EGAS MONIZ SCHOOL of HEALTH & SCIENCE | ESCOLA SUPERIOR DE SAÚDE EGAS MONIZ

ESCOLA SUPERIOR DE SAÚDE EGAS MONIZ

MESTRADO EM FISIOTERAPIA

VARIABILITY OF GROUND REACTION FORCES BETWEEN LOWER LIMBS DURING RUNNING IN MALE AND FEMALE RUGBY PLAYERS AFTER HAMSTRINGS INJURY: A CROSS-SECTIONAL STUDY

Trabalho submetido por
Nuno Miguel Toureiro Marques
para a obtenção do grau de Mestre em Fisioterapia

julho de 2025

EGAS MONIZ SCHOOL of HEALTH & SCIENCE | ESCOLA SUPERIOR DE SAÚDE EGAS MONIZ

ESCOLA SUPERIOR DE SAÚDE EGAS MONIZ

MESTRADO EM FISIOTERAPIA

VARIABILITY OF GROUND REACTION FORCES BETWEEN LOWER LIMBS DURING RUNNING IN MALE AND FEMALE RUGBY PLAYERS AFTER HAMSTRINGS INJURY: A CROSS-SECTIONAL STUDY

Trabalho submetido por
Nuno Miguel Toureiro Marques
para a obtenção do grau de Mestre em Fisioterapia

Trabalho orientado por
Professor Doutor Paulo Ricardo Miranda Oliveira

e coorientado por
Professor Doutor Orlando de Jesus Semedo Mendes Fernandes

julho de 2025

"Substituí os medos pelos sonhos, não sejais administradores de medos, mas empreendedores de sonhos!"

Papa Francisco, JMJ Lisboa (2023)

Esta dissertação é dedicada ao meu avô Octávio Toureiro

Acknowledgement

Concluir este trabalho representa o culminar de uma jornada que não teria sido possível sem o apoio de tantas pessoas e instituições.

Ao meu orientador, **Professor Doutor Paulo Oliveira**, agradeço pela paciência e excelente orientação e dedicação ao longo deste percurso e de todo o processo desta dissertação. Ao meu coorientador, **Professor Doutor Orlando Fernandes**, agradeço pelos conhecimentos e contributos que enriqueceram este trabalho.

Agradeço à **Escola Superior de Saúde Egas Moniz**, escola que me vê crescer desde 2016, ao **Professor Doutor João Vaz** e a todos os professores por todo o que me ensinaram e por tudo o que contribuíram para o meu enriquecimento pessoal e profissional. Foi sem dúvida, dois anos de muita aprendizagem, de muito trabalho, mas que valeu sem dúvida a pena. Aos meus colegas de mestrado, agradeço todos os momentos de apoio mútuo e pelos momentos de camaradagem que tornaram esta experiência inesquecível. Um agradecimento especial ao **Sporting Clube de Portugal** a oportunidade de ter realizado estágio numa área que tanto gosto. Foram sem dúvida, 5 semanas de muita aprendizagem, onde cresci muito profissionalmente.

À **minha família**, especialmente à minha mãe Lurdes, agradeço pelo amor incondicional e por sempre ter acreditado em mim. **A todos os meus amigos,** um profundo obrigado por terem apoiado sempre nestes 2 anos de mestrado.

Para construção desta dissertação de mestrado, agradeço muito a disponibilidade de todos os **clubes da região de Lisboa,** e em especial, à **Federação Portuguesa de Rugby,** todo o apoio, abertura e disponibilidade em colaborar na minha dissertação, não esquecendo todos os atletas que participaram no estudo e que se voluntariam/disponibilizaram. Foi sem dúvida um privilégio ter realizado testes a vários atletas desta modalidade desportiva, que gosto muito e onde cada vez mais tenho o privilégio de ser fisioterapeuta.

Por fim, agradeço às instituições onde colaboro, **Clínica Physiohub Expo e à Agronomia Rugby**, a disponibilidade que sempre me deram em realizar o meu mestrado. Agradeço em especial aos meus colegas de profissão destas 2 instituições, onde sempre me ajudaram.

A todos, o meu mais profundo e sincero obrigado!

Abstract

Hamstring injuries are among the most common in rugby, frequently affecting athletic performance due to their influence on lower limb biomechanics. This cross-sectional observational study aimed to evaluate the temporal structure of ground reaction force (GRF) variability between injured and uninjured lower limbs in rugby players with a history of unilateral hamstring injury. Using Detrended Fluctuation Analysis (DFA), the study assessed the temporal structure of motor variability during treadmill running in a sample of 20 athletes (95% male). The DFA alpha values for injured limbs (M = 0.735) and uninjured limbs (M = 0.706) indicated persistent correlations within a functional range ($0.5 < \alpha < 1.0$), with no statistically significant differences between limbs ($p = 0.317$). However, a slight trend toward increased motor rigidity in the injured limb was noted, potentially reflecting compensatory adaptations. DFA emerged as a sensitive tool capable of detecting subtle changes in motor control that may not be captured by conventional biomechanical analyses. Limitations included the small sample size, gender imbalance, and treadmill-only testing, which constrain generalizability. Nonetheless, the results highlight the potential of DFA as a valuable adjunct in return-to-play assessments and injury prevention protocols. Future research should adopt longitudinal designs and recruit more diverse samples valid settings to fully explore DFA diagnostic and rehabilitative applications in sports performance.

Keywords: Detrended Fluctuation Analysis (DFA); Ground Reaction Forces (GRF); Hamstring Injury; Human Variability; Rugby.

Resumo

As lesões nos isquiotibiais constituem uma das lesões mais frequentes no rugby, comprometendo frequentemente o desempenho desportivo devido ao seu impacto na biomecânica dos membros inferiores. O presente estudo observacional transversal investigou a variabilidade da força de reação do solo (GRF) entre os membros inferiores lesionados e não lesionados em jogadores de rugby com historial de lesão unilateral nos isquiotibiais. Recorreu-se à Análise de Flutuação Detrendida (DFA) para analisar a estrutura temporal da variabilidade motora durante a corrida numa passadeira instrumentada, numa amostra composta por 20 atletas (95% do sexo masculino). Os valores alfa de DFA para os membros lesionados (M = 0,735) e não lesionados (M = 0,706) revelaram correlações persistentes dentro de um intervalo funcional ($0,5 < \alpha < 1,0$), não se verificando diferenças estatisticamente significativas entre os membros ($p = 0,317$). Contudo, observou-se uma ligeira tendência para um aumento da rigidez motora no membro lesionado, o que poderá refletir adaptações compensatórias.

O DFA demonstrou ser uma ferramenta sensível na deteção de alterações subtis no controlo motor, frequentemente não detetadas através de análises biomecânicas convencionais. Entre as limitações do estudo destacam-se o reduzido tamanho amostral, o desequilíbrio de género e a utilização exclusiva da passadeira, fatores que condicionam a generalização dos resultados. Não obstante, os dados obtidos evidenciam o potencial do DFA como instrumento complementar em avaliações de prontidão para o regresso à competição e em protocolos de prevenção de lesões. Futuras investigações deverão privilegiar desenhos longitudinais e recorrer a amostras mais heterogéneas, de modo a aprofundar as aplicações diagnósticas e de reabilitação do DFA no âmbito do desempenho desportivo.

Palavras-chave: Análise de Flutuação Detrendida (DFA); Força de Reação do Solo (GRF); Lesão nos Isquiotibiais; Variabilidade Humana; Rugby.

Table of Contents

List of figures

List of tables

List of abbreviations

GRF – Ground Forces Reaction

LCRs - Long-Range Correlations

DFA - Detrended Fluctuation Analysis

OMVH - Optimal Movement Variability Hypothesis

FPR – Federação Portuguesa de Rugby

α – Alpha

Introduction

Rugby is a contact sport played worldwide, characterized by frequent high-impact collisions and high-speed locomotion. Consequently, rugby players are exposed to a high risk of injury, with epidemiological studies reporting incidence rates of up to 89.1 injuries per 1,000 player match-hours [1]. One of the most common are hamstring injuries, with an incidence ranging from 6% to 15% in male athletes [2] . In Portugal, the incidence is similar, reaching 14% [1]. According to data from the 2019 Rugby World Cup, hamstring injuries were the second most common injury, accounting for 9.8% of all injuries in the tournament and resulting in an average of 467 days of time-loss [3]. These injuries usually vary in severity and can be classified as strains or tears [4]. The main game events in which these injuries occur are often during the eccentric phases of running or kicking and when specific game-related movements are performed, such as tackling and contests for the ball on the ground (rucks), which are associated with external loads [5].

Given the high incidence of hamstring sports injuries in rugby, it is often difficult to collect data from this population that includes both sexes [6]. According to O'Sullivan and Tanaka (2021), female athletes also have a lower risk of hamstring injury due to greater activation of the gluteus maximus during running, with less hamstring activation. Female athletes also show greater flexibility and extensibility of the hamstrings compared to males [7].

These physiological changes may play a role in running, one of the activities in which hamstring injuries occur due to involvement in the stretch-shortening cycle [7]. A complete running cycle includes two main phases: the stance phase (foot in contact with the ground) and the swing phase (foot not in contact with the ground) [5]. The swing and initial stance phases (first subphase of the stance phase, where the foot contacts the ground) are the most associated with this type of injury, as they involve the maximum peak of muscle force and increased muscle stretch velocity, especially in faster athletes [5]. According to Sun et al. (2015), the hamstrings produce about 40% more force compared to an isokinetic assessment, with an increase in muscular load observed when the athlete performs this phase of running, caused by increased ground reaction forces (GRF) [8]. GRFs are the forces that runners exert on the ground with each step, evaluated through a three-dimensional analysis, considering the vertical, anteroposterior, and mediolateral directions [9]. Previous study suggest that initial contact is correlated with increased GRF and, consequently, a greater risk of injury [10]. In particular, hamstring injuries are generally associated with higher vertical GRF, greater hip flexion, and knee extension,

resulting in greater hamstring stretching and high eccentric load, and thus muscle activation levels greater than 100% of maximum voluntary contraction [11]. The risk of injury increases if the hamstrings are unable to counteract the joint torques generated by GRF [5].

Previous study on the biomechanical analysis of running show higher GRF in the injured limb compared to the non-injured limb; however, differences between the lower limbs of an individual after a hamstring injury have not yet been investigated [10]. To respond to increased GRF during running after a hamstring injury, our motor system tries to organize itself according to environmental, biomechanical, and morphological constraints to find the most stable solution to produce a given movement, considering variability as a definition [12]. The assessment of movement variability is crucial for understanding the intrinsic behaviour of dynamic systems (i.e., a way to evaluate running patterns and techniques) [13]. Studies show that individuals with injuries exhibit altered variability during running compared to healthy individuals[14]. An increase or decrease in movement variability may suggest inadequate motor control caused by the injury [15].

Thus, compared to healthy individuals, athletes with symptoms or a history of injury tend to deviate from "normal" variability, meaning they exhibit either increased or decreased variability [14]. The variability of the human running pattern contains temporal structures called long-range correlations (LRCs) [16]. One of the main methods used to quantify these correlations is Detrended Fluctuation Analysis (DFA) [17]. DFA is a nonlinear analysis method used to detect long-range correlations in physiological time series, where it quantifies the temporal structure of movement variability, assesses the "health" of the motor system, and identifies the balance between complexity and predictability in the movement pattern a key concept of the Optimal Movement Variability Hypothesis (OMVH) [16]. This concept proposes that variability in human movements is not merely error or noise, but a functional and essential feature for adaptability and flexibility of the motor system [16]. The DFA can be applied to any physiological or biomechanical time series that represents sequential fluctuations over time. In human movement research, it is most commonly calculated from stride or step intervals, stride length, or centre-of-pressure displacements, as these variables capture the temporal organization and adaptability of locomotor and postural control [17].

This hypothesis presents several principles: variability as a functional feature, meaning it is a natural and important characteristic of human movement, where the motor system has the ability to adapt to different conditions and tasks [16]. Other principles include optimal variability, where the motor system is flexible enough to adapt to environmental

changes but stable enough to perform tasks accurately; excessive or insufficient variability, which can lead to overly rigid and predictable movements, while too much variability may result in erratic and unstable movements [18]. These latter situations indicate less adaptable systems and may be associated with pathological conditions. Finally, there is also the chaotic structure of variability, characterized by a chaotic structure where complex deterministic patterns can be observed even in movements that seem random [16].

Previously injured athletes tended to have lower α than healthy runners, and DFA can serve as an early indicator of motor dysfunction before the appearance of clinical symptoms. The literature also states that treadmill running tends to have lower α at the preferred running pace and higher values at slower or faster speeds. The running context matters, as there are differences between treadmill and outdoor running [16]. This approach can thus facilitate the evaluation and understanding of the running performance mechanism, improve running technique, develop prevention strategies to minimize injury risk, and enhance performance [20]. Furthermore, GRF variability associated with hamstring injuries remains unexplored in comparisons between injuries and non-injured limbs[15]. Thus, this study aims to evaluate the temporal structure of GRF variability between the injured and uninjured lower limbs during running in male and female rugby players with a history of unilateral hamstring injury, using DFA to calculate the scaling exponent α. It is hypothesized that the DFA α-exponent, which represents the temporal correlation structure of GRF variability, will be significantly higher in the injured limb compared to the uninjured limb. This increase in α values may reflect greater persistence and reduced adaptive variability, suggesting more rigid motor control patterns following hamstring injury.

Methodology

Study Design

This cross-sectional observational study was conducted under controlled laboratory conditions. Each participant completed a single assessment session, and biomechanical data were collected during treadmill running (Figure A). The goal was to assess the temporal structure of stride-to-stride variability (DFA), particularly in the context of previous hamstring injury.

Figure A - Representative image of study design.

Participants

Twenty rugby players affiliated in clubs from the Lisbon region and the Portuguese Rugby Federation (FPR) (19 males and 1 female; age: mean = 23.5±4.65 years; Six participated in Portuguese National Team) participated in this study. A priori power analysis was performed using G*Power (version 3.1) to determine the required sample size for detecting differences between the injured and non-injured leg within the same participants using a two-tailed paired-sample t-test. Based on an estimated moderate effect size (Cohen's d = 0.58), with an alpha level of 0.05 and statistical power of 0.80, the analysis indicated that a minimum of 20 participants would be required. This configuration implies a 5% probability (α) of committing a Type I error - incorrectly concluding that a significant difference exists when it does not (false positive). Additionally, the 20% probability (β) of a Type II error reflects the chance of failing to detect a true difference between legs when one does exist (false negative). The selected parameters represent a common balance in experimental design between sensitivity and specificity, ensuring a high likelihood (80%) of identifying meaningful within-subject differences in the studied variable.

The study was approved by Egas Moniz School of Health and Science Ethics Committee (process no. 1407). Participants were recruited via direct contact with rugby clubs. Each participant completed the informed consent form (Appendix 1) and the sample characterization questionnaire (Appendix 2) before participating in the study. The inclusion criteria were as follows: (a) male and female rugby players; and (b) players aged 18 or older with a documented history of hamstring injuries occurring within the past eight years (between 2016 and 2024) [2,21,22]. Exclusion criteria included: (a) players who had sustained hamstring injuries in both lower limbs during the specified period; (b) players who had undergone surgery to the knee, hip, or foot within approximately the past nine months; and (c) players presenting

with any other musculoskeletal injuries, including low back pain or lower limb injuries, within the past month [23,24].

Experimental Protocol

Assessments were conducted at the Integrative Movement in Networking Systems Laboratory in Egas Moniz School of Health and Science. Participants were instructed to abstain from caffeine, alcohol, and intense activity for 24 hours prior [26]. Each session lasted approximately 40 minutes and began with a 25-minute orientation, followed by a 5-minute warm-up on a fully instrumented Bertec® treadmill (FIT5), equipped with a 1000 Hz force sampling platform (Bertec Corporation, Columbus, OH, USA) where participants ran at their typical maximum running speed during the warm-up [27]. After a 2-minute rest, 80% of this previously defined speed was then used for the 8-minute run test (Figure B), while ground reaction forces (GRF) and kinetic data were continuously recorded [30]. The choice of a submaximal and constant speed aimed to minimize fatigue, remaining within the range where step-by-step dynamics typically exhibit long-range functional correlations. It is important to note that α was not imposed or targeted by the speed selection; it was subsequently estimated from each athlete's time series [28,29].

Figure B - Representative images of a male and a female rugby player during the running test.

Data Analysis

The data analysis and evaluation of the force platform provided information about the ground reaction forces (GRFs), which were later correlated with hamstring injuries [9]. The vertical ground reaction force data were collected using an instrumented treadmill and recorded with Bertec Acquire (4.31 build 721, EUA). Subsequently, the raw data were processed using the Spyder IDE environment in Python [11]. Initially, the signals from the right and left force plates were analysed to identify which leg performed the first

contact (injury or non-injury). Next, the vertical ground reaction forces were summed, and a fourth-order low-pass Butterworth filter with a cut-off frequency of 6 Hz was applied to remove high-frequency noise [11]. Thereafter, peak forces corresponding to individual foot strikes during running were identified [11]. To ensure only valid steps, a threshold of 900 N was defined [11]. The detected peaks enabled the calculation of time intervals between successive foot contacts. The injury and non-injury stride-to-stride time series matrices were built considering the first contact with the ground. All data processing procedures were implemented in Python using the libraries NumPy, Matplotlib, glob, and the find_peaks function from scipy.signal module [11].

Following the creation of the stride-interval time series, DFA was applied to evaluate the temporal structure of motor variability [17]. In this study, DFA was not applied directly to the raw force data but to the derived temporal sequence representing stride intervals (in seconds)[17]. Each value corresponded to the time elapsed between two consecutive foot contacts of the same limb, and the total number of data points (N) reflected the number of strides recorded for each participant. This stride-to-stride time series captured the temporal rhythm of running and was used as the input for DFA [17]. To optimize window size selection and ensure statistical robustness, the approach proposed by Damouras et al. (2010) was followed, using window sizes ranging from 16 to N/9, where N represents the total number of strides. The scaling exponent (α) was obtained from a log–log linear regression, and the coefficient of determination (r^2) was computed for each limb and participant to assess the quality of the fit [17]. All preprocessing and analysis procedures, including filtering, event detection, stride-interval extraction, and DFA were applied identically to both limbs to maintain methodological consistency.

Variability was quantified using DFA, which characterizes the temporal structure of biological signals and detects long-range correlations [26,31]. Higher α values (approximately 1) indicate more regular and predictable patterns, whereas lower α values (approximately 0.5) suggest greater randomness and reduced predictability. Variations in the magnitudes of the two main force peaks were also examined, as these may indicate structural alterations in the signal and a reduced capacity for internal adjustment, reflected in the absence of long-range correlations [26,31].

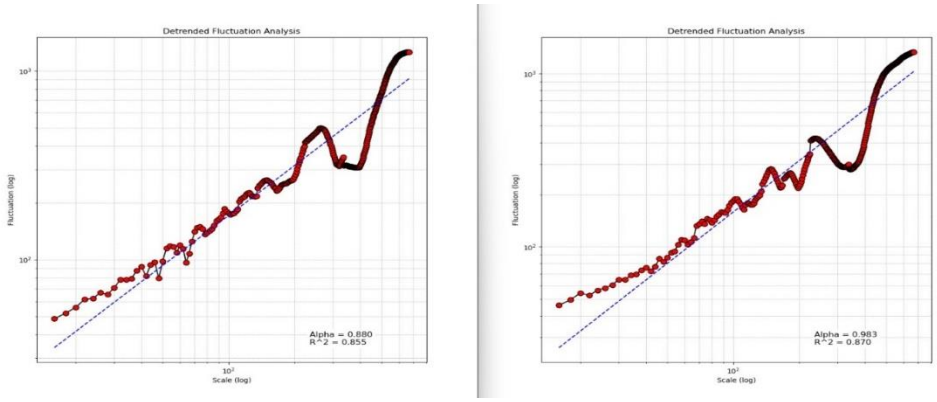


Figure C - DFA Output for Two Rugby Athletes - Detrended Fluctuation Analysis (DFA) of stride interval time series in two rugby players. **Note:** DFA = Detrended Fluctuation Analysis; α = scaling exponent; r^2 = coefficient of determination. Window sizes ranged from 16 to N/9 [17]. Athletes with $r^2 \geq 0.95$ exhibit excellent temporal consistency in stride-to-stride variability.

Statistical Analysis

All statistical analyses were conducted using Jamovi software. Descriptive statistics was calculated for all variables, including the mean, standard deviation, maximum and minimum coefficient of variation, skewness and standard error skewness for both the injured and non-injured limbs (Table 1) [31,32]. The Shapiro-Wilk test was used to assess the normality of the data distribution. If the data are normally distributed, the athletes in this study were evaluated using a paired-sample t-test, in which segments from the same individual. If normality is not confirmed, the Wilcoxon signed-rank test was applied as a non-parametric alternative [32]. The level of statistical significance was $p < 0.05$. Additionally, Cohen's d was calculated to estimate the effect size of any differences identified, and results will be reported with corresponding p-values and confidence intervals [32].

Results

Accordingly, the DFA was initiated with window sizes of 16 steps and progressively increased up to N/9. The resulting scaling exponent Alpha (α), derived from this specified range, served as an indicator of temporal persistence and dynamic stability in the running pattern. This approach minimizes noise associated with small windows and instability from excessively large windows, thereby ensuring that α is computed in a stable and reliable manner [17].

Regression analysis between the number of strides and the standard deviation of the α estimates yielded high coefficients of determination ($r^2 > 0.95$), indicating strong consistency and reliability of the computed values. Only three data points fell below the 90% threshold. According to the criteria established by Damouras et al.2010, coefficients

of determination exceeding 95% reflect very high data consistency, while values above 90% indicate good consistency [17]. (Appendix 4).

Table 1 presents the descriptive statistics for the DFA-α exponent in the injured (Alpha Injured and uninjured (Alpha No Injured) limbs. The mean α value for the injured limbs was (α =0.735; SD = 0.169), while that for the uninjured limbs was (α =0.706; SD = 0.109) (Appendix 3). On average, the DFA-α values for both limbs fall within the range of $0.5 < \alpha < 1.0$, which indicates the presence of long-range correlations and a persistent pattern of temporal variability. These findings are consistent with an adaptive and functionally organized movement structure.

Table 1 - Descriptive statistics of the DFA alpha (α) exponent in injured and non-injured lower limbs

	N	**M (± SD)**	**Min**	**Max**	**Skewness**	**SESkew**
α Injured	20	0.735 (±0.169)	0.315	1.20	0.406	0.512
α No Injured	20	0.706 (±0.109)	0.546	1.03	1.135	0.512

Note. α: Detrended Fluctuation Analysis exponent; SD: standard deviation; SEskew: standard error of skewness. Values within $0.5 < \alpha < 1.0$ indicate the presence of long-range correlations (LRCs), reflecting persistent variability patterns.

Prior to conducting inferential statistical analyses, the data were assessed for normality using both the Shapiro-Wilk test. Results indicated that the data were normally distributed for both injured and uninjured limb groups ($p > 0.05$) (Table 2).

Table 2- Shapiro-Wilk test for normality of DFA α values

			W statistic	**p**
α Injured	*α* No Injured	Shapiro- Wilk	0.978	0.907

Note. $p > 0.05$ indicates that the assumption of normality was not violated. Parametric testing was considered appropriate based on these results.

Subsequently, a paired-sample t-test was conducted to compare the DFA-α values between the injured and uninjured limbs of the athletes. The analysis yielded a non-significant result (p = 0.317), indicating that there was no statistically significant difference in DFA-α values between the two conditions (p > 0.05), despite a slight tendency toward higher values in the injured limbs (Table 3).

Table 3 - Paired-sample t-test and Cohen's d effect size for DFA α values

			t	**df**	**p**	**Cohen´s d**
α Injured	*α* No Injured	t- Student	1.03	19.0	0.317	0.230

Note. H_a: μ¡ - μ¢ ≠ 0. Statistical significance level set at $p < 0.05$. Cohen's d = 0.230 indicates a small effect size. df 3 degrees of freedom.

In statistical terms, this result does not provide sufficient evidence to reject the null hypothesis (H), meaning that with the current sample, no reliable difference in temporal variability (as measured by DFA-α) can be asserted between the injured and uninjured limbs with 95% confidence. To further explore the practical relevance of the observed difference, Cohen's *d* was calculated. The effect size was small (d = 0.23), suggesting that although the difference in variability may reflect a subtle trend toward altered movement dynamics in the injured limbs, it was insufficient to reach statistical significance within the current sample size (Table 3).

Discussion

The present study aimed to analyse the DFA (α) values of GRFs during running in male and female rugby players with a history of hamstring injury, comparing injured and non-injured lower limbs. DFA was employed to assess the temporal structure of GRF variability by calculating the scaling exponent α [17]. As shown in Appendix 4, data analysis confirmed that the r^2 values obtained from the regression between log- transformed fluctuations and log window sizes met the recommended methodological standards, using window sizes between 16 and N/9 (where N = number of steps) [17]. This approach ensures a statistically robust estimation of the scaling exponent by minimizing noise in smaller windows and avoiding instability in excessively large ones. Only three participants had values below the 90% confidence threshold, supporting the overall reliability of the analysis [17].

The DFA analysis is quantified through an alpha exponent (α): $\alpha \approx 0.5 \rightarrow$ random

pattern (no correlation); $0.5 < \alpha < 1.0 \rightarrow$ presence of LRCs (persistent correlations); $\alpha \approx 1.0 \rightarrow$ "pink noise", considered ideal/optimal; $\alpha > 1.0 \rightarrow$ excessive correlation, a sign of rigidity or pathology [12,34]. If we apply DFA to athlete performance evaluation, we realize that α values close to 1.0 indicate a healthy and adaptable running pattern, and lower values (<0.7) suggest fatigue, injury, or overload [16]. Previous running studies show that an α value close to 1.0 indicates that running is being performed efficiently, adaptably, and healthy [16]. If it drops to 0.63-0.7, it may indicate accumulated fatigue, overload, biomechanical imbalances (in this study, GRF), and injury history [18]. A systematically decreasing α value indicates that the motor system is losing the ability to maintain the "optimal" temporal structure, meaning this athlete may be at risk of injury [18]. The results revealed that, on average, α values for both injured ($M = 0.735$, $SD = 0.169$) and uninjured ($M = 0.706$, $SD = 0.109$) limbs fell within the range of $0.5 < \alpha < 1.0$. This range is indicative of long-range correlations in variability, suggesting a persistent and functionally adaptive temporal organization [16].

These findings align with previous studies showing that athletes with prior injuries can maintain relatively stable motor patterns, especially during asymptomatic or post-rehabilitation phases4particularly in cases of muscle injuries such as hamstring strains [12,16] . Although no statistically significant differences were found between limbs ($p = 0.317$), the slightly higher α values in the injured limbs may reflect a tendency toward adaptive rigidity in motor control, potentially indicating compensatory strategies. The effect size was small (Cohen's $d = 0.23$), reinforcing the subtle nature of the observed differences [25].

It is also important to note that α values below 0.7 have been linked to states of fatigue, functional overload, or biomechanical imbalances. These alterations may be attributed to the timing of the assessments, which were conducted during the competitive season a period often associated with accumulated fatigue due to game demands. In this sport, fatigue can significantly impair performance, manifesting through cognitive, neuromuscular, perceptual, physical, emotional, and tactical changes [35,36]. Although not prevalent in the current sample, such values were occasionally observed, suggesting that DFA may be a sensitive tool for early detection of motor alterations, even in athletes considered functionally recovered [19]. Conversely, α values greater than 1.0, as seen in one participant, may indicate overly structured variability4interpreted as increased rigidity or predictability in movement patterns, a phenomenon often observed following injury-related motor reorganizations [16,19]. The lack of significant differences may be due to the athletes' access to appropriate rehabilitation, neuromuscular training, and ongoing

monitoring, which likely mitigated long-term asymmetries. Thus, while variability is closely linked to injury risk and recovery, its interpretation must be contextualized and based on standardized methodology [37].

Although the statistical results were not significant, the findings are clinically meaningful. DFA, as a nonlinear analysis method, enables the detection of subtle changes in motor control dynamics before clinical symptoms emerge. α values that diverge from the <optimal= range may serve as early indicators for preventive intervention, such as running technique correction. This study reinforces the value of variability as a marker of motor system integrity [35,38,39]. Incorporating DFA into return-to-play protocols could enhance rehabilitation strategies by providing a functional and qualitative perspective on performance. Recent evidence suggests that DFA is sensitive to fatigue and that α values tend to normalize with rest, highlighting its potential as an early marker of cumulative overload [39]. In practical terms, α typically decreases during prolonged exertion4even in the absence of changes in traditional metrics like cadence or stride length signaling a loss in the temporal structure of movement, which may reduce motor efficiency and increase injury risk [38]. As such, DFA shows promise for continuous monitoring via inertial sensors or instrumented platforms, supporting injury prevention and performance optimization in sports contexts.

This study presents several important limitations. The small sample size (N = 20), while statistically justified, may have hindered the detection of differences between lower limbs. The low participation rate4considering the approximately 4,960 registered rugby players in Portugal and the restrictive eligibility criteria reflect challenges in participant recruitment and limit the generalizability of the findings. Furthermore, the sample was heavily skewed by gender, with 95% of participants being male, which limited meaningful gender-based comparisons. Although female participation in national rugby is relatively low, only one female athlete met the inclusion criteria. In addition to the lower overall participation of women in the sport, previous literature indicates a higher incidence of injuries among male athletes, likely due to factors such as the game's speed, physical contact, and the number of matches per season [40].

Another limitation may stem from the fact that the athlete completed only a single run at 80% intensity. Damouras et al. (2010) recommend using long time series with multiple windows to ensure the robustness of DFA analysis [17]. This suggests that multiple repetitions or sessions can enhance the reliability of the α value by minimizing the influence of random fluctuations within a single run [41]. Other researchers have examined the reliability of DFA in runners during a continuous 30-minute run and found that,

although inter-day reliability was high, segmenting the run into three equal time intervals revealed substantial variability in DFA-α values, with reliability coefficients ranging from 0.20 to 0.37 [41]. These findings indicate that DFA can vary considerably even within a single session, highlighting significant intra-individual variability. Therefore, relying on a single repetition, as done in this protocol, may not adequately reflect the true structure of the athlete's motor variability [41]. Including three repetitions at 80% of the individual's maximum running speed would help mitigate this issue, enhance data robustness, improve the consistency of the obtained α values, and reduce the risk of making clinical decisions based on atypical or transient results [17,42].

Another major limitation is the exclusive use of treadmill-based analysis. Treadmill running differs notably from overground running, typically resulting in longer contact times, higher GRFs, and greater variability especially in kinetic measures. GRF and DFA (α) patterns observed on a treadmill may not accurately represent those seen in natural running conditions, due to constant speed control, absence of visual cues, and altered proprioceptive feedback. Consequently, the findings may not be fully applicable to real-world athletic performance [41] .

Future studies should aim to increase sample size and achieve a more balanced gender distribution to enable analysis of sex-specific differences. It is also recommended to conduct assessments across various rehabilitation phases (acute, subacute, chronic) using longitudinal designs that track athletes from injury through to return-to-play. It is hypothesized that athletes recovering from hamstring injuries may exhibit more random α values. Incorporating additional variables such as kinematic, electromyographic, and fatigue-related parameters could offer a more comprehensive understanding of motor control reorganization following hamstring injury. Moreover, longitudinal monitoring could strengthen evidence for the utility of DFA as a functional assessment tool during rehabilitation and return-to-sport processes [42].

Conclusion

This study aimed to evaluate GRF variability between the lower limbs during running in rugby players with a history of hamstring injuries, using DFA as a nonlinear method for analysing the temporal structure of movement. The results showed that both the injured and uninjured limbs exhibited α values within the functional range ($0.5 < \alpha < 1.0$), with no statistically significant differences between them. These findings suggest that, even following injury, athletes can maintain temporal variability patterns indicative of a functionally adapted though not necessarily optimal motor control system.

Despite the absence of significant differences, the slight tendency toward increased rigidity in the injured limb may reflect compensatory motor reorganization. DFA proved to be a sensitive tool capable of detecting these subtle changes, with potential applications in rehabilitation monitoring (e.g., fatigue markers, recurrence prediction) and return-to-sport decision-making.

References

1. Cruz-Ferreira AM, Cruz-Ferreira EM, Ribeiro PB, Santiago LM, Taborda-Barata L. Epidemiology of Time-Loss Injuries in Senior and Under-18 Portuguese Male Rugby Players. *J Hum Kinet*. 2018;62(1):73-80. doi:10.1515/hukin-2017-0159
2. Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K. Hamstrings injury incidence, risk factors, and prevention in Rugby Union players: a systematic review. *Physician and Sportsmedicine*. 2023;51(1):1-19. doi:10.1080/00913847.2021.1992601
3. Fuller CW, Taylor A, Douglas M, Raftery M. Rugby World Cup 2019 injury surveillance study. *South African Journal of Sports Medicine*. 2020;32(1). doi:10.17159/2078-516X/2020/v32i1a8062
4. Yeomans C, Kenny IC, Cahalan R, et al. The Incidence of Injury in Amateur Male Rugby Union: A Systematic Review and Meta-Analysis. *Sports Medicine*. 2018;48(4):837-848. doi:10.1007/s40279-017-0838-4
5. Bramah C, Mendiguchia J, Dos'Santos T, Morin JB. Exploring the Role of Sprint Biomechanics in Hamstring Strain Injuries: A Current Opinion on Existing Concepts and Evidence. *Sports Medicine*. Published online 2023. doi:10.1007/s40279-023-01925-x
6. Kenneally-Dabrowski CJB, Brown NAT, Lai AKM, Perriman D, Spratford W, Serpell BG. Late swing or early stance? A narrative review of hamstring injury mechanisms during high-speed running. *Scand J Med Sci Sports*. 2019;29(8):1083-1091. doi:10.1111/sms.13437
7. O'Sullivan L, Tanaka MJ. Sex-based Differences in Hamstring Injury Risk Factors. *Journal of Women's Sports Medicine*. 2021;1(1):20-29. doi:10.53646/jwsm.v1i1.8
8. Sun Y, Wei S, Zhong Y, Fu W, Li L, Liu Y. How joint torques affect hamstring injury risk in sprinting swing-stance transition. *Med Sci Sports Exerc*. 2015;47(2):373-380. doi:10.1249/MSS.0000000000000404
9. Scheltinga BL, Kok JN, Buurke JH, Reenalda J. Estimating 3D ground reaction forces in running using three inertial measurement units. *Front Sports Act Living*. 2023;5. doi:10.3389/fspor.2023.1176466
10. Johnson CD, Tenforde AS, Outerleys J, Reilly J, Davis IS. Impact-Related Ground Reaction Forces Are More Strongly Associated With Some Running Injuries Than Others. *American Journal of Sports Medicine*. 2020;48(12):3072-3080. doi:10.1177/0363546520950731

11. Johnson CD, Davis IS. A comparison of ground reaction force waveforms and step length between recreational endurance runners with hamstring injuries and healthy controls. *Clinical Biomechanics*. 2021;84. doi:10.1016/j.clinbiomech.2021.105334
12. Stergiou N, Harbourne RT, Cavanaugh JT. *Optimal Movement Variability: A New Theoretical Perspective for Neurologic Physical Therapy*. Vol 120.; 2006.
13. Chen TLW, Wong DWC, Wang Y, Tan Q, Lam WK, 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*. 2022;11(1):67-74. doi:10.1016/j.jshs.2020.09.006
14. Murillo DB, Sánchez CC, Moreside J, Vera-García FJ, Moreno FJ. Can the structure of motor variability predict learning rate? *J Exp Psychol Hum Percept Perform*. 2017;43(3):596-607. doi:10.1037/xhp0000303
15. Ghahramani M, Mason B, Pearsall P, Spratford W. An Analysis of Lower Limb Coordination Variability in Unilateral Tasks in Healthy Adults: A Possible Prognostic Tool. *Front Bioeng Biotechnol*. 2022;10. doi:10.3389/fbioe.2022.885329
16. Wilson TJ, Likens AD. *Running Gait Produces Long Range Correlations: A Systematic Review*.; 2023.
17. Damouras S, Chang MD, Sejdić E, Chau T. An empirical examination of detrended fluctuation analysis for gait data. *Gait Posture*. 2010;31(3):336-340. doi:10.1016/j.gaitpost.2009.12.002
18. Iqbal ZA, Chow DHK. Exploring the Relations Between Running Variability and Injury Susceptibility: A Scoping Review. *Sports*. 2025;13(2). doi:10.3390/sports13020055
19. Likens AD, Mangalam M, Wong AY, Charles AC, Mills C. Better than DFA? A Bayesian Method for Estimating the Hurst Exponent in Behavioral Sciences. Published online January 26, 2023. http://arxiv.org/abs/2301.11262
20. Tenriwulan AF, Sinsurin K, Areerak K, et al. Comparisons of Gait Variability and Symmetry in Healthy Runners, Runners with a History of Lower Limb Injuries, and Runners with a Current Lower Limb Injury. *Asian J Sports Med*. 2022;13(1). doi:10.5812/asjsm.114922
21. Martin RRL, Cibulka MT, Bolgla LA, et al. Hamstring Strain Injury in Athletes. *Journal of Orthopaedic and Sports Physical Therapy*. 2022;52(3):CPG1-CPG44. doi:10.2519/jospt.2022.0301

22. van der Horst N, van de Hoef S, Reurink G, Huisstede B, Backx F. Return to Play After Hamstring Injuries: A Qualitative Systematic Review of Definitions and Criteria. *Sports Medicine*. 2016;46(6):899-912. doi:10.1007/s40279-015-0468-7
23. Silder A, Thelen DG, Heiderscheit BC. Effects of prior hamstring strain injury on strength, flexibility, and running mechanics. *Clinical Biomechanics*. 2010;25(7):681-686. doi:10.1016/j.clinbiomech.2010.04.015
24. Kalema RN, Schache AG, Williams MD, Heiderscheit B, Trajano GS, Shield AJ. Sprinting biomechanics and hamstring injuries: Is there a link? a literature review. *Sports*. 2021;9(10). doi:10.3390/sports9100141
25. Sullivan GM, Feinn R. Using Effect Size4or Why the P Value Is Not Enough . *J Grad Med Educ*. 2012;4(3):279-282. doi:10.4300/jgme-d-12-00156.1
26. Vaz JR, Cortes N, Gomes JS, Reis JF, Stergiou N. Stride-to-stride variability is altered when running to isochronous visual cueing but remains unaltered with fractal cueing. *Sports Biomech*. Published online January 2, 2024:1-13. doi:10.1080/14763141.2023.2298958
27. Folland JP, Allen SJ, Black MI, Handsaker JC, Forrester SE. Running Technique is an Important Component of Running Economy and Performance. *Med Sci Sports Exerc*. 2017;49(7):1412-1423. doi:10.1249/MSS.0000000000001245
28. Jordan K, Challis JH, Newell KM. Speed influences on the scaling behavior of gait cycle fluctuations during treadmill running. *Hum Mov Sci*. 2007;26(1):87-102. doi:10.1016/j.humov.2006.10.001
29. Zignoli A, Godin A, Mourot L. Indoor running temporal variability for different running speeds, treadmill inclinations, and three different estimation strategies. *PLoS One*. 2023;18(7 July). doi:10.1371/journal.pone.0287978
30. Girka A, Kulmala JP, Äyrämö S. Deep learning approach for prediction of impact peak appearance at ground reaction force signal of running activity. *Comput Methods Biomech Biomed Engin*. Published online 2020:1052-1059. doi:10.1080/10255842.2020.1786072
31. Winter SL, Challis JH. Classifying the variability in impact and active peak vertical ground reaction forces during running using DFA and ARFIMA models. *Hum Mov Sci*. 2017;51:153-160. doi:10.1016/j.humov.2016.12.003
32. Mishra P, Pandey C, Singh U, Keshri A, Sabaretnam M. Selection of appropriate statistical methods for data analysis. *Ann Card Anaesth*. 2019;22(3):297-301. doi:10.4103/aca.ACA_248_18

33. Santos-Rocha R, Anto´ A, Veloso A, Machado ML. *ANALYSIS OF GROUND REACTION FORCES IN STEP EXERCISE DEPENDING ON STEP PATTERN AND STEPPING RATE*. www.nsca-jscr.org
34. Harbourne RT, Stergiou N. *Movement Variability and the Use of Nonlinear Tools: Principles to Guide Physical Therapist Practice*. Vol 89.; 2009. http://ptjournal.apta.org/Downloadedfrom
35. Zignoli A, Godin A, Mourot L. Indoor running temporal variability for different running speeds, treadmill inclinations, and three different estimation strategies. *PLoS One*. 2023;18(7 July). doi:10.1371/journal.pone.0287978
36. Naughton M, Scott T, Weaving D, Solomon C, McLean S. Defining and quantifying fatigue in the rugby codes. *PLoS One*. 2023;18(3 March). doi:10.1371/journal.pone.0282390
37. Iqbal ZA, Chow DHK. Exploring the Relations Between Running Variability and Injury Susceptibility: A Scoping Review. *Sports*. 2025;13(2). doi:10.3390/sports13020055
38. Brahms CM, Zhao Y, Gerhard D, Barden JM. Long-range correlations and stride pattern variability in recreational and elite distance runners during a prolonged run. *Gait Posture*. 2022;92:487-492. doi:10.1016/j.gaitpost.2020.08.107
39. Fuller JT, Doyle TLA, Doyle EW, et al. The Cumulative Impacts of Fatigue during Overload Training Can Be Tracked Using Field-Based Monitoring of Running Stride Interval Correlations. *Sensors*. 2024;24(17). doi:10.3390/s24175538
40. Yeomans C, Kenny IC, Cahalan R, et al. Injury Trends in Irish Amateur Rugby: An Epidemiological Comparison of Men and Women. *Sports Health*. 2021;13(6):540-547. doi:10.1177/1941738121997145
41. Mo S, Chow DHK. Reliability of the fluctuations within the stride time series measured in runners during treadmill running to exhaustion. *Gait Posture*. 2019;74:1-6. doi:10.1016/j.gaitpost.2019.08.008
42. DeJong Lempke AF, Audet AP, Wasserman MG, et al. Biomechanical differences and variability during sustained motorized treadmill running versus outdoor overground running using wearable sensors. *J Biomech*. 2025;178:112443. doi:10.1016/j.jbiomech.2024.11244

Appendices

Appendix 1 – Informed Consent Form (in Portuguese)

EGAS MONIZ SCHOOL of HEALTH & SCIENCE

Consentimento Informado

Código | IMP-EM-PE-17_03

Monte de Caparica, __de ___de_____

Exmo.(a) Sr.(a),

No âmbito do Mestrado em Fisioterapia da Egas Moniz School of Health and Science, sob a orientação do Professor Doutor Paulo Oliveira e co-orientação do Professor Doutor Orlando Fernandes, solicita-se autorização para a participação no " Variabilidade das forças de reação ao solo entre membros inferiores, durante a corrida em jogadores de rugby masculinos e femininos, após lesão nos isquiotibiais: um estudo transversal " a aplicar em atletas masculinos e femininos de rugby da região de Lisboa e/ou inscritos na Federação Portuguesa de Rugby com o objetivo de avaliar as diferenças na variabilidade das forças de reação ao solo entre membros inferiores, durante a corrida, após lesão nos isquiotibiais.

A participação tem uma duração de 40 minutos e consiste nas seguintes etapas:

- Preencher o questionário de caraterização de amostra (considerando os critérios de inclusão e exclusão);
- Realizar a devida explicação do protocolo de recolha;
- Realizar aquecimento durante 5 minutos em passadeira.
- Realizar 2 minutos de descanso
- Realizar o teste de corrida durante 8 minutos, a um ritmo definido com os valores obtidos durante o aquecimento.

A participação neste estudo é voluntária e a sua não participação não lhe trará qualquer prejuízo.

Este estudo pode trazer benefícios tais como a otimização e potencialização da biomecânica da corrida, após lesão dos isquiotibiais, numa população que têm grande prevalência desta lesão. Irá também beneficiar o progresso do conhecimento na área da Fisioterapia como da investigação.

A informação recolhida destina-se unicamente a tratamento estatístico e/ou publicação e será tratada pelo(s) orientador(es) e/ou pelos seus mandatados. A sua recolha é anónima e confidencial.

Egas Moniz - Cooperativa de Ensino Superior, CRL
Campus Universitário - Quinta da Granja
2829-511 Monte da Caparica, Portugal
NIF 504 218 611

EGAS MONIZ SCHOOL of HEALTH & SCIENCE

Consentimento Informado

Código | IMP-EM-PE-17_03

(Riscar o que não interessa)

ACEITO/NÃO ACEITO participar neste estudo, confirmando que fui esclarecido sobre as condições do mesmo e que não tenho dúvidas.

_____

(Assinatura do participante ou, no caso de menores, do pai/mãe ou tutor legal)

Egas Moniz - Cooperativa de Ensino Superior, CRL
Campus Universitário - Quinta da Granja
2829-511 Monte da Caparica, Portugal
NIF 504 218 611

Appendix 2 - Sample Characterization Questionnaire (in Portuguese)

Questionário de Caracterização da Amostra

Caro/a atleta;

Chamo-me Nuno Marques, sou fisioterapeuta e aluno do mestrado em Fisioterapia na Egas Moniz School of Health and Science, e estou a elaborar a minha dissertação de mestrado sob orientação do Professor Doutor Paulo Oliveira e coorientação do Professor Doutor Orlando Fernandes.
O projeto está intitulado de ***"Variability of ground reaction forces between lower limbs during running in male and female rugby players after hamstrings injury: a cross-sectional study"***. Este estudo visa comparar o membro com histórico de lesão com o membro sem lesão. Este estudo poderá trazer informações importantes na otimização do rendimento desportivo, bem como na prevenção da lesão. O questionário é de resposta rápida e levará cerca de 5-10 minutos para ser preenchido.
Neste sentido, teria imenso gosto em solicitar a vossa especial ajuda, para que pudessem colaborar no meu estudo, preenchendo o questionário abaixo. Todas as respostas ficarão no cuidado dos envolvidos na investigação e ao longo de todo o estudo ficará anonimizado.
Queria agradecer a sua colaboração, acrescentando que tenho toda a disponibilidade para retirar qualquer dúvida, através do meu email: 112510@alunos.egasmoniz.edu.pt

Link de acesso ao Consentimento informado: https://egasmonizpt-my.sharepoint.com/:b:/g/personal/112510_alunos_egasmoniz_edu_pt/Ed3MWeH9QytKIbHI4jAlonIBuILEo2d6a-jwWUCI-PloKg?e=zbr3S

1. Considerando o objetivo do estudo e o consentimento informado, pretende participar no estudo? *

   ◯ Sim

   ◯ Não

2. **Se sim,**
   Descarregue o documento,

   (através do link: https://egasmonizpt-my.sharepoint.com/:w:/g/personal/112510_alunos_egasmoniz_edu_pt/EfUbIts51-IJsiz77IBL5Fo8AocI-07fG9Cbc50MEGWvwg?e=ujPMqd).

   assine e devolva para o e-mail: 112510@alunos.egasmoniz.edu.pt

   Para efetuar o agendamento da avaliação, indique o seu número de telemóvel (o mesmo será apenas utilizado para agendar a avaliação e será imediatamente eliminado após as recolhas de dados). *

3. Idade (mínimo 18 anos) *

4. Género *

   ◯ Feminino

   ◯ Masculino

5. O clube onde jogas, faz parte da região de Lisboa? *

- ◯ Sim
- ◯ Não

6. Se sim, qual? *

7. Jogas na Seleção Portuguesa de Rugby? *

- ◯ Sim
- ◯ Não

8. Já tiveste lesão nos isquiotibiais (região posterior da coxa)? *

- ◯ Sim
- ◯ Não

9. Se sim, em que membro inferior tiveste? *

- ◯ Esquerdo
- ◯ Direito
- ◯ Ambos

10. Esta lesão foi nos últimos 8 anos (entre 2016 e 2024)? *

- ◯ Sim
- ◯ Não

11. Foste intervencionado cirurgicamente (operado) à anca, joelho ou pé nos últimos 9 meses? *

- ◯ Sim
- ◯ Não

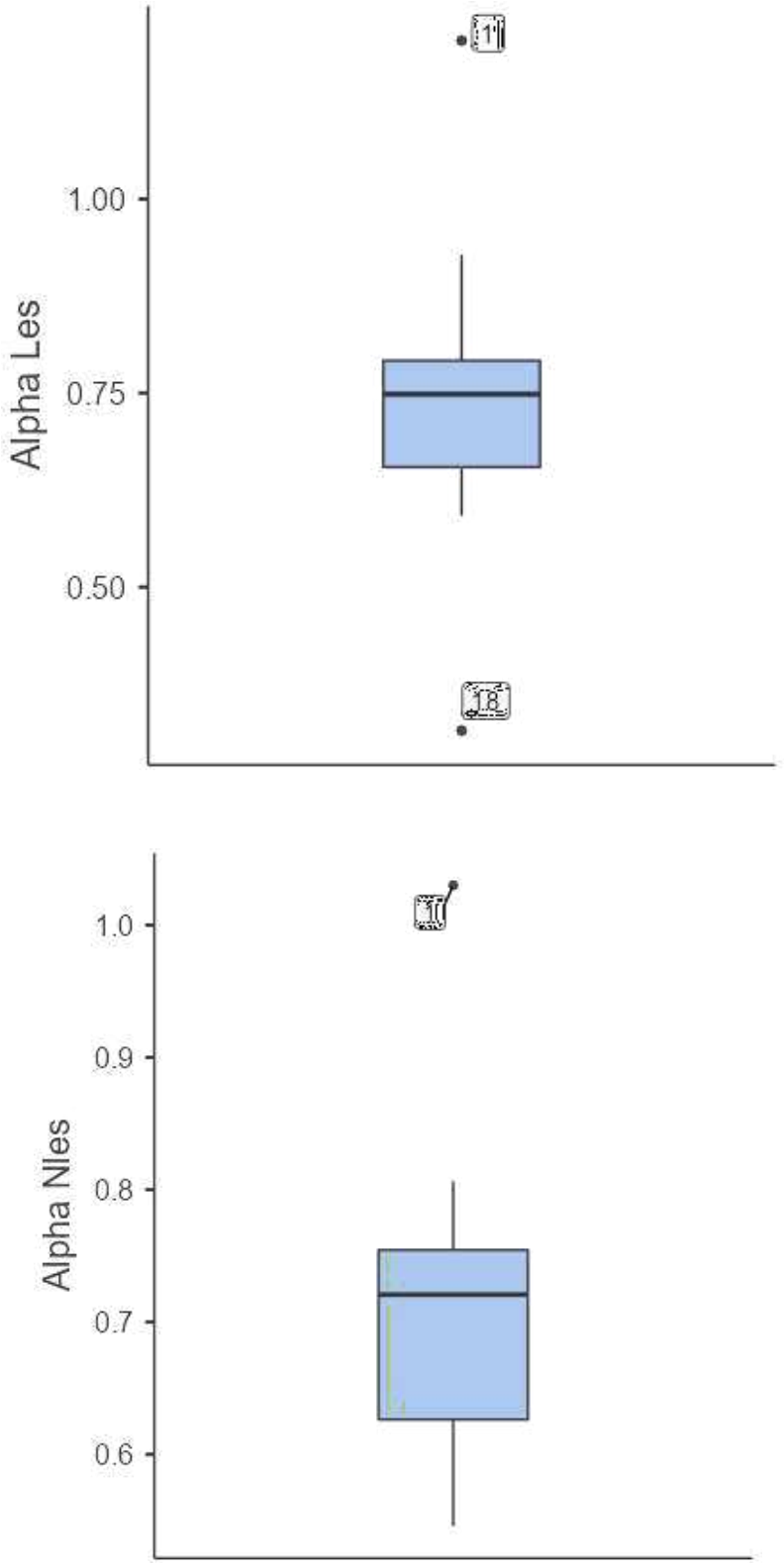
12. No último mês, tiveste alguma lesão na lombar ou nos membros inferiores (anca, pé ou joelho)? *

- ◯ Sim
- ◯ Não

Este conteúdo não foi criado nem é aprovado pela Microsoft. Os dados que submeter serão enviados para o proprietário do formulário.

Microsoft Forms

Appendix 3 - Box plots on the value of DFA in injured and non-injured athletes



Note: Box plots illustrating the distribution of DFA-α values for non-injured (α N les) and injured (α Les) lower limbs. The plots depict central tendency and dispersion, highlighting potential outliers. These values reflect the temporal structure of stride-to-stride variability, with higher α values indicating increased persistence and potential motor rigidity following injury.

Appendix 4 - Descriptive and Comparative Values of DFA-α Between Injured and Non-Injured Limbs for Each Participant

Athlete	Injured Limb	α R	r^2	α L	r^2	α Injured	α No Injured
1	R	1,20417	0,960444	1,03017	0,97108	1,20417	1,03017
2	R	0,643057	0,966577	0,590229	0,949103	0,643057	0,590229
3	L	0,59188	0,934127	0,633725	0,933722	0,59188	0,633725
4	R	0,723578	0,91986	0,748527	0,95254	0,748527	0,723578
5	R	0,723578	0,91986	0,748527	0,95254	0,748527	0,723578
6	L	0,795465	0,945999	0,751616	0,881876	0,795465	0,751616
7	R	0,65844	0,901709	0,719298	0,89337	0,65844	0,719298
8	R	0,790562	0,972417	0,714919	0,894663	0,790562	0,714919
9	L	0,763087	0,951148	0,63481	0,961664	0,63481	0,763087
10	R	0,806313	0,955163	0,667718	0,966461	0,667718	0,806313
11	L	0,577462	0,900319	0,76192	0,925622	0,76192	0,577462
12	R	0,604052	0,923807	0,928115	0,967526	0,928115	0,604052
13	L	0,584585	0,957678	0,679136	0,949116	0,679136	0,584585
14	L	0,85485	0,949937	0,790235	0,92943	0,85485	0,790235
15	R	0,764818	0,962198	0,769788	0,949687	0,764818	0,769788
16	L	0,851537	0,968677	0,748201	0,957393	0,851537	0,748201
17	L	0,667957	0,944069	0,6476	0,948809	0,667957	0,6476
18	R	0,545686	0,84523	0,315146	0,870441	0,315146	0,545686
19	L	0,675663	0,960731	0,763477	0,963918	0,763477	0,675663
20	R	0,722153	0,976088	0,628634	0,881812	0,628634	0,722153

Note: R-Right; **L**-Left; **α L** - Alpha of left lower limb**;** **α** R 3 Alpha of right lower limb**;** r^2 - Coefficient of determination - how well a regression model fits the observed data (**r^2 = 1.00** → perfect fit; **$r^2 \geq 0.95$** → excellent consistency (highly reliable; **$r^2 \geq 0.90$** → good consistency (acceptable); **$r^2 < 0.90$** → weak consistency (may indicate noise, limited variability, or error))