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NO ASSOCIATION BETWEEN RATE OF TORQUE DEVELOPMENT AND ONSET OF MUSCLE ACTIVITY WITH INCREASED RISK OF HAMSTRING INJURY IN ELITE FOOTBALL

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ABSTRACT

Introduction

Hamstring injuries remain a significant burden in sports that involve high speed running. In elite male football, hamstring injury has repeatedly been identified as the most common noncontact injury, representing 12% of all injuries. As the incidence remains high, investigations are aimed at better understanding how to improve prevention efforts. Intrinsic risk factors such as strength have been investigated extensively in a cohort of professional football players; however, other intrinsic measures of neuromuscular function have not been studied in this cohort. This study aims to investigate the association between timing of hamstring muscle activity onset and the rate of torque development during the early phase of isokinetic strength testing with risk of hamstring injury in professional football players in a prospective cohort study. All teams (n=18) eligible to compete in the premier football league in Qatar underwent a comprehensive strength assessment during their annual periodic health evaluation at Aspetar Orthopaedic and Sports Medicine Hospital in Doha, Qatar. Variables included rate of torque development and timing of muscle activity onset. A total of 367 unique players (60.6% of all QSL players) competed for 514 player seasons (103 players competed both seasons) and sustained 65 hamstring injuries. There was no difference in the onset of muscle activity between the biceps femoris and medial hamstrings comparing the injured to uninjured players. For both onset of muscle activity and rate of torque development, there were no significant differences between any of the variables ($p>0.05$), with small effect sizes detected across all the different variables ($d<0.3$). Rate of torque development and onset of muscle activity were not associated with a risk of future hamstring injury. The use of these measures as part of a periodic health evaluation to identify risk of hamstring injury is unsupported.

Key words:

hamstrings, muscle injury, injury prevention, risk factors, rate of torque development,

INTRODUCTION

Hamstring injuries remain a significant burden in sports that involve high speed running.[1–3] In elite male football, hamstring injury has repeatedly been identified as the most common noncontact injury,[4,5] representing 12% of all injuries.[5] As the incidence remains high,[5,6] with serious financial implications,[3,5] investigations are aimed at better understanding how to improve prevention efforts. A key component to better understand injury risk and to develop targeted prevention programmes is the identification of both intrinsic and extrinsic risk factors. Intrinsic risk factors such as strength and range of motion have been investigated extensively. Van Dyk et al[7] a reported that lesser isokinetic concentric quadriceps strength and eccentric hamstring strength were significantly associated with an increased risk of injury. Another investigation in the same cohort found that greater isokinetic concentric quadriceps strength were associated with hamstring injury. Therefore, the relationship between strength and risk of injury, albeit significant, is weak and offers little clinical value.[7–10] However, risk factors that have not been thoroughly investigated in the same cohort of players are intrinsic measures of neuromuscular function such as rate of torque development and the timing of muscle activity onset.

The term neuromuscular function is wide-ranging, and is used to describe different aspects needed for optimal motor output. Although recognizing that skilled motor performance (as is required in football) requires a feed-forward mechanism where information is continually fed into sensory-motor loops from peripheral to central neural networks,[11,12] previous risk factor studies, all of them retrospective, have predominantly focused on specific aspects of neuromuscular function, such as rate of force development and muscle activity.[13–17]

Rate of torque development is important for all athletes participating in sports that require explosive muscle action.[18] In high speed running, a primary role of the hamstring muscle group is active deceleration of the forward moving thigh and lower leg during the terminal swing phase.[15] This terminal swing phase is considered as the phase in the gait cycle where most of the hamstring injuries occur with high eccentric force contraction decelerating the limb with the hamstrings in a

lengthened position.[3,14,15,19] During this phase, the biomechanical load is greatest, with the largest peak musculotendinous strain in the biceps femoris.[15] Therefore, the ability to generate torque during this phase of rapid deceleration is of great importance. Although many studies have examined the rate of torque development in performance testing, these investigations mainly focus on isometric contractions,[20,21] or the effect of either concentric or eccentric training on muscle strength and mass,[22] mainly in healthy individuals. The development of force during rapid concentric and eccentric movement has been largely overlooked.

The first study to provide experimental evidence for differences in rate of torque development and muscle activity with injury found significantly lower hamstring activation with the muscle in a lengthened position in previously injured athletes.[13] Opar et al identified an absolute deficit of 13% in muscle activity during eccentric activity, and a 22% difference in the rate of torque development during rapid force generation.[14,23]

To date, all results are from retrospective studies[13,14,23,24] and no adequately powered prospective study has investigated rate of torque development or the onset of muscle activity as a potential risk factor for hamstring injury. Methodological limitations in previous studies also include the use of self-reported injury data that may be subject to recall bias, and a lack of recorded exposure for the athletes included.[13,14,23]

The purpose of this study was therefore to investigate the association between the timing of hamstring muscle activity onset and the rate of torque development during the early phase of isokinetic strength testing, with risk of hamstring injury in professional football players in a prospective cohort study.

METHODS

Study design

A prospective cohort study was performed which covered two football seasons (September 2013 to May 2015), with players included in season 1, season 2, or both seasons. All teams (n=18) eligible to compete in the Qatar Stars League (QSL), the premier football league in Qatar, agreed to participate in the study. Each player from the respective teams underwent an annual periodic health evaluation (PHE) at Aspetar Orthopaedic and Sports Medicine Hospital in Doha, Qatar. The PHE was performed from May to September, with the official start of the season in September of each year. However, if players performed PHE outside of this period and met the inclusion criteria, they were still included in the study.

All players over the age of 18 years and eligible to compete in the QSL, who had provided written consent, were uninjured at the time and able to perform the strength testing, were included. If no isokinetic test was performed at the start of a season, or no exposure or injury surveillance data were recorded over an entire season, players were excluded. Figure 1 depicts the inclusion methodology during the two study seasons.

Ethical approval was obtained from the Institutional Review Board, Anti-doping Lab, Qatar (IRB F2013000003).

Player information

Non-modifiable risk factors that were considered included a history of previous hamstring injury in the past 12 months, age, team, regular season, leg dominance, playing position, and ethnicity. We measured height and weight, and calculated body mass index (BMI). History of previous hamstring injury was self-reported at the time of screening and cross-checked with their hospital medical file.

Isokinetic strength testing with surface EMG measurement

Prior to the isokinetic strength test procedure described below, both limbs were prepared for surface electromyography (sEMG) measurement. Bipolar pre-gelled Ag/AgCl sEMG electrodes (Ambu

Blue sensor T, Ambu A/S, Denmark; diameter 9 mm; interdistance electrode 30 mm) were used to record sEMG activity from the medial hamstrings and biceps femoris. After skin preparation via shaving, light abrasion, and sterilisation, electrodes were placed on the posterior thigh half way between the ischial tuberosity and tibial epicondyles.[14] Electrodes were placed on the muscle bellies that were identified via palpation during strong isometric knee flexion as per Surface Electromyography for Non-Invasive Assessment of Muscles (SENIAM) guidelines.[25] The reference electrode was placed on the lateral head of the right fibula. To minimise movement artifact from sEMG electrodes on the dynamometer seat, players were positioned on a custom made pad placed on top of the original seat, with two holes at the level of the posterior mid-thigh where the electrodes were placed.[14] Muscle activity via sEMG was recorded in the medial hamstrings and biceps femoris while the isokinetic test was performed.

Knee flexion and extension muscle strength were tested using an isokinetic dynamometer (Biodex Multi-joint System 3, Biodex Medical Systems Inc. New York, USA). After an explanation of the testing methodology, prior to the electrodes being affixed to the limb, the player performed a 5-10 min warm up routine, consisting of cycling on a stationary exercise bike at approximately 1 W/kg bodyweight (Bike Forma, Technogym®, Cesena, Italy), and familiarization with the test procedure. Each player was positioned on the dynamometer so that the hip was flexed to 90°, ensuring that the dynamometer was aligned with the knee joint angle. The trunk, waist and tested thigh were fixed with straps to minimize secondary joint movement. Vigorous verbal encouragement was provided by the assessors during the testing.[7] Isokinetic testing comprised of three different modes and speeds, with the selection of speed and repetition based on the findings from previous meta-analyses.[8] The order (i.e. left, right) was randomized and maintained for each of the three different testing modes and speeds for each subject. First, the players were tested over five repetitions of concentric knee flexion and extension at 60°/s, followed by 10 repetitions of concentric knee flexion and extension at 300°/s. These test modes measure the concentric strength of the quadriceps (knee

extension) and hamstring (knee flexion) muscles. Finally, players performed five repetitions of eccentric knee extension at 60°/s which measures the eccentric strength of the hamstring muscles.[9]

Dynamometer torque and lever position data were synchronously collected with EMG data. EMG data were collected using commercially available hardware (Biopac MP35, systems Inc) and software (Acqknowledge 3.6.7, Biopac Systems Inc) operating at 1000 Hz (bandwidth 10–500 Hz, common mode rejection ratio >115 dB at 60 Hz). Data were transferred to a personal computer for later analysis.

Data Analysis

Concentric and Eccentric Torque

The onset (start) and offset (end) points for each repetition during each contraction mode were automatically detected. Firstly, the raw torque data was smoothed at 3 Hz (low pass Butterworth digital filter) and the first derivative of the signal was determined, after which the maximum value (peak torque) for each repetition was determined through a peak detection method. For concentric trials, once the peak was identified, the onset and offset points for each repetition were determined by searching through the raw torque data until values exceeding -3 Nm and 3 Nm were found (figure 2).[14] For eccentric trials, the onset and offset points were identified for each repetition by searching from each repetition's peak both backwards (onset) and forwards (offset) until the points where the gradient was zero (figure 3). The onset and offset points were then visually confirmed via comparison with the original torque signal.

Rate of torque development

For repetitions of both concentric and eccentric contraction modes, the rate of torque development was determined to be the mean of the average slope of the torque-time trace (Dtorque/Dtime) from

the onset of contraction until 30, 50, and 100 ms through the contraction.[14] The peak rate of torque development for each contraction across all repetitions was determined for further analyses.

Muscle activity (sEMG)

Raw sEMG data were demeaned, full-wave rectified and low-pass filtered at 4 Hz using a fourth-order dual pass Butterworth digital filter to form a linear envelope.[26] The onset of myoelectrical activity for each repetition was automatically determined to be when it rose three standard deviations (SD) from the baseline sEMG activity.[27] While the computerized automatic detection method to determine onset was typically successful; when it was not, manual detection was implemented. Visual inspection was performed within the customized software programme for each onset determination to ensure accurate measurement.[28,29] The peak onset (measurement that displayed the earliest timing) as well as average onset from all the measurements as recorded during each isokinetic strength contraction were determined for medial hamstrings and biceps femoris. The above processes were all implemented using a customized software programme written in Labview V7.0 (National Instruments, Austin, Texas).

Injury surveillance

All participating QSL teams are provided with medical services by the National Sports Medicine Programme, a department with the Aspetar Orthopaedic and Sports Medicine Hospital. This centralized system with a focal point for the medical care of each club competing in the QSL allowed for standardization of the ongoing injury surveillance through the Aspetar Injury and Illness Surveillance Programme (AIISP).[30]

The AIISP includes prospective injury and exposure (minutes of training and match play) recording from all QSL teams. The injury data were collected monthly from the club, with regular communication with the responsible team physician/physiotherapist to encourage timely and accurate reporting. Throughout the 2013 and 2014 season (July to May; 44 weeks per season),

training and match exposure for each team were recorded by the team physician (or lead physiotherapist if no team physician was available). At the conclusion of each season, all the data from the individual clubs were collated into a central database, and inconsistencies were identified and followed up to be resolved with club medical personnel.

A hamstring injury was defined as acute pain in the posterior thigh that occurred during training or match play, and resulted in immediate termination of play and inability to participate in the next training session or match.[4] These injuries were confirmed through follow-up clinical examination (identifying pain on palpation, pain with isometric contraction and pain with muscle lengthening) by the club medical staff, not more than three days post-injury. If indicated, the clinical diagnosis was supported by ultrasonography and/or magnetic resonance imaging at the study centre. A recurrent injury was defined as a hamstring injury that occurred in the same limb and within two months of the initial injury.[31]

Statistical analyses

For each player included, all repetitions for each isokinetic mode of contraction for both limbs (40 trials) were used in the statistical analyses, except if any repetition in a specific trial was found unusable due to the quality of the data. All repetitions for each mode of contraction were used to determine the average rate of torque development and onset of muscle activity, and this average, together with the peak effort within each set of repetitions was also used in the analyses. Univariate analyses (independent t-tests) were performed between the limbs of the injured and the uninjured players for the sEMG and rate of torque development measures. Injured limbs were compared to uninjured limbs among injured players, and then to all uninjured limbs among the uninjured players. For categorical variables, a chi-square analysis was performed.

Due to the consistency in our sample, the repeated measures performed over the two seasons, as well as the fact that not every player had the same number of measurements (i.e. some subjects would have test results including both limbs for both seasons, while other subjects might only have

been tested once), standard errors would have increased when using general estimating equations in a traditional Cox regression model. Therefore, we performed a clustered univariate Cox regression analysis in STATA (version 11.0, College Station, Texas, USA) using the limb as the unit of analyses, adjusting for the interdependence of the limbs by using the player as a cluster factor. Due to the skewness of the sEMG and rate of torque development measurements, the natural log transformation was used. Exposure was totaled as duration in hours for game and training combined from the start to the end of each season, or time to first injury. Variables independently associated with hamstring strain injury were determined from the univariate analyses. A p-value of ≤0.05 was considered statistically significant. Effect size, which is the quantitative measure of the strength of an observed occurrence, was calculated and interpreted using thresholds as suggested by Cohen et al as small (> 0.2), medium (> 0.5), and large (> 0.8).[32]

RESULTS

Participants

During the two-season study period, 592 elite male soccer players (age 25.8 ± 4.8 yrs, height 177 ± 7 cm, weight 72.4 ± 9.3 kg, BMI 23.1 ± 2) reported for screening and were considered for isokinetic testing. Players who were unable to perform the test (n=70), who did not provide consent (n=4), or had no injury surveillance data recorded during the subsequent season (n=105) were excluded from the final analyses (n=179, age 25.3 ± 4.5 yrs, height 177 ± 7 cm, weight 73.5 ± 9.8 kg, BMI 23.4 ± 1.8). Of the remaining 413 players, 46 did not have any sEMG measurements recorded, and were also excluded. In total, 367 unique players (60.6% of all QSL players) competed for 514 player seasons (103 players competed both seasons) (figure 1). The only demographic difference between the injured and uninjured players were age and player position ($p<0.05$) (table 1).

New hamstring strain injuries

Overall, 62 of the 367 players sustained 65 index hamstring injuries. The three players who had more than one injury were retained in the analyses (none of these injuries met the criteria for re-injury).

Electromyography and rate of torque development measurements

Muscle activity (sEMG) was recorded for 367 players while performing a total of 1018 isokinetic test procedures (considering both limbs) over the two seasons. There was no difference in the onset of muscle activity between the medial hamstrings and biceps femoris (table 2), or the rate of torque development (table 3) for both the injured and uninjured players. The results of the univariate analyses are shown in table 2 and 3 for sEMG muscle onset and rate of torque development, respectively. Among injured players, comparing the injured to the uninjured limb (n=62), no significant differences in the onset of muscle activation or rate of torque development were observed for any of the test modes.

Comparing the injured limbs to the limbs of uninjured players (n=963), there were no significant differences between any of the variables ($p>0.05$), with no to small effect size detected across all the different variables ($d<0.3$) (table 2).

Cox regression analysis

Age, weight, body mass index, previous hamstring injury, season, side (left or right limb), team, limb dominance and player position were tested as potential confounding variables. The parameter estimates of the regression analyses are presented in table 4 and 5 expressed as hazard ratios. Age and player position were significantly associated with increased risk of injury, while the onset of muscle activation or rate of torque development were not during any of the different contraction modes.

DISCUSSION

Neither rate of torque development nor onset of muscle activity during concentric and eccentric isokinetic contractions were found to be associated with risk of hamstring injury in this study.

Strength variables have been investigated thoroughly in the same cohort of players, where quadriceps strength was the only significant, albeit weak, risk factor identified. To compliment these previous findings, this is the first large prospective cohort study to examine the association between rate of torque development and the onset of muscle activity with risk of hamstring injury. Previous studies have examined these measures when players have returned to sport after hamstring injury, suggesting that they persist for a prolonged period after injury, or that rehabilitation may have been inadequate. [23] However, the current investigation examined these aspects in healthy players while performing isokinetic strength tests in an elite football screening environment.

Rate of torque development

Concentric muscle action

We were able to investigate the rates of torque development for isokinetic concentric muscle action at 60°/s and 300°/s in 367 healthy professional football players. Our results indicate higher rates of torque development in the concentric contraction modes compared to eccentric contractions at 60°/s, although no differences were observed between injured or uninjured players, neither in the concentric nor eccentric modes. We might consider that because the concentric contractions represent a transition from knee extension to knee flexion, the resultant rate of torque development will artificially be higher, compared to the eccentric contraction which starts from rest.

A decline in the rate of torque development from 30 to 100ms was observed, supported by previous findings.[30,34] Although variability between individual players might lead to different rates of torque development, the decline we observed would suggest that the majority of force development occurs early in the movement. However, the concentric action was not isolated, and we urge caution when interpreting this result.

Eccentric muscle action

There was no difference between injured and uninjured limbs for rate of torque development during anticipated eccentric contractions at any of the time intervals in the present study. Contrary to previous findings,[14] we observed little to no change in the rate of torque development over the 100 ms period.

Most explosive sporting activities such as running or jumping involve stretch-shortening cycle movements where a concentric muscle action is preceded by an eccentrically stretched muscle-tendon complex.[12] In football, a key feature of hamstring muscle function is the ability to generate rapid force at the terminal swing phase during high speed running. [3] This rapid deceleration of the hip (flexion) and knee (extension) is imperative to maintain function of the limb during explosive action. The ability to rapidly develop force is important because of the limited time available for deceleration (~100 ms),[34] which prevents the development of peak torque.[35]

The only previous study to investigate the relationship between rate of torque development during anticipated eccentric contraction @60°/s and hamstring injury found lesser rates of torque development at 50 ms and 100 ms in previously injured players.[14] Since the methodology in this study was similar to ours, the results in our study would suggest that the difference in rate of torque development identified in a previous study [14] is a result of the hamstring injury, and not present prior to injury.

Onset of muscle activity

Our findings indicate no difference in the onset of muscle activity between injured and uninjured players, or between different hamstring muscles for any of the contraction modes. The myoelectrical activity during the early phase of the contraction onset has been shown to have a positive relationship with rate of torque development,[18,20] and the initial onset of muscle activity might therefore influence the rate of torque development. Sole et al reported the onset of both the biceps femoris and medial hamstrings were shown to be earlier among previously injured players, highlighting differences in the muscle activity after injury.[24]

Although the present investigation did not measure the amplitude of myoelectrical activity, previous investigations have found significant differences in muscle activity of previously injured hamstring muscles. Indeed, Sole et al demonstrated a significant decrease in biceps femoris myoelectrical activity in the lengthened range of eccentric contraction.[13] This was confirmed by another retrospective study where the myoelectrical activity in the biceps femoris was decreased at 100 ms after the onset of the eccentric contraction.[23] In this study, the myoelectrical activity at 60°/s in the biceps femoris was significantly lower in previously injured limbs during anticipated eccentric contractions.[23]

Other prospective investigations profiling the muscle activity patterns of the trunk and lower limb have identified associations with the risk of hamstring injury in football players.[17,36,37] These studies suggest that other components such as muscle recruitment patterns between the biceps femoris and medial hamstrings, or activation profiles of different muscles such as the erector spinae and gluteus medius during sprinting, might be related to hamstring injury.[37] However, the present investigation does not provide any evidence that the timing of muscle activity onset during isokinetic contractions, either concentrically or eccentrically, is associated with an increased risk of injury.

Strengths and limitations

It has been proposed that 30 to 40 injury cases are needed to detect strong to moderate associations between risk factors and injury in prospective cohort studies, while 200 injury cases are needed to detect small to moderate associations.[38] With 65 cases, this is the largest prospective study to date on rate of torque development and the onset of muscle activity as risk factors for hamstring injury, yet it was insufficient to detect small associations. However, it should be noted that none of the effect sizes calculated for these variables exceeded 0.3, failing to reach clinical importance.

As with the investigation by Opar et al, we acknowledge that the lag between the dynamometer lever arm and the onset of torque development limits our ability to accurately measure muscle

activity onset.[14] The use of isokinetic dynamometry at 60°/s and 300°/s to assess the rate of torque development might also be influenced by other factors, in particular fatigue during 10 repetitions at high speed of concentric action.

All tests performed utilized the same isokinetic testing system with highly experienced assessors in a multinational, multi-language clinical setting for professional athletes. Although the aim was to ensure players understood the test procedure and instructions, it is possible that some players did not comprehend the instructions fully. Intra-season variability in the repeated measures over the two-year observation period may have limited our ability to identify an association between rate of torque development and the onset of muscle activity with injury risk. We must consider that a once-off test at a specific time point in the season does not necessarily reflect the actual status of the player at the time of injury.

In addition, even though every effort was made in the data analysis to account for variability, we accept that there may be a large amount of "noise" in the data. The larger inter-electrode distance of the electrodes used in this study (30mm) compared to previous investigations (25mm) may increase the risk of signal contamination from adjacent muscles. However, this is representative of current clinical practice.

We also acknowledge the homogeneity of our study population of professional male football players, which limits the generalization of these findings to other sports, age groups, or female players. Other factors such as training culture and possible prevention strategies within different teams, or climate specific to the Middle East region, could have influenced the results.

Clinical implications

The results of this investigation indicate that the previous findings of lower rates of torque development, as well as reduced biceps femoris activation during maximal eccentric contractions, are more likely the result of changes in response to injury. Previously injured hamstring muscles (in

particular biceps femoris) have a reduced ability to generate torque with anticipated eccentric movements.[23] This holds important consequences for rehabilitation and risk of recurrent injury.

Although it is not possible to determine the muscle activity or rate of torque development of the hamstring muscle at the precise moment of injury, interestingly, we did not find any association between these measures with risk of future hamstring injury.

Seated isokinetic dynamometry strength testing does not reflect the functional demands placed on the hamstrings during sport specific activity such as high-speed running or changing direction,[14] urging caution when translating these findings to the clinical setting.

CONCLUSION

Rate of torque development and onset of muscle activity was not associated with a risk of future hamstring injury. Our results provide insights previously unknown into the causal relationship between rate of torque development and the onset of muscle activity with risk of hamstring injury. The use of these measures as part of a periodic health evaluation is unsupported.

PERSPECTIVE

Our findings would suggest that deficits observed in rate of torque development and muscle activation is the consequence rather than the cause of hamstring injury. This holds specific implications for rehabilitation. To be effective, adequate rehabilitation for players with hamstring injuries might address components such as rate of torque development and muscle activation to constrain potential neuromuscular inhibition. Furthermore, pre-injury measures may be useful as a baseline to compare to during rehabilitation from subsequent injury.

In our results, rate of torque development and onset of muscle activity do not represent risk factors for hamstring injury. It is also clear that once-off testing during the season is not valuable in identifying athletes at risk of hamstring injury.

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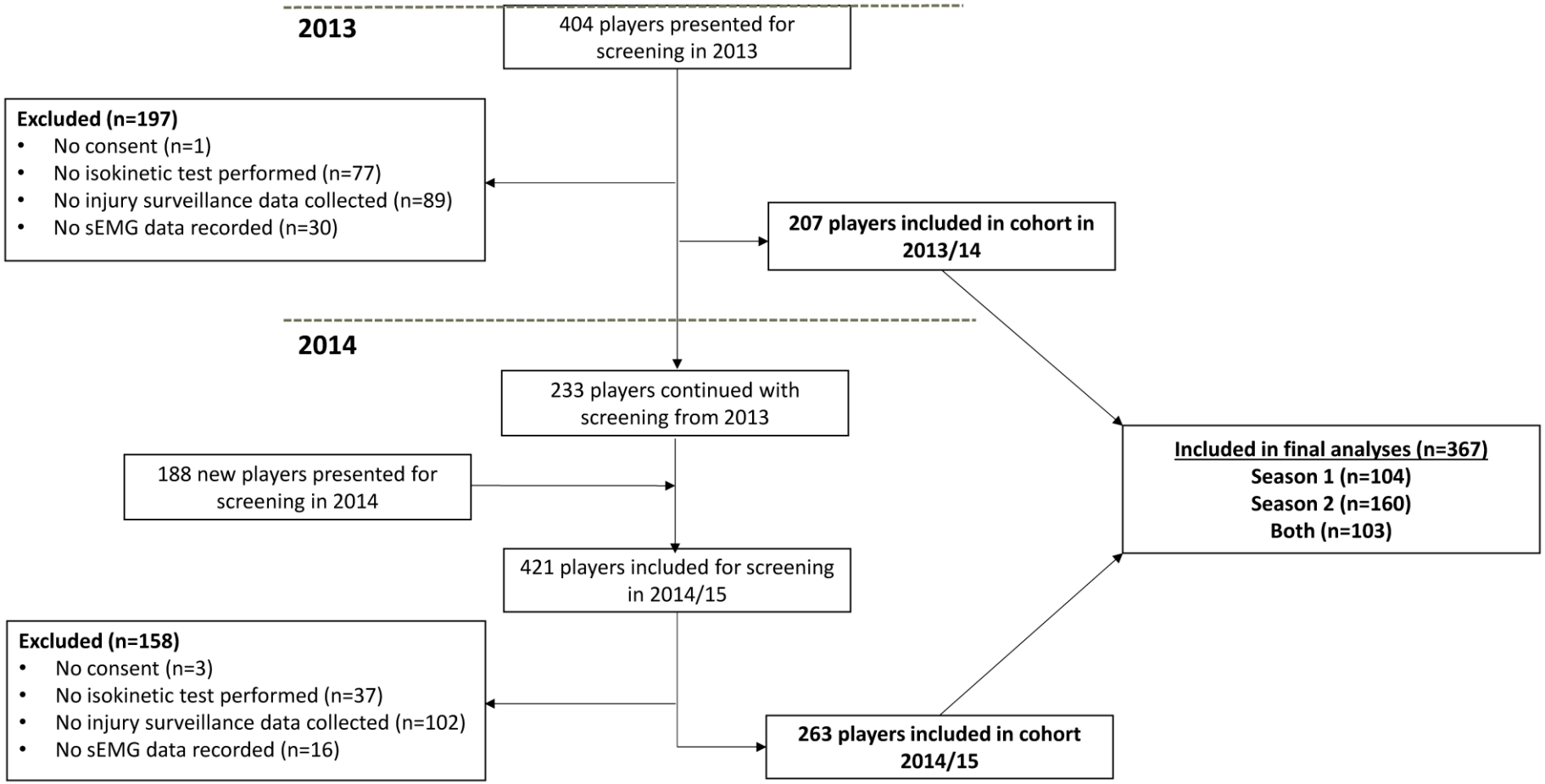

Figure 1 Flowchart demonstrating the movement of players and repeated measurements between different seasons

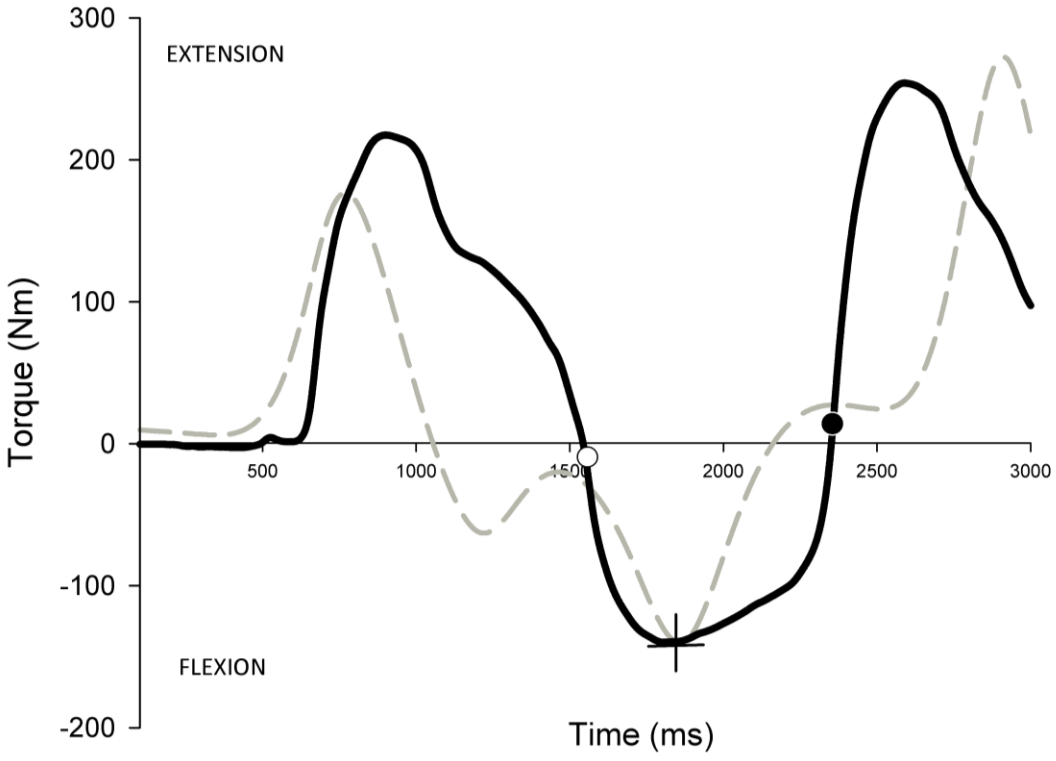

Figure 2 Concentric torque onset detection. The peak (indicated by cross) was detected from the 1st derivative (dashed line), and mapped onto the raw torque (solid line). The onset (open symbol) and offset (closed symbol) points were identified moving backwards (onset) and forwards (offset) for each repetition in the raw torque data until values exceeding -3 Nm and 3 Nm, respectively, was found.

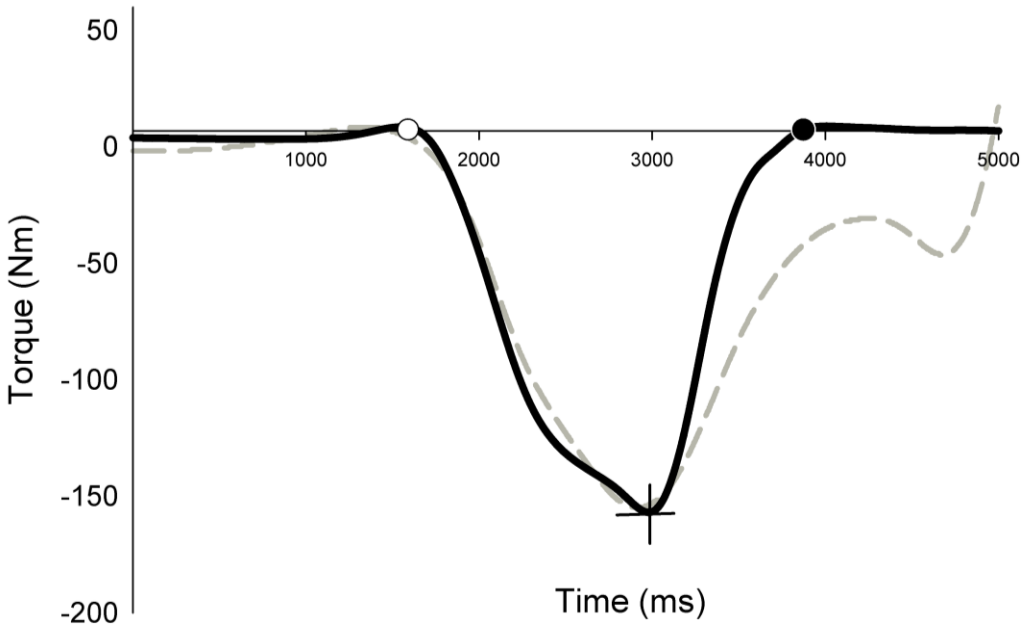

Figure 3 Eccentric torque onset detection. The peak (indicated by cross) was detected from the 1st derivative (dashed line), and mapped onto the raw torque (solid line). The onset (open symbol) and offset (closed symbol) points were identified moving backwards (onset) and forwards (offset) for each repetition in the raw torque data until the points where the gradient was zero.

Table 1 Characteristics of the injured (n=62) and uninjured players (n=305). Data are shown as mean values with SD or percentages.

	Injured (n=62)	**Uninjured (n=305)**	**p-value**
Age	27.8 (4.3)	26.1 (4.8)	**0.01**
Body mass (kg)	72.3 (7.8.)	72.3 (9.2)	0.94
Body height (m)	176 (7)	177 (6.8)	0.32
BMI	23.4 (1.9)	23.1 (1.9)	0.50
Previous hamstring injury (yes)	30.6%	29.2%	0.73
Player position (n)			**<0.01**
- Goalkeeper[a]	1 (1.6%)	33 (10.8%)	
- Defender	26 (41.9%)	94 (30.8%)	
- Midfielder	25 (40.3%)	119 (39.1%)	
- Forward	10 (16.2%)	59 (28.8%)	
Limb dominance (n)			0.36
- Left	15 (24.4%)	44 (14.4%)	
- Right	47 (75.6%)	261 (85.6%)	

[a] Comparator value used in Chi-square analysis for categorical variable

Table 2 Comparison of surface electromyography (sEMG) measuring the onset of muscle activity relative to the onset of torque between the injured and a) the uninjured limb in the injured players, and b) all uninjured limbs in the uninjured players. Absolute values for sEMG are displayed for medial hamstrings (MF) and biceps femoris (BF) in seconds as mean values with SD. [a]Paired t-test, [b]unpaired t-test

	Injured players				Uninjured players		
	Injured limb (n=65)	**Uninjured limb (n=65)**	**p-value[a]**	**Effect Size (d)**	**Uninjured limbs (n=963)**	**p-value[b]**	**Effect Size (d)**
Medial hamstrings							
Concentric @60°/s							
Peak onset sEMG	-0.167 (0.024)	-0.162 (0.031)	0.38	0.20	-0.172 (0.029)	0.42	0.17
Average onset sEMG	-0.147 (0.026)	-0.141 (0.034)	0.31	0.23	-0.149 (0.027)	0.52	0.09
Concentric @300°/s							
Peak onset sEMG	-0.172 (0.025)	-0.174 (0.024)	0.73	0.06	-0.177 (0.027)	0.28	0.19
Average onset sEMG	-0.150 (0.027)	-0.170 (0.036)	0.69	0.07	-0.152 (0.023)	0.82	0.08
Eccentric @60°/s							
Peak onset sEMG	-0.205 (0.053)	-0.201 (0.036)	0.68	0.07	-0.204 (0.047)	0.56	0.03
Average onset sEMG	-0.157 (0.050)	-0.155 (0.037)	0.85	0.03	-0.158 (0.041)	0.83	0.04
Biceps Femoris							

Concentric @60°/s							
Peak onset sEMG	-0.158 (0.038)	-0.152 (0.038)	0.42	0.16	-0.157(0.035)	0.71	0.02
Average onset sEMG	-0.132 (0.033)	-0.124 (0.037)	0.24	0.24	-0.132 (0.032)	0.96	0.01
Concentric @300°/s							
Peak onset sEMG	-0.166 (0.032)	-0.170 (0.036)	0.61	0.10	-0.167 (0.031)	0.80	0.01
Average onset sEMG	-0.142 (0.028)	-0.141 (0.030)	0.87	0.03	-0.141 (0.028)	0.68	0.05
Eccentric @60°/s							
Peak onset sEMG	-0.211 (0.052)	-0.207 (0.050)	0.67	0.08	-0.206 (0.047)	0.48	0.11
Average onset sEMG	-0.159 (0.041)	-0.157 (0.047)	0.84	0.05	-0.160 (0.040)	0.98	0.02

Table 3 Comparison of the rate of torque development measurements between the injured and a) the uninjured limb in the injured players, and b) all uninjured limbs in the uninjured players. Absolute values for rate of torque development are displayed in Nm/s as mean values with SD. [a]Paired t-test, [b]unpaired t-test

	Injured Players				**Uninjured players**		
	Injured limb (n=65)	**Uninjured limb (n=65)**	**p-value[a]**	**Effect Size (d)**	**Uninjured limbs (n=963)**	**p-value[b]**	**Effect Size (d)**
Concentric @60°/s							
30 ms	1019 (373)	1025 (463)	0.93	0.02	1058 (460)	0.53	0.08
50 ms	952 (333)	901 (385)	0.44	0.15	950 (391)	0.99	0.01
100 ms	864 (226)	815 (264)	0.29	0.22	864 (261)	0.83	0.01
Concentric @300°/s							
30 ms	1404 (432)	1388 (403)	0.83	0.03	1418 (389)	0.96	0.03
50 ms	961 (234)	914 (235)	0.28	0.20	949 (221)	0.56	0.05
100 ms	682 (173)	670 (202)	0.71	0.07	677 (173)	0.62	0.04
Eccentric @60°/s							
30 ms	355 (252)	357 (213)	0.97	0.01	377 (213)	0.33	0.10
50 ms	365 (246)	360 (207)	0.92	0.02	389.09 (207)	0.31	0.12
100 ms	342 (225)	325 (161)	0.66	0.07	374 (176)	0.20	0.18

Table 4 Univariate Cox regression analysis demonstrating parameter estimates (95% confidence intervals, CI) with all possible muscle onset sEMG variables for medial hamstrings (MH) and biceps femoris (BF) included (n=367)

	Hazard Ratio	95% CI	p-value
Medial hamstrings			
Concentric @60°/s			
Peak onset sEMG	0.45	0.10 to 2.01	0.30
Average onset sEMG	0.59	0.24 to 1.46	0.25
Concentric @300°/s			
Peak onset sEMG	0.63	0.34 to 1.18	0.15
Average onset sEMG	0.79	0.37 to 1.71	0.55
Eccentric @60°/s			
Peak onset sEMG	1.15	0.32 to 4.06	0.83
Average onset sEMG	0.71	0.30 to 1.67	0.43
Biceps femoris			
Concentric @60°/s			
Peak onset sEMG	1.36	0.42 to 4.40	0.61
Average onset sEMG	0.93	0.42 to 2.08	0.86
Concentric @300°/s			
Peak onset sEMG	1.10	0.31 to 3.86	0.89
Average onset sEMG	1.20	0.39 to 3.72	0.75
Eccentric @60°/s			
Peak onset sEMG	1.40	0.48 to 4.13	0.54
Average onset sEMG	0.88	0.42 to 1.83	0.73

Table 5 Univariate Cox regression analysis demonstrating parameter estimates (95% confidence intervals, CI) with all peak rate of torque development variables for each of the different isokinetic contraction modes (n=367)

	Hazard Ratio	95% CI	p-value
Concentric @60°/s			
30 ms	0.85	0.50 to 1.43	0.54
50 ms	0.98	0.56 to 1.74	0.96
100 ms	0.94	0.48 to 1.84	0.85
Concentric @300°/s			
30 ms	0.84	0.35 to 2.06	0.71
50 ms	1.32	0.41 to 4.26	0.64
100 ms	1.23	0.45 to 3.38	0.68
Eccentric @60°/s			
30 ms	0.68	0.38 to 1.23	0.20
50 ms	0.64	0.34 to 1.18	0.15
100 ms	0.54	0.30 to 1.03	0.06