Sports Medicine
https://doi.org/10.1007/s40279-022-01672-5

ORIGINAL RESEARCH ARTICLE

Return to Play Prediction Accuracy of the MLG-R Classification System for Hamstring Injuries in Football Players: A Machine Learning Approach

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Accepted: 15 March 2022

Abstract

Background and Objective Muscle injuries are one of the main daily problems in sports medicine, football in particular. However, we do not have a reliable means to predict the outcome, i.e. return to play from severe injury. The aim of the present study was to evaluate the capability of the MLG-R classification system to grade hamstring muscle injuries by severity, offer a prognosis for the return to play, and identify injuries with a higher risk of re-injury. Furthermore, we aimed to assess the consistency of our proposed system by investigating its intra-observer and inter-observer reliability.

Methods All male professional football players from FC Barcelona, senior A and B and the two U-19 teams, with injuries that occurred between February 2010 and February 2020 were reviewed. Only players with a clinical presentation of a hamstring muscle injury, with complete clinic information and magnetic resonance images, were included. Three different statistical and machine learning approaches (linear regression, random forest, and eXtreme Gradient Boosting) were used to assess the importance of each factor of the MLG-R classification system in determining the return to play, as well as to offer a prediction of the expected return to play. We used the Cohen's kappa and the intra-class correlation coefficient to assess the intra-observer and inter-observer reliability.

Results Between 2010 and 2020, 76 hamstring injuries corresponding to 42 different players were identified, of which 50 (65.8%) were grade 3^r, 54 (71.1%) affected the biceps femoris long head, and 33 of the 76 (43.4%) were located at the proximal myotendinous junction. The mean return to play for grades 2, 3, and 3^r injuries were 14.3, 12.4, and 37 days, respectively. Injuries affecting the proximal myotendinous junction had a mean return to play of 31.7 days while those affecting the distal part of the myotendinous junction had a mean return to play of 23.9 days. The analysis of the grade 3^r biceps femoris long head injuries located at the free tendon showed a median return to play time of 56 days while the injuries located at the central tendon had a shorter return to play of 24 days ($p=0.038$). The statistical analysis showed an excellent predictive power of the MLG-R classification system with a mean absolute error of 9.8 days and an R-squared of 0.48. The most important factors to determine the return to play were if the injury was at the free tendon of the biceps femoris long head or if it was a grade 3^r injury. For all the items of the MLG-R classification, the intra-observer and inter-observer reliability was excellent ($k>0.93$) except for fibres blurring ($\kappa=0.68$).

Conclusions The main determinant for a long return to play after a hamstring injury is the injury affecting the connective tissue structures of the hamstring. We developed a reliable hamstring muscle injury classification system based on magnetic resonance imaging that showed excellent results in terms of reliability, prognosis capability and objectivity. It is easy to use in clinical daily practice, and can be further adapted to future knowledge. The adoption of this system by the medical community would allow a uniform diagnosis leading to better injury management.

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Published online: 24 May 2022

Key Points

The main determinant for a longer return to play after a hamstring injury is the injury affecting the connective tissue structures of the hamstring.

Injuries affecting the biceps femoris long head/semitendinosus free tendon have a longer return to play than those located at the central tendon.

Extracellular matrix structure and its role in force generation and transmission is a likely key factor in the prognosis of muscle injuries.

1 Introduction

Muscle injuries are very common in sports that require explosive movements such as football [1], rugby [2], American Football [3], or track and field [4]. In professional football, between 92 and 97% of all muscle injuries are located in the lower extremity: hamstrings (28–37%), quadriceps (19–32%), adductors (19–23%), and calf muscles (12–13%) [1]. Deciding when a player is ready to return to play (RTP) following a muscle injury is challenging because of the high variability in recovery and types of injuries [5, 6]. A premature RTP can be one of the reasons for the high re-injury rates (12–43%) and prolonged time loss [1, 5, 7, 8].

Top-level professional sports place such a high demand on an athlete's body that despite all preventive strategies, the incidence of muscle injuries seems to keep growing [9]. The problem is even worse, as many athletes recovering from the muscle injury succumb to re-injury during rehabilitation. Several reasons could explain this situation: the lack of a clear consensus regarding RTP criteria for hamstring muscle injuries (HMIs) [10], large variability in recovery times and types of injuries [5], the higher physical demands during games [11], different criteria to design rehabilitation protocols [12], or the influence of a congested period of games on players' health [13].

Furthermore, even sophisticated imaging modalities such as magnetic resonance imaging (MRI) have not yielded an accurate predictive tool. Current evidence on the predictive value indicates that even a complete resolution of the injured tissue on MRI is not a predictive indicator of a safe RTP [14].

One of the fundamental problems using MRI as a predictive tool is that the skeletal muscle injury induces a large number of imaging signs such as oedema, haematoma, variable rupture of the myotendinous unit, and varying retraction length of the ruptured muscle stumps; and sometimes these acute/subacute signs are also associated with scars or fat infiltration due to previous injuries [15]. Thus, there is a demand to develop a classification system for the evaluation of the magnetic resonance images that would assist in providing an accurate prognosis.

A classification system should avoid ambiguous terms to reduce subjectivity, be easy to apply, facilitate communication with the staff and other colleagues, and describe clearly demonstrable objective findings [16]. It should also have prognostic validity to help healthcare professionals with rehabilitation protocols and RTP decisions.

For years, multiple muscle injury grading and classification systems have being published, based on clinical parameters first, then ultrasound and lately on MRI [17]. Recently, several classification systems based on MRI are being tested with good intra-observer and inter-observer reliability [18, 19]. Unfortunately, they have failed to provide accurate RTP prognosis [20].

The MLG-R is a MRI-based, four-letter initialism classification system (MLG-R), referring to the mechanism of skeletal muscle injury (M), its location (L), grading of severity (G), and number of muscle re-injuries (R). The complete description of the proposal and the scientific background has been previously published [16], along with a second article about how to apply this classification system [21].

The connective tissue surrounding each individual muscle fibre as well as forming myotendinous junctions (MTJs) at both ends of the muscle plays a key role in muscle injuries, clinical symptoms, and severity [22]. The connective tissue structures of the injured skeletal muscle have not received as much clinical attention as they warrant until recently [23]. It has become evident that the extent of the damage to the connective tissue structure could be the main determinant of the severity of the injury and could provide the most accurate predictive value for clinicians. Hence, the main aim of our new classification proposal is to evaluate by MRI how much connective tissue structure is being affected by the injury [16]. The MRI-based evaluation of connective tissue structures is not limited to the main connective tissue structures at the end of the muscle–tendon unit, i.e. tendons, but to evaluate its complete structure, endomysium, perimysium, and epimysium, independently of its density or anatomy [24]. Therefore, to correctly use the MLG-R proposal, a deep knowledge about the anatomy of muscles and their MTJs is needed.

The principal aim of the present study was to evaluate the capability of the MLG-R classification system to grade injuries by severity, offer a prognosis for RTP, and identify injuries with a higher risk of re-injury in a sample of hamstring injuries from top-level professional athletes (FC Barcelona [FCB] football teams). The secondary goal of this study was to assess the consistency of our proposed system by investigating its intra-observer and inter-observer reliability.

2 Methods

2.1 Study Population and Ethics

The FCB medical department offers medical care for the FCB athletes, and registers all medical assistances in a private electronic medical record named COR ("Conocimiento, Organización y Rendimiento"). All medical episodes are coded using the Orchard Sports Injury Classification System, Version 10 [25, 26]. The COR contains all data from FCB athletes' injuries and illnesses from every episode (diagnosis, physical exploration, complementary studies, injury date, time off, treatment performed, and reinjures) in a prospectively collected database.

All male professional football players from FCB (senior A and B and the two U-19 teams) with injuries that occurred between February 2010 and February 2020 were approached for eligibility. Only players with HMIs were included in the present study. The project has been assessed and approved by the Ethics Committee of the "Consell Català de l'Esport" with the number 10/CEICGC/2020. The present study was performed in accordance with the standards of ethics outlined in the Declaration of Helsinki.

2.2 Data Collection and Extraction

We reviewed episodes coded under the Orchard Sports Injury Classification System section "Thigh Muscle strain/ Spasm/ Trigger Points" to filter HMIs. All episodes with symptoms compatible with a HMI were included and evaluated.

Each injury was assessed individually and only injuries with a clinical presentation matching a HMI, and confirmed by MRI (within 72 h after the injury) were included in the final analysis. If diagnosis was confirmed only by ultrasound or the MRI from the acute phase of the injury was not available, the injury was excluded from the final sample. In each case, a rehabilitation programme aiming at the RTP was carried out by team physicians in accordance with the club's clinical practice guidelines for HMIs [27]. The RTP was defined as the moment when the player returned to full unrestricted practice with the team, or game participation and was always recorded in electronic medical records.

Re-injuries were recorded in medical records according to our previous definition. A re-injury is the occurrence of a muscle injury affecting the same muscle and/or MTJ as the initial injury during the rehabilitation process or within the next 2 months after the RTP [16].

2.3 MRI Protocol

The MRIs were performed with two different MRI devices. The great majority of them (54 cases) were performed in the FCB's medical center using a 3.0 T MRI system (Vantage Titan; Canon Medical Systems, Sant Joan Despí, Spain). The rest of the cases (22 players) were evaluated in an external medical center by a 3.0 T system (Magnetom VERIO; Siemens Medical Solutions, Barcelona, Spain). In all cases, the magnetic resonance images were evaluated by the same researchers (see Sect. 2.4). The patients were positioned in supine decubitus, the examination was performed focused on the injured limb and the symptomatic area marked on the patient with a cutaneous vitamin marker. A multi-purpose coil was used, with speeder technology. This allowed the acquisition of five sequences according to the standardised protocol for evaluating muscle injuries in the lower extremities. Axial, Sagittal and Coronal T2 Fat Sat, TR 5200, 5000 and 3700 ms, TE 44–60 ms, Eco train 7.5, SL 2.5–3.5 mm, in-plane resolution $0.9–1.4 \times 0.88–0.97$ mm^2, FOV 256×256, 192×272, 288×320 mm, and Axial and Coronal TSE T1, TR 900–980 ms, TE 11 ms, Eco train 7.5, SL 2.5–3.5 mm, in-plane resolution $0.71–0.9 \times 0.71–0.9$ 9 mm^2, and FOV 352×352, 288×320 mm were acquired and evaluated.

2.4 Image Review

A cross-sectional review of each injury's MRI was performed independently by one musculoskeletal radiologist (SM), and one sports medicine physician (XV). All injuries were classified using the MLG-R classification system [16]. Both researchers were familiar with this classification, have years of experience working with muscle injuries, and evaluating magnetic resonance images from soft-tissue injuries [15].

To summarise the MLG-R proposal, the category M stands for mechanism, i.e. direct (T), and indirect (I) muscle injuries. Subcategories of the mechanism category were created to define stretching type (subindex s) and sprinting-type (subindex p) indirect HMIs, as they can influence the outcome. The category L (location) informs of the anatomical location of the injury at the proximal (P), middle (M), or distal (D) third of the muscle belly and a subindex describes the relationship of the injury either with the proximal (p) or distal (d) MTJ. The MLG-R classification system does not quantify oedema; the oedema characteristics will be relevant to differentiate between grade 1 and 2. Grade 3 is defined as quantifiable gap between fibres in craniocaudal or axial planes. Grade 3 implies that there are torn fibres located affecting the muscle, the connective tissue or both. If the fibre ruptures affects the connective tissue, the superscript "r" is added to the grade. For injuries affecting the MTJ at two different locations, we use the one located proximally to define the grade (i.e. code). Finally, a grade 0 injury is an indirect injury with clinical suspicion but negative MRI. In these cases, the second letter describes the pain locations in the muscle belly. The category R informs of the injury chronology, the index injury will be R0, and the first reinjury classified as R1. Examples of grades, loss of tension, and cross-sectional area measurement are available in the Electronic Supplementary Material (ESM).

Magnetic resonance images from each injury were reviewed three times in a patient-blinded manner by the two researchers. The first review was not performed independently so as to review the classification system before MRI readings and unify criteria on how to apply it. A second MRI review was performed independently by the radiologist (SM) and the sport medicine physician (XV) after 3–8 months from the first evaluation. Finally, all injuries were evaluated for the third time by both evaluators and discrepancies discussed altogether in order to reach a consensus regarding the injuries classification.

2.5 Outcome

The primary outcome variable was RTP, measured in days. The independent variables, or covariates, included in the models derived from magnetic resonance images were: injury location at the tendon (free tendon, central tendon, or other location), location at the muscle belly (proximal, medial, or distal third), MTJ injury location (proximal or distal), grade of injury (0, 1, 2, 3, or 3^r), re-injury (0, 1, or 2) and the muscle injured (biceps femoris long head [BFlh], biceps femoris short head, semimembranosus, or semitendinosus [SMT]). We entered the variables in the models in a binary format.

2.6 Statistical Analysis

In order to validate the classification and understand the factors that determine the RTP, we used three different statistical models. First, multiple linear regression as a baseline model; second, random forest; and third, eXtreme Gradient Boosting (XGBoost). This approach was used to check if different models lead to the same conclusions.

We chose linear regression as it is the gold-standard model for analysing RTP data and it has been used in previous studies of hamstring injuries [28, 29]. Random forest, which is based on bagging and uses ensemble learning, was used as a second model as it can efficiently handle non-linearities in the data, it does not tend to overfit, and it reduces the variance, leading in turn, to an improvement in accuracy with respect to multiple linear regression (30). Finally, XGBoost offers increased accuracy and predictive power by using an ensemble of weak learners [31]. We optimised the hyperparameters by conducting a grid search. We performed leave-one-out cross-validation as a model validation technique to assess the generalisability of the results in order to leverage as much as possible the information provided by each observation.

We computed mean absolute error (MAE), root mean squared error (RMSE), and the coefficient of determination (R^2) as measures of the quality of the predictors. Moreover, we computed the accumulated local effects (ALEs) to understand the relative importance and contribution of each feature on average in predicting the RTP [32, 33]. Positive ALEs contributed to a longer average RTP while negative ALEs decreased the average RTP. The alpha level was set at 0.05. All analyses were conducted in R 3.6.3 [34].

In addition, weighted and unweighted Cohen's kappa as well as the intra-class correlation coefficient were used to assess the MLG-R classification reliability. First, we quantified the diagnostic reliability between the two physicians (inter-observer reliability). Second, we measured the reliability of the diagnosis within each independent physician at two different timepoints (intra-observer reliability).

3 Results

From a sample of 3875 injuries during the period of study, all episodes with symptoms compatible with an HMI were included and evaluated (Fig. 1). The patients and injury characteristics are shown in Table 1. Of note, most of the hamstring injuries affected the BFlh ($N=54$; 71.1%), were grade 3^r ($N=50$; 65.8%), and were located at the proximal third [proximal MTJ] ($N=33$; 43.4%). Among all BFlh and SMT injuries located at the proximal third ($N=41$), seven were located at the FT, 19 at the central tendon, and 15 at other locations of the MTJ.

When assessing the difference in the RTP by the severity of injury (grade), the interquartile range (25.2) of the RTP was the longest for grade 3^r injuries. Grade 3^r injuries exhibited the longer RTP than the other grades when all muscle injuries were assessed and also when the BFlh injuries were analysed independently (Fig. 2). In contrast, there were no statistically significant differences among any other grades (Fig. 2). The mean RTP of the BFlh injuries between grades 1, 2, and 3, were 11, 15, and 18 days, respectively.

In grade 3^r BFlh injuries, there were no statistically significant differences in the RTP among the several locations (Fig. 3). Injuries located at the proximal third and affecting the proximal MTJ (P_p) had a larger variance in the RTP compared with the other locations. The RTP for injuries located

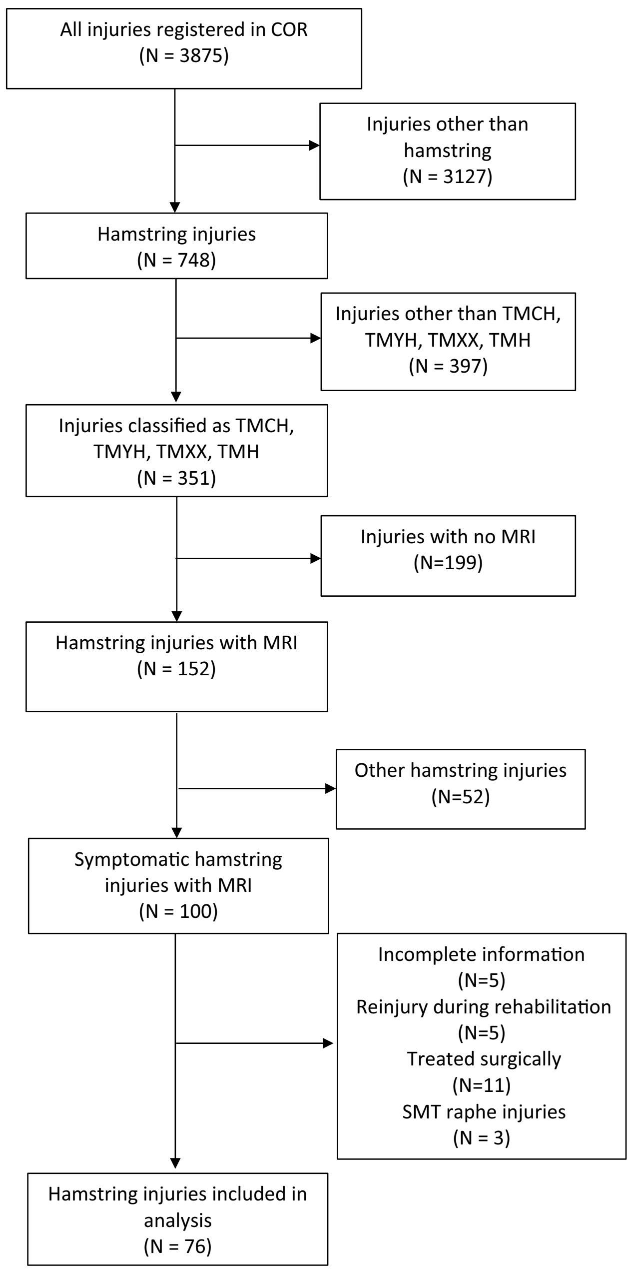

Fig. 1 Flowchart of included injuries in the analysis. *COR* Conocimiento, Organización y Rendimiento, *MRI* magnetic resonance imaging, *SMT* semitendinosus, *TMCH* hamstring cramping suring exercise, *TMH* hamstring strain, *TMXX* thigh muscle strain/ spasm/ trigger points, *TMYH* hamstring trigger points

Table 1 Sample description

	Overall
N	76
RTP days, mean (SD)	29.1 (16.9)
Age, years, mean (SD)	24.2 (5.0)
Team senior, *n* (%)	62 (81.6)
Muscle injured, *n* (%)	
BFlh	54 (71.1)
BFsh	1 (1.3)
SMB	12 (15.8)
SMT	9 (11.8)
Grade, *n* (%)	
0	1 (1.3)
1	3 (3.9)
2	17 (22.4)
3	5 (6.6)
3^r	50 (65.8)
Reinjury = 1 (%)	9 (11.8)
Injury location, *n* (%)	
D_d	20 (26.3)
D_p	3 (3.9)
M_d	7 (9.2)
M_p	13 (17.1)
P_p	33 (43.4)
Stretching injury mechanism, *n* (%)	13 (17.1)
Tendon location, *n* (%)	
Other	50 (65.8)
Central	19 (25.0)
Free	7 (9.2)

BFlh biceps femoris long head *BFsh* biceps femoris short head, Injury located at the distal third affecting the distal myotendinous junction (MTJ) (D_d), injury located at the distal third affecting the proximal MTJ (D_p), injury located at the middel third affecting the distal MTJ (M_d), injury located at the middel third affecting the proximal MTJ (M_p), injury located at the proximal third affecting the proximal MTJ (P_p), *RTP* return to play, *SD* standard deviation, *SMB* semimembranosus, *SMT* semitendinosus

at the medial third affecting the proximal MTJ (M_p) and the distal MTJ (M_d) was very similar. Likewise, injuries closer to the insertion, Dd and Pp, had a similar RTP as no statistically significant differences ($p = 0.91$) were found (Fig. 3).

The analysis of the grade 3^r BFlh injuries located at the FT showed a median RTP time of 56 days while the injuries located at the central tendon had a shorter RTP of 24 days ($p = 0.038$) (Fig. 4). For the SMT, injuries located at the FT still had a worse prognosis (median RTP of 54.5 days) than those located at the central tendon (median RTP of 34 days), but the differences were not statistically significant ($p = 0.43$) (Fig. 4). For the BFlh, the RTP after sustaining a complete MTJ gap was significantly longer ($p = 0.0087$) compared with partial injuries (Fig. 4). Imaging of partial and complete tendon injuries is provided in Fig. 4 of the ESM.

The three models (linear regression, random forest, and XGBoost) converged with respect to variable importance and accumulated local effects (Table 1 and Figs. 1–6 of the ESM). However, it was the XGBoost model that yielded the best performance according to all the metrics as shown in Table 2. The MAE, the RMSE and the R-squared were 9.7884, 12.145, and 0.4847, respectively. In addition, when

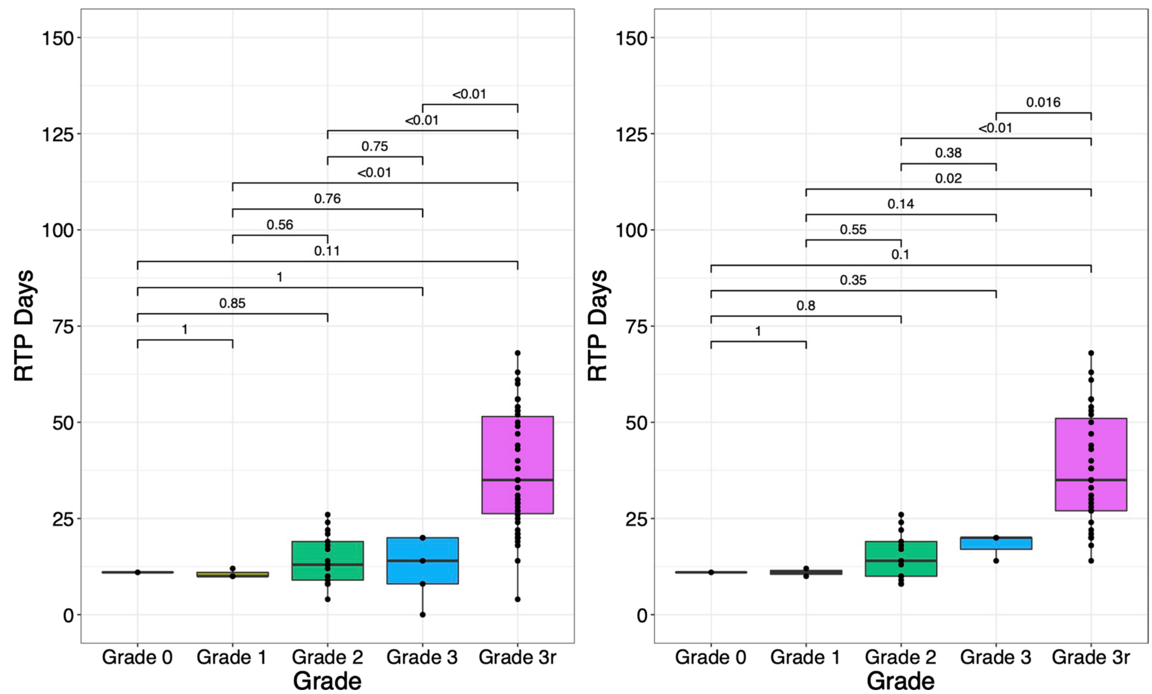

Fig. 2 Return to play (RTP) by grade: all muscles (left), and for biceps femoris long head (right)

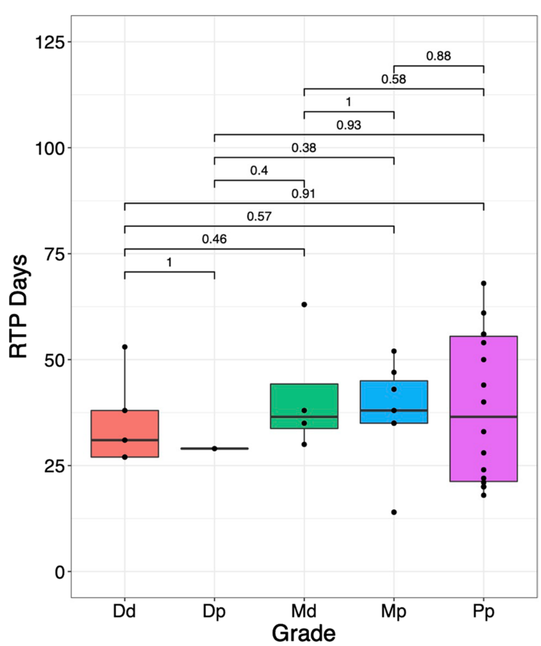

Fig. 3 Return to play (RTP) biceps femoris long head grade 3^r by location, and related to the myotendinous junction. Injury located at the distal third affecting the distal myotendinous junction (MTJ) (D_d), injury located at the distal third affecting the proximal MTJ (D_p), injury located at the middel third affecting the distal MTJ (M_d), injury located at the middel third affecting the proximal MTJ (M_p), injury located at the proximal third affecting the proximal MTJ (P_p)

looking at the performance measures stratified by grade, we observed that the predictive power was higher in injuries of lower grade compared with those of grade 3 (Table 3). These results could not be compared with other classification systems as these performance measures were not reported [35, 36].

We observed that the grade of the injury was the most important variable to determine the RTP followed by the MTJ location (free, central, other) or muscle injury. Furthermore, when looking at the ALE, we identified FT injuries as the most relevant factor driving the long RTP (Fig. 6 of the ESM). Moreover, grade 3^r was identified as the second most relevant factor for long RTP followed by re-injuries (Fig. 6 of the ESM). In terms of inter-rater and intra-rater reliability, the Cohen's kappa and the intra-class correlation coefficient showed an excellent level of agreement between the different measurements (Table 2 of the ESM).

4 Discussion

We demonstrate in this study that the MRI-based MLG-R classification system provides an accurate prognosis on hamstring injuries sustained by professional athletes. Our study shows that the main determinant for long RTP after hamstring injury is the injury affecting the connective tissue

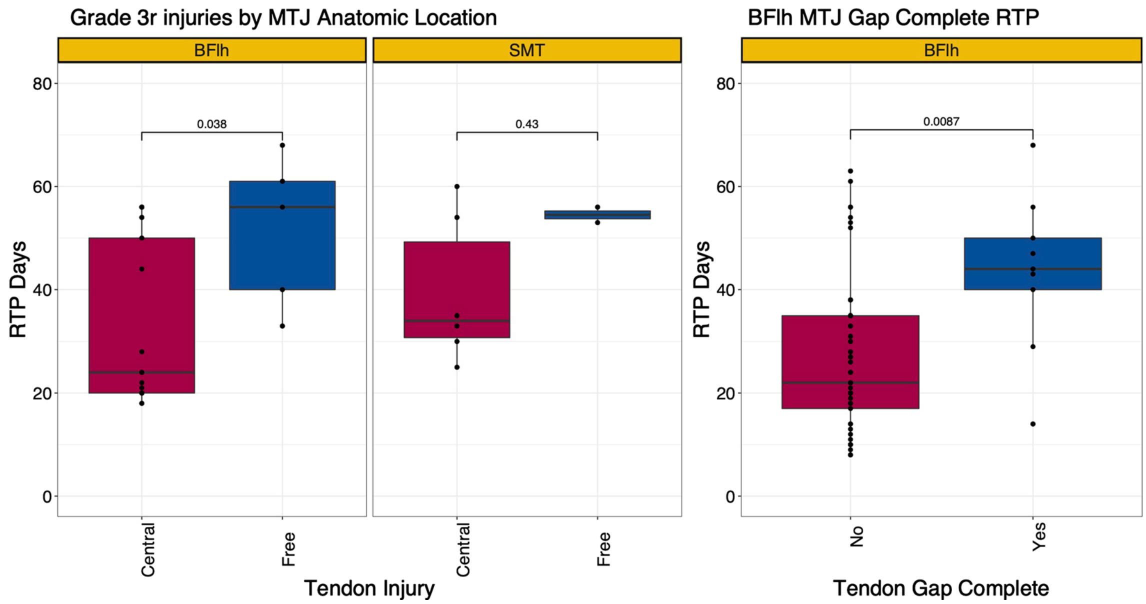

Fig. 4 Return to play (RTP) of grade 3[r] biceps femoris long head (BFlh) and semitendinosus injuries (left). Return to play of grade 3[r] BFlh in partial vs complete tendon injury (right). *MTJ* myotendinous junction

Table 2 Performance measures of validation models

	Linear regression	Random forest	XGBoost
MAE	10.3609	10.1037	9.7884
RMSE	12.8070	12.5296	12.1450
R-squared	0.4345	0.4195	0.4847

MAE mean absolute error, *RMSE* root mean squared error, *XGBoost* eXtreme Gradient Boosting

Table 3 XGBoost performance by grade

Grade	*N*	Re-injuries	IQR	MAE	RMSE
0	1	0	0.0	4.0	4.0
1	3	0	1.0	5.0	5.1
2	17	2	10.0	5.9	7.4
3	5	0	12.0	6.2	7.6
3[r]	50	7	25.2	11.8	14.0

IQR interquartile range of observed values, *MAE* mean absolute error, *N* number of observations, *RMSE* root mean squared error, *XGBoost* eXtreme Gradient Boosting

structures of the hamstring. The strength of our study is that our results came from a very homogeneous sample of professional football players, with the same resources and philosophy for diagnostic, rehabilitation, and RTP criteria. All the players were followed up for at least one season after the injury, which also allowed us to monitor re-injuries or new injuries in the same region. The distribution of injuries within different hamstring muscles in our patient samples is similar to previous studies [5], as is also the number of re-injuries [2].

When we explored for the predictive MRI findings, the difference in RTP between 3[r] and all other grades was statistically significant for all injuries, and individually for BFlh injuries. The small number of injuries with a grade other than 3 is a limitation of our study. Although the mean RTP time increased from grades 1 to 3 in the BFlh sample, the differences are not statistically significant because of the low number of injuries.

The longer RTP time for 3[r] injuries in the BFlh or the SMT FT compared with those injuries located at the central tendon supports the concept that injuries affecting the proximal part of the MTJ are worse than the more distal injuries [37]. We could not find a similar outcome in the RTP between BFlh 3[r] injuries involving the middle and distal part of the proximal MTJ. However, we were again hampered by the low number of these injuries.

The role of central tendon injuries on the RTP has been evaluated in thigh muscles, where it was reported that a significant injury to the intramuscular tendon is associated with a prolonged RTP and an increased re-injury risk [38]. In line with the literature, we found a statistically significant difference between BFlh proximal MTJ with partial vs complete tendon gap injuries. In general, any injury involvement of the proximal MTJ will have a great impact in the RTP. This may be due to the fact that the time needed for the connective tissue to heal is longer than for the muscle fibres [39]. Based on the data from our sample, we should state that the injury in any grade of the principal connective tissue structure, which is the MTJ, will be the main factor that needs to be considered to estimate the RTP.

The fact that the grade, followed by the involvement of tendon injury (free, central or other), are the most important variables to determine the RTP in hamstring injuries, support our concept that the extent of the damage to the connective tissue structures is key for the RTP. The small difference in the mean RTP of the BFlh injuries between grades 1, 2, and 3, without connective tissue structure damage (11, 15, and 18 days) strengthens the idea that the main driver for longer RTP is to have an injury affecting the MTJ.

Indirect/strain muscle injuries are typically located close to a MTJ [40, 41]. A recent publication highlights the notion that damage in muscle injuries is located in places where muscle fibres attach to connective tissue structures. This shows evidence that damage to the connective tissue plays a more important role than for the muscular component in terms of recovery [23]. The data from our sample show that 50 (65.8%) injuries are grade 3^r, which means that the MTJ is injured at some point on its length. From the 55 (72.4%) injuries of grade 3 and grade 3^r, 24 (43.6%) have no muscle fibre injury other than oedema described in grades 1 or 2. We refer to all of these injuries as muscle injuries when we are really describing injuries of the MTJ in most of the cases.

We present a novel approach to validate and understand the clinical prognosis of hamstring injuries by using three advanced statistical models. The approach we used is clearly superior to previous studies [28, 29] as we compared the performance of three different statistical and machine learning models. These models allow the capture of nonlinearities in the data, they are more prone not to overfit and they have reduced variance. The best model in all the performance measures, the XGBoost, managed to obtain a MAE of 9.8, implying that on average, for any given injury, the RTP time prediction will only fail by 9.8 days. Nonetheless, better results in terms of the RMSE and MAE were observed for less severe injuries as shown in Table 3. Therefore, one has to bear in mind the nature and complexity of the injury when using the MLG-R to predict the RTP. Moreover, the R^2 presented was more than double that of previous studies with similar characteristics [28]. Thus, the approach presented is robust as all models converged to similar results, had a high predictive power, the MAE and RMSE were very good, and we managed to explain a large proportion of the variance in the RTP time with very few variables. In addition, we provided a clear interpretation to the contribution of each factor to the RTP by means of the variable importance and the ALEs, something that has never been applied in the sports medicine field to the best of our knowledge.

This comprehensive approach showed evidence that the grade of the injury was the most important variable to determine the RTP followed by the MTJ injury location (free, central, other) and the muscle injured as shown (Fig. 5 of the ESM). When looking at the accumulated local effects, we identified FT injuries as the most relevant factors driving the RTP. Moreover, grade 3^r was identified as the second most relevant factor for RTP followed by re-injuries. Because of the anatomy of the distal BFlh MTJ, the location of the injuries is in a smaller area than in the proximal MTJ, which has a higher length, this could be one of the reasons why the dispersion is higher in the injuries affecting the proximal MTJ.

4.1 Injuries Affecting the Free Tendon

Although the injured patients were obtained from four professional teams with a substantial number of experienced players in them, all 11 free tendon ruptures that required surgery, and were not included in the statistical analysis, took place exclusively in players between 17 and 21 years of age. The finding is striking and novel, but there could be several plausible explanations for it. The injuries were located at the ischial tuberosity avulsion in younger athletes [42], but we do not have a clear explanation why we only saw injuries affecting the central tendon in older/more experienced football players. However, our results suggest that there might be remodelling/maturation in the hamstring bone-tendon–muscle unit well into the mid-20 s in professional athletes and should warrant further investigation. If this is indeed the case, then we see avulsion fractures during puberty, injuries affecting the central tendon in fully mature players, and in this window of 4 years, the most severe injuries take place at the FT. We cannot emphasise the importance of this type of injury enough owing to its high re-injury tendency, the heavy burden of time loss related to it, and because we eventually treat these injuries surgically to restore the structure function of the hamstrings and the player performance [39, 43].

4.2 Extracellular Matrix

A.R. Gillies already quoted: "skeletal muscle are primarily contractile material. However, because muscle is a composite tissue of connective tissue, blood vessels, and nerves, as well as contractile material, these "minor tissues" (in terms of relative mass) may strongly influence muscle function" [22]. In the context of the major findings of this study, we believe that focus should be shifted to the connective tissue structures of the muscle–tendon unit in the evaluation of its injuries.

The skeletal muscles and their tendons are not the only structures transmitting and bearing tensile loads. In some muscles, less than 20% of the muscle fibres span the entire distance between the origin and the insertion, while the remaining fibres end in the muscle belly, being connected only via their endomysium or by adhering to the myofascial junction, which is the extension of the MTJ [44].

Muscle contraction has been analysed for years as linear and unidimensional, in a simplistic model, as the extracellular matrix (ECM), organised in three independent passive layers. Muscle contraction happens in three dimensions, and it is necessary to evaluate the muscle as a whole to understand its structure, function, mechanics and pathology [45]. This three-dimensional transmission of force generated at the sarcomere level is of importance also when evaluating the superior organisation beyond the sarcomere, and draws attention to the role of the structural components of the muscle in muscle function [45].

Despite the important role of the ECM in muscle function and pathology, the amount of research on it is very limited; knowledge on the muscular functional properties of the ECM [22] and its geometry [46, 47] is very limited. It is clear now that the three layers of the ECM, classically described as endomysium, epimysium and perimysium, are not individual layers covering the muscle structure from small to bigger levels; instead, it has being described as a three dimensions network, with a complex geometry and multiple connexions between layers [47]. The ECM is a three-dimensional structure going from a higher to a lesser density structure with an asymmetric distribution [24], because of that, complete knowledge of the anatomy of the MTJ muscles is key to correctly understanding muscle injuries.

4.3 Confusing Terminology

Despite the high prevalence and the challenging nature of hamstring injuries, some anatomical regions in the hamstrings need to be clarified more thoroughly especially in light of describing magnetic resonance images. Namely, the "SMT raphe" or the "semimembranosus membrane" are two classic examples of terms used to describe hamstring anatomy. The "raphe" is not yet fully understood, and we do not know if it is part of the proximal or distal MTJ, or if it should be considered an independent element. The injuries affecting the semimembranosus membrane should be classified as affecting the proximal MTJ. However, unlike injuries affecting the MTJ, they do have a good prognosis.

In addition to the certain anatomic regions not defined universally, we also describe injury "patterns" with descriptive, but not universally accepted terms such as myotendinous [48], musculotendinous [49], myoaponeurotic [50], myofascial [48], epimysial [51], peripheral [52], superficial involvement [53] or distal aponeurosis [54], and it still happens, despite recent efforts to reach agreement in terminology [55]. The only aim of all these names is to describe the topographical location of the injury related to the length of the affected MTJ and to provide an idea whether the connective tissue structures were torn.

Another example of the subjectivity in this field is the medical meaning of the term fascia, it has evolved during history [56], with several attempts to reach an agreement about the nomenclature of the fascial system and its elements [57]; and despite its extensive use in the literature, the variable application of the name still creates confusion [57].

4.4 Limitations

As described in the methods sections, our sample came from football, one club, and one medical team with the same philosophy and own experience in the use of this classification and in the field of football. Further studies should be conducted to test this classification system in different sports, and by different people with different degrees of experience, perhaps through a multicentre study. This will help to evaluate the external validity of this classification system and the possibilities of generalisation to other sports and application conditions. The normal learning curve implied in any new medical procedure (i.e. classifying a muscle injury) should be seen as a universal limitation in medical research, but we believe that this is a very important first step with promising possibilities for the complex topic of classification of muscle injuries.

5 Conclusions

With the introduction of our classification system, we strongly believe that there is no need to use any of these subjective terms to describe a muscle injury. With our four letters initialism, we report the muscle belly and mechanism of injury, and offer an objective topographic (where), chronologic (how many times), and structural (grade of injury) description of the injury, minimising the subjectivity of the description.

Our study shows that the main determinant for long RTP after hamstring injury is the injury affecting the connective tissue structures of the hamstring. Therefore, the ECM structure and its role in force generation and transmission is the key factor in the signs, symptoms and prognosis of muscle injuries [58], and because of that, we designed our proposal of classification with the main aim to evaluate the amount and severity of the ECM damage [16]. The concept of evaluating and quantifying ECM damage as a key point in a muscle injury classification was first described in our previous paper [16].

With this work, we tested the theoretical model published before [16]. The proposal proved to have a good inter-observer and intra-observer reliability, being capable of grading injuries based on their severity, and offering a good prognosis. Our model can predict RTP with greater accuracy than previous proposals; and with a further adoption of our proposal, thus a larger sample size, the model will be able to generate more knowledge helping us to better manage HMIs.

In light of the results showed in this work, we strongly believe that the use of our proposal will represent a scientific advance, a more objective approach to muscle injury management, and with the capability to adapt and incorporate future knowledge into our classification system. We welcome future replication studies in other football teams and indeed other sports.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40279-022-01672-5.

Declarations

Funding No funding was received for the present study.

Conflict of interest None of the authors has a conflict of interest related to the present investigation.

Ethics Approval This study was assessed and approved by the Ethics Committee of the "Consell Català de l'Esport" with the number 10/CEICGC/2020. The present study was performed in accordance with the standards of ethics outlined in the Declaration of Helsinki.

Consent to Participate Appropriate written informed consent to participate in research projects was obtained from all FC Barcelona football players.

Consent for Publication Appropriate written informed consent for publication was obtained from all participants in the present study.

Availability of Data and Material The datasets generated during and/or analysed during the current study are not publicly available because of the fact that many of the players had their injury status publicly informed in the mass media and, therefore, some personal information from the players regarding their injuries could be deduced. This could imply a violation of the patients' privacy and confidentiality noted in statement number 24 of the Declaration of Helsinki. We could make it available from the corresponding author on reasonable request, from a medical institution.

Code Availability Not applicable.

Author Contributions XV and XY collected all the data. XV and SM analysed the magnetic resonance images. AM conducted all the statistical analyses. XV, SM, EAG, TJ and AM prepared the manuscript. RP, LL, GR, JCM, JI, MG and RB were the major contributors to the preparation of the manuscript. All authors contributed to the last editing and approval of the final manuscript.

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