Acute Effects of a Fatiguing Protocol on Peak Force and Rate of Force Development of the Hamstring Muscles in Soccer Players

Authors:

Francesco Bettariga[abcd], Chris Bishop[d], Luca Martorelli[e], Anthony Turner[d], Stefano Giuseppe Lazzarini[f], Cristiano Algeri[e], Luca Maestroni[de]

[a] Exercise Medicine Research Institute, Edith Cowan University, Joondalup, Australia

[b] School of Medical and Health Sciences, Edith Cowan University, Joondalup, Australia

[c] StudioErre, Via della Badia, 18, 25127 Brescia (BS), Italy

[d] London Sport Institute, School of Science and Technology, Middlesex University, Greenlands Lane, London, United Kingdom

[e] ReAct, Via Madonna della Neve 24, 24121, Bergamo (BG), Italy

[f] IRCCS Fondazione Don Carlo Gnocchi, Milan, Italy

Corresponding author:

Francesco Bettariga

Exercise Medicine Research Institute

Edith Cowan University

270 Joondalup Drive, Joondalup, WA 6027

Australia

Orcid: 0000-0002-4977-5494

Email: francescobettariga@gmail.com

All authors have reviewed and approved the final version of this manuscript

Francesco Bettariga mail: francescobettariga@gmail.com

Chris Bishop mail: C.Bishop@mdx.ac.uk

Luca Martorelli mail: luca11m@yahoo.it

Anthony Turner mail: a.n.turner@mdx.ac.uk

Stefano Giuseppe Lazzarini mail: slazzarini@dongnocchi.it

Cristiano Algeri mail: algericristiano@gmail.com

Luca Maestroni mail: lucamae@hotmail.it

ABSTRACT

Hamstring strain injuries (HSI) represents a significant burden in soccer. High speed running is one of the most common HSI mechanism, in particular during match congested periods. Peak force and rate of force development (RFD) of the hamstring muscles tested at long muscle length have shown reductions following fatiguing tasks. However, no study has used a meticulous fatiguing protocol nor reliability scores have been provided. Hamstring peak force, RFD_{50-100} and $RFD_{100-150}$ were assessed at long muscle length in 19 soccer players (26.0 ± 4.1 years) before and after the repeated sprint ability (RSA) test. We aimed to calculate reliability scores for both limbs before and after the fatiguing task, and to compare peak force, RFD_{50-100} and $RFD_{100-150}$ following the RSA test to baseline values. Peak force displayed "excellent" reliability scores before and after the RSA test, whereas RFD ICC showed "good" values in both time points, but CV scores were not acceptable (i.e., > 10%). Significant moderate to large decreases were found in peak force (g = -1.11 to -0.90), RFD_{50-100} (g = -1.37 to -1.11) and $RFD_{100-150}$ (g = -0.84 to -0.69) in both dominant and non-dominant limbs. Maximal isometric peak force, RFD_{50-100} and $RFD_{100-150}$ of the hamstrings tested at long muscle length reduced following the RSA test. However, only peak force displayed "excellent" reliability scores, whereas RFD measures could not be considered acceptable owing to their lower reliability scores. Thus, practitioners can be confident about peak force changes, whilst caution should be used when examining such changes in RFD.

Keywords: Football, posterior chain, rapid muscle contraction, strength

INTRODUCTION

Hamstring strain injuries (HSI) represent a significant burden in soccer, typically resulting in approximately 17 days lost from training and competition per season [1, 2]. These account for 37% of all muscular injuries in soccer [2], and it has been reported that 70% of HSI among soccer players occur during high-speed running [3, 4]. HSI mechanisms likely involve high muscle-tendon unit forces and rapid elongation during the terminal swing-phase of sprinting [5], and, despite preventative strategies often being implemented (e.g., Nordics) [6, 7], HSI rates have not decreased in recent years [8-13]. It is worth noting that high-intensity running distance, actions and number of sprints increased by approximately 30%, 50% and 85% in men's professional soccer in recent observations across multiple seasons [14]. In addition, being unavailable to play due to HSI has been shown to have a detrimental effect on individual [15] and team performance [16], squad match physical outputs [17], and overall team success [18]. Thus, it seems logical that all staff involved in injury prevention and performance enhancement should strive to examine and explore variables associated with HSI.

During competitive matches, soccer players are required to perform repeated actions such as sprinting, jumping and change of directions, which require both high forces and high velocities over short periods of time, while concurrently covering large total running distances [19]. As a consequence, a decline in performance during competition occurs as result of fatigue [20]. A common method of assessment to determine an athlete's neuromuscular fatigue is the countermovement jump (CMJ), where a range of metrics are available if practitioners have access to force platforms (e.g., jump height, force, impulse, etc.). However, for those who do not have access to this equipment, smartphone apps such as My Jump 2 are able to accurately determine how high an athlete can jump, enabling some method of assessing jump performance to virtually the same degree of accuracy as a force platform (ICC = 0.997, 95% CI: 0.996–0.998, $p < 0.001$) [21, 22]. Although jump height represents only the performance measure of a CMJ, previous research has highlighted it is sensitive to change after competition in soccer players [23]. Also, the rate of torque development (RTD) of the hamstrings tested at long muscle lengths (i.e., 30° of knee flexion) between 0-50 ms and 0-200 ms, rather than maximal strength, has been shown to be negatively affected by a soccer match (~16% decrease in $RTD_{0–50}$ [95% CI: 3.15–50.4] $p = 0.029$, and ~11% $RTD_{0–200}$ [95% CI: 2.64–17.2] $p = 0.011$)

[19]. However, rate of force development (RFD) measures during the early phase of contraction commonly display lower reliability scores than peak force values [24, 25]. Therefore, to detect if "real" changes in RFD occur following fatigue, these need to be greater than the subsequent test variability (coefficient of variation [CV]). Naturally, this highlights the importance of including reliability data in research studies so practitioners can distinguish between 'the signal and the noise' [26].

Undertaking an in-depth analysis of sprinting (beyond measures such as time and velocity) on the field is challenging owing to the time needed to analyse videos and methods needed to gather detailed biomechanical variables (e.g., ground reaction forces, ground contact time, and limb stiffness, for example). For this reason, surrogate measures associated with sprinting biomechanics appear imperative when dealing with the prevention and management of HSI. For instance, strength (especially peak force) represents a key foundational quality of velocity [27], and it is one of the most recommended physical qualities to be included in HSI prevention and rehabilitation programmes [28, 29]. Similarly, RFD, which represents the rate of force expressed in a pre-defined time period, can be useful when examining rapid muscle contractions. Indeed, significant strain and rapid eccentric overloading on the hamstring muscles occur at long lengths and in less than 250ms [30]. In addition, most HSI occur at the end of each half, when athletes are in a fatigued state [31, 32]. Owing to the aetiology of HSI, investigating how both peak force and RFD respond to fatigue seems of utmost importance for practitioners.

Isokinetic dynamometry (IKD) has the potential to isolate the hamstring muscles and examine both concentric and eccentric values at different range of movements and velocities [33]. Similarly, the Nordbord has shown high test-retest reliability (ICC = 0.91 [0.76 to 0.96]) and good validity (ICC = 0.82 [0.58 to 0.93]) compared with peak forces shown during IKD [34]. However, IKD testing is time-consuming and only suitable to a laboratory setting, whereas the Nordbord provides information on hamstring strength at shorter muscle lengths. Therefore, when considering the angles at which HSI most commonly occur during sprinting (i.e., 30° of knee flexion), it seems logical to assess hamstring muscle peak force and RFD in such a position. Furthermore, such information is currently unavailable in the literature, especially after competition or repeated high-intensity exercise. However, due to the different playing positions and match demands, not all soccer players will be exposed to the same amount of external load during competition. Therefore, a fatiguing protocol which pre-defines the distance each player has to run, may help in mitigating such issues by ensuring each athlete is exposed to the same volumes of running. In this regard, a repeated sprint ability (RSA) test may represent a useful protocol for practitioners to expose their athletes to [35].

Therefore, this study aimed to 1) calculate reliability scores of maximal isometric peak force and RFD between 50-100 ms and 100-150 ms (RFD_{50-100} and $RFD_{100-150}$) of the hamstrings tested at long muscle length before and after the RSA test; and 2) examine the fatigue-induced changes in maximal isometric peak force and in RFD_{50-100} and $RFD_{100-150}$ following the RSA test.

METHODS

Experimental approach to the problem

An experimental trial design was used to determine the effects of an RSA test on maximal isometric peak force and RFD_{50-100} and $RFD_{100-150}$ in semi-professional soccer players. After a standardized warm-up, subjects performed 3 maximal CMJ and 3 maximal isometric contractions, followed by 6 x 40-meter sprints (i.e., RSA) on a soccer pitch. Immediately after, subjects were required to repeat the tests in the same order (i.e., CMJ and maximal isometric contraction) in a fatigued state. To ascertain the degree of fatigue, an objective measure (i.e., jump height during a CMJ) was collected (Figure 1). This protocol provided the ability to evaluate isometric peak force and RFD before and after a fatiguing test (i.e., RSA). Such results were used to run a reliability analysis and to detect if “real” changes occurred following the RSA test.

Subjects

Nineteen semi-professional male adult soccer players from a soccer club (competing at regional and national level, regularly training 4 times per week [identifiable as Tier 2 [36]) volunteered to participate in this before-and-after study on the same day (subject characteristics are in Table 1). A minimum of 18 subjects was established from a priori power analysis using G*Power (Version 3.1, University of Dusseldorf, Germany) implementing statistical power of 0.8 and a type 1 alpha level of 0.05, which has been used in comparable literature [37]. Subjects were included if they fulfilled the following inclusion criteria: 1) older than 18 years of age, 2) no muscle injuries occurred in the last 6 months, 3) no absence from competition > 28 days over the last 12 months and, 4) no orthopaedic surgery in the last 12 months (e.g., anterior cruciate ligament reconstruction). The dominant limb was established asking the subjects which limb they prefer to perform a unilateral vertical jump [38]. All subjects were informed about the purpose of the study and the informed consent was given before the start of the experimental study according to the Declaration of Helsinki 2013. Ethical approval was granted by the London Sport Institute research and ethics committee, Middlesex University, UK.

Procedures

All procedures and analysis were conducted by the authors (with > 5 years of experience in the relevant test procedures). A standardized dynamic warm up was performed before the testing protocol, consisting of 2 sets of 10 repetitions of overhead squats, forward lunges, crab walks, glute bridges, and pogo jumps. Subsequently, 5 trials of CMJs and 5 incremental 20-meter linear sprint and 180° change of direction (COD) speed tests at 60, 80 and 100% of their maximal perceived effort were completed [37].

Then, subjects were required to perform 3 trials of CMJ, with the average value used for the subsequent analysis. A sixty-second rest period was provided between trials during the CMJ test. A 3-minute rest period was given between the CMJ test and maximal isometric contractions. For the maximal isometric contraction, subjects completed 3 unilateral maximal isometric contractions on each leg. They laid on the floor with one heel on the force plate and the heel of the non-working leg resting on the floor below the plinth, with the average value used for subsequent analysis (Figure 2). A sixty-second rest period was provided between trials during the same maximal isometric contraction [25]. All subjects were required to start the test with the right leg first.

Subsequently subjects were required to complete 6 rounds of 40-meter sprints (i.e., RSA test), consisting of 20 meters sprint, 180° change of direction and 20 meters sprint. Twenty-second rest period was given between each trial. For the RSA test, the starting leg was arbitrarily chosen by the subjects. However, subjects were asked to alternate both the right and left leg during the 180° COD. Three CMJs were also executed immediately after the RSA and CMJ height measures were collected [39, 40]. After that, subjects performed 3 trials of maximal isometric contractions with each leg, as previously described, but in a fatigued state. Maximal isometric contractions and jump testing were conducted in the gym with trainer shoes, whilst RSA test was completed on the grass football pitch with football boots. Assessments were conducted in the morning (i.e., 10 am, 24° degrees and sunny) and subjects were asked to refrain from any strenuous physical activity at least 48 -hours before the testing protocol.

Countermovement Jump. Subjects were instructed to jump bilaterally and place their hands on their hips for the duration of the test. The jump was performed executing a countermovement immediately followed by an explosive vertical jump, with an aggressive extension at the ankle, knee, and hip. Subjects were instructed to jump whenever they wanted after the signal “go”. Examiners’ verbal instruction was to “jump as high as possible”. During the jump, the limbs had to remain completely extended during the flight phase before landing on the floor. Subjects were required to maintain the position described after the landing for 3 seconds. Jump height in centimetres was recorded using the validated and reliable “My Jump 2” smartphone app [41].

Maximal isometric contraction. Subjects were instructed to lie on the floor, with 30° flexion at knee joint (measured with a goniometer), the heel of the working leg on the force plate, the heel of the non-working leg resting on the floor below the plinth, and arms across their chest (Figure 2). The test was performed on each leg executing an explosive downward contraction with the heel stable on the force plate and without lifting their buttocks [25]. Subjects were instructed to push whenever they wanted after the signal "go". Examiners' verbal instruction was to "push as hard and fast as possible". Subjects were required to push for 5 seconds. All data were recorded at a sampling rate of 1000 Hz using 2 PASCO (PS-2142, PASCO, Pass-port PS-2142, Roseville, USA) force platforms [42]. The force-time curve was obtained using Spark software. Maximal isometric peak force was defined as the highest force value produced (N). RFD was calculated as the average slope of the force-time curve (N/s^{-1}) over time intervals of 50-100 ms and 100-150 ms relative to the onset of contraction.

6 x 40-meter Repeated Sprint Ability Protocol. Subjects were instructed to stand behind the starting line with both feet in a crouching position. They were allowed to choose independently the preferred leg to start the test. Vertical poles were placed at 0 and 20 meters. Subjects were instructed to sprint, whenever they wanted after the signal "go", 20 meters through the poles and then perform a 180° turn off, with both the right and the left leg, and sprint for other 20 meters. Examiners' verbal instruction was "sprint and turn off as fast as possible" [35].

Statistical Analyses

All data were initially recorded as mean and standard deviation (SD) in Microsoft Excel and later transferred to SPSS (version 25.0; SPSS, Inc., Armonk, NY). Normality was analysed using the Shapiro-Wilk test, with p value > 0.05 meaning that data were normally distributed. An average-measures two-way random intraclass correlation coefficient (ICC) with absolute agreement and 95% confidence intervals, and coefficient of variation (CV) were used to assess the within session reliability of tests. ICC values were interpreted as follows: > 0.9 = excellent, 0.75–0.9 = good, 0.5–0.75 = moderate, and < 0.5 poor [43]. The CV was calculated using the formula: (SD [trials 1–3] / average [trials 1–3] x 100), with values < 10% deemed acceptable [44].

Paired samples *t*-tests were used to calculate changes in CMJ jump height, peak force, $RFD_{50\text{-}100}$ and $RFD_{100\text{-}150}$ from pre- to post-RSA test, with statistical significance set at $p < 0.05$. Bonferroni correction was applied to reduce the risk of type I error with multiple statistical tests. Percentage changes (% change) from pre- to post-RSA test were also calculated for each player, using the formula: [(final value - initial value) / initial value] and then averaged. Hedges' *g* effect sizes with 95% confidence intervals, were also determined to showcase practical significance from pre- to post-RSA [45]. Hedges' *g* was classified as follows: 0.0-0.25 = trivial, 0.25–0.50 = small, 0.50–1.00 = moderate, > 1.00 = large [46].

Kappa coefficients were used to determine levels of agreement for how consistently limb dominance favoured the same limb from pre- to post-RSA test, and values were interpreted as: ≤ 0 = poor, 0.01-0.20 = slight, 0.21-0.40 = fair, 0.41-0.60 = moderate, 0.61-0.80 = substantial, 0.81-0.99 = nearly perfect [47].

*****Table 1 and 2, and Figure 1 and 2 here*****

RESULTS

All subjects were included in the analysis. Data were normally distributed ($p > 0.05$). Table 2 shows within-session reliability data. Relative reliability (ICC) of all metrics ranged from "good" to "excellent". Absolute reliability (CV) showed acceptable values (i.e., CV < 10%) in both pre- and post-RSA scores in CMJ and peak force values, apart from $RFD_{50\text{-}100}$ and $RFD_{100\text{-}150}$ (i.e., CV > 10%).

Table 3 reports raw scores and percentage change from pre- to post-RSA. Results showed a significant large decrease in CMJ (jump height) ($p < 0.05$; $g = -1.26$; % change = -16%). Similarly, significant moderate to large decreases were found in peak force ($p < 0.05$, $g = -1.11$ to -0.90; % change = -24% to -16%) and $RFD_{50\text{-}100}$ ($p < 0.05$, $g = -1.37$ to -1.11; % change = -58% to -51%) in both dominant and non-dominant limbs. $RFD_{100\text{-}150}$ reported a significant moderate decrease from pre- to post-RSA in both limbs ($p < 0.05$; $g = -0.84$ to -0.69; % change = -51% to – 26%). Kappa coefficients ranged from poor (i.e., peak force and RFD $_{100\text{-}150}$) to slight (i.e.,

$RFD_{50\text{-}100)}$ (Kappa = -0.41 to 0.16). Finally, mean and individual CMJ, peak force and RFD values are reported in Figures 3-6.

*****Table 3 and Figures 3-6 here*****

DISCUSSION

The aims of this study were to: 1) calculate reliability scores of maximal isometric peak force and $RFD_{50\text{-}100}$ and $RFD_{100\text{-}150}$ of the hamstrings tested at long muscle length before and after the RSA test; and 2) examine the fatigue-induced changes in maximal isometric peak force and in $RFD_{50\text{-}100}$ and $RFD_{100\text{-}150}$ following the RSA test. The results showed that isometric peak force of the hamstrings at long muscle length displayed "excellent" reliability scores (ICC > 0.91 and CV < 10%) before and after the RSA test. In contrast, $RFD_{50\text{-}100}$ and $RFD_{100\text{-}150}$ ICC showed "good" values in both time points, but CV scores were not acceptable (i.e., CV > 10%). With regard to the fatigue-induced changes from pre- to post-RSA test, our results showed that significant moderate to large decreases were found in CMJ (g = -1.26), peak force (g = -1.11 to -0.90), $RFD_{50\text{-}100}$ (g = -1.37 to -1.11) and $RFD_{100\text{-}150}$ (g = -0.84 to -0.69) in both dominant and non-dominant limbs.

Isometric peak force of the hamstrings at long muscle lengths can be confidently used in the assessment of soccer players before and after a competitive match. Our study corroborates previous findings [25], which demonstrated "excellent" reliability scores using our identical testing position. In contrast, despite our strict methodological procedures, $RFD_{50\text{-}100}$ and $RFD_{100\text{-}150}$ displayed CV values which could not be considered acceptable. RFD reliability scores have consistently been found to be worse during the early phase of contraction than peak force [24, 48], and thus, changes or variations over time need to be carefully interpreted before concluding that meaningful differences have occurred. For example, reductions in hamstrings muscle rapid force capacity at long muscle length have been recently found in professional soccer players following a match, but no reliability data was provided [19]. This further strengthens the importance of including reliability data in primary research studies, given it can be used to determine whether change is inside or outside of the variance of the test [26]. In addition, a somewhat overlooked aspect of RFD is that it is a ratio number (i.e., made up of two component parts – force and time). Previous literature has outlined that ratio data is often 'noisier' than individual metrics [49], as each component will exhibit error and this is then exacerbated when two metrics are combined to create one single value – in this instance, RFD. Whilst the rate at which an athlete produces force is undoubtedly important, practitioners are advised to be cautious of using RFD for any kind of monitoring purposes, owing to its inherent noise.

CMJ height showed a significant large decrement (*g* = -1.26) after the RSA test. Numerous CMJ kinetic and performance variables (e.g., peak and mean power, peak and mean force, flight time, total impulse) derived from CMJ analysis can be sensitive to fatigue-induced changes in neuromuscular function [50, 51]. Among these, CMJ height reductions following repeated sprints have been previously reported [52, 53]. Given that take-off velocity underpins how high an athlete can jump [44], it stands to reason that reduced rapid muscle contraction capabilities occurred following our RSA protocol. Although CMJ performance is determined by other muscle groups not including hamstrings (e.g., quadriceps, glutes, and plantar flexors), it may be assumed the fatigue have contributed to reductions in jump performance. This reinforces the notion that CMJ height is a simple and useful metric that can be used to indicate neuromuscular fatigue post intense exercise, which is actually not in agreement with some previous studies [50, 54]. The underlying reasons are not fully understood and, to the best of our knowledge, further research is necessary to clearly elucidate whether or not reductions in jump performance may represent an individual response to fatigue.

With regard to maximal isometric peak force from pre- to post-RSA test, our study indicated that peak force showed significant large decreases (*g* = -1.11 to -0.90) in both dominant and non-dominant limbs during the hamstring test at long muscle length. Importantly, when interpreting changes in test scores, this is best done by determining whether the difference is greater than the associated noise (CV) in the test [55, 56]. In this instance, changes in peak force can be considered "real", given that CV values were ≤ 8.61% and the percentage change in raw scores ranged from 16-24%. Whilst the same can be said for RFD (i.e., percentage change was greater than the baseline CV), the absolute reliability values were unacceptable prior to the fatigue protocol. As such, we do not advocate their implementation for practitioners whose aim is to assess hamstring rapid muscle contraction capacity.

Interestingly, as an additional form of analysis in the present study, we examined Kappa coefficients which establish the consistency of limb dominance from pre- to post-RSA test, and our findings showed poor to slight levels of agreement (Kappa = -0.41 to 0.16) across metrics. This shows that from pre- to post-fatigue, the superior performing limb often shifted, which is synonymous with recent research investigating the direction of asymmetry (or limb dominance characteristics) [35]. Again, this supports the notion that examination should be performed in both conditions (i.e., in rested and fatigued states) in order to fully understand if the stronger limb continues to be superior in both scenarios. Consequently, this may inform practitioners about whether existing strength deficits are consistent between time points or whether they are fluctuations in natural performance variability.

Overall, these observations suggest that force production capacity can be reduced at long hamstrings muscle lengths in fatigued states, thus increasing the vulnerability to muscular strain in high speed actions [57]. Considering the utilization of elastic energy during sprinting occur within 100 ms [58], reductions in rapid force production (i.e., RFD_{50-100} and $RFD_{100-150}$) alter hamstring muscles force-time characteristics in fatigued states, thus theoretically increasing load and elongation on the contractile muscle units [57]. In conclusion, our study demonstrated that only peak force scores were reliable when examining a maximal isometric strength test of the hamstring tested at long muscle length before and after a fatiguing protocol. Additionally, the fatigue-induced by the RSA test negatively affected peak force, RFD_{50-100} and $RFD_{100-150}$.

The present study is not without limitations, which we must acknowledge. Firstly, our data were limited to adult male football players. Therefore, generalisation of these results to paediatric, adolescent and female athletes should not be done. Our strength assessment was conducted at only one time point following a rigorous repeated sprint protocol, and included hamstring muscle testing in a specific isometric position. Future work is needed to examine if different testing methods can improve RFD reliability scores, and if the magnitude of variation in hamstring peak force and rapid muscle contraction capacity following a fatiguing task, can discriminate subjects at higher risk of injury or those who have sustained a previous HSI.

PRACTICAL APPLICATIONS

The findings of the current study indicate that maximal isometric peak force, $RFD_{50\text{-}100}$ and $RFD_{100\text{-}150}$ of the hamstrings tested at long muscle length, reduced following the RSA test in male soccer players. However, only peak force displayed “excellent” reliability scores, whereas RFD measures could not be considered acceptable owing to their lower reliability scores. Our findings suggest a shift in force-time characteristics of the hamstrings at long muscle length in response to a controlled fatiguing task, and strongly recommend the inclusion of reliability scores to ascertain if such changes can be confidently considered meaningful. Therefore, practitioners can use hamstrings assessment at long muscle length in both rested and fatigued states (e.g., following the RSA protocol). This can be adopted, together with other performance tests (e.g., CMJ), to examine the effects of a fatiguing session in soccer players. However, although peak force is reliable and does show “real” changes following fatiguing tasks, particular caution should be used when examining such changes in RFD.

DECLARATIONS

Conflict of interest Francesco Bettariga, Chris Bishop, Luca Martorelli, Anthony Turner, Stefano Giuseppe Lazzarini, Cristiano Algeri, and Luca Maestroni declare that they have no conflicts of interest relevant to the content of this review.

Funding No funding was received for this project.

Authorship Contributions FB: conceptualization, methodology, formal analysis, investigation, data curation and writing. LMae: conceptualization, methodology, formal analysis, investigation and supervision. CB, LMar, AT, CA, and SGL: edited and revised the manuscript.

Data availability statement The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. Bourne, M.N., et al., *An Evidence-Based Framework for Strengthening Exercises to Prevent Hamstring Injury.* Sports Medicine, 2017.
2. van der Horst, N., et al., *The preventive effect of the nordic hamstring exercise on hamstring injuries in amateur soccer players: a randomized controlled trial.* Am J Sports Med, 2015. **43**(6): p. 1316-23.
3. Ekstrand, J., et al., *Hamstring muscle injuries in professional football: the correlation of MRI findings with return to play.* Br J Sports Med, 2012. **46**(2): p. 112-7.
4. Danielsson, A., et al., *The mechanism of hamstring injuries–a systematic review.* BMC musculoskeletal disorders, 2020. **21**(1): p. 1-21.
5. Hickey, J.T., et al., *Current clinical concepts: hamstring strain injury rehabilitation.* J Athl Train, 2021.
6. Impellizzeri, F.M., A. McCall, and M. van Smeden, *Why methods matter in a meta-analysis: a reappraisal showed inconclusive injury preventive effect of Nordic hamstring exercise.* Journal of Clinical Epidemiology, 2021. **140**: p. 111-124.
7. Fanchini, M. and I.B. Steendahl, *Exercise-Based Strategies to Prevent Muscle Injury in Elite Footballers: A Systematic Review and Best Evidence Synthesis.* 2020. **50**(9): p. 1653-1666.
8. Ekstrand, J., M. Waldén, and M. Hägglund, *Hamstring injuries have increased by 4% annually in men's professional football, since 2001: a 13-year longitudinal analysis of the UEFA Elite Club injury study.* 2016. **50**(12): p. 731-7.
9. Ekstrand, J., et al., *Hamstring injury rates have increased during recent seasons and now constitute 24% of all injuries in men's professional football: the UEFA Elite Club Injury Study from 2001/02 to 2021/22.* British Journal of Sports Medicine, 2022.
10. Biz, C., et al., *Hamstring Strain Injury (HSI) Prevention in Professional and Semi-Professional Football Teams: A Systematic Review and Meta-Analysis.* International Journal of Environmental Research and Public Health, 2021. **18**(16): p. 8272.
11. Medeiros, D.M., C. Marchiori, and B.M. Baroni, *Effect of nordic hamstring exercise training on knee flexors eccentric strength and fascicle length: a systematic review and meta-analysis.* Journal of Sport Rehabilitation, 2020. **30**(3): p. 482-491.
12. Ripley, N.J., et al., *The effect of exercise compliance on risk reduction for hamstring strain injury: a systematic review and meta-analyses.* International Journal of Environmental Research and Public Health, 2021. **18**(21): p. 11260.
13. Opar, D.A., et al., *Is pre-season eccentric strength testing during the Nordic hamstring exercise associated with future hamstring strain injury? A systematic review and meta-analysis.* Sports Medicine, 2021. **51**(9): p. 1935-1945.
14. Barnes, C., et al., *The evolution of physical and technical performance parameters in the English Premier League.* International journal of sports medicine, 2014. **35**(13): p. 1095-1100.
15. Drew, M.K., B.P. Raysmith, and P.C. Charlton, *Injuries impair the chance of successful performance by sportspeople: a systematic review.* Br J Sports Med, 2017. **51**(16): p. 1209-1214.
16. Hagglund, M., et al., *Injuries affect team performance negatively in professional football: an 11-year follow-up of the UEFA Champions League injury study.* Br J Sports Med, 2013. **47**(12): p. 738-42.
17. Windt, J., et al., *Does player unavailability affect football teams' match physical outputs? A two-season study of the UEFA champions league.* J Sci Med Sport, 2018. **21**(5): p. 525-532.
18. Williams, S., et al., *Time loss injuries compromise team success in Elite Rugby Union: a 7-year prospective study.* British Journal of Sports Medicine, 2016. **50**(11): p. 651.
19. Grazioli, R., et al., *Hamstring rate of torque development is more affected than maximal voluntary contraction after a professional soccer match.* Eur J Sport Sci, 2019. **19**(10): p. 1336-1341.
20. Knicker, A., et al., *Interactive Processes Link the Multiple Symptoms of Fatigue in Sport Competition.* Sports medicine (Auckland, N.Z.), 2011. **41**: p. 307-28.
21. Balsalobre-Fernández, C., M. Glaister, and R.A. Lockey, *The validity and reliability of an iPhone app for measuring vertical jump performance.* Journal of sports sciences, 2015. **33**(15): p. 1574-1579.

22. Gallardo-Fuentes, F., et al., *Intersession and intrasession reliability and validity of the My Jump app for measuring different jump actions in trained male and female athletes.* Journal of strength and conditioning research, 2016. **30**(7): p. 2049-2056.
23. Bishop, C., et al., *Effects of Soccer Match-Play on Unilateral Jumping and Interlimb Asymmetry: A Repeated-Measures Design.* Journal of strength and conditioning research, 2020.
24. Maffiuletti, N.A., et al., *Rate of force development: physiological and methodological considerations.* Eur J Appl Physiol, 2016. **116**(6): p. 1091-116.
25. McCall, A., et al., *Reliability and sensitivity of a simple isometric posterior lower limb muscle test in professional football players.* Journal of Sports Sciences, 2015. **33**(12): p. 1298-1304.
26. Turner, A.N., et al., *Assessing Group-Based Changes in High-Performance Sport. Part 2: Effect Sizes and Embracing Uncertainty Through Confidence Intervals.* Strength & Conditioning Journal, 9000. **Publish Ahead of Print**.
27. Suchomel, T.J., S. Nimphius, and M.H. Stone, *The Importance of Muscular Strength in Athletic Performance.* Sports Med, 2016. **46**(10): p. 1419-49.
28. Tyler, T.F., et al., *Rehabilitation After Hamstring-Strain Injury Emphasizing Eccentric Strengthening at Long Muscle Lengths: Results of Long-Term Follow-Up.* J Sport Rehabil, 2017. **26**(2): p. 131-140.
29. Hickey, J.T., et al., *Hamstring Strain Injury Rehabilitation.* J Athl Train, 2022. **57**(2): p. 125-135.
30. Rodriguez-Rosell, D., et al., *Physiological and methodological aspects of rate of force development assessment in human skeletal muscle.* Clin Physiol Funct Imaging, 2018. **38**(5): p. 743-762.
31. Bisciotti, G.N., et al., *Hamstring Injuries Prevention in Soccer: A Narrative Review of Current Literature.* Joints, 2019. **7**(3): p. 115-126.
32. Hawkins, R.D., et al., *The association football medical research programme: an audit of injuries in professional football.* British Journal of Sports Medicine, 2001. **35**(1): p. 43.
33. Burigo, R.L., et al., *Concentric and eccentric isokinetic hamstring injury risk among 582 professional elite soccer players: a 10-years retrospective cohort study.* BMJ Open Sport Exerc Med, 2020. **6**(1): p. e000868.
34. Lodge, C., et al., *Reliability and Validity of a New Eccentric Hamstring Strength Measurement Device.* Arch Rehabil Res Clin Transl, 2020. **2**(1): p. 100034.
35. Bishop, C., et al., *Acute Effect of Repeated Sprints on Interlimb Asymmetries During Unilateral Jumping.* Journal of strength and conditioning research, 2019.
36. McKay, A.K., et al., *Defining training and performance caliber: a participant classification framework.* International journal of sports physiology and performance, 2022. **17**(2): p. 317-331.
37. Bettariga, F., et al., *The Effects of a Unilateral Strength and Power Training Intervention on Inter-Limb Asymmetry and Physical Performance in Male Amateur Soccer Players.* Journal of Science in Sport and Exercise, 2022.
38. Virgile, A. and C. Bishop, *A Narrative Review of Limb Dominance: Task- Specificity and the Importance of Fitness Testing.* The Journal of Strength and Conditioning Research, 2020. **Publish Ahead of Print**.
39. Sánchez-Medina, L. and J.J. González-Badillo, *Velocity loss as an indicator of neuromuscular fatigue during resistance training.* Med Sci Sports Exerc, 2011. **43**(9): p. 1725-34.
40. González-Hernández, J.M., et al., *Mechanical, Metabolic, and Perceptual Acute Responses to Different Set Configurations in Full Squat.* J Strength Cond Res, 2020. **34**(6): p. 1581-1590.
41. Balsalobre-Fernández, C., M. Glaister, and R.A. Lockey, *The validity and reliability of an iPhone app for measuring vertical jump performance.* J Sports Sci, 2015. **33**(15): p. 1574-9.
42. Peterson Silveira, R., et al., *Validity of a portable force platform for assessing biomechanical parameters in three different tasks.* Sports Biomechanics, 2017. **16**(2): p. 177-186.
43. Koo, T.K. and M.Y. Li, *A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research.* Journal of chiropractic medicine, 2016. **15**(2): p. 155-163.
44. Cormack, S.J., et al., *Reliability of measures obtained during single and repeated countermovement jumps.* Int J Sports Physiol Perform, 2008. **3**(2): p. 131-44.

45. Dasborough, M., *Book Review: Grissom, R. J., & Kim, J. J. (2005). Effect Sizes for Research: A Broad Practical Approach. Mahwah, NJ: Lawrence Erlbaum.* Organizational Research Methods, 2007. **10**(3): p. 542-545.
46. RHEA, M.R., *DETERMINING THE MAGNITUDE OF TREATMENT EFFECTS IN STRENGTH TRAINING RESEARCH THROUGH THE USE OF THE EFFECT SIZE.* The Journal of Strength & Conditioning Research, 2004. **18**(4): p. 918-920.
47. Viera, A.J. and J.M. Garrett, *Understanding interobserver agreement: the kappa statistic.* Fam Med, 2005. **37**(5): p. 360-3.
48. Buckthorpe, M.W., et al., *Reliability of neuromuscular measurements during explosive isometric contractions, with special reference to electromyography normalization techniques.* Muscle Nerve, 2012. **46**(4): p. 566-76.
49. Bishop, C., et al., *A Framework to Guide Practitioners for Selecting Metrics During the Countermovement and Drop Jump Tests.* Strength & Conditioning Journal, 2022. **44**(4).
50. Gathercole, R.J., et al., *Comparison of the Capacity of Different Jump and Sprint Field Tests to Detect Neuromuscular Fatigue.* J Strength Cond Res, 2015. **29**(9): p. 2522-31.
51. Gathercole, R., et al., *Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue.* Int J Sports Physiol Perform, 2015. **10**(1): p. 84-92.
52. Gorostiaga, E.M., et al., *Vertical jump performance and blood ammonia and lactate levels during typical training sessions in elite 400-m runners.* J Strength Cond Res, 2010. **24**(4): p. 1138-49.
53. Armada-Cortés, E., et al., *Evaluation of Neuromuscular Fatigue According to Injury History in a Repeat Sprint Ability Test, Countermovement Jump, and Hamstring Test in Elite Female Soccer Players.* Applied Sciences, 2022. **12**(6): p. 2970.
54. Gathercole, R., et al., *Alternative Countermovement-Jump Analysis to Quantify Acute Neuromuscular Fatigue.* International Journal of Sports Physiology and Performance, 2015. **10**(1): p. 84-92.
55. Bishop, C., *Interlimb Asymmetries: Are Thresholds a Usable Concept?* Strength & Conditioning Journal, 2021. **43**(1): p. 32-36.
56. Turner, A.N., et al., *Assessing Group-Based Changes in High-Performance Sport. Part 2: Effect Sizes and Embracing Uncertainty Through Confidence Intervals.* Strength & Conditioning Journal, 2021. **43**(4).
57. Huygaerts, S., et al., *Mechanisms of Hamstring Strain Injury: Interactions between Fatigue, Muscle Activation and Function.* Sports (Basel, Switzerland), 2020. **8**(5): p. 65.
58. Taylor, M.J. and R. Beneke, *Spring mass characteristics of the fastest men on Earth.* Int J Sports Med, 2012. **33**(8): p. 667-70.

Table 1. Subject characteristics with data shown as mean ± standard deviations (SD).

Age (Y)	Body Mass (Kg)	Height (cm)	Dominant Limb
26 ± 4.1	74 ± 5.3	179.7 ± 3.8	R = 13; L = 6

Legend. y = year; kg = kilogram; cm = centimetre; R = right; L = left.

Table 2. Within session reliability for each test measures at pre- and post-RSA.

Metrics	Pre		Post	
	CV	*ICC*	*CV*	*ICC*
CMJ (jump height)	2.19	0.98(0.92, 0.99)	1.41	0.99(0.98, 0.99)
Peak force D	8.61	0.91(0.62, 0.93)	7.41	0.94(0.86, 0.98)
Peak force ND	6.73	0.93(0.85, 0.96)	6.49	0.96(0.90, 0.97)
RFD 50-100 D	27.44	0.77(0.60, 0.87)	23.12	0.78(0.68, 0.87)
RFD 50-100 ND	28.77	0.76(0.63, 0.84)	22.29	0.79(0.69, 0.87)
RFD 100-150 D	18.42	0.83(0.66, 0.90)	21.81	0.78(0.68, 0.83)
RFD 100-150 ND	19.91	0.81(0.69, 0.88)	20.72	0.79(0.65, 0.85)

Legend. CV = coefficient of variation; ICC = intraclass coefficient of variation; D = dominant; ND = non-dominant; CMJ = countermovement jump; RFD = rate of force development; Peak force measured in Newton; RFD measured in Newton / seconds.

Table 3. Mean test scores ± SDs for pre- and post-RSA, Hedges' *g* effect sizes and percentage change.

Metrics	**Pre**	**Post**	**Hedges g**	**% change**	**Kappa coefficients**
CMJ (jump height)	37.92 ± 5.33	31.60 ± 4.40 *	-1.26 (-1.99, -0.54)	-16%	*Pre to Post*
Peak force D	1245.46 ± 223.89	1004.77 ± 198.34 *	-1.11 (-1.82, -0.40)	-24%	-0.41
Peak force ND	1233.89 ± 218.17	1039.88 ± 201.65 *	-0.90 (-1.60, -0.21)	-16%	
RFD 50-100 D	1708.44 ± 1180.73	720.82 ± 331.61 *	-1.11 (-1.82, -0.41)	-51%	0.16
RFD 50-100 ND	1605.95 ± 960.52	610.96 ± 290.58 *	-1.37 (-2.11, -0.64)	-58%	
RFD 100-150 D	1170.23 ± 1451.69	261.17 ± 347.88 *	-0.84 (-1.53, -0.15)	-26%	-0.34
RFD 100-150 ND	1093.85 ± 1631.11	254.82 ± 391.29 *	-0.69 (-1.37, -0.01)	-51%	

Legend. D = dominant; ND = non-dominant; CMJ = countermovement jump; RFD = rate of force development; * = *p*-value < 0.05; Peak force measured in Newton; RFD measured in Newton / second.

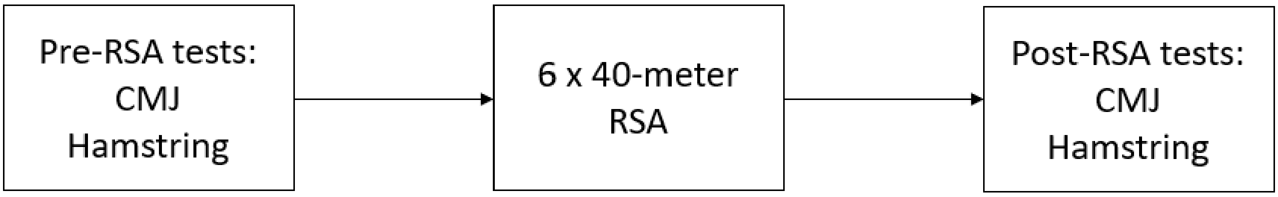

Figure 1. Pre- and post-RSA procedure.

Legend. CMJ = countermovement jump; RSA = repeated sprint ability.

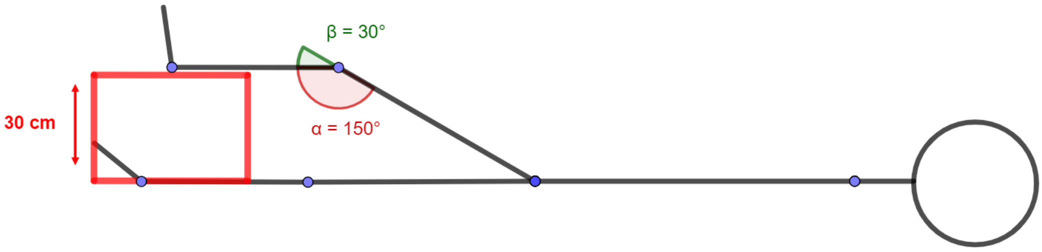

Figure 2. Hamstring testing position.

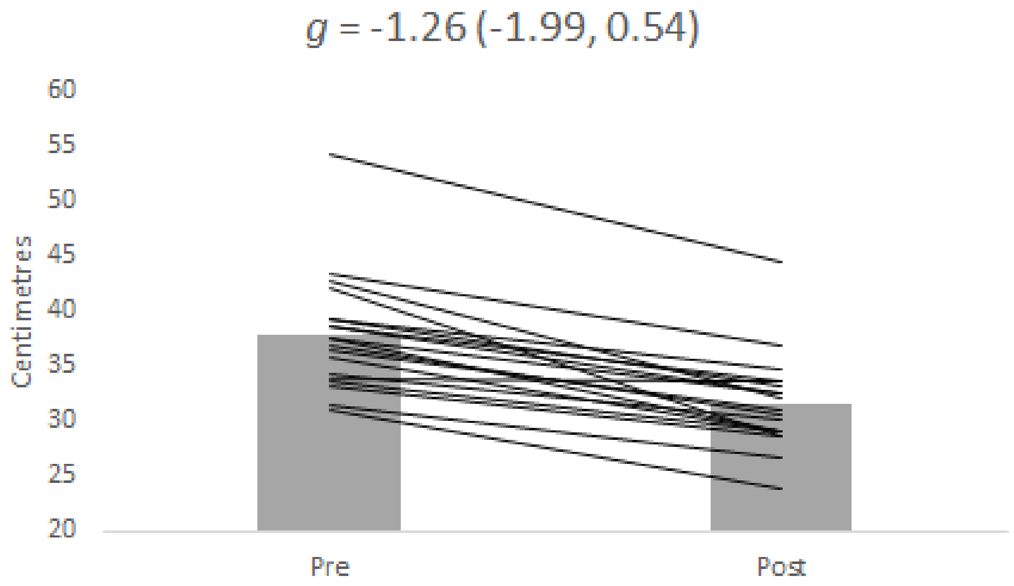

Figure 3. Mean and individual CMJ changes from pre- to post-RSA test.

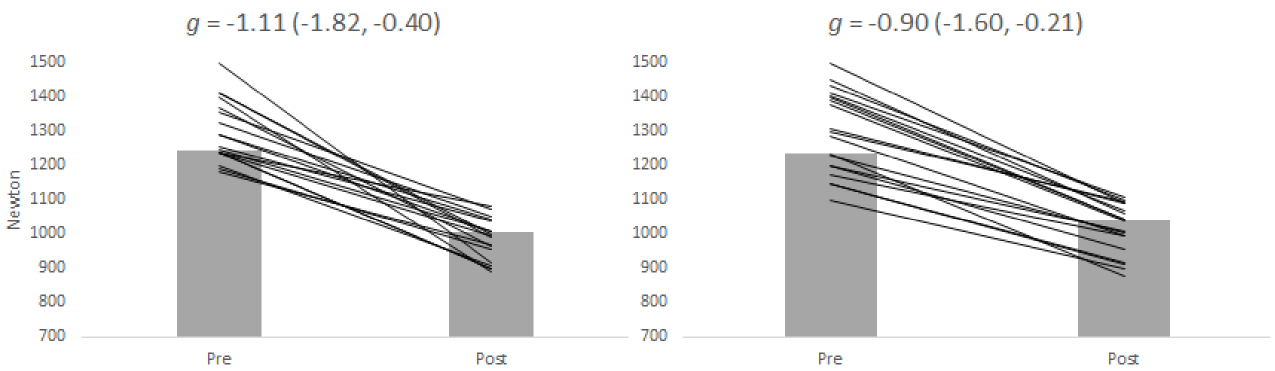

Figure 4. Mean and individual peak force changes from pre- to post-RSA test in dominant (left side) and non-dominant limbs (right side).

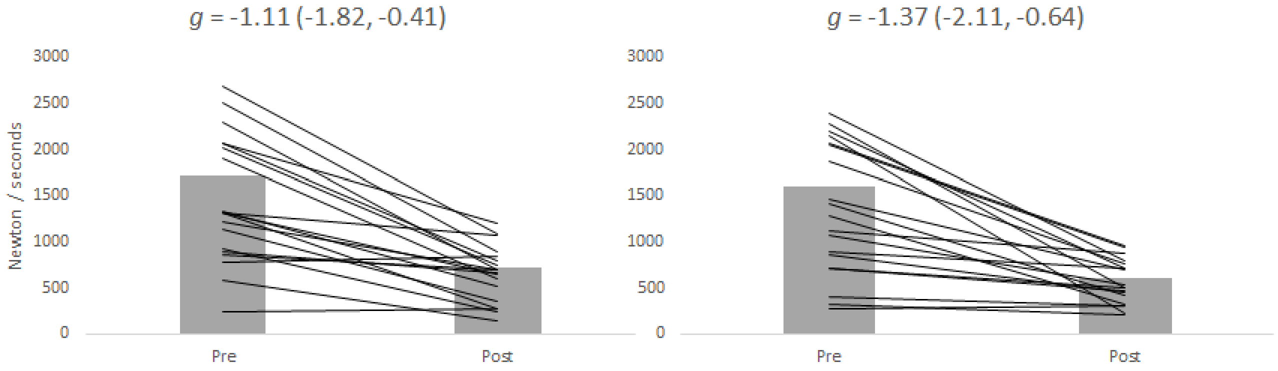

Figure 5. Mean and individual $RFD_{50\text{-}100}$ changes from pre- to post-RSA test in dominant (left side) and non-dominant limbs (right side).

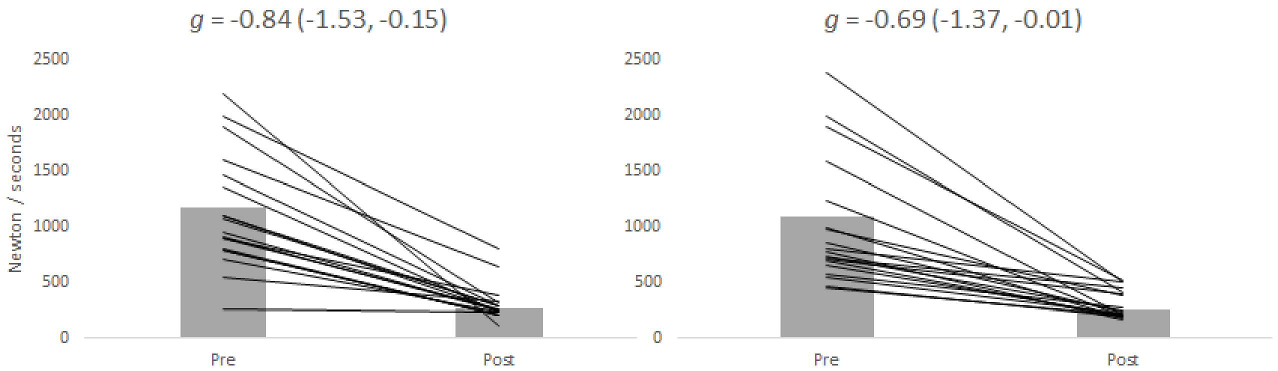

Figure 6. Mean and individual $RFD_{100\text{-}150}$ changes from pre- to post-RSA test in dominant (left side) and non-dominant limbs (right side).