

ESCOLA SUPERIOR DE SAÚDE EGAS MONIZ

MESTRADO EM FISIOTERAPIA

COMPARISON OF GROUND REACTION FORCE VARIABILITY BETWEEN SPRINT ATHLETES WITH AND WITHOUT HAMSTRING INJURY HISTORY: A CROSS-SECTIONAL STUDY

Trabalho submetido por
Margarida Nobre Feliciano
para a obtenção do grau de Mestre em Fisioterapia no Desporto

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Trabalho orientado por
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Resumo

A corrida de velocidade expõe os músculos isquiotibiais a elevada carga mecânica, particularmente na fase final de balanço e na fase inicial de contacto com o solo, ambas reconhecidas pelo alto risco de lesão neste grupo muscular. Em velocistas com historial de lesão nos isquiotibiais (C/HLI), podem persistir alterações nos padrões de variabilidade da força de reação vertical do solo (vGRF) mesmo após a reabilitação, refletindo potenciais adaptações ou restrições neuromusculares. Identificar se esta variabilidade se encontra dentro de um intervalo funcional é fundamental, uma vez que tanto a rigidez excessiva como a instabilidade podem comprometer o desempenho e aumentar o risco de nova lesão. Neste estudo transversal, 17 velocistas (7 C/HLI, 10 sem HLI [S/HLI]) realizaram um sprint submáximo de 60 segundos numa passadeira instrumentada. A variabilidade das vGRF foi avaliada através da Entropia Amostral (SaEn) e da análise da relação força-tempo (log-log slope). O grupo C/HLI apresentou valores médios de log-log slope mais baixos ($0,175 \pm 0,342$; intervalo de $-0,417$ a $0,627$) do que o grupo S/HLI ($0,497 \pm 0,546$; intervalo de $-0,137$ a $1,875$), embora esta diferença não tenha atingido significância estatística ($p = 0,195$). Verificou-se ainda uma tendência para valores mais baixos de entropia no grupo C/HLI (SaEn_Força: $1,80 \pm 0,433$ vs. $2,16 \pm 0,402$; $p = 0,103$; SaEn_Tempo: $2,26 \pm 0,382$ vs. $2,50 \pm 0,337$; $p = 0,219$), sugerindo perfis distintos de controlo motor. Nos atletas C/HLI, a maior variabilidade da força não comprometeu a responsividade, o que poderá refletir uma reorganização compensatória do sistema motor. Já os atletas S/HLI evidenciaram maior robustez na relação força-tempo, mas também sinais de instabilidade na força que parecem ser compensados pela variabilidade temporal. Estes resultados reforçam a relevância da avaliação da estrutura temporal da variabilidade da vGRF em velocistas, uma vez que permitem identificar tendências de adaptação e reorganização motora, ou não, associadas ao historial de lesão. Para além disso, sublinham a importância de integrar programas de reeducação neuromuscular nos protocolos de fisioterapia e prevenção, com o objetivo de restabelecer variabilidade funcional específica para as exigências do sprint, promovendo assim um retorno seguro à performance, a sua otimização e reduzindo o risco de recidiva.

Palavras-chave: Análise cinética; Entropia Amostral (SaEn); Prevenção de Lesão; Fisioterapia.

Abstract

Sprint running exposes the hamstring muscles to high mechanical loads, particularly during the late swing and early stance phases, which are recognized as critical periods of elevated injury risk for this muscle group. In sprinters with a history of hamstring injury (W/HHI), alterations in vertical ground reaction force (vGRF) variability may persist even after rehabilitation, reflecting potential neuromuscular adaptations or constraints. Determining whether this variability falls within a functional range is essential, as both excessive rigidity and instability can compromise performance and increase the risk of reinjury. In this cross-sectional study, 17 sprinters (7 W/HHI, 10 WO/HHI) performed a 60-second submaximal sprint on an instrumented treadmill. VGRF variability was assessed using Sample Entropy (SaEn) and analysis of the force–time relationship (log-log slope). The W/HHI group presented lower mean log-log slope values (0.175 ± 0.342 ; range from -0.417 to 0.627) compared to the WO/HHI group (0.497 ± 0.546 ; range from -0.137 to 1.875), although this difference did not reach statistical significance ($p = 0.195$). A tendency toward lower SaEn values was also observed in the W/HHI group (SaEn_Force: 1.80 ± 0.433 vs. 2.16 ± 0.402 ; $p = 0.103$; SaEn_Time: 2.26 ± 0.382 vs. 2.50 ± 0.337 ; $p = 0.219$), suggesting distinct motor control profiles. In the W/HHI group, greater variability in force did not compromise responsiveness, which may reflect compensatory motor reorganizations. By contrast, the WO/HHI group demonstrated greater robustness in the force–time relationship but also signs of force instability that appeared to be counterbalanced by temporal variability. These findings underscore the relevance of assessing the temporal structure of vGRF variability in sprinters, as it allows the identification of trends in motor adaptation and reorganization associated with injury history. Moreover, they highlight the importance of integrating neuromuscular re-education programs into physiotherapy and prevention protocols, with the aim of re-establishing functional variability specific to the demands of sprinting, thereby promoting a safe return to performance, optimizing performance and reducing reinjury risk.

Keywords: Kinetics analysis; Sample Entropy (SaEn); Injury prevention; Physiotherapy.

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List of Abbreviations

C/HLI – Com Historial de Lesão nos Isquiotibiais
DFA – Detrended Fluctuation Analysis
FPA – Federação Portuguesa de Atletismo
GRF – Ground Reaction Forces
HHI – History of Hamstring Injury
p – P-value
RTR – Return to Running
ROM – Range of Motion
SaEn – Sample Entropy
SD – Standard Deviation
S/HLI – Sem Historial de Lesão nos Isquiotibiais
vGRF – Vertical Ground Reaction Forces
WO/HHI – Without History of Hamstring Injury
W/HHI – With History of Hamstring Injury

Introduction

Sprint running is one of the most explosive events in athletics, aiming to cover a set distance in the shortest time possible (Edouard et al., 2016; Slater et al., 2019). Data from the 2015 to 2017 international athletics championships show that explosive events such as sprinting accounted for 41% of all injuries, with the hamstrings being the most frequently affected muscle group, representing 17.1% of all cases (Edouard et al., 2016). Several characteristics of sprinting contribute to the high mechanical demands placed on the hamstrings (Johnson & Davis, 2021; Sun et al., 2015).

In the late swing phase, the hip reaches its highest internal extension moment, while the biarticular hamstrings muscles achieve maximum muscle-tendon length and produce peak force, increasing injury susceptibility (Sun et al., 2015; Yu et al., 2017). The early stance phase also carries high risk, as maximal hip flexion and knee extension occur at initial ground contact. At this moment, the hamstrings play a key role in force production, making them vulnerable to strain injuries (Kenneally-Dabrowski et al., 2019; Kalema et al., 2021; Johnson & Davis, 2021).

Biomechanical studies on running injuries often focus on the vertical ground reaction force (vGRF), the primary force acting during running (Munro et al., 1987; Nilsson & Thorstensson, 1989; Rice et al., 2016). Among its components, the vertical load rate is particularly important, as it reflects how quickly the vGRF rises at foot-ground contact, a factor consistently linked to injury risk. Higher loading rates are associated with increased hip flexion and knee extension too, placing additional stress on the hamstrings (Kenneally-Dabrowski et al., 2019). These loads coincide with the sharp vGRF peak observed during early stance (Johnson & Davis, 2021; Sun et al., 2015). At this moment, pronounced anterior and posterior force components are also observed, reflecting the high mechanical demands placed on the lower limbs (Johnson & Davis, 2021; Sun et al., 2015). Injured runners have shown significantly higher impact variables, such as vertical average and instantaneous load rates, and vertical stiffness at initial loading, although these alterations are not always linked to a specific injury type (Johnson et al., 2020). In endurance runners, hamstring injury cases have been associated with higher mean vertical loading rates compared with controls, with small to moderate effect sizes (Johnson & Davis, 2021). However, the slower speeds of endurance running reduce hamstring lengthening and activation during late swing compared with sprinting, where peak forces are substantially greater (Schache et al., 2014).

These findings illustrate the limitations of conventional biomechanical analyses, which often focus on mean values of forces or loading rates but may overlook the subtle fluctuations that occur from step to step. Since running is a cyclical task, these fluctuations commonly referred to as variability can provide complementary insight into motor control strategies and potential injury mechanisms (Stergiou & Decker, 2011; Wilson & Likens, 2023). In this sense, linking traditional biomechanical indicators with measures of variability may offer a more comprehensive understanding of the demands placed on the hamstrings during sprinting. Variability refers to the natural fluctuations in motor performance when a task is repeated, such as step-to-step differences in force or timing within the running cycle (Stergiou & Decker, 2011). It can be described in terms of magnitude (standard deviation) and structure (patterns over time). Healthy movement tends to follow a chaotic yet organized structure of variability. When this balance is disrupted, systems may become excessively rigid or overly unstable, both of which reduce adaptability and are often linked to pathology or decreased skill (Harbourne & Stergiou, 2009).

In this context, analyzing how variability is organized becomes crucial, as it reflects the capacity of the motor system to adapt to the mechanical demands of sprinting. This perspective leads to the functional interpretation of variability proposed by Hamill et al. (2012), who emphasize that moderate variability in coordinative structures reflects a motor system capable of adapting to changing demands, whereas both very low and very high variability may indicate maladaptive states. Understanding this balance highlights the functional role of variability in movement and its potential relevance to optimizing performance and injury prevention.

In physiotherapy, promoting optimal variability is essential for both rehabilitation and performance enhancement. Nevertheless, significant gaps remain in literature. Although hamstring injuries are well established as the most common and recurrent problem in sprinting (Edouard et al., 2016; Edouard et al., 2022), the biomechanical mechanisms distinguishing previously injured athletes from uninjured peers are not yet fully understood. Moreover, conventional research focusing on vGRF and loading rates, have shown to be limited for not capturing the complexity of sprinting demands (Munro et al., 1987; Nilsson & Thorstensson, 1989; Rice et al., 2016; Johnson et al., 2020; Kenneally-Dabrowski et al., 2019). Finally, most studies of variability have been restricted to walking or submaximal running in healthy or clinical populations, leaving uncertainty about how variability manifests in sprint athletes with a history of hamstring

injury (W/HHI) and whether altered patterns reflect maladaptive motor strategies and greater reinjury risk (Harbourne & Stergiou, 2009; Hamill et al., 2012).

This study aims to address these gaps by comparing vGRF variability between sprint athletes W/HHI and without a HHI (WO/HHI) during sprinting. The hypothesis is that athletes W/HHI will present differences in vGRF variability compared with WO/HHI. These differences may appear as either highly irregular, unstable patterns (higher SaEn values) or overly predictable, rigid patterns (lower SaEn values), both suggesting a less adaptable and more constrained motor strategy (Harbourne & Stergiou, 2009). In contrast, healthy athletes are expected to exhibit SaEn values within a range typically associated with functional and adaptable movement, aligning with a structured variability that supports optimal performance (Stergiou & Decker, 2011).

Methodology

Experimental Design

This study employed a cross-sectional design, enabling the assessment of sprint athletes with and without a HHI at a single point in time. The research was conducted at Clínica de Fisioterapia da Egas Moniz, under standardized conditions. The study protocol included the distribution of a sample characterization questionnaire (appendix 1) through the athletes' coaches, who had been previously contacted and formally invited to collaborate. Participants were then selected based on their responses to this questionnaire.

Participants

A total of forty-two sprint athletes from the Lisbon and Setúbal districts (Portugal) initially completed the sample characterization questionnaire. From this pool, twenty-five athletes were excluded for the following reasons: recent lower limb injury within the previous three months ($n = 3$), current lower limb injury ($n = 5$), pregnancy ($n = 1$), no response to follow-up contact ($n = 8$), or inability to schedule testing ($n = 8$). The final sample therefore comprised seventeen athletes who met the inclusion criteria and were available for participation. These athletes were allocated into two groups: one W/HHI ($n = 7$; 3 women and 4 men) and one WO/HHI ($n = 10$; 1 woman and 9 men). The mean age

of the sample was 22 years. Athletes in the group W/HHI had sustained clinically diagnosed hamstring injuries between 2018 and 2025. These diagnoses were confirmed by medical doctors and physiotherapists affiliated with the athletes' teams and the Portuguese Athletics Federation (Federação Portuguesa de Atletismo, FPA). The criteria included pain originating specifically from the hamstrings or hamstring tendon regions, following the exclusion of other potential causes of posterior thigh discomfort, in accordance with established clinical guidelines (Heiderscheit et al., 2010). At least three months prior to data collection, all athletes had been training and competing without restrictions. The athletes in the group WO/HHI had never experienced hamstring injuries. Exclusion criteria included any lower-limb or trunk injury within the last three months, history of hamstring surgery, or relevant physical adaptations that could compromise participation (Johnson et al., 2020). Participation was voluntary, and all athletes provided written informed consent (appendix 2).

Ethical Considerations

The research protocol received approval from the Ethics Committee of Egas Moniz School of Health & Science (internal reference no. 1406). All participants' data were handled with strict confidentiality and securely stored under the responsibility of the principal investigator.

Sample Size Calculation

Sample size was calculated a priori using G*Power 3.1.9.7 (Faul et al., 2007). Assuming $\alpha = 0.05$, power = 0.80, and an allocation ratio of 0.6, 16 athletes were estimated as sufficient to detect an effect size of $d = 0.86$. The present study included 17 sprinters, thus meeting this requirement. Determining adequate sample size is essential to reduce the risk of type II error (Burmeister & Aitken, 2012).

Procedures

All study participants underwent running analysis at an Bertec® Fully Instrumented Treadmill v5 (FIT5) equipped with 2 force plates sampling at 1000 Hz (Columbus, OH, USA) (figure 2). The protocol applied to participants was previously explained to participants

and was applied by a Master of Sports Physiotherapy student from the Egas Moniz School of Health and Science and his supervisor. Prior to the test, athletes were instructed to complete an individual warm-up lasting 10 minutes. During the testing phase, all participants were required to wear their usual footwear. Following the warm-up, an adaptation trial was conducted at the target pace, allowing participants to familiarize themselves with the treadmill conditions. After this trial, a 2-minute rest period was provided before initiating the data collection phase. For safety reasons, the treadmill's speed was restricted by its security system. As a result, athletes were limited to running at a pace equivalent to 40-50% of their personal best time at 400 meters. An illustration of the intervention protocol is provided in figure 1 and the experimental setup is represented in figure 2.

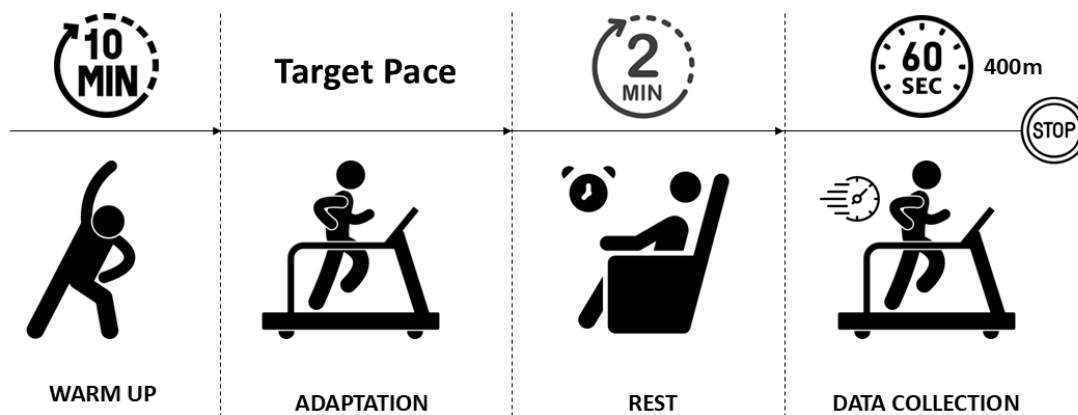


Figure 1: Intervention protocol illustration.



Figure 2: Experimental setup.

Data Collection and Management

The vertical ground reaction force data was collected for 60 seconds using an instrumented treadmill and recorded with Bertec Acquire (Bertec Corporation, Columbus, OH, USA). Subsequently, the raw data were processed using the Spyder IDE environment in Python. Initially, the signals from the right and left force plates 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. Thereafter, peak forces corresponding to individual foot strikes during running were identified. To ensure only valid steps, a threshold of 900 N was defined. The detected peaks enabled the calculation of time intervals between successive foot contacts. As the primary objective of this study was to analyze the variability in force production, the maximum force associated with each identified peak was extracted. Finally, two matrices were constructed: one representing stride intervals and another representing the maximum force values across peaks. All data processing procedures were implemented in Python using the libraries NumPy, Matplotlib, glob, and the `find_peaks` function from `scipy.signal` module.

To study the temporal structure of movement, Detrended Fluctuation Analysis (DFA) is frequently used to detect long-range correlations in time-series data (Peng et al., 1995; Damouras et al., 2010). However, DFA requires relatively long recordings to produce reliable estimates, with a recommended minimum of approximately 600 data points (Damouras et al., 2010). In the present dataset, the mean number of data points available per athlete was 172 ± 55 , with the lowest length observed in athlete OB2 (95 points; see appendix 3). This limitation does not recommend the use of DFA unsuitable for the current study design, which involves short, high-intensity sprint tasks. For shorter time series, an alternative nonlinear approach is Sample Entropy (SaEn) (Yentes et al., 2013). This measure quantifies signal regularity and complexity (Richman & Moorman, 2000), performs reliably with reduced data lengths (Yentes et al., 2013), and captures meaningful aspects of movement dynamics (Rhea et al., 2014). SaEn is particularly useful for detecting changes in signal structure that may reflect alterations in motor control strategies (Stergiou & Decker, 2011). Accordingly, SaEn was selected as the more appropriate nonlinear measure for this study. After preprocessing, SaEn was calculated for each vGRF time series. SaEn estimates the negative natural logarithm of the conditional probability that two sequences of length m , similar within a tolerance r ,

remain similar when extended by one data point (Richman & Moorman, 2000). For this analysis, the embedding dimension m was set to 2, the tolerance r was set to 0.2, and the full series length N was considered. To examine the relationship between signal complexity and scaling properties, the slope of the fluctuation function was derived in a log-log representation. The use of the log-log scale is standard in fractal analyses such as DFA, as it linearizes the relationship between fluctuation magnitude and window size, allowing the estimation of a scaling exponent as the slope of the regression line (Peng et al., 1995; Hardstone et al., 2012). In this study, this slope (Slope_log) was not interpreted as a conventional DFA parameter due to the short data lengths but was instead compared with sample entropy (SaEn) values to explore potential associations between local signal regularity and broader scaling characteristics. Relationships between Slope_log and SaEn were examined separately for force and for interval time series, allowing the assess whether these variables exhibit distinct patterns of association between local irregularity and scaling properties.

In terms of interpretation, Yentes et al. (2013) note that a repeatable time series would yield a SaEn value close to 0, whereas a completely random signal would approach values around 2. Therefore, very low values (close to 0) suggest overly repetitive and stereotypical patterns with limited adaptability, while very high values (close to 2) reflect excessive randomness or noise, indicating a loss of control. Healthy motor behavior is therefore typically characterized by intermediate values, which reflect a balance between regularity and variability that enables adaptive responses to changing task demands (Rhea et al., 2014; Stergiou & Decker, 2011).

Statistical Analysis

Statistical analyses were performed to assess differences in SaEn values of the vGRF time series between groups with and without HHI. Data normality was assessed using the Shapiro-Wilk test, which indicated no violation of normality. Accordingly, independent samples t-tests (two-tailed Student's t-test) were used to compare group means. For completeness, Mann-Whitney U tests were also computed, although t-tests were considered the primary analysis. Effect sizes (Cohen's d) were also calculated to quantify the magnitude of between-group differences. Data are reported as mean \pm standard deviation (SD). Statistical significance was set at $p < 0.05$. All the analyses were performed in Python (Python Software Foundation, Wilmington, DE, USA) using the

Spyder IDE (Spyder Project Contributors) and statistical tests were conducted using Jamovi (The jamovi project, Sydney, Australia) software.

Results

Participants W/HHI presented a mean slope of 0.175 ± 0.342 , with values ranging from -0.417 to 0.627 (N = 7). In contrast, participants WO/HHI showed a mean slope of 0.497 ± 0.546 , with values ranging from -0.137 to 1.875 (N = 10) (table 1). Overall, the W/HHI group displayed lower and less dispersed slopes, while the WO/HHI group showed a broader distribution that included the highest values observed in the sample. Although this difference did not reach statistical significance ($p = 0.195$), the effect size indicated a large magnitude ($d = 0.86$)."

Table 1: Summary of slope values for W/HHI and WO/HHI groups.

Group	N	Mean slope	SD	Min	Max	P-value	Cohen's d
W/HHI	7	0,175	0,342	-0,417	0,627	0,195	0,86
WO/HHI	10	0,497	0,546	-0,137	1,875		

Participants W/HHI presented a mean SaEn_Force of 2.16 ± 0.402 , with values ranging from 1.59 to 2.85 (N = 7). In contrast, participants WO/HHI showed a mean SaEn_Force of 1.80 ± 0.433 , ranging from 1.04 to 2.43 (N = 10) (table 2). Regarding SaEn_Interval, the W/HHI group presented a mean value of 2.50 ± 0.337 , with a minimum of 1.92 and a maximum of 2.93, while the WO/HHI group showed a mean of 2.26 ± 0.382 , ranging from 1.62 to 2.93 (table 3). Although differences did not reach statistical significance ($p = 0.103$ for SaEn_Force; $p = 0.219$ for SaEn_Interval), effect sizes indicated a moderate-to-large magnitude ($d = 0.86$ and $d = 0.66$, respectively). Overall, participants W/HHI tended to present higher entropy values in both force and interval domains compared to WO/HHI, suggesting greater signal complexity in this group.

Table 2: Summary of SaEn_Force values for W/HHI and WO/HHI groups.

Group	N	Mean SaEn_Force	SD	Min	Max	P-value	Cohen's d
W/HHI	7	2,16	0,402	1,59	2,85	0,103	0,86
WO/HHI	10	1,80	0,433	1,04	2,43		

Table 3: Summary of SaEn_Interval values for W/HHI and WO/HHI groups.

Group	N	Mean SaEn_Interval	SD	Min	Max	P-value	Cohen's d
W/HHI	7	2,50	0,337	1,92	2,93	0,219	0,66
WO/HHI	10	2,26	0,382	1,62	2,93		

The relationship between SaEn and the log-log slope was examined through scatter plots (figure 3). For SaEn of force (figure 3 - left panel), opposite trends were observed between groups: the group WO/HHI (red line) showed a negative association, such that higher entropy values were related to lower slopes, whereas the group W/HHI (black line) showed a flat to slightly positive trend. For SaEn of the interval (figure 3 - right panel), both groups exhibited positive associations, with a steeper slope in the group WO/HHI compared to the group W/HHI. In both analyses, data points from the group WO/HHI were generally distributed across higher ranges of entropy and slope values, while participants W/HHI clustered in the lower ranges.

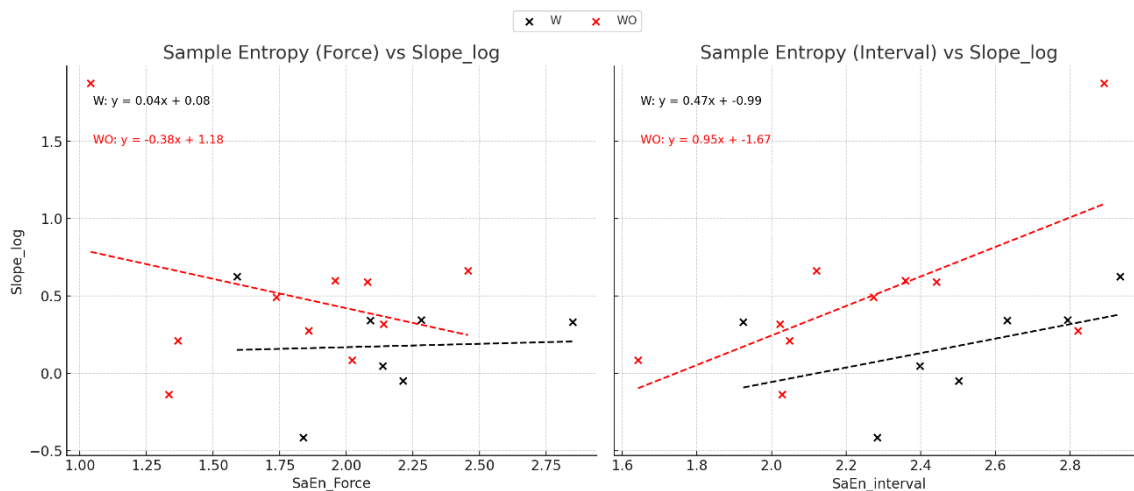


Figure 3: Relationship between SaEn and the log-log slope of force–interval scaling. Left Panel - SaEn of force (SaEn_Force) vs. Slope_log; Right Panel - SaEn of step intervals (SaEn_Interval) vs. Slope_log. Red points and dashed lines indicate sprinters without a history of hamstring injury (WO); black points and dashed lines indicate sprinters with a history of hamstring injury (W).

Discussion

This study aimed to investigate the variability of vGRF in sprint athletes with and without a HHI while sprinting. It was hypothesized that athletes with an HHI would exhibit different vGRF patterns compared to the group WO/HHI. Specifically, it was expected that these differences would emerge as either highly irregular and unstable fluctuations (higher SaEn values), or overly rigid and predictable patterns (lower SaEn values). Both are indicative of reduced adaptability or more constrained motor strategies (Harbourne & Stergiou, 2009; Hamill et al., 2012). By contrast, it was expected that athletes WO/HHI would display SaEn values within the range typically associated with functional and adaptable movement, reflecting structured variability that supports optimal performance (Stergiou & Decker, 2011).

Despite the absence of statistically significant differences between groups, the data analysis highlights relevant trends that may contribute to a deeper understanding of vGRF variability during sprinting. The group W/HHI showed lower mean slopes with a narrower range of values, including some negative slopes that may reflect reduced or inconsistent coupling between force and timing. In contrast, the group WO/HHI demonstrated higher mean slopes and a broader distribution, encompassing the largest values observed in the sample. This pattern suggests that athletes W/HHI may converge toward more homogeneous and constrained responses (Heiderscheit et al., 2010; Meardon et al., 2011), while athletes WO/HHI retain access to a more flexible repertoire of motor solutions, consistent with the concept of functional variability (Stergiou et al., 2006; Hamill et al., 2012). In line with these observations, entropy analyses revealed moderate-to-large effect sizes between groups ($d = 0.86$ for force and $d = 0.66$ for interval), with W/HHI athletes presenting higher SaEn values than WO/HHI. In terms of interpretation, very low SaEn values indicate stereotypical and overly repetitive patterns with limited adaptability, whereas very high values approach excessive randomness and loss of control (Yentes et al., 2013; Rhea et al., 2014). Healthy motor behavior is therefore typically characterized by intermediate entropy values, reflecting a balance between regularity and variability that enables adaptive responses (Stergiou & Decker, 2011). Accordingly, the elevated SaEn values observed in W/HHI may not reflect greater adaptability, but rather altered motor control strategies following injury, potentially representing compensatory adjustments or increased variability bordering on noise. Conversely, the slightly lower values found in WO/HHI (closer to 2) suggest a more optimal balance between regularity

and variability, consistent with the maintenance of functional variability in uninjured athletes. Beyond group differences in SaEn values, the relationship between entropy and Slope_log provided additional insights into how variability interacts with responsiveness in force and timing domains.

The analysis of the relationship between force entropy and Slope_log revealed distinct patterns between the two groups, demonstrating how ground reaction force variability exhibits different patterns in athletes with and without a HHI. Contrary to expectations, in the WO/HHI group, a negative association was observed, whereby higher irregularity in force production was accompanied by a decrease in Slope_log. This result suggests that more chaotic or less predictable force control leads to reduced responsiveness in the WO/HHI condition. In other words, these participants may experience greater difficulty in controlling force as task complexity increases, resulting in less efficient force dynamics. This aligns with the concept of loss of complexity, which describes the inability of the motor system to organize fluctuations in a functional manner (Lipsitz & Goldberger, 1992; Stergiou & Decker, 2011). In contrast, the W/HHI group displayed a near-flat or slightly positive slope. Although they exhibited greater variability in force, these athletes did not demonstrate a decline in responsiveness, suggesting a compensatory reorganization of motor control. Nevertheless, given that the slope was positive but nearly null, further development of this component may be necessary to achieve a more adaptable biological system, one that possesses a varied and flexible repertoire of movement patterns available to respond to different task demands, consistent with the notion of “optimal variability” (Stergiou et al., 2006).

In the interval entropy, both groups demonstrated that greater irregularity in timing was associated with higher Slope_log values, suggesting that temporal variability plays an adaptive role in locomotor control across conditions. Interestingly, and in line with the study hypothesis, the WO/HHO group presented a steeper positive slope, which may indicate that, in the absence of HHI, these athletes rely more strongly on step-time variability as a compensatory mechanism for force instability. The literature indicates that such a profile may result from continuous micro adjustments mediated by strategies such as modulation of co-activation, alterations in reflex gain, and variations in motor unit recruitment (Enoka & Duchateau, 2017). This interpretation is consistent with the view that variability, particularly in the temporal domain, reflects motor system flexibility and its ability to adapt to the demands of dynamic tasks (Stergiou & Decker, 2011). Furthermore, this difference in slopes may also be related to previous findings showing

that systems in an injured or unhealthy state are associated with more constrained control strategies (Heiderscheit et al., 2010; Meardon et al., 2011; Miller et al., 2008; Stergiou et al., 2006).

In the WO/HHI group, excessive and unstructured variability in force appears to compromise efficiency, highlighting the need for training interventions that reinforce the stabilization of force production under complex and variable conditions. By contrast, in the W/HHI group, the presence of variability in force alongside maintained responsiveness suggests that injury may induce motor reorganizations that preserve efficiency through a functional use of variability, even if this remains an aspect that could be further improved. On the other hand, temporal variability emerged as a consistently adaptive feature in both groups, standing out as a robust and trainable dimension of locomotor control. This framework aligns with principles of sprint training, where step frequency is often prioritized as an indicator of neuromuscular efficiency over step amplitude. Cadence is modulated by specific neural mechanisms related to the tonic activity of the lower-limb muscles during the swing phase, and altering this tonic activity can modify the resonance frequency of the limb around the hip joint (Zijlstra et al., 1995; Bonnard & Pailhous, 1993). Within this context, the present findings reinforce the idea that variability, when structured and functional, constitutes a fundamental resource for motor performance and resilience, with temporal aspects of locomotion being particularly relevant for adaptation and training.

Clinical and Rehabilitation Implications

Since reduced variability in motor behavior shown to be commonly observed following injury and even in healthy states, physiotherapy interventions should be directed toward restoring and improve this characteristic in order to optimize performance and minimize reinjury risk. From a clinical perspective, these findings highlight the importance of developing targeted rehabilitation strategies that not only recover motor adaptability but also support long-term performance enhancement and injury prevention. This raises important practical considerations for physiotherapists, as the persistence of reduced variability and complexity after rehabilitation may indicate that conventional approaches centered only on stretching and strengthening are insufficient. From a clinical perspective, this highlights the need to incorporate neuromuscular re-education strategies that re-establish functional variability within the context of sprint-specific demands in

rehabilitation and prevention programs. Evidence ranging from early work on progressive agility and trunk stabilization programs (Sherry & Best, 2004) to more recent trials emphasizing eccentric loading protocols in sprinters (Askling et al., 2014; Van Dyk et al., 2019) and reviews highlighting the role of sprint biomechanics and force variability in both hamstring injury risk and recovery (Bramah et al., 2024; Tedeschi et al., 2022) supports this shift in focus.

Rehabilitation and prevention strategies should therefore extend beyond working on strength and tissue integrity, integrating interventions that actively re-establish functional variability in vGRF patterns to support a safe return to sprinting and optimize performance, in line with recommendations by Harbourne and Stergiou (2009), who highlight the role of movement variability as a key therapeutic target in rehabilitation.

Physiotherapy Rehabilitation Focused on Hamstring Neuromuscular Re-education: a Sprinter's Protocol (PRFHNR:SP) is a detailed example of how such a sprint-specific neuromuscular re-education program could be structured (table 2). This protocol outlines a neuromuscular re-education program designed for sprinters recovering from hamstring injuries and it can be adaptable to be used as a prevention program. The program emphasizes restoring and working on neuromuscular control and optimal variability in vGRF dynamics during sprinting, progressing from foundational motor control to sprint integration. It is intended to complement conventional physiotherapy approaches, including flexibility, general strength, and manual therapy, which remain important components of rehabilitation (Shumway-Cook & Woollacott, 2016; Opar et al., 2012).

Phases

PRFHNR:SP can be structured into four progressive phases, each with specific objectives that align with the principles of recovery, progressive overload, and sport-specific adaptation, consistent with recent frameworks for return-to-sport decision-making (Draovitch et al., 2022). It is also adaptable to a prevention program.

Phase 1 (P1) – Initial Recovery

The primary focus of this stage is to restore pain-free range of motion (ROM), while simultaneously reactivating the hamstrings and gluteal muscles. Basic motor control exercises are introduced to re-establish fundamental neuromuscular patterns and

provide a stable structure for subsequent phases of more demanding loads. Early activation of the posterior chain is essential given its role in sprint mechanics (Contreras et al., 2015).

Phase 2 (P2) – Eccentric Strength and Coordination

During this phase, emphasis is placed on the development of eccentric strength in the hamstrings, which plays a key role in injury prevention and performance optimization (Bourne et al., 2015; Timmins et al., 2016). Unilateral control exercises are progressively incorporated to address potential asymmetries and improve stability under sport-specific demands (van der Horst et al., 2015).

Phase 3 (P3) – Controlled Variability and Agility

Building upon the strength and coordination regained in earlier phases, this stage introduces greater task complexity through exercises that challenge proprioception, controlled variability, and adaptability. The aim is to enhance the athlete's ability to respond efficiently to unpredictable stimuli, thereby bridging the gap between rehabilitation and the dynamic requirements of competition (van der Horst et al., 2015).

Phase 4 (P4) – Sprint Integration

The final phase focuses on sprint-specific reintegration or optimization, under progressively more demanding conditions. This includes exposure to high velocity running, where hamstring stretch and activation increase with speed (Schache et al., 2013), and training designed to optimize vGRF production, a key determinant of sprinting performance (Weyand et al., 2000). Moreover, monitoring load and performance under fatigue is essential, as excessive or mismanaged running volumes are associated with heightened injury risk (Gabbett & Ullah, 2012). This stage ensures that the athlete's return to sprinting is both safe and performance-oriented (Draovitch et al., 2022).

Progression Criteria

Progression between phases is based on clinical and functional benchmarks, a practice that reduces the risk of reinjury (Opar et al., 2012). The following benchmarks are proposed:

P1 to P2

- Absence of pain in daily activities.
- No pain during or after the execution of prescribed exercises.
- Exercises were performed without compensatory movement patterns.
- Hip and knee ROM restored to at least 90% of the contralateral, uninjured side.

P2 to P3

- Pain-free execution of unilateral exercises.
- Ability to tolerate the introduction of increased task complexity, with enhanced demands on proprioception and adaptability.

P3 to P4

- Absence of pain during exercise execution and within 24 hours post-exercise.
- Correct technical execution and postural stability during exercises and sport-specific drills, with no evidence of compensatory strategies.
- Unilateral eccentric hamstring strength restored to at least 90% of the contralateral, uninjured side.

P4 to Return to Running (RTR)




- Consistently correct technical execution and stability during advanced exercises and sport-specific drills.
- For full integration and frequency of high-intensity tasks: eccentric strength equal to or greater than the uninjured side, or within a <10% difference.
- Completion of a maximal sprint test without pain, technical breakdown, or compensatory movement patterns.
- Acceptable inter-limb asymmetry indices in jumping or timing-based assessments ($\leq 10\%$).
- High subjective confidence ($\geq 90\%$ on a validated readiness-to-return scale).
- Stable and efficient running techniques are maintained under conditions of fatigue.

Integration and Frequency





This program should be applied after injury acute phase. However, athletes whose regular rehabilitation has already emphasized the objectives of P1 and P2 may begin the

protocol from P3, if the established progression criteria are fulfilled (van der Horst et al., 2015; Peterson et al., 2011). Also, healthy athletes can use the protocol as a prevention program working exclusively with P3 and P4 of the protocol, being its integration in training be discussed a priori with the respective coaches. The expected duration of each phase ranges from 2 to 3 weeks and the last phase from 2 to 4 weeks, depending on the nature of the athlete's injury, and should involve consistent progression of the exercises performed. It is recommended 3 times per week as core rehabilitation, with up to 2 additional weekly sessions focused on eccentric strength and sprint drills. It is designed to complement conventional physiotherapy (flexibility, global strength, mobility, and manual therapy) and should be adapted according to the athlete's tolerance, motor control and sprint performance metrics (Veugelers et al., 2016). Exercises from P3 and P4 are recommended to remain in the athletes training plan routine, playing a role in injury prevention and performance optimization.

Table 2: Physiotherapy Rehabilitation Focused on Hamstring Neuromuscular Re-education: a Sprinter's Protocol (PRFHR:SP)

Phase	Exercise	Sets/Reps/Time	Orientations/Neuromuscular Progression	Example
1. Initial recovery (2-3 weeks)	Slider eccentric hamstring (bilateral)	3x8, 3s descent	Start slow, double-leg support, control ROM	
	Vertical bird-dog hold, with dumbbells	3x30s	Perturbations or unstable surface (foam pad), once stable	
	March A (walking) frontward and backward	3x10 steps each leg	Slow execution, bodyweight only	

2. Eccentric strength and coordination (2-3 weeks)	Nordic hamstring (partial)	3x6-8,3-5s descent	Increase ROM, reduce support	
	Single-leg RDL, with dumbbells	3x8 each leg	Had unstable surface (foam pad)	
	Single-leg hip-thrust	3x10 each	Progress load	
	March A and B (cadence variation)	3x15 steps each leg	Alternate slow and fast cadence	
3. Controlled Variability and Agility (2-3 weeks)	Cone drills	3x20m	Sprint or side-step between cones, use verbal orientations, vary cone distance and angles	
	Mini-hurdle drills (A/B skippis)	3x15 hurdles	Emphasize rhythm and orientation, vary hurdle height and spacing	
	Split stance elastic perturbations	3x30s	Add multi-directional pulls	
	Full Nordic Hamstring	3x8-8	Full eccentric ROM, add resistance or weight	

4. Sprint Integration (2-4 weeks)	Sprint-specific adaptation	Progressive sprints (30m)	6x30m, start at 60% and increase gradually to 100%	
	Horizontal bounding	3x10 bounds	Increase distance and height, had weight vest	
	Fatigue-controlled sprints (50m)	4x50m (80%)	Reduce rest to stimulate fatigue	
	Multi-surface sprint	4x20m (grass vs. track)	Alternate surfaces	

Limitations and Future Research

This study presents some limitations that should be acknowledged. The small sample size ($N = 17$) reduces the statistical power and limits the generalizability of the findings, which may partly explain the absence of statistically significant differences. Furthermore, the sprint task was performed at a controlled submaximal velocity (40–50% of each athlete’s best time), a constraint imposed by the safety mechanisms of the instrumented treadmill. While necessary for safety, this condition may not fully replicate the neuromuscular demands of maximal sprinting. Another limitation is that only one sprint trial per athlete was analyzed, and a single trial may not fully capture the intra-individual variability of vGRF patterns (James et al., 2007). Finally, treadmill running does not perfectly reproduce overground sprinting, particularly in terms of mechanical, proprioceptive, and perceptual demands, which could have influenced the variability patterns observed (Van Hooren et al., 2020). Future studies should validate these findings in larger cohorts and further clarify how force-related and temporal aspects of vGRF variability contribute to sprint performance, injury risk, and recovery. In addition, this research should include multiple trials to enhance the reliability of the measurements and ensure that the observed variability is representative of each athlete’s motor behavior. Field-based protocols that better replicate the demands of competitive sprinting, as well as longitudinal designs that allow monitoring variability throughout rehabilitation, are recommended. Such approaches would provide stronger evidence on the role of vGRF

variability in sprinting. Within this context, the implementation of PRFHNR:SP in sprinters recovering from hamstring injuries and applied as prevention and performance optimization for healthy athletes would be particularly valuable, as it could test its effectiveness in restoring optimal variability of vGRF during sprinting while simultaneously supporting long-term performance enhancement and injury prevention.

Conclusion

Although no statistically significant differences were detected, this study revealed distinct trends in vGRF variability during sprinting between athletes with and without a HHI. In the W/HHI group, greater variability in force did not compromise adaptability, suggesting compensatory reorganizations that may preserve efficiency through a functional use of variability, although not yet fully optimized. In contrast, the WO/HHI group showed evidence of force instability, seemingly counterbalanced by greater reliance on temporal variability, which emerged as a more robust and adaptive component of motor control. These findings highlight the importance of addressing variability, rather than strength alone, in both performance and rehabilitation. Sprint-specific neuromuscular re-education strategies may be essential to re-establish functional variability in vGRF patterns, supporting safe return to sport and optimizing performance.

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Appendecis

Appendix 1 - Sample Characterization Questionnaire
(portuguese version)

Questionário de caracterização de amostra

Caro/a atleta,

O presente questionário tem como objetivo caracterizar a amostra para o estudo "**Comparação da Variabilidade das Forças de Reação ao Solo entre Atletas de Velocidade com e sem Historial de Lesão nos Isquiotibiais: Um Estudo Transversal**".

O estudo faz parte de uma dissertação do Mestrado de Fisioterapia no Desporto da *Egas Moniz School of Health and Science* e tem como objetivo avaliar a variabilidade das forças de reação ao solo durante a corrida de velocidade, entre atletas de velocidade com e sem historial de lesão nos isquiotibiais. Através da caracterização da variabilidade das forças de reação ao solo durante a corrida do atleta a uma intensidade elevada pretendemos compreender a sua relação com o histórico de lesão nos isquiotibiais e de que forma é que a mesma interfere na variabilidade e assim ajudar não só na otimização da performance do atleta, mas também na prevenção da lesão.

No link seguinte poderá ter acesso ao Consentimento Informado:

https://drive.google.com/file/d/1sdqj2OOyZG7RnOGPrOSWlg-wx8Z_JEGU/view?usp=sharing

O questionário é de resposta rápida e levará cerca de 2 minutos para ser preenchido. Todas as respostas ficarão ao cuidado dos intervenientes responsáveis pelo estudo.

Obrigada pela colaboração!

Obrigatória

1. Considerando os objetivos e o consentimento informado, pretende participar no estudo? *

Sim

Não

2. Indique o seu contacto telefónico (o contacto será eliminado após as recolhas de dados) *

3. Assine e envie o consentimento informado

(link: https://drive.google.com/file/d/1sdqj2OOyZG7RnOGPrOSWlg-wx8Z_JEGU/view?usp=sharing)

para o e-mail: 114273@alunos.egasmoniz.edu.pt
(introduzir o e-mail de envio na resposta) *

4. Idade (mínimo 18 anos) *

5. Sexo *

Feminino

Masculino

6. És atleta de atletismo federado? *

Sim

Não

7. Treinas na região de Lisboa ou Setúbal? *

Sim

Não

8. Qual o teu clube? *

9. Já representaste a seleção numa prova internacional (Campeonato da Europa, Mundo ou Jogos Olímpicos)? *

Sim

Não

10. Treinas e participas em provas de velocidade da modalidade de atletismo (100/200/400) de forma regular? *

Sim

Não

11. Já tiveste alguma lesão diagnosticada nos isquiotibiais (região posterior da coxa)? *

Sim

Não

12. Em que membro inferior? *

Esquerda

Direita

Ambos

13. Essa lesão foi nos últimos 8 anos (entre 2016 e 2024)? *

Sim

Não

14. Há quanto tempo teve a lesão nos isquiotibiais (região posterior da coxa)? (se teve mais que uma lesão, indique a data de todas as lesões que já teve) *

15. Quanto tempo teve parado devido a essa lesão (se teve mais que uma lesão, indique para todas as lesões) *

16. Já foste submetido a alguma intervenção cirúrgica nos isquiotibiais (região posterior da coxa)? *

Sim

Não

17. Tiveste alguma outra lesão no membro inferior, nos últimos 3 meses? *

Sim

Não

18. És atleta de Desporto Adaptado? *

Sim

Não

19. Descreve a classificação funcional desportiva *

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

 Microsoft Forms

Appendix 2 – Informed Consent Form (portuguese version)



EGAS MONIZ SCHOOL
of HEALTH & SCIENCE

Consentimento Informado

Código | IMP-EM-PE-17_03

Monte de Caparica, 20 de maio de 2024

Exmo.(a) Sr.(a),

No âmbito da Unidade Curricular de Dissertação do Mestrado de Fisioterapia no Desporto da Egas Moniz School of Health & Science, sob a orientação do Professor Doutor Paulo Ricardo Miranda Oliveira e coorientação do Professor Doutor Orlando de Jesus Semedo Mendes Fernandes, solicita-se autorização para a participação no estudo “Comparação da Variabilidade das Forças de Reação ao Solo entre Atletas de Velocidade com e sem Historial de Lesão nos Isquiotibiais: um Estudo Transversal”, a aplicar a atletas de velocidade com e sem historial de lesão dos isquiotibiais, com o objetivo de comparar a variabilidade das forças de reação ao solo durante a corrida de velocidade.

A participação no estudo tem a duração de cerca de 20 minutos e consiste em:

- Preencher o questionário de caracterização de amostra e selecionar os participantes considerando os critérios de inclusão e exclusão;
- Realizar durante cerca de 10 minutos o aquecimento predefinido com os treinadores e atletas;
- Realizar uma corrida de adaptação, numa passadeira instrumentada com plataformas de força, que permite obter informação relativamente às forças de reação ao solo continuamente;
- Correr durante cerca de 60 segundos na passadeira instrumentada, no ritmo definido com o atleta e treinador (40-50% da velocidade máxima do atleta aos 400m), para recolher os dados pretendidos.

Este estudo pode trazer benefícios pois permitirá caracterizar a variabilidade das forças de reação ao solo do atleta durante a corrida de velocidade, compreender a sua relação com o histórico de lesão nos isquiotibiais e de que forma é que a mesma interfere na variabilidade. Desta forma, não só poderá melhorar a performance do atleta, mas também prevenir a lesão. A participação neste estudo é voluntária e não lhe trará qualquer prejuízo.

Consentimento Informado

Código | IMP-EM-PE-17_03

A informação recolhida destina-se unicamente a tratamento estatístico e publicação e será tratada pelos orientadores e pelos seus mandatados. A sua recolha é anónima e confidencial.

(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)

Appendix 3 – Number of data points in vGRF time series per athlete

Athlete	Group	Data points (N)
AF	W/HHI	263
AM	WO/HHI	111
AO	WO/HHI	157
CK	W/HHI	184
EN	WO/HHI	155
GA	W/HHI	222
JO	W/HHI	199
LR	WO/HHI	118
MB	W/HHI	252
OB1	W/HHI	173
OB2	W/HHI	95
SS	W/HHI	142
TM	WO/HHI	115
GJ	WO/HHI	183
GM	W/HHI	184
IO	WO/HHI	94
MF	W/HHI	227
SB	WO/HHI	250

