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Multifactorial hamstring assessment protocol including ultrasound, strength, and running kinematics parameters

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ABSTRACT

Purpose: To present a protocol comprising a combination of measurements related to hamstring strain injuries (HSIs) and to report on its feasibility, advantages, limitations, and interpretation of findings.
Methods: The protocol consists of a sequence of tests totalling about 60 min. After collecting participant data, an evaluation of hamstring muscle architecture (fascicle length, muscle thickness, pennation angle, and cross-sectional area) is performed using extended field of view ultrasound. Participants then complete knee flexion isometric and Nordic eccentric peak torque evaluations. Following a standardized warm-up consisting of 5 min of low-intensity aerobic activity and 8 min of dynamic mobility work, participants undergo a running linear and angular kinematics assessment composed of 15 30-m trials at 80% of their maximum speed on a treadmill. Parameters such as stride length, cadence, and trunk and pelvic angles during running are then derived from this assessment. The players' maximum speed can be determined using match data. The treadmill assessment is followed by repeated isometric and eccentric torque measurements. We estimate that sample sizes of 21 and at least 120 players would be required to establish reliability and the diagnostic ability of a composite risk measure based on this protocol, respectively.
Conclusions: The presented protocol is designed to explore potential underlying HSI mechanisms, with the aim of moving beyond simply identifying who may be at risk. It presents some limitations in terms of material requirements and personnel skills, which may limit its applications in settings with lower resources. The value of this protocol for identifying HSI risk patterns should be confirmed in further studies.

Introduction

Hamstring strain injury (HSI) is the most common non-contact muscle injury in high-speed running sports such as football, comprising 24% of all injuries. HSIs also show a recurrence rate of 17–30% across elite football cohorts [1–3]. These injuries also present a major performance and financial burden. On the performance aspect, HSIs represent 10–20% of all absence days in football, with an increasing trend over time [2], and are reported to lead to post-injury decreases in playing time in defenders compared to non-injured controls even after two seasons [4]. On the financial side, HSIs are reported to cost La Liga clubs over €11 million/year in direct costs, with muscle injuries in general leading to a further €45 million loss in audiovisual income due to poorer performance [5].

In line with this massive burden, a great amount of research effort has been dedicated to HSIs, and several modifiable risk factors have been associated with hamstring injuries. These include parameters related to muscle architecture [6–8], maximal strength production [6,9,10] muscle activity [11], and running kinematics, especially during sprinting [12,13]. Individually, these assessments have shown varying degrees of association with HSI occurrence. Regarding muscle architecture, shorter fascicle length (FL) has been identified as a potential risk factor for HSIs, especially that of the biceps femoris long head (BFlh) [6, 14]. Moreover, due to the shorter BFlh FL with an unaltered pennation angle (PA) [6,14], it could be expected that individuals with a previous HSI would have a lower muscle volume, thickness, or cross-sectional area (CSA) of their injured hamstring compared to controls. However, studies that examined volume and CSA differences between injured participants and controls did not measure the FL and PA of the injured muscle [15,16] or vice versa [6–8]. A simultaneous assessment of all architectural parameters therefore remains needed.

Maximal isometric force production has provided inconsistent findings in the differentiation between athletes with and without HSI. On one hand, a decrease in isometric strength was reported after a repeated sprint task [10]; on the other hand, no differences were observed before or after a fatigue task induced by repeated sprints [9]. Moreover, low levels of eccentric knee flexor strength are reported to increase the risk of an HSI occurring in the subsequent season [6], indicating that eccentric strength may be more relevant to HSI risk. It should also be noted that injuries occur more frequently in the later stages of each match half [17], which suggests the relevance of analyzing the pre-post fatigue behavior of the peak strength variables described above.

Previous studies have based the association between eccentric hamstring strength and HSI risk on its role in running kinematics, as the hamstrings are primarily injured during the late swing phase, where hamstrings are contracting eccentrically [18]. Athletes with previous HSI also seem to exhibit increased pelvic anteversion and thoracic lateral flexion when sprinting, especially during the swing phase [12, 13], placing the hamstrings in a further elongated position.

In football, pre-season fitness testing is common, with players, especially those competing at higher levels, completing an array of assessments related to strength, agility, speed, and cardiorespiratory capacity [19]. Nevertheless, despite the extensive literature regarding HSI risk factors, the prevailing high incidence and recurrence rates suggest that analyzing isolated factors is not representative of the multifactorial nature of HSIs [20]. Even so, most previous studies have only analyzed one [13,15] or a limited simultaneous number of HSI risk factors [7,8, 21]. Another relevant limitation is that most parameters analyzed in previous studies represent performance outcomes. Including mostly performance and/or behavioral measures may limit the usefulness of protocols, as these mostly inform about who may be at risk but not the underlying reasons for that risk. This may not allow for addressing the root cause of the risk, limiting the contribution to designing preventive strategies. Baize et al. proposed a multidisciplinary HSI risk assessment protocol which showed very good predictive performance (area under the curve=0.815) [22]; however, this predictive model included non-modifiable variables (e.g., age, sex, previous HSI), and no individual variable showed a high predictive ability. The same lack of association with individual parameters was found by Lahti et al., who, despite the inclusion of multiple variables in their screening protocol, found that only the theoretical maximal horizontal force during sprinting had value in predicting HSIs within 90 days after measurement [23]. Moreover, that protocol also did not cover the underlying reasons for the observed risk. Establishing a protocol that includes various measures of HSI risk, including parameters hypothesized to reflect underlying structural and mechanical mechanisms while ensuring feasibility, would therefore represent a potentially relevant contribution in terms of redefining HSI risk estimation.

Accordingly, this study aims to present a hamstrings testing protocol comprising a combination of ultrasound, strength, and running kinematics measurements related to HSIs and to report on its feasibility, advantages, limitations, and interpretation of findings. The subsequent implementation of such a protocol in future studies may allow for a composite measure of HSI risk to be created, which is potentially more informative than isolated measurements.

Materials and Methods

Participant selection

Participants should be instructed to avoid any strenuous activities 24 h before the test to minimize confounding factors. In order to further minimize confounding factors and avoid limiting performance, we advise excluding participants with 1) injuries that could compromise sprint and maximal voluntary isometric contraction (MVIC) performance; 2) current low back complaints; 3) less than 5 years of experience in competitive football; and 4) electronic implants, foreign bodies (ferromagnetic) close to the thigh region. In terms of sample size estimation for future studies, two scenarios can be outlined. For an initial feasibility/validation study focused on test-retest reliability, based on two measurements and a one-tailed test with minimum acceptable ICC= 0.60, expected ICC= 0.85, alpha= 0.05, and power= 0.80, a sample size of 21 participants would be required. This means that the initial feasibility can be determined using a single squad. For future prospective cohort studies aiming to differentiate between 'high-risk' and 'low-risk' profiles, larger sample sizes are required. Assuming a seasonal HSI incidence rate of 25%, an a priori power analysis (d=0.65, alpha=0.05, power=0.80) indicates a minimum of 100 players. Furthermore, to construct multivariable logistic regression models combining structural, neuromuscular, and kinematic risk variables without overfitting, an events per variable threshold of 10 injuries per predictor is recommended, necessitating a prospective pool of at least 120 players (40 injuries) across multiple squads.

Protocol

Protocol general description

After collecting demographic and anthropomorphic data (age, height, weight), architecture parameters (FL, PA, and MT) are measured for both limbs. Subsequently, participants perform a warm-up protocol, followed by 10 submaximal KFs at a self-perceived low intensity to prepare and familiarize with the equipment for the MVIC evaluation, which consists of two 3-s trials with 30 s of recovery between trials. Two repetitions of the Nordic exercise are then performed. Then, individuals run 15 times on the treadmill at 80% of maximal speed for 30 m with 30 s of rest between sets. After this task, individuals perform two more MVIC trials and finally two more repetitions of the Nordic exercise. The entire protocol has a duration of about 60 min. The procedures for each test are described below in detail; the timeline of the protocol can be seen in Fig. 1 and a full equipment list is provided in Table 1.

Muscle architecture assessment (20 min)

Individuals should be placed lying prone with the pelvis in neutral position and knee in full extension with the ankle supported (Fig. 2). An ultrasound scanner capable of acquiring images in Extended Field of View (EFOV) coupled with a probe should be used to assess BFlh and semitendinosus (ST) CSA and BFlh architecture. The device should have a frequency of 10 MHz, with depth adjustable to 4–5 cm according to muscle thickness. During data acquisition, it is crucial to apply minimal pressure to the skin and to use conductive gel to improve acoustic contact between the probe and skin and therefore improve image quality. Two sonograms should be recorded for each limb and three fascicles should be analyzed in each sonogram. For the CSA measurements, a line is drawn at 40% and 50% of the distance between the greater trochanter and the mid-patella point, traced with the participant placed in the testing position described above. The probe is then moved along each line from the border of the vastus lateralis muscle to the border of the gracilis muscle [25].

Warm-up

The warm-up routine begins with a period of low-intensity aerobic activity consisting of 5 min of treadmill running at 7.2 km/h. This is

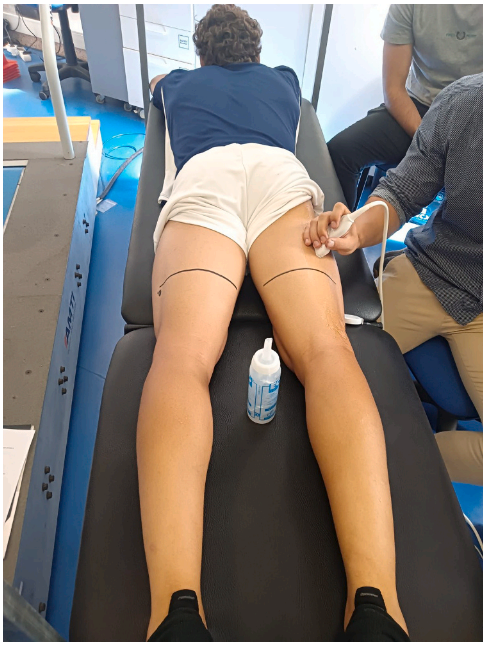

Fig. 1. Experimental set up and participant positioning for the ultrasound assessment of hamstring muscle architecture.

followed by approximately 8 min of dynamic mobility work structured into three circuit sets, each including six squat jumps and skipping exercises performed across low, medium, and high ranges of motion, with each skipping variation maintained for 10 s. The low, medium, and high modes should be standardized by researchers prior to protocol application. A 30-second rest interval should be given between consecutive sets.

Dynamometry (20 min - 10 min pre- and post-fatigue)

The knee flexor MVIC and Nordic hamstring exercise torque should be measured at a sampling rate of at least 50 Hz. This can be done with a device consisting of a cushioned testing table and ankle straps attached to force transducers which also stabilize the foot for the Nordic exercise (Fig. 3) [26]. For the isometric knee flexion assessment, participants are placed in the prone position, with the hips in neutral position and knees flexed at 30º (0° = full extension). For the Nordic exercise, participants start with the thighs perpendicular to the testing surface. The descent phase should be executed continuously over a target duration of 3–4 s. A trial is considered complete when the athlete reaches the 'break point' where eccentric hamstring force can no longer overcome gravity, at which point they catch themselves in a prone position using their hands.

High-speed running kinematics (20 min)

For the high-speed running assessment, participants run 15 times on a conventional motorized flat treadmill at 80% of peak maximal sprint speed for 30 m with 30 s of rest between trials. The calculation of peak sprint speed can be performed using field-based GPS data from the participants; this should be done by looking at the peak value that was maintained for a sufficient period to avoid misinterpreting data spikes (e.g., 1 s) and over a period representative of recent performance (e.g., 4 weeks). If not available, a radar system can be used during linear maximal sprinting. Three trials should be sufficient to accurately obtain maximum speed, as it is unlikely that higher values will be achieved after these attempts. Full body kinematics are ideally recorded with a markerless motion capture system comprising at least eight cameras operating at a sampling rate of at least 240 Hz [27], a resolution of at least 720 p, and a calibration residual < 1 mm. The transition from the treadmill back to the post-fatigue testing station must occur within 60 s to prevent neuromuscular recovery.

Table 1
List of equipment necessary to conduct the protocol.

Measurement	Equipment	Comments
EFOV ultrasound	Ultrasound device + probe	The probe should be positioned consistently across trials, with careful alignment relative to the muscle fascicles to minimize measurement error. Probe pressure must be controlled to avoid tissue deformation, which may influence architectural measurements. A linear-array transducer is typically recommended for superficial muscles, and standardized imaging settings (e.g., frequency, gain, and depth) should be maintained across all measurements to ensure reliability and comparability.
	Conductive gel	An adequate amount of conductive gel must be applied to ensure optimal acoustic coupling between the probe and the skin, thereby minimizing signal loss and improving image quality. Care should be taken to avoid excessive pressure during gel application, as this may alter muscle thickness and architecture.
Dynamometry	Cushioned surface Load cells Heel frame/straps	The equipment must allow for maximal knee flexion to be comfortably performed without the structure moving as well as to be able to fixate the foot for Nordic exercise performance. A minimum sampling rate of 50 Hz is recommended for the load cells, as this has been found not to affect peak torque measurements in isometric testing [24].
Running kinematics	Treadmill	A conventional motorized flat treadmill capable of reaching velocities up to 30 km/h should be used.
	Motion capture cameras	A camera-based motion capture is recommended to record the running kinematics. While a conventional marker-based system is adequate, issues related to adequate positioning of anatomical markers and them falling at high running speeds should be considered. Alternatively, it is possible to use a validated markerless motion capture system, as long as the calibration error is kept below 1 mm.
	GPS or radar system	GPS: peak speed defined as the highest instantaneous speed achieved over the previous 4 weeks and sustained for a minimum duration of 1 s, identified using a rolling average window to eliminate anomalous data spikes. Radar: peak speed measured during a maximal linear sprint test.

Analyzing data

EFOV ultrasound

Sonograms need to be digitized using software such as ImageJ (NIH, 1.47 v, Bethesda, MD). FL, PA, and CSA measurements can then be performed using these images. FL is measured directly using the insertion points on the superficial and mid-muscle aponeurosis using a non-linear method, where the examiner follows the fascicle along the entire muscle length, from the ischial tuberosity to the lateral aspect of the head of the fibula [28]. The PA is defined as the angle between the distal visible portion of the fascicle and the mid-aponeurosis. Then, the average of the three FLs and PAs in each sonogram should be calculated and used as the final value. For MT, one measurement should be performed for each sonogram, using the distance from the superficial to the mid-muscle aponeurosis. The BFlh and ST CSA should be measured in each sonogram following the guidelines of Franchi et al. [25].

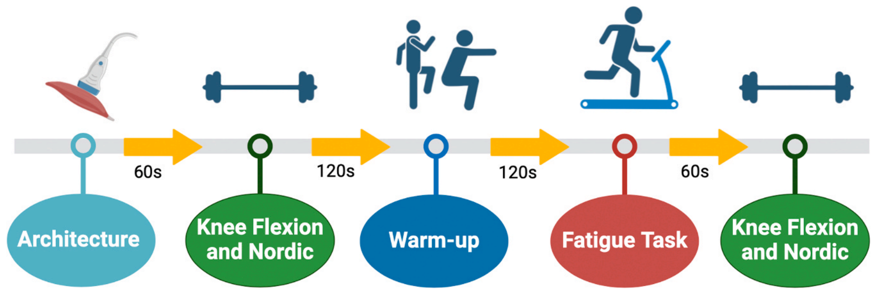

Fig. 2. Timeline of the data collection protocol.

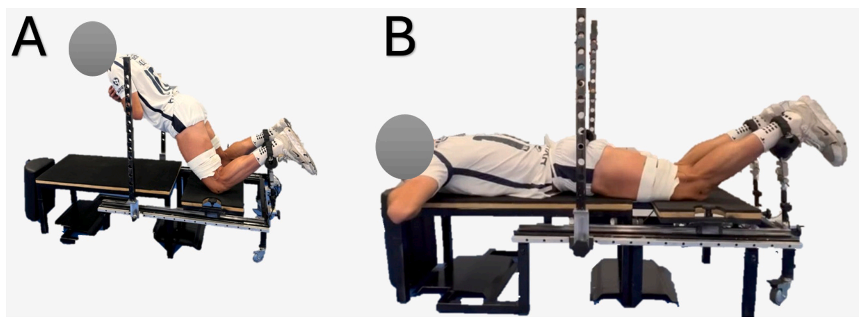

Fig. 3.

Dynamometry

Knee torque is estimated using the perpendicular distance between the force transducer center and the femoral lateral condyle. In order to allow for a comparison between individuals, torque values should be normalized to body mass. Torque curves should be filtered using a zero-lag second-order Butterworth low-pass filter with a cutoff frequency of 7 Hz to remove high-frequency noise. This approach is appropriate for isometric and eccentric contractions, where the primary signal content lies at low frequencies. PT values can then be obtained either through the software used for data collection or through dedicated code (e.g., R, Python, Matlab). To avoid the effect of data spikes, especially during the eccentric measurement, PT should be calculated as a windowed average of 100 ms centered around the highest value.

High-speed running kinematics

The frame corresponding to the initial contact and toe off of each foot needs to be visually identified from the video camera recordings for maximum accuracy. These video recordings are then converted to a full-body model with six degrees of freedom using appropriate software. This model can then be imported into a biomechanical analysis software such as Visual3D v2023.06.3 (HAS-Motion, Ontario, Canada), for further calculation of linear and angular kinematics. Ten consecutive strides from a steady-state speed period (i.e., excluding the initial acceleration period) should be taken for analysis. The extracted variables should include both temporal (stance, swing, step, cycle, and flight time and cadence) and distance (step and stride length) parameters. Distance variables should be normalized to trochanteric height if between-player comparisons are intended. Angular kinematics should be extracted for the trunk (flexion/extension), pelvis (anterior/posterior and lateral tilt), hip (flexion/extension, abduction/adduction, lateral/medial rotation), knee (flexion/extension, valgus/varus, tibial rotation), and ankle (dorsiflexion/plantarflexion, inversion/eversion). The duration of the included strides should be normalized to 100% of the running cycle; future comparisons between injured and non-injured players should then be done using statistical parametric mapping (e.g., as in Higashihara et al. [29]) to determine what stages of the running cycle differ for each joint/plane.

A full description of the variables obtained in the ultrasound, strength, and running analysis assessments, as well as expected ranges and the direction of risk, is displayed in Table 2.

Interpreting results

BFlh FLs shorter than 10.56 cm have been reported to increase hamstring injury risk in footballers (relative risk 4.1) [6]. For peak force/torque measurements, an absolute knee flexion MVIC force < 400 N has been associated with a relative risk of 2.0; for normalized measures, a relative risk of 1.6 has been reported for a threshold of 2.07 Nm/kg. As for eccentric Nordic torque, absolute and normalized thresholds of 337 N and 4.35 N/kg have been proposed for footballers, with relative risks of 4.4 and 2.5, respectively [6,30]. If performing between-limb comparisons, a 15% threshold has been previously adopted in relation to hamstring injury risk increase for the Nordic exercise [31].

A pre-post fatigability index should be calculated for the isometric and Nordic strength tests as $FI (\%) = (torque_{post} - torque_{pre}) / torque_{pre} \times 100$. Compared to isolated strength measurements, less information is available regarding fatigability thresholds; it has been generally described that an increased hamstring fatigability index increases injury risk in a continuous manner [22].

Regarding the high-speed running kinematics, a greater anterior pelvic tilt and trunk flexion is expected to increase hamstring load during the swing phase, as these movements pre-stretch the hamstrings proximally [13,32]. Overstriding has also been reported to increase HSI risk by increasing the braking force and eccentric hamstring activity during the late swing phase [33]. In terms of the spatiotemporal parameters, lower-risk sprinters have been noted to favor higher cadence over longer strides for speed development, with ground contact times < 0.10 s at maximum speed. More stable running parameters were also seen in these sprinters [34]. Attention should therefore be paid to the individual values but also to their within- and between-trial variability.

As mentioned previously, one of the advantages of this protocol is providing high-fidelity data that may not be possible to capture using more field-based measurements. As such, it is especially important to

Table 2
Description of the expected ranges and hamstring injury risk direction relative to the expected range.

Assessment method	Metric		Expected normative range	Risk Direction
Ultrasound	Fascicle Length (cm)		10.5–12.5 cm (for BFlh) [6]	Lower (threshold: 10.56 cm) [6]
	Pennation Angle (°)		BFlh: 10–24° [36,37] SM: 20–32° [37] Should be compared with the contralateral muscle and considered in conjunction with fascicle length	Higher (> 10% inter-limb asymmetry)
	Cross-Sectional Area (cm^2)		ST: 7–12 cm^2 BFlh: 7–12 cm^2 [25] Should be compared with the contralateral muscle	Absolute value: lower % asymmetry: higher (threshold: 10–15%)
Torque	Isometric Pre		320–450 N [6,38] 100–135 Nm [39] 3–5 N/kg [38,40] Consider individual baseline values.	Lower (threshold: 400 N and 2.07 Nm/kg) [6]
	Isometric Loss (%)		Expected range: 5–15%. Continuous risk scale; no binary cut-off [22].	Higher
	Eccentric Pre		Absolute: 350–500 [6] N Normalized: 3.5–4.5 N/kg [41]	Absolute and normalized: lower (thresholds: 337 N and 4.35 N/kg) [6,30]
	Eccentric Loss (%)		Expected range: 10–20% [6]. Continuous risk scale; no binary cut-off	Higher
Running analysis	Angular kinematics (sagittal, coronal, transverse planes)		No absolute angular thresholds; high within-trial variability flags risk [34]	
		Trunk	Lateral flexion during late swing/early stance: 0–5° [13] Flexion: 6–12° [42]	Higher
		Hip/pelvis	Anterior pelvic tilt during late swing/early stance: 10–20° [13]	Higher
			Hip flexion in late swing: 60–80 [29]	Higher
			Pelvic/hip drop during contralateral stance phase [43] - compared between limbs	Higher (>10
		Knee	Knee flexion at initial contact: 15–30° [29]	Lower
	Spatiotemporal parameters (≥80% maximum speed)	Stride/step length	Stride length: 1.6–2.4 m [44]	Higher (relative to limb length)
		Cadence	3.8–4.2 steps/s [44]	Lower (for the same running speed)
		Flight time	0.1–0.16 s [44]	Lower (relative to speed)
		Stance time	0.10–0.16 s [44]	Higher (relative to speed)
		Swing time	Evaluated through inter-limb asymmetry and the relative duration spent in late swing (terminal deceleration) [13]	Asymmetry: higher
		Step time	Step-to-step CV flags a lack of neuromuscular control and mechanical stability [34]	Variability: higher (CV > 2–3%)

CV: coefficient of variation

consider the findings as a whole. For example, coupling the Nordic eccentric or MVIC torque measurement with FL may provide more useful information than both measures in isolation. This is also in agreement with the reported low value of isolated strength measurements for detecting hamstring injury risk [35]. We therefore recommend interpreting the FL and MVIC results together.

The ultimate endpoint of this protocol is to originate a composite outcome measure of HSI risk. If validated, this measure should avoid simply determining how many variables are outside the expected range or above/below published thresholds. Rather, after obtaining sufficient experimental data, any constructed measure should:

- Consider the contribution of each variable to injury risk; this can be done by attributing a weighting coefficient to each measurement that will add up to 1 based on the obtained data.
- Consider the magnitude of the difference between the expected and obtained values. One highly practical method to achieve this would be applying a Z-score transformation to the raw values of each variable. By converting structurally distinct metrics (e.g., FL in cm, torque in Nm/kg, and pelvic tilt in degrees) into standardized, dimensionless Z-scores based on a baseline cohort mean, binary cutoffs can be avoided, and the exact magnitude of an athlete's variance is reflected on their risk measure.

Troubleshooting

EFOV ultrasound

When performing EFOV ultrasound imaging, it is crucial to ensure that 1) enough conductive gel is used so that the probe is in contact with gel at all times and 2) a smooth motion of around 1–2 cm/s with constant pressure is performed so that good quality images are obtained. To help maintain this motion, a line can be drawn on the skin from the muscles' origin to their insertion. Common problems with EFOV ultrasound images include dark bands in the image and a "stitched" or warped appearance. These distortions may lead to errors, especially in FL and PA measurements. If these issues are detected, a new image should be obtained.

Torque measurements

During the performance of the Nordic exercise, care should be taken to ensure that the trunk is maintained in the same position throughout the execution of the test. This is highly relevant, as trunk movements may cause peaks in the torque curve, therefore potentially confounding the measurement.

High-speed running kinematics

In order to accurately detect joint centers, it is recommended that the room has adequate lighting. Care should also be taken that sufficient contrast between the participant, treadmill, and background is present. Tight-fitting clothes are recommended to reduce inaccuracies in joint center determination. Cameras need to be positioned in a way that avoids blind spots; positioning details will vary depending on the treadmill model and the room configuration. Movements in the transverse plane (e.g., hip or tibial external/internal rotation) tend to be more difficult to capture accurately; greater caution should be taken when interpreting these measures. The use of a markerless system is crucial to avoid prolonging the data collection time. Regardless of the motion capture system selected, it is fundamental to use an adequate video resolution and sampling frequency (e.g., at least 720 p and 240 Hz [27]) to avoid spatial inaccuracies and blurring effects.

Advantages and limitations

Here, we present a hamstrings evaluation protocol that can be performed in a single session while still providing both pre- and post-fatigue mechanical output (i.e., isometric and eccentric strength) and the associated structural and kinematic basis (through EFOV ultrasound and high-speed running analyses, respectively).

Most existing hamstring field-based protocols focus on measuring outputs such as strength, flexibility or running performance [19], therefore leaving out the factors underlying those measures. By integrating performance outputs with structural and kinematic parameters, we believe this protocol may contribute to investigating potential drivers of risk rather than focusing on output-based screening. This protocol may also offer baseline data that could potentially serve as an individual reference point; in case a player subsequently suffers a HSI, the healthy ultrasound and kinematics data can be used as reference to determine the extent of the injury and track how these two sets of variables change throughout the recovery process. Moreover, by combining force and ultrasound measurements, it may be possible to identify athletes whose FL may place them at a higher risk even in cases where the mechanical output is unremarkable. The fact that running kinematics are measured during high-speed running is also particularly useful considering the relevance of running speed for HSIs [45]. Another potential benefit of this protocol is the possibility of using the measured outcomes to create a composite measure of HSI risk using each factor's contribution to create a weighting for the final score, as outlined in the "Interpreting Results" section. This should be the focus of future work.

Nevertheless, this protocol presents limitations that must be acknowledged. The inclusion of sonographic measurements, despite being informative, requires skilled operators and a considerable amount of time. The nature of pre- and post-fatigue peak torque measurements also requires time due to not only performing two measurements but also due to the need to include a fatigue task. This last factor also constitutes a further potential limitation due to load-related implications for daily training and integration into frequently busy schedules. The total protocol has a duration of around 60 min; although this is a considerable duration, we consider that the potential benefits of the obtained information make this acceptable in terms of the balance between effort/duration and outcomes. We have performed this protocol using three people; therefore, 3 person-hours are required for each athlete. The time necessary for data processing also limits the ability to provide real-time feedback for some measurements, especially on the running kinematics analysis. The equipment necessary for these measurements also constitutes a limitation, as the devices used can be expensive, especially the ultrasound scanner and motion analysis system. This is likely to limit access in lower income settings.

Conclusion

We present a protocol for assessing footballers' hamstrings architecture, isometric and eccentric torque, and running kinematics. This protocol provides high-fidelity data that may contribute to identify why rather than only who is at risk of sustaining a hamstring strain; nevertheless, it has technical and material requirements that may limit access in lower competitive settings. The value of this protocol now needs to be tested in longitudinal studies of HSI risk in footballers.

Authors' Contributions

RP designed the study, collected, processed, and analyzed the data, wrote the initial draft of the manuscript, and reviewed and revised subsequent versions. JPC contributed to writing the initial draft of the manuscript and reviewed subsequent versions. PF contributed to data processing and analysis. AP and JPVB critically reviewed the manuscript for important intellectual content. All authors reviewed and approved the final version of the manuscript and agreed to its submission.

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CRediT authorship contribution statement

Vilas Boas João Paulo: Writing – review & editing, Writing – original draft, Supervision. **António Veloso:** Writing – review & editing, Supervision, Conceptualization. **Pedro Fonseca:** Writing – review & editing, Methodology, Investigation, Data curation. **Correia José Pedro:** Writing – review & editing, Writing – original draft, Conceptualization. **Ricardo Pimenta:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare no conflict of interests

Data availability

No data was used for the research described in the article.

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