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afxentios kekelekis * , Rabiu Muazu Musa , Pantelis Nikolaidis , Filipe Clemente , Eleftherios Kellis

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Hip and Pelvic Muscle Isometric Strength Measurements and Ratios as Hamstring Injury Predictors in Male Soccer Players: A Multivariate Machine Learning—Based Study with Specific Analysis of Symmetrical Uncertainty Attribute Evaluation. A Prospective Study

Afxentios Kekelekis [1,*], Rabiu Muazu Musa [2], Pantelis Nikolaidis [3], Filipe Clemente [4] and Eleftherios Kellis [5]

1 Laboratory of Neuromechanics, School of physical education and Sport science at Serres, Aristotle University of Thessaloniki, 62100 Serres, Greece
2 Centre for Fundamental and Continuing Education, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia
3 .School of Health and Caring Sciences, University of West Attica, Athens, Greece
4 Escola Superior Desporto e Lazer, Instituto Politécnico de Viana do Castelo, Rua Escola Industrial e Comercial de Nun'Álvares, 4900-347 Viana do Castelo, Portugal. Gdansk University of Physical Education and Sport, 80-336 Gdańsk, Poland . Sport Physical Activity and Health Research & Innovation Center, Viana do Castelo, Portugal
5 Laboratory of Neuromechanics, School of physical education and Sport science at Serres, Aristotle University of Thessaloniki, 62100 Serres, Greece

* Correspondence: akekelekis@gmail.com

Abstract: ***Background:*** Despite the tremendous effort in hamstring injury prevention, injury rates in soccer remain elevated. ***Hypothesis:*** Hamstring and hip/pelvic isometric strength imbalances may increase the likelihood of hamstring strain injury (HSI) occurrence amongst soccer players. ***Study design***: Case-control study. ***Methods***: In 120 male soccer players (mean age: 20.0 +/- 6.96 years) pre-season maximum isometric strength of the hip adductors, abductors, flexors, and knee flexors were measured, and strength ratios were calculated. Previous injury and anthropometric data were registered. Injury data were collected following the FIFA/UEFA consensus. A multivariate and Machine learning-based Logistic Regression model was employed to estimate the likelihood of players sustaining a hamstring injury. ***Results:*** 21 players sustained 32 hamstring injuries. Players with higher abduction strength in the dominant leg had an 18.5% lower risk of sustaining a hamstring injury (OR = 0.818, CI 95% = [(0.695-0.964]). No other significant contributor variables were found to be significant predictors of hamstring injury in the player group (p> 0.05). ***Conclusion***: Isometric strength of the abductor muscles in the dominant limb had a significant association with hamstring injury. ***Clinical relevance***: Our findings indicate the utilization of hip strength measurements as an integral component of the pre-season screening assessment, thereby affirming prior research on the correlation between lumbo-pelvic stability and incidence of hamstring injuries. Consequently, clinicians should contemplate incorporating hip strengthening exercises into regular training sessions, rehabilitation programs, and injury prevention protocols especially indicated when lower hip strength levels are observed.

Keywords: hamstring injury; injury prediction; hip muscle strength asymmetries; lumbo-pelvic complex; machine learning;

What Is Known About the Subject?

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Although the process of screening to identify the injury risk profile of players is an invaluable tool to assist practitioners in implementing effective preventive interventions, research findings indicate that the HSI etiology remains unclear.

The logistic regression model is currently considered the gold standard statistical method employed to estimate the risk of groin injury. Such models do indeed examine the role of various factors in injury; however, they fail to thoroughly investigate the inter-relationships between potential factors and injury.

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What This Study Adds to the Existing Knowledge

This is the initial occasion in which a correlation between isometric strength of the hip abductor muscles and the incidence of HSI has been ascertained through the implementation of a machine learning approach. The significance of lumbo-pelvic stability on the functionality of the hamstring muscles and subsequent occurrence of injuries necessitates further attention. However, considering the heightened vulnerability to HSI during high-speed running, we propose that biomechanical alterations in the lumbo-pelvic region may augment the risk for hamstring injuries.

Introduction

Hamstring strain injury (HSI) remain prevalent across sporting activities that involve sprinting, jumping, acceleration, deceleration, and rapid change in direction, resulting in significant time loss from sport [25,29]. Despite excessive efforts in the area of hamstring injury prevention [3] HSI rates increased from 12% to 24% during a 21-year UEFA Elite club injury surveillance, reporting a frequency of 1.7 injuries per 1000 h of total play, while match injury rates were 10 times higher than training (4.99/1000 h vs 0.52/1000 h; RR 9.67, 95% CI 8.93 to 10.47) with a median time loss of 13 days [14] resulting in high cost for both the athletes and the teams [15].

A variety of modifiable and nonmodifiable risk factors have been shown to increase the risk of potential HSI in professional football with older age and previous injury highlighted as the strongest nonmodifiable risk factors for HSI [17]. Hamstring strength properties have been reported as a modifiable risk factor for HSI [17], remains however a topic of contention [12,26]. Although increased rates of recurrent injury are attributed to residual weakness following a previous HSI [14], the correlation between hamstring strength and the susceptibility to injury remains uncertain.

The Hip and the lumbo-pelvic complex have been suggested as an integral element with highly important contribution in hamstring functionality [43], especially during high-speed running [50]. The hamstring function depends on pelvic posture and kinematics, just as much as the lumbo-pelvic stability is reliant on hamstring mechanics [21]. Hip abductors have been indicated as an integral part of lumbopelvic functionality, especially during the gait cycle [43] The functional role of each Gluteus Medius (GMed) segment throughout the gait cycle can be understood within the context of their function as either pelvic stabilizers or femoral head stabilizers [38] . Lumbopelvic stability has been defined as the ability of an individual to attain and then maintain optimal body segment alignment of the spine, pelvis, and thigh, in both a static position and during dynamic activity [27]. The lumbo-pelvic muscle complex provides excessive influence on the overall stretch of the biceps femoris muscle [9], while vacillations in neuromuscular control at high-speed running could create stride-to-stride variability in hamstring stretch, altering musculotendinous properties, therefore increasing the risk for injury over time [8]. Given that, the hamstring muscle regulates the degree of knee extension during the late swing phase, an excessive amount of anterior pelvic tilt angle would predispose the hamstring to higher tension loads, thus increasing the likelihood of sustaining an injury while sprinting [37]. Increased anterior pelvic tilt during running results in a change in pelvis position, causing the ischial tuberosities to move superiorly, affecting the length of the hamstrings leading to premature fatigue [8,9,50]

Considering the anatomical connections between Biceps Femoris Long head (BFLh), the sacrotuberous ligament and the pelvis, it was suggested that altered lumbo-pelvic control may lead to ineffective force transfer across the trunk and pelvis, thus increasing the strain on the hamstrings [22,43] especially during high- speed running [37,50]. Poor lumbopelvic control has been proposed as a risk factor for lower limb muscle strain injury [51], while deficits in hip strength and altered motor control have been associated with lower limb injury [7,44]. Although increased activation of GMed during running has been recognized as a potential risk factor for HSI in professional Australian football players [16] their findings were based solely on biomechanical assessment rather than strength measurements [7].

Taking into consideration the multifaceted and intricate nature of injuries [6], machine learning (ML) algorithms have been proposed as a solution to address complex problems in sports science [33,45] and sports medicine [13]. Recent research has presented conflicting results regarding the

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predictability of ML algorithms in identifying players with an increased risk of musculoskeletal injury [19,30,46] . However, notwithstanding the fact that an augmented sustainability of HSI was reported from a study [5] that encompassed hip isometric strength measurements as a constituent part of an extensive dataset, the lack of regression analysis to compute odds ratios impeded the determination of which players had exhibited an elevated risk of injury. Consequently, the use of new, multivariate and machine Learning-based Logistic Regression (LR) analysis models may provide better reflection of complex associations between HSI and various factors, such as strength, anthropometric characteristics, age, player position, and previous injury history. To our knowledge, no previous studies have examined the impact of hip muscle strength on the incidence of hamstring strain injury in men amateur soccer players. Furthermore, considering the increased susceptibility to hamstring injury during high-speed running, it is worth exploring the impact of muscle strength on HSI susceptibility, not only pertaining to the hamstring strength but also encompassing other muscles in the lumbopelvic region, such as the adductors and abductors. Clinicians can enhance their understanding of injury prevention strategies to mitigate the occurrence of HSI in soccer.

There is limited knowledge pertaining to the comprehension of the correlation between the lumbo-pelvic complex and its impact on the hamstring muscles functionality and susceptibility to hamstring injury (HSI), particularly during high-speed running. We hypothesized that hip or knee flexor muscle imbalances establish a direct or indirect association with the susceptibility to HSI.

The objectives of the current study were: (1) to investigate whether isometric hamstring strength offers valuable information on predicting hamstring strain injuries (HSI), (2) to determine if asymmetries in hip muscle strength could serve as a predictive tool for identifying soccer players at risk of sustaining an HSI, and (3) to examine the predictive accuracy of the machine learning algorithm based on the provided dataset. Our preliminary hypothesis was that the potency of each hip muscle group (the hamstrings, the adductors, and abductors) could potentially serve as noteworthy predictors of HSI. Furthermore, it was anticipated that previous injury would be correlated with HSI.

Methods

Study Design

This study followed an observational cohort design spanning of 30 weeks from August 2018 and concluded in April of 2019, aligning with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines [11]. Bilateral isometric strength of hip adduction (ADD), hip abduction (ABD), hip flexion (HFL), and knee flexion (HMS) was examined at the beginning of the season in amateur soccer players, and they were followed throughout the season to register their injury and participation characteristics.

Participants

In the current study, a priori sample size analysis was conducted using G*Power (latest ver. 3.1.9.7; Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) [24] indicated that a sample size of 100 respondents is sufficient to detect a medium effect size of 0.25 for multivariate analysis with a power equivalent to 0.95 and an alpha of 0.05 while for an analysis of variance, a sample of 120 respondents would be effective in identifying an effect size of 0.05 with a power of 0.80 and an alpha level of 0.05. Therefore, a sample of 120 was considered sufficient to avoid the problem of Type II error [10,31]

To be eligible for participation, participants had to be men amateur soccer players aged 14 years or older, participate in the regional amateur soccer league, have been injury-free for the previous three months before the start of the preseason, limit their exposure to only training and match sessions. A total of 253 male players from 11 teams in the Greek football association's regional amateur league participated in the study during the 2018/19 off-season period (June to August). Of these, 176 players initially agreed to participate in the study, but 46 players were excluded due to non-compliance with the exposure limitations or inability to follow the data collection procedures.

Ten players were excluded due to injury before the pre-season. Regarding the general characteristics of the participants, they engaged in training sessions four days a week, typically culminating in an official competition over the weekend. This study is part of a larger survey (partially under peer-review) aimed to identify the injury profile of amateur soccer players. A total of 120 players provided informed consent and the study protocol was approved by the Aristotle University Ethical Committee (ERC-012/2019) in accordance with the Declaration of Helsinki.

Data Collection and Registration

A handheld dynamometer (HHD) (KFORCE Muscle Controller, K-Invent, Biomecanique, Montpellier, France) was used to assess isometric muscle strength. This method has been examined for intra reliability and validity [23] . This HDD has been shown to have high reliability [2] (Intraclass correlation coefficient [ICC] > .80 and > .84, for force and torque respectively) and validity (ICC > .79 and 0.89, for force and torque, respectively [40]. The precise methodology that had been adhered to during the testing protocol can be located in comprehensive detail within **supplementary file 1.** The survey used to document and report the injuries is located in **Supplementary file 2.** Both, testers, and the players, were blinded to the results of the entire testing protocol prior to the completion of the study.

Data Treatment and Statistical Analysis

Pre-processing of the data was carried out prior to the full analysis. To ensure fair comparisons, the data was normalized using the min-max normalization technique to account for differences in units of measurement. Input variables were age, history of previous injury, physical characteristics (Body-Mass-Index), and the absolute isometric strength and ratios **(supplementary file 3).** The dependent variable was hamstring injury status of the players (injured and non-injured athletes).

Development of the Logistic Regression Model

A logistic regression model (LR) was employed to ascertain the efficacy of the models in classifying the status of players' injuries, that is, hamstring injury or non-hamstring injury. A four-fold stratified cross-validation technique was used [35]. This technique is considered useful as it mitigates overfitting, especially when minority classes are present in a dataset. As such, the data are split such that each portion has the same percentage of all the different classes that exist in the dataset. The average performance over all folds was computed. This approach is preferred because it mitigates overfitting, which is a common issue when training models on a specific subset of data. The data were split into a ratio of 70:30 for training and test sets [53]. Eighty-three sets of data were used to train the model, while the remaining 37 observations were used for testing in view to evaluate the predictability of the classifiers in determining hamstring injuries. Moreover, a sensitivity analysis using feature importance using symmetrical uncertainty attribute evaluations was applied to identify the significance isometric strength-related variables in influencing the model's accuracy while a multivariable binary logistic regression was further applied to the variables identified through the feature importance analysis. This technique serves as a follow-up to identify the most significant isometric strength variables that can predict the probability of players sustaining hamstring injuries. Pycaret libraries were used to develop the LR model via the Spyder IDE. Other statistical analyses were implemented using the add-in software and Orange Canvas version 3.4.0 and XL STAT add-in software version 2014 for Windows.

Model Evaluation

We evaluated the LR model using several performance measures: classification accuracy (ACC), area under the curve (AUC), recall, precision (PREC), and F1 score. ACC is the fraction of correctly classified instances. The AUC is a curve that shows the ability of the model to separate classes. Recall is the proportion of true positives among the actual positives, and PREC is the proportion of true positives among the predicted positives. The F1 score is the harmonic mean of PREC and recall, which

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measures the average accuracy for both classes. In addition, the confusion matrix was used to evaluate the classifier's ability to distinguish between hamstring-injured and non-injured players using reserved and holdout training test data.

Results

Of the 120 participants, (mean age: 20.0 ± 6.96 years; BMI: 22.53 ± 2.28 kg/m [2], Height: 1.77 ± 0.07 m, body mass: 70.66 ± 10.08 Kg), a total of 21 players sustained 32 hamstring injuries, (9 re-injuries, 28%). The predictive model achieved a mean accuracy score of 70%, indicating a reasonable prediction of the players' injury status **(Table 2)** as the model correctly identified more than 90% of positive cases and accurately identified 70% of the actual positive classes.

Table 2. Performance Evaluation of the Logistic Regression model for Predicting hamstring injury risk of players from isometric strength variables.

	Accuracy	AUC	Recall	Prec.	F1
Mean	0.699	0.792	0.7000	0.901	0.787
Std	0.038	0.064	0.073	0.053	0.040

The Training and validation scores of the model for the training dataset are displayed in **Figure 1.** It is evident from the graph that the training score was higher than the validation score by 78 and 69% respectively. The decrease in scores after validation can be attributed to the data splitting for training and testing. It can be inferred that the training score prior to the implementation of cross-validation may have included noise and errors, resulting in a relatively high accuracy [52]. However, during the validation stage, the prediction accuracy score was approximately 70%, indicating the model's efficiency and optimal fit.

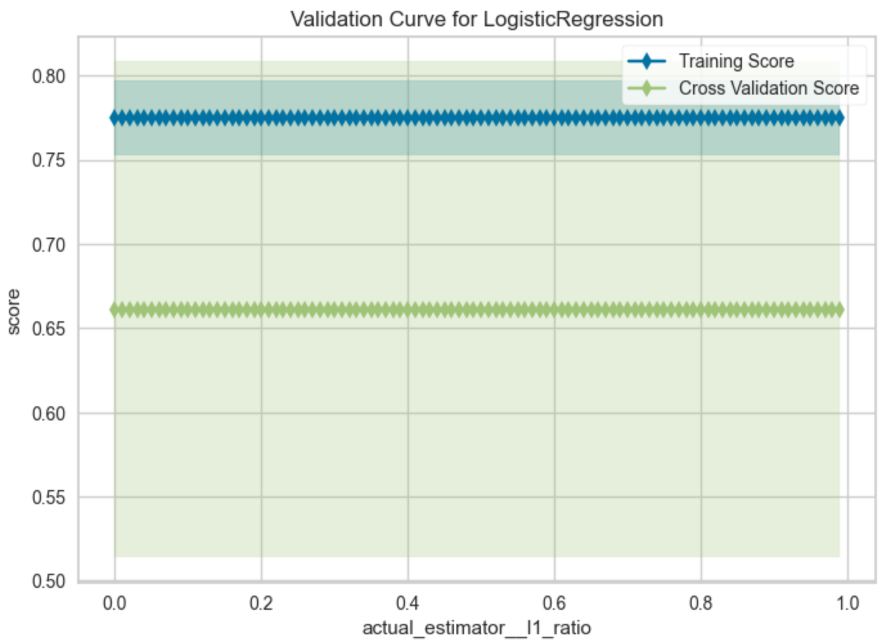

Figure 1. Performance of the logistic regression model on training data.

The confusion matrix in **Figure 2** shows the performance of model after cross-validation. This technique was used to evaluate the classifier's ability to distinguish between hamstring-injured and non-injured players using reserved and hold-out training test data. The model correctly predicted three instances of injured players, while 16 misclassifications were observed for non-injured players

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on the training datasets. On the testing datasets, the model incorrectly classified two instances of hamstring-injured athletes, while 11 misclassifications occurred for non-injured players. Overall, the model performed well in the classification task against the test data, despite the group being relatively unbalanced and the low number of observations.

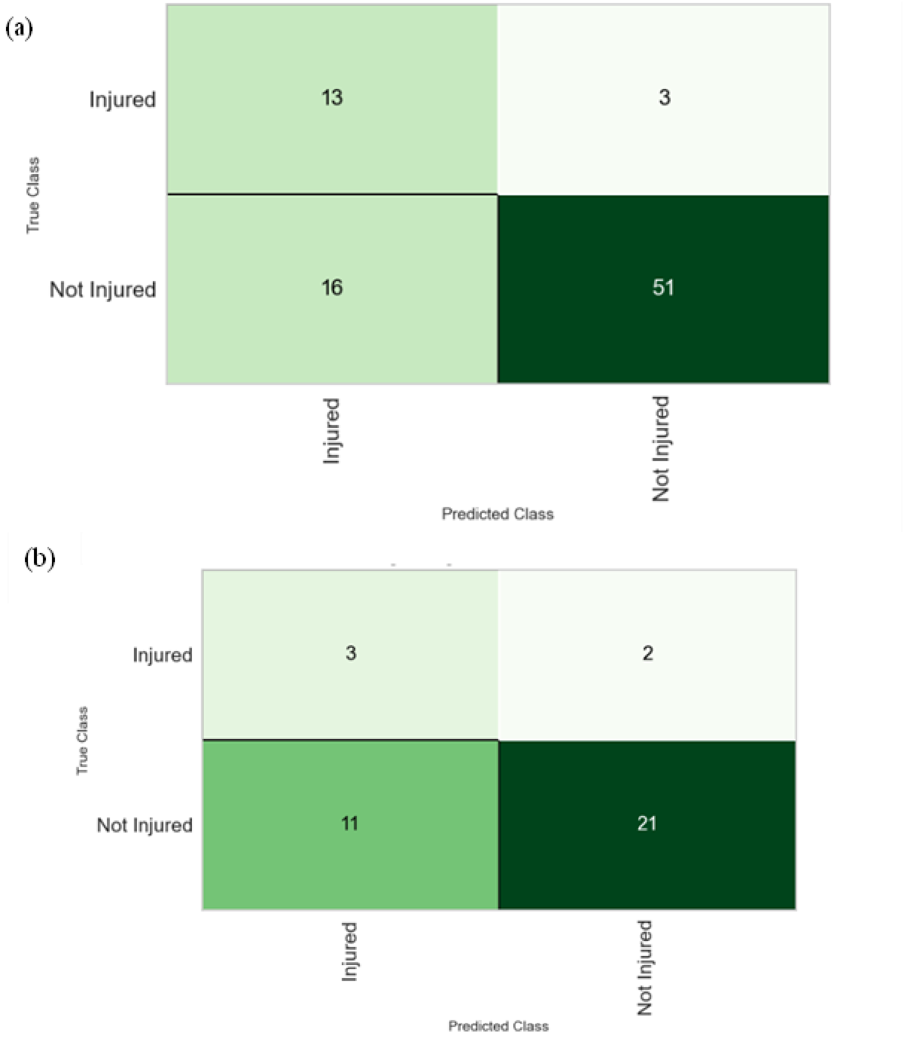

Figure 2. Confusion matrix of the Logistic Regression model: (a) training data set and (b) test data set.

Figure 3 illustrates the graphical representation of the variable's significance toward the performance of the model pipeline via the symmetrical uncertainty attribute evaluation analysis. It is evident that 10 out of the 20 variables initially examined were crucial for the likelihood of suffering a hamstring injury. These 10 variables were further analyzed using multivariate logistic regression analysis to determine their contribution to the probability that players will suffer hamstring injuries based on odds analysis.

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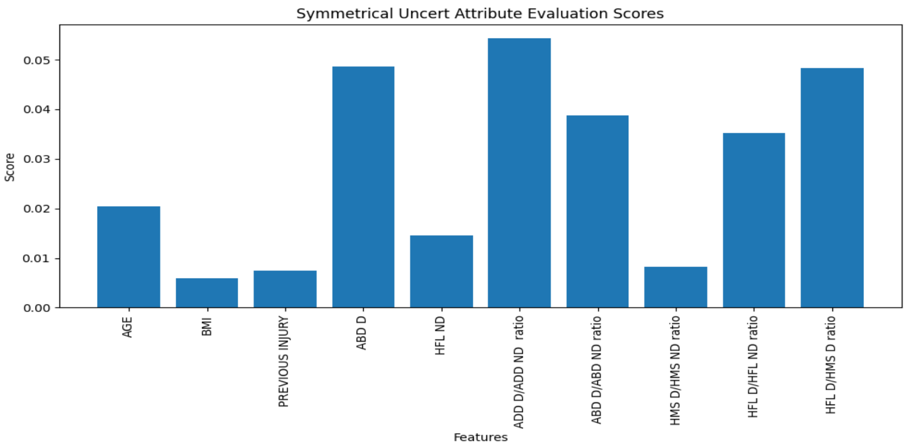

Figure 3. Variables importance analysis via the symmetrical uncert attribute evaluation analysis.

The multivariate regression model's results are presented in Table 3. The model showed a good fit (Hosmer-Lemeshow >.05), a high correct global classification (85%), and notable discriminant capacity with an AUC of 81% at a 95% confidence level. The model accounted for 29% of the players' probability of sustaining a HSI, that is, injured or non-injured (Negelkerke R2=0.29). The study revealed that the participants' risk of injury depended on a single isometric variable ($p < .05$): Isometric hip abduction strength of the dominant leg is a significant predictor of hamstring injury. Specifically, players with higher isometric hip abduction strength in the dominant leg had a 18.5% lower risk of sustaining a HIS (OR = 0.818, CI95% = [(0.695-1.038]). No other significant variables were found to be significant predictors of hamstring injury in the player group (p> 0.05).

Table 3. A multivariate LR sensitivity analysis of significant variables on the hamstring injury risk of football players.

Predictors	*B*	SE	Z	p	Odds ratio	95% Confidence Interval	
						Lower	Upper
Intercept	0.963	4.334	0.222	0.824	2.620	0.001	12.800.098
AGE	-0.012	0.050	-0.243	0.808	0.988	0.895	1.090
BMI	0.034	0.136	0.247	0.805	1.034	0.792	1.350
PREVIOUS INJURY	-1.283	0.805	-1.594	0.111	0.277	0.057	1.343
ABD D	**-0.200**	**0.083**	**-2.404**	**0.016***	**0.818**	**0.695**	**0.964**
HFL ND	0.108	0.067	1.603	0.109	1.114	0.976	1.270
ADD D/ADD ND ratio	0.939	1.520	0.618	0.536	2.558	0.130	50.274
ABD D/ABD ND ratio	-0.414	1.121	-0.369	0.712	0.661	0.074	5.949
HMS D/HMS ND ratio	-0.346	1.541	-0.224	0.822	0.708	0.035	14.509
HFL D/HFL ND ratio	2.304	2.251	1.023	0.306	10.015	0.121	826.220
HFL D/HMS D ratio	-0.621	0.947	-0.656	0.512	0.537	0.084	3.436

Note: * p<0.05, Nagelkerke R [2]=0.29; Hosmer Lemeshow (p=0.98); AC= 0.85; AUC = 0.81. ABD Abductors, ADD: Adductors, HMS: Hamstrings, HFL Hip Flexors, D: Dominant, ND: non dominant

Discussion

The primary findings derived from this investigation revealed that (a) hip muscle strength asymmetries, and particularly the isometric strength of the hip abductor muscles in the dominant limb emerged as a significant contributing factor to the HSI (b) the isometric strength of the hamstring exhibited limited efficacy as an indicator of prognosis of the HSI, (c) previous HIS and age did not appear as significant risk factors, and (e) sprinting or high-speed running emerged as the most prevalent mechanism for the HSI.

Our study is the first to highlight the effect of hip abductor muscles strength asymmetries to HSI incidence, indicating that players with weak hip abductor muscles of the injury site had increased

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risk to sustain an HSI. Although a substantial amount of research was mainly sightseeing risk factors within the muscle anatomical and functional properties (strength, fibers length, endurance strength, flexibility) less is known regarding the role of the neighbor anatomical structures (lumbar and pelvic soft tissue structures and muscle complexes) on hamstring mechanics. The contribution of hip abductors in running kinematics and how abductor muscles' weakness affects primary hamstring performance need further research. It is plausible that the kinematic alterations between the strong and weak hip abductor groups could predispose the weaker group to a variety of overuse knee injuries [1,34] . Weakness in the hip abductors may cause an increased valgus vector at the knee resulting in greater tension on the iliotibial band especially during early stance when maximal deceleration occurs to absorb ground reaction forces [18] ,which also supports previous suggestions on the association between HSI and GMed function during running [16]. The results enforce previous evidence showing that soccer players with higher levels of gluteus maximus surface electromyographic activity during hip flexion in maximal sprinting and increased oblique abdominal electromyographic activity during hip extension were less prone to subsequent HSI compared to those with lower levels of muscle activation [49]. Collectively, our findings support the hypothesis that advanced control of the lumbopelvic complex may reduce the rates of hamstring injury.

Muscle injury etiology provides a complex multifactorial profile, therefor it would be misplaced to highlight our results as the milestone of hamstring injury incidence. However, our findings highlighted high-speed running or acceleration as the most common injury mechanism of HSI [22,28], which links with the hypothesis that hip abductors strength asymmetries or lumbo-pelvic instability limit the ability of the hamstring muscles to generate maximum horizonal force, or alter the kinematics in pelvis- and trunk, contributing to a less safe running pattern, making the running athlete more prone to sustaining (repeated) hamstring injuries [50] . Although no strong direct evidence exists to explain the direct effect of hip abductors weakness on hamstring injury incidence, indirect evidence indicated that strengthening exercises targeting core and pelvic musculature had positive effect on running performance [47] and lower limb injury prevention [4]. Increased anterior tilt of the pelvis during running results in a change of the pelvis position, causing the ischial tuberosities to move superiorly, affecting the length of the hamstrings leading to premature fatigue [8,9,50], increasing the likelihood of sustaining an injury while sprinting [37]

The pelvic tilt has a significant impact on the surrounding joints and the mechanical relationships between muscles that are attached to the pelvis. Consequently, any changes in the anterior pelvic tilt can affect these interactions and cause alterations in the functioning of the musculoskeletal system [32]. High-speed running has been linked to a greater overall anterior pelvic tilt in sprinters [36] due to the combined effect of increased anterior pelvic tilt and trunk flexion, which leads to biceps femoris elongation during the late stance and late swing phase of running [20]. A comprehensive biomechanical analysis conducted on men soccer players who experienced an initial hamstring injury revealed an increase in anterior pelvic tilting and thoracic side-bending during the back- and front swing phases of acceleration [50]. Furthermore, the GMed's function as hip abductor enhancing pelvic stability in men soccer players during running, has been previously highlighted [16]. A kinematical analysis showed that previous HSI allters pelvis kinematics and stability during the stance phase of sprinting [39]. These findings present compelling evidence suggesting that lumbo-pelvic motion or positioning may indeed contribute to the occurrence of hamstring injuries. It is important to clarify that, our study did not encompass any kinematic analysis, thus precluding the establishment of any correlation with variations in pelvic kinematic behavior during high-speed running.

The relationship between isometric hamstring strength and HSI occurency in soccer remains debated. Although a recent meta-analysis found inconsistencies between HSI and strength properties [42] , it is widely acknowledged that assessing isometric strength is significant in predicting HSI and the subsequent decline in strength following an injury [17], while prior research has indicated that deficits in eccentric strength may increase the risk of acute hamstring injuries [54]. A recent prospective study [55] revealed the opposite, that eccentric hamstring strength provided limited predictive capacity for identifying athletes at high risk for HSI. Our analysis did not uncover the link

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between hamstring isometric strength and the risk of hamstring injury, which is consistent with previous findings [28], but in contrast with others [48] .An explanation might be that factors others than hamstring strength may have a greater impact on hamstring function while sprinting, hence contributing significantly to HSI occurrence.

It is unclear why our study deviates from the previously established strong linear correlation between previous injury and an increased risk for a future hamstring injury [17]. A possible explanation could be the algorithm's capacity to analyze the intricate interactions between various variables, including injury history, rather than focusing solely on the linear relationship between two independent variables. Furthermore, the age of the participants in the present study (Mean ± (SD) 20 years old) was young enough to justify a relatively small number of previous injuries. Similarly, our statistical analysis results revealed that age was not a strong indicator for hamstring injury, which aligns with previous research. [41]

A recent comprehensive review examined the utilization of various machine learning algorithms in the prediction of injuries, resulting in promising outcomes [13]. In our study, the Area Under the Curve (AUC) for the model had been determined to be 0.79, indicating a commendable level of modelling for the prediction of injury risk. Similarly, the study of Ayala and colleagues [5] reported a notably high AUC score of 0.83 in the prediction of hamstring injuries. However, their study, which encompassed hip isometric strength measurements as a constituent part of an extensive dataset, failed to ascertain which players exhibited an elevated risk of injury due to the absence of regression analysis to calculate odds ratios (ORs). Despite the authors' suggestion that their model exhibited moderate predictive accuracy, they were unable to identify the underlying cause of the injuries. Artificial intelligence and Machine learning algorithms are presently highly popular prediction tools, however, there exists a significant degree of uncertainty and ambiguity surrounding their application. It is imperative to acquire a more profound comprehension of the "know-how" behind these models, including the requisite data, precise models, and factors that determine their accuracy. Given the multifactorial nature of hamstring injuries, machine learning algorithms that are capable of handling complexity offer promising outcomes. It is suggested that further research be conducted to ascertain the most effective machine learning algorithms and to gain a better understanding of the factors that influence their accuracy.

Our research meets several limitations when interpreting our findings. Initially, it is important to note that the study had a relatively small sample of players, resulting in a low number of injury incidents. It's worth noting that this study focused on participants in an amateur league comprising 11 teams. Despite our efforts to contact all teams, only 6 teams ultimately took part, resulting in a recruitment rate of aprox. 55% which is considered reasonable. Additionally, our analysis didn't encompass players' problems that demanded medical assistance but didn't result in time loss, introducing another limitation. Furthermore, it's worth noting that the measurements took place in a field setting, making belt-fixation impossible. When interpreting our findings, it's important to consider these limitations. Conversely, the study's internal validity was a strength due to the consistent measurements conducted by a single investigator. In our analysis, most of hamstring injuries were sustained during high-speed running or sprinting, however since external load monitoring methods (Global Positioning System) were not applied, it was uncertain to estimate the injury conditions as high accelerations ($3m/s^{-}$ [1]), high-speed running (20-25km/h) or total sprint (>25km/h). Lastly, due to time constrains hip extension, and hip internal and external strength measurements were not performed. This study achieved partial internal validity as all measurements were conducted by the same investigator. However, due to the nature of the study, internal validity regarding the medical examination and diagnosis of the injury could not be established.

Conclusions

Muscle strength asymmetries, specifically the isometric strength of the hip abductor muscles in the dominant limb, were found to be significantly correlated with hamstring injury using multivariate machine-learning logistic regression analysis. Conversely, hamstring isometric strength, age, and history of previous injury exhibited no correlation with injury. These findings reinforce previous indications regarding the relationship between lumbo-pelvic stability and the incidence of hamstring injury. Consequently, healthcare professionals should consider incorporating hip strengthening exercises into regular training sessions, rehabilitation programs, and injury prevention protocols.

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