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Research Article

Effects of fatigue on ground reaction force can be minimized with advanced footwear technology

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HIGHLIGHTS
- Fatigue increases the vertical loading rate in recreational male runners
- Advanced Technology Footwear (AFT) reduces impact loading under muscle fatigue
- AFT shoes delay the time to the first peak of ground reaction force
- Resilient midsoles mitigate the biomechanical effects of neuromuscular fatigue
- Midsole energy return is key for injury protection in long-distance running

ABBREVIATIONS

AFT	Advanced Technology Footwear
Fz1	Force of the first peak
GRF	ground reaction force
IA	Impulse Acceleration
ID	Impulse Deceleration
i_Fz1	Time of occurrence of the first peak of GRF
LR100	Loading Rate
STROBE	Strengthening the Reporting of Observational Studies in Epidemiology

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BACKGROUND: Running has gained popularity for purposes ranging from health promotion to high performance, driving demand for equipment that enhances performance and prevents injuries. Footwear, in particular, plays a critical role in influencing footfall, cushioning, and stability. However, the impact of footwear on performance under fatigue remains unclear.
AIM: This study evaluated the biomechanical effects of fatigue on recreational runners using three types of midsoles: Advanced Technology Footwear (AFT), Plate Shoe, and Control.
METHODS: Twenty male runners (age 39.6±8.2 years, weight 71.4±6.1 kg, height 1.70±0.05 m) ran at ±11 km/h on a track equipped with force platforms, with assessments conducted pre- and post-fatigue.
RESULTS: Fatigue was confirmed by elevated lactate levels, while ground reaction force (GRF) variables were analyzed. Significant differences in Loading Rate (LR100) were observed pre- and post-fatigue across all conditions. AFT shoes demonstrated a lower (LR100 compared to other footwear, suggesting better injury protection even under fatigue.
INTERPRETATION: These findings underscore the importance of footwear choice in mitigating injury risks, particularly during fatigued states.

KEYWORDS: Fatigue | Footwear | Biomechanics | Running

INTRODUCTION

Leisure running, one of the most popular forms of physical exercise for health maintenance, has shown significant growth in the number of participants in recent times [1]. In addition to its health benefits, running has become a form of socialization, stress relief, and even an opportunity for personal development, attracting individuals with motivations ranging from the pursuit of aesthetics to participation in competitive activities [2]. This growth has led to increased economic investment in more specialized equipment, especially in the footwear sector, which stands out as one of the main elements for both performance and leisure in running practice. Footwear, in particular, has undergone significant evolution in recent years, with the introduction of technological foams in midsoles, creating a new category of products that have shown significant performance gains, especially among elite athletes [3].

These innovations have been described in the literature as Advanced Technology Footwear (ATF), a term that encompasses shoes designed with novel midsole materials, increased stack height, curved carbon-fiber plates, and optimized rocker geometries [3]. Such features aim to improve running economy, reduce energy cost, and enhance propulsion efficiency. Importantly, ATF differ from traditional running shoes not only in cushioning and material properties but also in their mechanical capacity to store and return energy during stance [3]. Although these technologies have demonstrated clear benefits in performance, questions remain about their broader biomechanical and injury-prevention implications.

When it comes to injury protection, the evidence is not as clear. Studies have questioned the effectiveness of footwear technologies in protecting athletes and recreational runners [4]. Interestingly, from the perspective of fatigue, few studies have analyzed its influence on performance and the increased injury risk in runners using different types of footwear [5,3,6]. Muscle fatigue is widely discussed in the scientific literature, being defined as the inability to maintain the necessary strength for performance, increasing the perception of effort and compromising sports performance [7].It can be divided into acute and chronic, with the first related to physiological changes during training and competitions, and the second to the accumulation of incomplete recovery processes over extended training periods [8].

Fatigue can also be classified as central, affecting neuronal motor control, or peripheral, associated with the malfunction of the motor unit and skeletal muscle [8]. Studies on peripheral muscle fatigue, which is particularly relevant in running due to the cyclical and repetitive nature of the activity, point to a series of mechanisms that affect performance, such as neuromuscular transmission and calcium regulation by the sarcoplasmic reticulum [9]. Considering that footwear may act as a protective tool in fatigue situations, it is essential to understand how different midsole technologies, especially ATF, can influence running biomechanics under these conditions.

Therefore, the aim of this study is to evaluate the biomechanical changes in running induced by fatigue using three different footwear midsole technologies, including models representative of ATF. The secondary objectives include comparing the influence of these technologies pre- and post-fatigue and determining which midsole offers the greatest performance support and biomechanical protection under these conditions.

METHODS

This study was approved by the Ethics Committee of the Serra Gaúcha University Center - FSG, with CAAE number 79320124.9.0000.5668 and Approval Opinion number 6.931.128. The study was conducted between August and October 2024, following all appropriate ethical procedures in accordance with the Helsinki resolution and adapted to resolution 466/12 and Law No. 14.874/2024 regarding research involving human beings.

Participants read and signed the informed consent form agreeing to participate in the study. For the writing of this study, we followed the recommendations of "The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) Statement: guidelines for reporting observational studies" 10.

Participants

The study included recreational male runners, aged between 18 and 55 years, who are familiar with running in footwear, train at least 5 times a week, and accumulate a minimum of 50 kilometers per week. The average pace for a 10km race was 4:00 min/km, with the methodological requirement being that all participants wore shoe sizes 42 EUR or 43 EUR. Participants were excluded if they had an injury, cardiovascular, neurological, musculoskeletal impairments, or if they did not meet the shoe size requirements.

Sample Size

The sample size was calculated using G*Power 3.1 software, based on the following parameters: an effect size of 0.25, a statistical power ($1 - \beta$) of 0.80, and a significance level (α) of 0.05. This effect size was derived from a previous study that reported higher values for the variable analyzed [11]. Based on these calculations, a minimum of 20 participants was determined for inclusion in the study.

Equipment and Measure

Lactate Measure

The maximum blood lactate concentration after exhaustive exercise, often associated with muscle fatigue, is frequently considered a measure of anaerobic glycolytic capacity [10]. Therefore, this is an important parameter widely used to determine endurance capacity, as excessive lactate production limits the duration and intensity of exercise [12].

The physiological lactate parameters were measured using an Accutrend® Plus (Roche Diagnostics, Mannheim, Germany), a portable device validated for measuring lactate in capillary blood samples. The blood samples were obtained through a puncture in the earlobe, using a 1.5 mm lancet from G-Tech, ensuring precise and minimally invasive perforation.

Ground Reaction Force

The Ground Reaction Force (GRF) can be explained as the force exerted by the ground in response to the impact of the human body touching the ground, as during walking or running. This force acts in the opposite direction to the body's movement and is essential for understanding load distribution and the impact effect on joints and muscles. Evaluating ground reaction force allows for the study of the mechanical interactions between the body and the ground, helping to identify movement patterns and potential deviations that might affect the muscles [13]. For measuring the ground reaction force, two force platforms (AMTI BP600600, Watertown, MA), embedded in the floor and sampling at 1200 Hz. The speed of the test was monitored by two photodetectors placed 3 meters apart, one positioned immediately before platform 1 and the other after platform 2.

Procedures and Measurements

Participants were evaluated in a single experimental session during which three different midsole technologies were tested. Each test was separated by a minimum interval of 20 minutes to ensure full recovery from the fatigue induced by the previous condition. Upon arrival, participants completed a health history questionnaire, and anthropometric data were collected using a stadiometer, scale, measuring tape, and caliper. Subsequently, they underwent a habituation phase, during which they became accustomed to the laboratory environment, the equipment, and the running procedures prior to data collection (Figure 1).

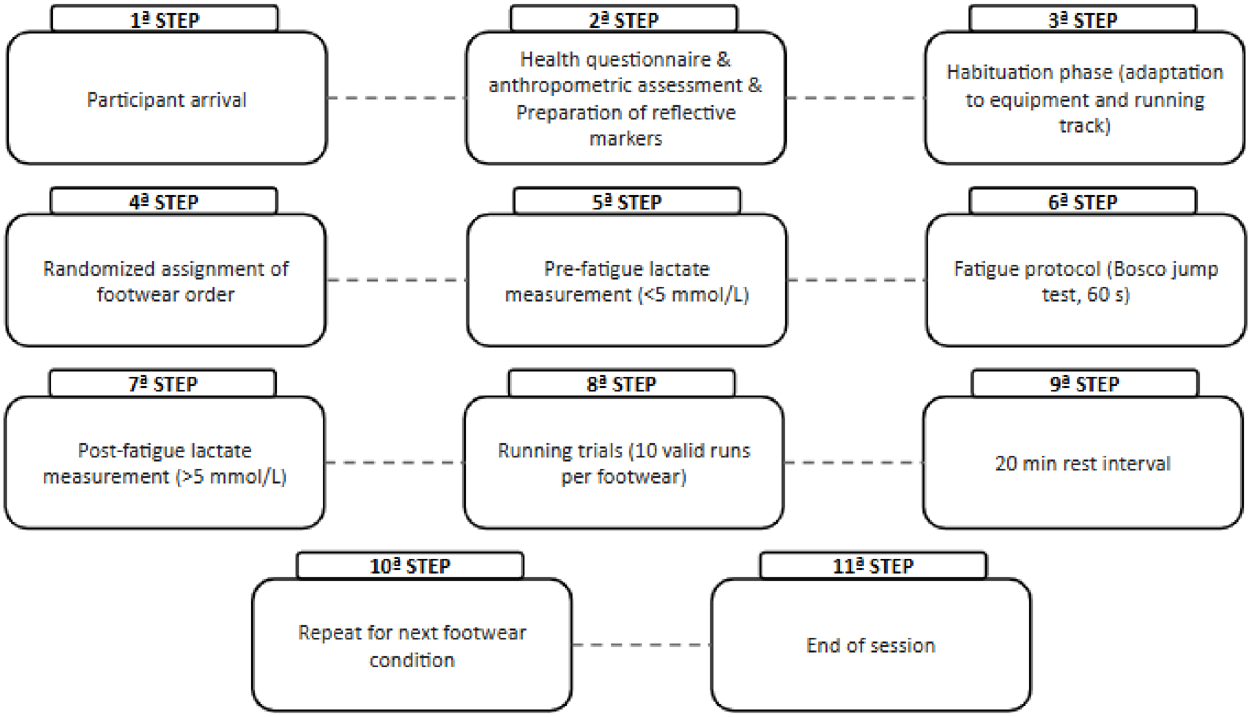

Figure 1. Flow chart data collect.

Fatigue Protocol

After the familiarization phase, a lactate test was performed prior to fatigue, with values expected to be < 5.0 mmol/L. The fatigue protocol began with a 5-minute warm-up at a light jog, followed Bosco jump protocol [14], which consists of performing a countermovement jump, bringing the knee to a 90-degree flexion multiple times with maximum effort during 60 seconds. After these consecutive jumps, lactate was collected using a lactometer, with a small puncture in the earlobe for blood sample collection. Immediately after lactate collection, dynamic assessments were conducted, repeating the process with each footwear condition.

Running Protocol

Prior to the running measurements, a calibration procedure was performed following the habituation phase. Each participant was instructed to run along a straight 25-meter runway, maintaining a self-selected, constant speed and a natural stride pattern, with the objective of landing with the dominant foot on at least one of the force platforms positioned at the center of the runway (12.5 meters from the starting point) (Figure 2). Participants completed a 5-minute familiarization run for each footwear condition to adapt to the shoes and testing environment. This procedure followed methodological recommendations adopted in previous studies on running biomechanics6. Each participant performed running trials using 3 different shoe models: one Control Shoe with an EVA midsole, other with similar Control Shoe however using a carbon plate and the other with a AFT shoe, in which PEBA midsole and carbon plate. These shoes featured and the order of footwear conditions was randomized.

The main experimental phase consisted of 10 valid running trials for each footwear condition, divided into 2 time points: pre-fatigue and post-fatigue. A trial was considered valid when the participant hit at least one force platform with the dominant foot without altering their natural running pattern. The order of testing conditions was randomized, and a minimum 20-minute rest interval was provided between conditions to avoid the influence of residual fatigue.

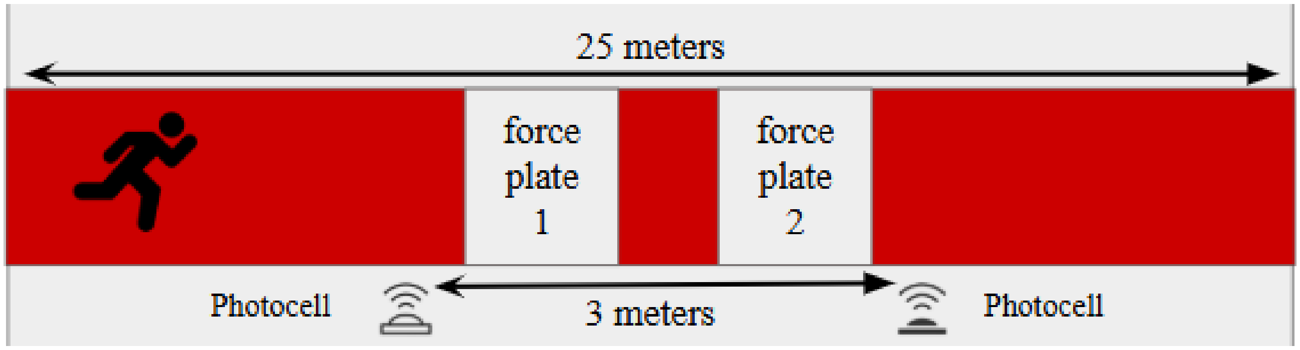

Figure 2. Set of laboratory to running protocol, photocell and force plate.

Conditions - Types of Footwear

To ensure an impartial and comprehensive approach to evaluating athlete performance and the study's results, each participant was provided with three distinct pairs of footwear, randomly assigned before the start of the data collection: ATF (Advanced Technology Footwear), Plate Shoe, and Control.

The characteristics of each shoe was performed the mechanical characterization of the midsoles, using uniaxial compression tests in which consisted of a universal testing machine (Instron model 5944), equipped with a load cell. The testing protocol followed the guidelines established by ASTM F1976-24. The compression system was adapted with a vertically mounted linear actuator attached to the load cell, allowing controlled compression at specific midsole regions. Each shoe was placed on a rigid anatomical support platform, and the compressive force was applied orthogonally to the ground (Figure 3). For forefoot testing, the actuator was positioned at the region corresponding to the metatarsal heads, whereas for rearfoot testing, the actuator was repositioned to the posterior region near the heel counter, in accordance with anatomical load distribution zones described in the literature [13,15] (Figure 4). Force and displacement data were recorded continuously, generating load-deformation curves from which elastic energy, dissipated energy, and system stiffness values were extracted. Additional calculations included stored energy, energy loss, and material response time. A standardized load of 750 N was applied at a compression velocity of 1.00 m/s. The location of the force application on the shoe followed the protocol recommended by World Athletics [16]: 12% of the internal shoe length for the rearfoot (heel region) and 75% for the forefoot (metatarsal region) (Figure 4).

Figure 3. Equipment for measuring energy loss, force apply in rearfoot and forefoot.

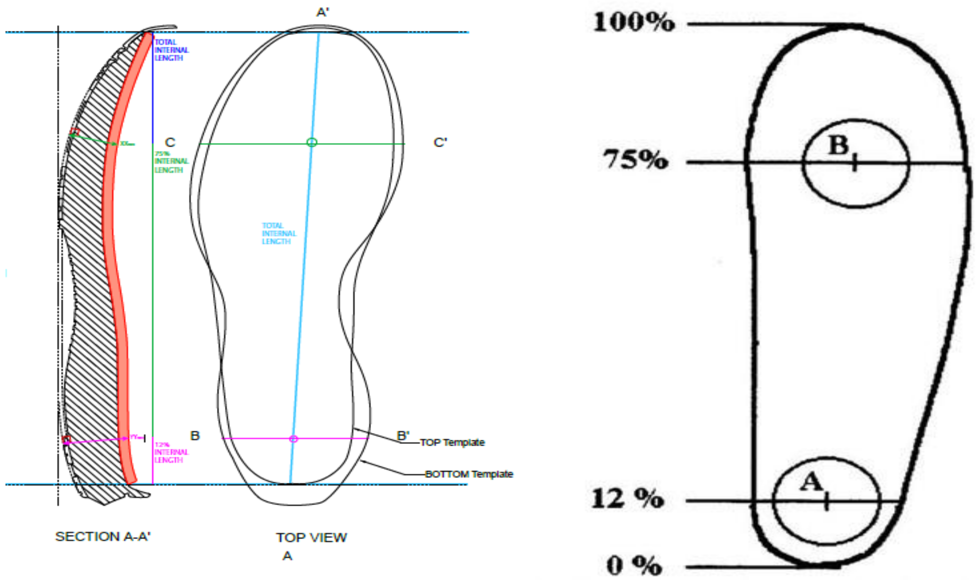

Figure 4. Position of the applied force in agreed of the recommendation Word Athletics rules and ASTM F1976:24.

Signal Analysis and Processing

The GRF data were exported in txt format into the Nexus® software (Oxford, UK). After export, these files were processed in Matlab® software (Stanford, USA) using algorithms to calculate and obtain the variables of interest for this study. The extracted and calculated variables for this study were as follows, presented by their equations (Figure 5 and Figure 6):

- Fz1 = Force of the first peak
- i_fz1 = Time of occurrence of the first peak of ground reaction force

Equation 1	Equation 2	Equation 3	Equation 4
$\int_{T1}^{T0} Fz$	$\Delta F / \Delta tempo$	$\int_{Iníciofy}^{Início \propto Fy}$	$\int_{Início \propto} Fimy\ Fy$
Vertical Impulse	LR100	ID	IA

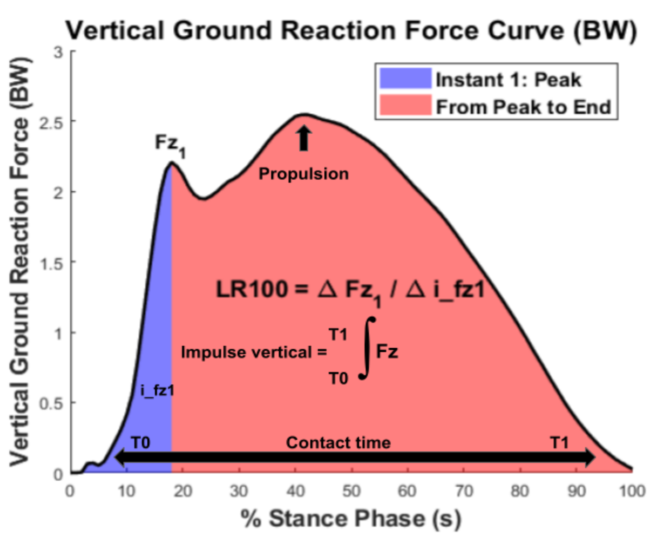

Figure 5. Vertical ground reaction force curve and the variables extracted for analysis.

In addition to the vertical ground reaction force variables, two anteroposterior impulse variables were calculated: Impulse Deceleration (ID) and Impulse Acceleration (IA). These variables represent the integral of the anteroposterior ground reaction force (Fy) over time, corresponding respectively to the braking and propulsion phases of the stance. ID was obtained from the negative portion of the Fy–time curve, reflecting the total impulse generated to decelerate the body's forward momentum at ground contact. Conversely, IA was computed from the positive portion of the curve, representing the propulsive impulse that accelerates the body forward during toe-off. Both variables were calculated using the trapezoidal numerical integration method and are expressed in N·s [17,18].

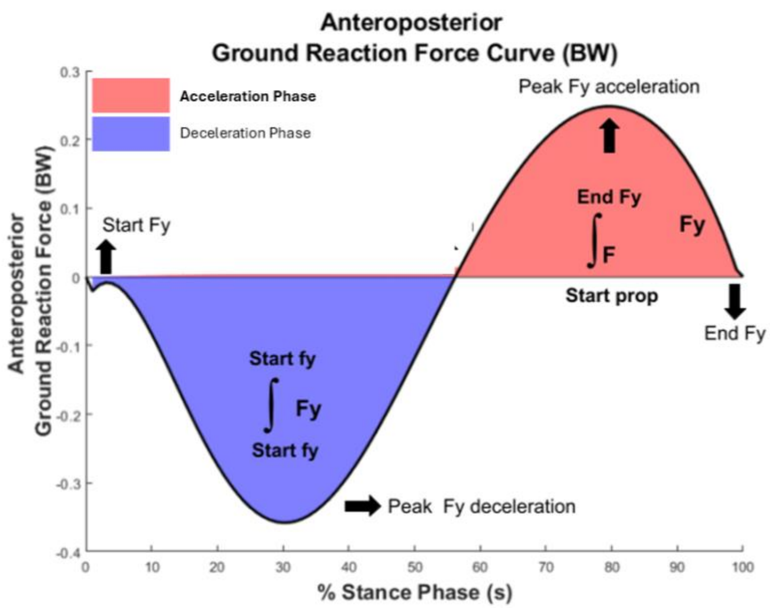

Figure 6. Anteroposterior ground reaction force and its analyzed variables.

Statistical Analysis

The statistical analysis was performed using SPSS 20.0 software and a Google Sheets spreadsheet for organizing, building tables, and calculating the means of the analyzed variables. First, the normality of the data was checked using the Shapiro-Wilk test, which has the null hypothesis that the variables follow a normal distribution, with no significant difference between our dataset and the normality distribution curve ($p > 0.05$).

For the comparative analysis between the footwear conditions, a 2-factor ANOVA (Fatigue and Footwear) was used, with fatigue having 2 levels and footwear having 3 levels (3x2 ANOVA). After performing the ANOVA, differences between the conditions were determined using the post-hoc Bonferroni test. The significance level adopted for all tests was $\alpha < 0.05$.

RESULTS

The mechanical characterization of the midsoles revealed clear differences between the Control Shoe (EVA), Plate Shoe and the Advanced Technology Footwear (ATF – PEBA). The ATF condition demonstrated a higher peak acceleration (9.63 G vs. 9.40 G) and greater peak energy absorption (5.40 J vs. 5.05 J) when compared to the Control Shoe and Plate, the inserted of the carbon plate unaffected this characteristic of the midsole in this test. In terms of temporal dynamics, time to peak force was slightly longer in the ATF (0.214 s) than in the Control (0.195 s) and Plate (0.197). Material stiffness was substantially higher in the ATF (38.0 N/mm) compared to the Control Shoe and Plate (13.5 N/mm), while energy dissipation was reduced (20% vs. 35%) resulting in greater energy return in the ATF (80%) compared to the Control and Plate (65%). Interestingly, although the EVA shoe presented a slightly higher hardness value (45 vs. 42 Asker C), the ATF had a denser midsole (0.13 vs. 0.11 g/cm³) and slightly greater total mass (ATF 240 g vs. Control 230 g and Plate 238 g) Table 1.

Twenty runners participated in this study, with an average age of 39.8 ± 7.6 years, height of 1.75 ± 0.05 meters, and body mass of 71.4 ± 6.3 kg. All athletes had an average weekly training frequency of 6 times and a training volume of 90.00 ± 19.0 km.

The lactate test showed a significant mean difference between pre- and post-test values ($p < 0.05$; 2.93 ± 1.47 mmol/L and 6.76 ± 2.16 mmol/L, respectively). The mean differences between the footwear conditions are presented in Table 2.

Table 1. Physical measures results.

Physical Variables	**Shoe EVA (Control Shoe)** 	**Shoe EVA (Plate)** 	**Shoe PEBA (ATF)** 
Peak G (G)	9,40	9,40	9,63
Peak Energy (J)	5,05	5,05	5,40
Time to Peak (s)	0,195	0,198	0,214
Stiffness Material (N/mm)	13,5	13,5	38,0
Energy Loss (%)	35%	35%	20%
Return Energy (%)	60%	60%	80%
Hardness (Asker C)	45	45	42
Density (gcm³)	0,11	0,11	0,13
Mass (g)	230	238	240

Table 2. Descriptive data of the lactate measurement statistics for the footwear conditions and PRE and POST fatigue situations.

	Pre			**Post**		
	ATF	Plate	Control	ATF	Plate	Control
Mean	3,1	1,3	2,9	6,4	6,5	7,1
SD	1,3	1,7	1,4	1,5	2,1	2,2
Interval Confidence 95%	1,5 – 0,3	1,7 – 0,2	1,5 -0,3	2,8-1,5	3,8-2,0	4,6-2,6

Regarding the running speed during the test, it was controlled across the subjects so that each one ran at their comfortable pace, but maintaining a consistent speed across the different footwear and physical conditions. Thus, the average speed of the test was 11.2 ± 0.9 km/h.

With respect to the evaluation of Ground Reaction Force (GRF), we highlight the results found for i_fz1 and LR100. For i_fz1, a statistically significant difference ($p < 0.05$) was observed between the conditions, showing a higher i_fz1 for the ATF compared to the Plate and Control conditions (Table 3). Regarding LR100, a significant difference ($p < 0.05$) was identified between the pre- and post-fatigue conditions for all footwear types (Table 3). There was also a significant difference between the footwear conditions, with the ATF showing a lower LR100 compared to the other footwear types ($F = 4.52$, $P = 0.01$, $\eta^2 = 0.07$), as shown in Figure 7.

For the other variables analyzed, no statistically significant differences were found ($p > 0.05$). However, some of these variables showed important effects, such as Fz1 (first peak of vertical ground reaction force) across the footwear conditions. Both pre- and post-fatigue, the average values varied from 2.00 PC to 2.12 PC.

Table 3. Results of the factorial ANOVA for the ground reaction force measurements, in the three footwear.

	PRE						POST					
	ATF		**PLATE**		**CONTROL**		**ATF**		**PLATE**		**CONTROL**	
Fz1	2,12	±0,43	2,02	±0,43	2,00	±0,44	2,08	±0,44	2,07	±0,50	2,01	±0,49
i_fz1	***0,042**	**±0,01**	0,034	±0,007	0,035	±0,007	0,040	±0,007	0,036	±0,008	0,034	±0,008
LR100	***†50,0**	**±12,3**	**†59,5**	**±14,2**	**†58,4**	**±14,6**	***53,8**	***±11,91**	61,6	±15,0	61,8	±15,0
VerticalImpulse	383,4	±28,3	386,7	±27,09	383,08	±27,2	385,8	±26,21	384,4	±26,8	384,3	±24,9
Moment of Propulsion	0,157	±0,013	0,161	±0,015	0,161	±0,015	0,160	±0,014	0,161	0,016	0,164	±0,015
Moment Fy	0,053	±0,013	0,049	±0,012	0,050	±0,014	0,051	±0,015	0,047	±0,015	0,049	±0,016
Deceleration	-25,1	±6,25	-26,0	±6,15	-25,0	±7,90	-24,9	±6,19	-25,5	±6,86	-25,8	±5,99
Fy Peak	-0,422	±0,088	-0,42	±0,084	-0,416	±0,099	-0,42	±0,074	-0,42	±0,078	-0,41	0,075
Acceleration	23,0	±5,2	22,9	±4,5	23,1	±5,6	22,8	±4,0	22,9	±5,0	22,2	±3,3
Contact Time	0,207	±0,017	0,210	±0,016	0,208	±0,017	0,211	±0,015	0,210	±0,015	0,212	±0,015

Legend: Advanced Technology Footwear (ATF); Moment of occurrence of the first ground reaction force peak (i_fz1); First peak force (Fz_1); Force Application Rate (LR100).
*Statistically significant p<0.05, compared to the PLATE SHOE and CONTROL SHOE conditions.
†Statistically significant PRE and POST p<0.05.
Data are presented as mean ± SD.

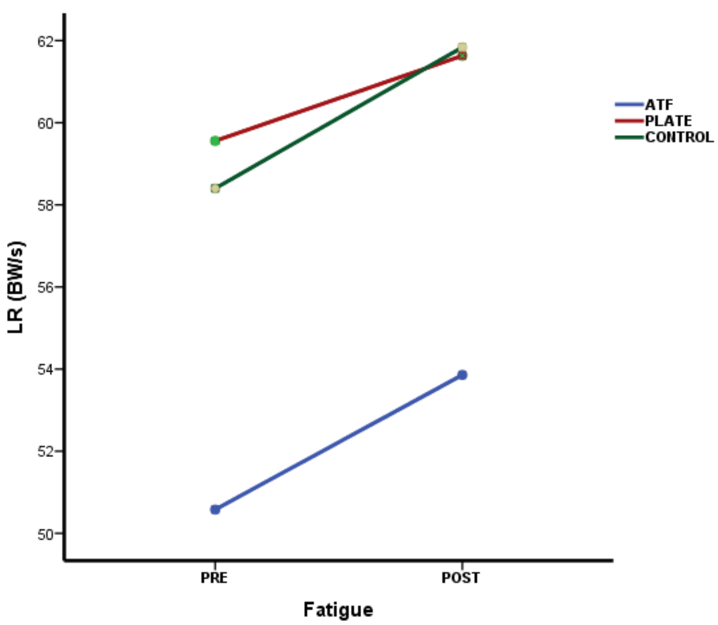

Figure 7. Graph of LR100 for the footwear conditions and PRE and POST fatigue situations.

DISCUSSION

This study aimed to evaluate the biomechanical changes in running induced by fatigue using three different midsole technologies (ATF, Plate Shoe, and Control). The primary findings were that (1) fatigue significantly affected the Loading Rate (LR100), whereas other kinetic variables remained relatively stable, (2) the ATF shoe preserved lower loading rates post-fatigue compared with the Plate and Control shoes, and (3) fatigue was effectively induced, as confirmed by increased lactate concentrations and perceptual exhaustion, validating the reliability of the fatigue protocol, and (4) footwear physical properties, particularly energy return and stiffness, appeared to play a critical role in modulating fatigue-related alterations. These results collectively suggest that footwear technology may mitigate some of the deleterious effects of fatigue on impact mechanics, with implications for performance and injury prevention.

The elevation in blood lactate concentrations across all footwear conditions confirms that the fatigue protocol was effective. Although one participant did not surpass the 5 $mmol \cdot L^{-1}$ threshold, subjective reports of exhaustion and increases in lactate relative to baseline support the validity of fatigue induction, consistent with recommendations in exercise physiology [19]. The mean lactate values post-fatigue (6.4–7.1 mmol·L⁻¹) fall within the range typically reported in fatigue protocols involving high-intensity running [20], reinforcing the reliability of the protocol. The combination of objective (lactate) and subjective measures aligns with prior studies that highlight the multidimensional nature of fatigue, encompassing both peripheral metabolic disturbances and central neuromuscular impairments [21,22].

Physical characterization revealed marked differences between the ATF and the other shoe conditions. The ATF midsole, constructed with PEBA, exhibited greater stiffness (38 $N \cdot mm^{-1}$ vs. 13.5 $N \cdot mm^{-1}$), higher energy return (80% vs. 65%), and lower energy loss (20% vs. 35%). These properties are consistent with recent findings that highly resilient midsoles enhance elastic energy reutilization and reduce metabolic cost during running [3]. The greater density and mass of the ATF shoe (0.13 $g \cdot cm^3$; 240 g) compared with the control shoe (0.11 $g \cdot cm^3$; 230 g) did not appear to offset these mechanical benefits. Previous work has demonstrated that small increases in shoe mass have negligible effects compared with the energy savings provided by resilient midsole materials [3]. Thus, the superior physical characteristics of the ATF shoe likely contributed to the observed attenuation of loading rates under fatigue.

Consistent with prior literature, fatigue was associated with an increase in loading rate (LR100), reflecting a diminished capacity of the neuromuscular system to attenuate impact forces [9]. Elevated loading rates have been repeatedly linked to overuse injuries, such as tibial stress fractures and tendinopathies [23], underscoring the clinical relevance of this finding. Interestingly, while most footwear conditions exhibited significant increases in LR100 post-fatigue, the ATF shoe preserved lower values both pre- and post-fatigue. This suggests a potential protective effect of advanced midsole resilience, supporting the hypothesis that footwear can act as an external protective factor; however, this assumption should be further tested in future prospective clinical studies to confirm its practical implications. The moment of occurrence of the first vertical force peak (i_fz1) was also influenced by footwear, ATF exhibited slightly delayed timing compared with the control and plate conditions, both pre- and post-fatigue. A later occurrence of the first peak force is consistent with greater cushioning capacity, as it reflects a longer time to load application, distributing forces more gradually. Prior work has shown that delayed peak force can reduce mechanical stress on musculoskeletal tissues [11,24]. The combination of reduced loading rates and delayed peak timing in ATF provides converging evidence for its protective role under fatigue.

Interestingly, other kinetic variables, such as vertical impulse, peak forces, and moments of deceleration and propulsion, did not differ significantly across shoe conditions or fatigue states. This apparent stability in these variables, may reflect compensatory neuromuscular strategies. Experienced runners often adapt their kinematics, including ankle, knee, and hip joint angles, to maintain performance under fatigue, even in the face of altered kinetics [25,26]. Such adaptations may buffer the differences across footwear, thereby reducing the likelihood of detecting significant effects in secondary outcomes. The absence of kinematic or EMG data in the present study limits our ability to confirm this explanation, but the hypothesis aligns with prior studies demonstrating the interplay between kinetics, kinematics, and muscle activation in fatigued states [20,22]. Our findings both corroborate and challenge existing evidence regarding the role of footwear under fatigue. However, the protective effect of ATF aligns with recent studies demonstrating that resilient midsoles enhance running economy and alter impact mechanics [27]. On the other hand, they contrast with the hypothesis proposed by Kulmala et al. (2018), who suggested that softer midsoles may impair cushioning at higher speeds due to rapid compression-rebound cycles. In the present study, the ATF shoe, despite being relatively soft (42 Asker C vs. 45 in the control), reduced loading rates under fatigue. This apparent contradiction may be explained by the unique material composition of ATF, which combines softness with high resilience, enabling both cushioning and efficient energy return. Thus, not all “soft” midsoles behave equivalently, material composition and rebound properties are key determinants of biomechanical outcomes. These results also contribute to the ongoing debate about whether footwear effects are more pronounced in non-fatigued or fatigued states. While some studies report minimal footwear effects during fresh running conditions [20], the current findings suggest that differences may become more evident under fatigue, when the intrinsic shock absorbing capacity of the musculoskeletal system is compromised. This perspective aligns with the mass-spring model, in which external devices such as footwear can provide compensatory resilience when biological tissues are unable to do so efficiently [28]. From a broader theoretical standpoint, the results highlight the complex interaction between fatigue, biomechanics, and external conditions. Fatigue induces alterations in neuromuscular control, including reduced muscle firing frequency, impaired calcium handling, and metabolic disturbances [21,29]. These impairments reduce the musculoskeletal system’s capacity to attenuate impact forces, increasing the reliance on external aids. In this context, footwear emerges not merely as a performance enhancing device but as an external factor that directly modulates fatigue. This perspective underscores the need to evaluate footwear technologies not only in fresh conditions but also under fatigue, which more closely reflects real-world training and competition.

Study Limitations

Several limitations should be acknowledged. First, the laboratory environment may not perfectly replicate outdoor running, although such protocols are widely adopted and validated. Second, although lactate is a standard fatigue marker, it does not capture central fatigue mechanisms; complementary measures (e.g., EMG, heart rate variability) could enrich the analysis. Third, one participant did not reach 5 mmol/L of lactate, but clear subjective and observable fatigue signs justified inclusion. Finally, the relatively small sample size may have limited statistical power for secondary outcomes, suggesting caution in interpreting nonsignificant results.

Applications

This study provides practical implications for coaches, physiotherapists, and footwear designers. For practitioners, understanding that LR100 increases under fatigue reinforces the need for customize training strategies, recovery planning, and appropriate footwear prescriptions. The superior performance of ATF shoes in attenuating loading rate suggests they may reduce injury risk in long-distance runners, particularly under fatigue. For the footwear industry, our findings highlight the importance of combining material softness with high energy return to maximize both cushioning and resilience.

A randomized clinical trial would be essential to provide a more solid understanding of the chronic effects of these footwear-related alterations. Additionally, simulating more realistic fatigue conditions, such as post-race states, could enhance the ecological validity of the findings. Future research should also compare other biomechanical and physiological measures (e.g., oxygen uptake, EMG) would contribute to a more comprehensive understanding of the multi-system effects of fatigue and footwear technology.

CONCLUSION

The results showed that fatigue significantly affects running biomechanics, particularly the Loading Rate (LR100), which was influenced by both fatigue condition and shoe type. The ATF shoe demonstrated superior performance in attenuating LR100, indicating that advanced midsole technologies may contribute to reducing mechanical loading on the musculoskeletal system, even under fatigue conditions.

The capacity of the ATF shoe to modulate force application throughout the running cycle regardless of fatigue emerges as a potentially relevant factor when selecting footwear for training or competition, especially among high-performance athletes. Additionally, the timing of the first vertical force peak (i_fz1) was also affected by shoe type, reinforcing the role of mechanical characteristics in influencing impact dynamics. Overall, this study adds to the understanding of how footwear properties interact with fatigue to influence impact mechanics during running. While the findings suggest a possible biomechanical advantage of advanced midsole designs, these interpretations should be viewed in the context of the study's acute design. Future longitudinal investigations are needed to verify whether such biomechanical adaptations translate into measurable effects on injury incidence or performance outcomes.

From a practical standpoint, trainers and physiotherapists may consider these biomechanical responses when advising runners on footwear selection and training strategies, particularly under conditions of muscular fatigue.

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