/10.1016/j.gaitpost.2020.08.10>.
- Borg, G. (1982). Physiological bases of perceived exertion. *Medicine and Science in Sports and Exercise*, 14, 5, 377–381.
- Carter, J. A., Rivadulla, A. R., & Preatoni, E. (2022). A support vector machine algorithm can successfully classify running ability when trained with wearable sensor data from anatomical locations typical of consumer technology. *Sports Biomechanics*. <https://doi.org/10.1080/14763141.2022.2027509>.
- Catalá-Vilaplana, I., Encarnación-Martínez, A., & Pérez-Soriano, P. (2023). Changes in frequency domain accelerations during prolonged running on different surfaces. <https://ssrn.com/abstract=5092565>.

- Catalá-Vilaplana, I., Liu, T., Vienneau, J., Nigg, S. R., Pérez-Soriano, P., & Encarnación-Martínez, A. (2023). Curved non-motorized treadmills do not biomechanically replicate overground running better than motorized treadmills. *Journal of Sports Sciences*, 41(21), 1927–1933. <https://doi.org/10.1080/02640414.2024.2307774>.
- Ceyssens, L., Vanelderen, R., Barton, C., Malliaras, P., & Dingenen, B. (2019). Biomechanical Risk Factors Associated with Running-Related Injuries: A Systematic Review. In *Sports Medicine* (Vol. 49, Issue 7, pp. 1095–1115). Springer International Publishing. <https://doi.org/10.1007/s40279-019-01110-z>.
- Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences* Second Edition.
- Derrick, T. R., Dereu, D., & Mclean, S. P. (2002). Impacts and kinematic adjustments during an exhaustive run. <http://journals.lww.com/acsm-msse>.
- Dillon, S., Burke, A., Whyte, E. F., O'Connor, S., Gore, S., & Moran, K. A. (2022). Are impact accelerations during treadmill running representative of those produced overground? *Gait and Posture*, 98, 195–202. <https://doi.org/10.1016/j.gaitpost.2022.09.076>.
- Encarnación-Martínez, A., García-Gallart, A., Gallardo, A. M., Sánchez-Sáez, J. A., & Sánchez-Sánchez, J. (2018). Effects of structural components of artificial turf on the transmission of impacts in football players. *Sports Biomechanics*, 17(2), 251–260. <https://doi.org/10.1080/14763141.2017.1285347>.
- Encarnación-Martínez, A., García-Gallart, A., Sanchis-Sanchis, R., & Pérez-Soriano, P. (2022). Effects of Central and Peripheral Fatigue on Impact Characteristics during Running. *Sensors*, 22(10). <https://doi.org/10.3390/s22103786>.
- Encarnación-Martínez, A., Sanchis-Sanchis, R., Pérez-Soriano, P., & García-Gallart, A. (2023). Relationship between muscular extensibility, strength and stability and the transmission of impacts during fatigued running. *Sports Biomechanics*, 22(10), 1364–1380. <https://doi.org/10.1080/14763141.2020.1797863>.
- Encarnación-Martínez, A., Sánchez-Ribes, E., Bruna-Lázaro, R., Sanchis-Sanchis, R., Ashby, J., & Pérez-Soriano, P. (2025). Fatigue effects on angular kinematics in male recreational runners grouped by functional response. *Sports Medicine - Open*, 11(1). <https://doi.org/10.1186/s40798-025-00878-x>.
- García-Pérez, J. A., Pérez-Soriano, P., Llana Belloch, S., Lucas-Cuevas, Á. G., & Sánchez-Zuriaga, D. (2014). Effects of treadmill running and fatigue on impact acceleration in distance running. *Sports Biomechanics*, 13(3), 259–266. <https://doi.org/10.1080/14763141.2014.909527>.
- Gómez-Molina, J., Ogueta-Alday, A., Stickley, C., Cámara, J., Cabrejas-Ugartondo, J., & García-López, J. (2017). Differences in spatiotemporal parameters between trained runners and untrained participants. *Journal of Strength and Conditioning Research*, 31(8), 2169–2175. <https://doi.org/10.1519/JSC.0000000000001679>.
- Gruber, A. H., Boyer, K. A., Derrick, T. R., & Hamill, J. (2014). Impact shock frequency components and attenuation in rearfoot and forefoot running. *Journal of Sport and Health Science*, 3(2), 113–121. <https://doi.org/10.1016/j.jshs.2014.03.004>.
- Hamill, J., Derrick, T. R., & Holt, K. G. (1995). Shock attenuation and stride frequency during running. In *Human Movement Science* (Vol. 14).

- Hoenig, T., Hamacher, D., Braumann, K. M., Zech, A., & Hollander, K. (2019). Analysis of running stability during 5000 m running *. *European Journal of Sport Science*, 19(4), 413–421. <https://doi.org/10.1080/17461391.2018.1519040>.
- Izquierdo-Renau, M., Queral, A., Encarnación-Martínez, A., & Perez-Soriano, P. (2021). Impact Acceleration During Prolonged Running While Wearing Conventional Versus Minimalist Shoes. *Research Quarterly for Exercise and Sport*, 92(1), 182–188. <https://doi.org/10.1080/02701367.2020.1726271>.
- Jones, A. M., & Doust, J. H. (1996). A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. *Journal of Sports Sciences*, 14(4), 321–327. <https://doi.org/10.1080/02640419608727717>.
- Kiernan, D., Hawkins, D. A., & Christiansen, B. A. (2025). Differences in 10–20 Hz ‘shock’ attenuation emerge between injured and uninjured runners across a 30-minute run. *Journal of Biomechanics*, 112955. <https://doi.org/10.1016/j.jbiomech.2025.112955>.
- K-means clustering algorithm: a brief review. (2021). *Academic Journal of Computing & Information Science*, 4(5). <https://doi.org/10.25236/ajcis.2021.040506>.
- Langley, B. (2023). Fatigue related changes in rearfoot eversion: a means of functionally grouping runners? *European Journal of Sport Science*, 23(3), 363–371. <https://doi.org/10.1080/17461391.2022.2064768>.
- Lucas-Cuevas, A. G., Camacho-García, A., Llinares, R., Quesada, J. I. P., Llana-Belloch, S., & Pérez-Soriano, P. (2017). Influence of custom-made and prefabricated insoles before and after an intense run. *PLoS ONE*, 12(2). <https://doi.org/10.1371/journal.pone.0173179>.
- Lucas-Cuevas, A. G., Priego Quesada, J. I., Giménez, J. V., Aparicio, I., Jimenez-Perez, I., & Pérez-Soriano, P. (2016). Initiating running barefoot: Effects on muscle activation and impact accelerations in habitually rearfoot shod runners. *European Journal of Sport Science*, 16(8), 1145–1152. <https://doi.org/10.1080/17461391.2016.1197317>.
- Lucas-Cuevas, A. G., Priego-Quesada, J. I., Aparicio, I., Giménez, J. V., Llana-Belloch, S., & Pérez-Soriano, P. (2015). Effect of 3 Weeks Use of Compression Garments on Stride and Impact Shock during a Fatiguing Run. *International Journal of Sports Medicine*, 36(10), 826–831. <https://doi.org/10.1055/s-0035-1548813>.
- Mai, P., Robertz, L., Robbin, J., Thelen, M., Kurz, M., Trudeau, M. B., Weir, G., Hamill, J., & Willwacher, S. (2022). An analytical framework to understand individual running-related injury risk response patterns to footwear. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*. <https://doi.org/10.1177/17543371221100044>.
- Martínez, A. E., Sánchez-Ribes, E., Bruna-Lázaro, R., Sanchis-Sanchis, R., Ashby, J., & Pérez-Soriano, P. (2024). Fatigue Effects on Angular Kinematics in Recreational Runners Grouped by Functional Response. <https://doi.org/10.21203/rs.3.rs-4592427/v1>.
- Mercer, J. A., Bates, B. T., Dufek, J. S., & Hreljac, A. (2003). Characteristics of shocks attenuation during fatigued running. *Journal of Sports Sciences*, 21(11), 911–919. <https://doi.org/10.1080/0264041031000140383>.
- Mercer, J. A., Vance, J., Hreljac, A., & Hamill, J. (2002). Relationship between shock attenuation and stride length during

- running at different (leído) velocities. *European Journal of Applied Physiology*, 87(4–5), 403–408. <https://doi.org/10.1007/s00421-002-0646-9>.
- Meyer, F., Falbriard, M., Mariani, B., Aminian, K., & Millet, G. P. (2021). Continuous Analysis of Marathon Running Using Inertial Sensors: Hitting Two Walls? *International Journal of Sports Medicine*, 42(13), 1182–1190. <https://doi.org/10.1055/a-1432-2336>.
- Mizrahi, J., Verbitsky, O., Isakov, E., & Daily, D. (2000). Effect of fatigue on leg kinematics and impact acceleration in long distance running. In *Human Movement Science* (Vol. 19). www.elsevier.com/locate/humov.
- Nigg, B. M., Baltich, J., Hoerzer, S., & Enders, H. (2015). Running shoes and running injuries: Mythbusting and a proposal for two new paradigms: “Preferred movement path” and “comfort filter.” In *British Journal of Sports Medicine* (Vol. 49, Issue 20, pp. 1290–1294). BMJ Publishing Group. <https://doi.org/10.1136/bjsports-2015-095054>.
- Oja, P., Memon, A. R., Titze, S., Jurakic, D., Chen, S. T., Shrestha, N., Em, S., Matolic, T., Vasankari, T., Heinonen, A., Grgic, J., Koski, P., Kokko, S., Kelly, P., Foster, C., Podnar, H., & Pedisic, Z. (2024). Health Benefits of Different Sports: a Systematic Review and Meta-Analysis of Longitudinal and Intervention Studies Including 2.6 Million Adult Participants. In *Sports Medicine - Open* (Vol. 10, Issue 1). Springer Science and Business Media Deutschland GmbH. <https://doi.org/10.1186/s40798-024-00692-x>.
- Olaya-Cuartero, J., & Villalon, L. (2024). Influence of Fatigue on the Modification of Biomechanical Parameters in Endurance Running: A Systematic Review. <http://www.intjexersci.com>.
- Pedisic, Z., Shrestha, N., Kovalchik, S., Stamatakis, E., Liangruenrom, N., Grgic, J., Titze, S., Biddle, S. J. H., Bauman, A. E., & Oja, P. (2020). Is running associated with a lower risk of all-cause, cardiovascular and cancer mortality, and is the more the better? A systematic review and meta-analysis. In *British Journal of Sports Medicine* (Vol. 54, Issue 15, pp. 898–905). BMJ Publishing Group. <https://doi.org/10.1136/bjsports-2018-100493>.
- Peterson, B., Hawke, F., Spink, M., Sadler, S., Hawes, M., Callister, R., & Chuter, V. (2022). Biomechanical and Musculoskeletal Measurements as Risk Factors for Running-Related Injury in Non-elite Runners: A Systematic Review and Meta-analysis of Prospective Studies. In *Sports Medicine - Open* (Vol. 8, Issue 1). Springer Science and Business Media Deutschland GmbH. <https://doi.org/10.1186/s40798-022-00416-z>.
- Raghunandan, A., Charnoff, J. N., & Matsuwaka, S. T. (2021). The Epidemiology, Risk Factors, and Nonsurgical Treatment of Injuries Related to Endurance Running. <http://journals.lww.com/acsm-csmr>.
- Redmond, A. C., Crosbie, J., & Ouvrier, R. A. (2006). Development and validation of a novel rating system for scoring standing foot posture: The Foot Posture Index. *Clinical Biomechanics*, 21(1), 89–98. <https://doi.org/10.1016/j.clinbiomech.2005.08.002>.
- Reenalda, J., Maartens, E., Buurke, J. H., & Gruber, A. H. (2019). Kinematics and shock attenuation during a prolonged run on the athletic track as measured with inertial magnetic measurement units. *Gait and Posture*, 68, 155–160. <https://doi.org/10.1016/j.gaitpost.2018.11.020>.
- Riazati, S., Caplan, N., Matabuena, M., & Hayes, P. R. (2020). Fatigue Induced Changes in Muscle Strength and Gait Following Two Different Intensity, Energy Expenditure Matched Runs. *Frontiers in Bioengineering and Biotechnology*, 8. <https://doi.org/10.3389/fbioe.2020.00360>.

- Rivadulla, A. R., Chen, X., Cazzola, D., Trewartha, G., & Preatoni, E. (2024). Clustering analysis across different speeds reveals two distinct running techniques with no differences in running economy. *Sports Biomechanics*. <https://doi.org/10.1080/14763141.2024.2372608>.
- Rousseeuw, P. J. (1987). Silhouettes: a graphical aid to the interpretation and validation of cluster analysis. In *Journal of Computational and Applied Mathematics* (Vol. 20).
- Sheerin, K. R., Reid, D., & Besier, T. F. (2019). The measurement of tibial acceleration in runners—A review of the factors that can affect tibial acceleration during running and evidence-based guidelines for its use. In *Gait and Posture* (Vol. 67, pp. 12–24). Elsevier B.V. <https://doi.org/10.1016/j.gaitpost.2018.09.017>.
- Trudeau, M. B., Hoerzer, S., von Tscharnen, V., & Nigg, B. (2015). Functional grouping of runners based on plantar pressure patterns. *Footwear Science*, 7, S148–S149. <https://doi.org/10.1080/19424280.2015.1039078>.
- van Poppel, D., van der Worp, M., Slabbekoorn, A., van den Heuvel, S. S. P., van Middelkoop, M., Koes, B. W., Verhagen, A. P., & Scholten-Peeters, G. G. M. (2021). Risk factors for overuse injuries in short- and long-distance running: A systematic review. *Journal of Sport and Health Science*, 10(1), 14–28. <https://doi.org/10.1016/j.jshs.2020.06.006>.
- Weston, L. R., Karamizrak, O., Smith, A., Noakes, T. D., Myburgh, K. H., & le, A. R. (1999). African runners exhibit greater fatigue resistance, lower lactate accumulation, and higher oxidative enzyme activity. <http://www.jap.org>.
- Willwacher, S., Kurz, M., Robbin, J., Thelen, M., Hamill, J., Kelly, L., & Mai, P. (2022). Running-Related Biomechanical Risk Factors for Overuse Injuries in Distance Runners: A Systematic Review Considering Injury Specificity and the Potentials for Future Research. In *Sports Medicine* (Vol. 52, Issue 8, pp. 1863–1877). Springer Science and Business Media Deutschland GmbH. <https://doi.org/10.1007/s40279-022-01666-3>.