Eccentric knee flexor strength profiles of 341 elite male academy and senior Gaelic football players: do body mass and previous hamstring injury impact performance?

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Abstract

Objective

Report eccentric knee flexor strength values of elite Gaelic football players from underage to adult level whilst examining the influence of body mass and previous hamstring injury.

Design

Cross-sectional study.

Setting

Team's training facility.

Participants

Elite Gaelic football players (n=341) from under 14 years to senior age-grades were recruited from twelve teams.

Main Outcome Measures

Absolute (N) and relative ($N \cdot kg^{-1}$) eccentric hamstring strength as well as corresponding between-limb imbalances (%) were calculated for all players.

Results

Mean maximum force was 329.4N (95% CI 319.5 – 340.2) per limb. No statistically significant differences were observed in relative force values (4.4 $N \cdot kg^{-1}$, 4.2 – 4.5) between age-groups. **Body mass had moderate-to-large and weak associations with maximum force in youth (r=.597) and adult (r=.159) players, respectively.** Overall 40% (95 CI 31.4 – 48.7) presented with a maximum strength between-limb imbalance >10%. Players with a hamstring injury had greater relative maximum force (9.3%, 95% CI 7.0 – 11.8; p>0.05) and a 28% (95% CI 10.0 – 38.0) higher prevalence of between-limb imbalances ≥15% compared to their uninjured counterparts.

Conclusions

Overlapping strength profiles across age-groups, combined with greater strength in previously injured players, suggests difficulties for establishing cut-off thresholds associated with hamstring injury risk.

Keywords

Gaelic football; eccentric hamstring strength

Highlights

1. The mean strength value of elite senior Gaelic football players was 22% greater than all other elite players. However, when standardised to body mass ($N.kg^{-1}$), senior players were 15% weaker than younger age-groups.
2. Players with a history of hamstring injury in the 12 months prior to testing had relative strength values 9% stronger than uninjured players.
3. Overall 40% of elite Gaelic football players presented had absolute strength imbalances >10% with quartiles revealing overlaps in metrics across the age-groups.

Introduction

Gaelic football is a multidirectional, running-based field sport that originated in Ireland. Since 1884, Gaelic football has been governed by the Gaelic Athletic Association (GAA). Presently, there are over 334,000 players with 2600 registered clubs (GAA, 2014). Community clubs represent sub-elite levels of Gaelic football, while select players aged 14 years and upwards are chosen to participate with their county team, representing the elite levels of Gaelic games.

During match-play two opposing teams of 14 outfield players and a goalkeeper play on a grass pitch 145 m long by 90 m wide. The aim is to outscore the opposition at H-shaped goal posts by kicking or striking a round ball over (1 point) or under (1 goal equating to 3 points) a crossbar. Match-play consists of two 30 minute periods **separated** by a 10 minute interval, however, at the elite senior level two 35 minute periods are played. Shoulder-to-shoulder contact is permitted, yet 68% of injuries are incited by non-contact mechanisms (Murphy et al., 2012).

Elite underage players (15 ± 0.7 years) run on average 5700 m or 93 $m \cdot min^{-1}$ during match-play, with 15% of the total distance performed at high-speed (>17 $km \cdot h^{-1}$) (Reilly et al., 2015). Additionally, elite senior players run on average 9200 m (131 $m \cdot min^{-1}$) with 18% of the total distance performed at high-speed (Malone et al., 2016). It has been hypothesised that these workrates may contribute to the high incidence of non-contact lower limb injuries in Gaelic football and field sports with similar demands (Roe et al. 2017). For instance, elite Australian football players covering >653 m at ≥24 $km \cdot h^{-1}$ each week are 3.3 times more likely to sustain a hamstring injury compared to their peers (Ruddy et al., 2016).

Hamstring injuries are the most common injury in elite Gaelic football affecting 21% of players per 32 week season (Roe et al., 2016). An elite Gaelic football squad of 38 players can expect to sustain 9 hamstring injuries per season, each resulting in an average of 26 time-loss days (Roe et al., 2016). Furthermore, following return to sport players with a previous hamstring injury are 230% more likely to sustain a future hamstring injury in comparison to their uninjured peers (Roe et al., 2016). Hamstring injury incidence have been illustrated to be greater among elite Gaelic football players aged 18-20 and ≥30 years identifying the need for modifiable risk factors and characteristics across age groups (Roe et al., 2016).

Modifiable risk factors for hamstring injuries have been identified in other elite field sports using metrics derived from eccentric knee flexor strength assessment. For example, in elite rugby union, between-limb imbalances of ≥15% and ≥20% were associated with a relative risk ratio (RR) of 2.4 and 3.4 for future injury, respectively (Bourne et al., 2015). Similarly, preseason eccentric knee flexor strength of <256 N was associated with increased injury risk in elite Australian football players (RR = 2.7) (Opar et al., 2015). Conversely, van Dyk et al. (2017) found no association between knee flexor strength and hamstring injury risk in soccer players. Although targeting interventions at players presenting with these characteristics may mitigate hamstring injury risk, the absence of normative data makes it difficult for practitioners to compare a player's characteristics to their peers to individualise interventions (Fox et al., 2014; Chalker et al., 2016). Such data may guide clinical practise in performance-orientated environments where stakeholders seek information for establishing intervention targets (Roe et al., 2017).

Considering that 1-in-5 elite Gaelic football players will sustain a hamstring injury per season, and that metrics derived from assessing eccentric knee flexor strength have been shown to alter risk of injury, it is important that these mechanical characteristics are described. Therefore, the primary aim of the current study was to describe eccentric knee flexor strength in elite male Gaelic football players from under-age to senior level. The secondary aim was to determine the influence of **body mass** and previous hamstring injury on eccentric knee flexor strength.

Methods

A cross-sectional study was designed to measure eccentric knee flexor strength in elite Gaelic football players from under 14 years to senior level.

Participants

Players (n=341; 20.8 yrs ± 6.0; 75.3 kg ± 13.1) were recruited from twelve inter-county male teams. The number of participants varied between age groups: under 14 years (n=26; 13.6 years ± 0.3; 55.0 kg ± 11.2), under 15 years (n=33; 14.8 years ± 0.3; 62.6 kg ± 8.7), under 16 years (n=21; 15.5 years ± 0.5; 68.6 kg ± 8.4), under 17 years (n=25; 16.5 years ± 0.5; 69.7 kg ± 6.4), under 21 years (n=88; 20.2 years ± 0.8; 81.6 kg ± 6.7), and senior level (n=148; 26.6 years ± 3.1; 84.0 kg ± 7.1).

Ethical Approval and Consent

Ethical approval for this study was granted by the Human Research Ethics Committee at the respective university.

Procedures

Players were required to complete a questionnaire prior to strength testing to establish their dominant leg and previous injury history. Testing was completed during the preseason or initial competitive cycle of the 2016/17 season. A prototype of the portable strength testing device (Nordbord, Vald Performance, Australia) has previously shown high-to-moderate reliability (intraclass correlation coefficient = 0.83-0.90; typical error, 21.7-27.5 N; typical error as a coefficient of variation, 5.8%-8.5%) (Opar et al., 2013). A previously described protocol was utilised for the current study (Opar et al., 2015). That is, following a warm-up set, participants performed one set of three maximal repetitions of the Nordic hamstring exercise on the device. Participants were instructed to gradually lean forward at the slowest possible speed while maximally resisting the fall with both legs and maintaining an upright posture with their spine and pelvis in a neutral position ("stay as tall as you can", "imagine a straight line from your knees to head"). The proprietary software provided instantaneous raw data that were then exported into a customised Microsoft Excel spreadsheet (Microsoft, Redmond, USA). Data relating to maximum force and average force for each leg, as well as between-limb imbalances, were derived from the excel sheet.

Analysis

All data were analysed using SPSS (version 21.0; IBM, Inc., Chicago, IL, USA). Descriptive statistics were used to report performance markers per age grade. Data are presented as mean values with 95% confidence intervals (95% CI). The presented strength metrics are the mean between left and right limbs. Quartiles were used to report performance markers across 25th, 50th, and 75th percentile intervals. The maximum and average forces between limbs across all three repetitions were compared to report percentage imbalances. Between-limb imbalances were graded as <5%, ≥5% to <10%, ≥10% to <15%, or ≥15%. Strength metrics were standardised to body mass to report the relative force ($N \cdot kg^{-1}$) for each player and these were termed relative maximum and relative average force. To compare metrics between age grades, data for each age grade were compared to the mean for all others producing a relative strength ratio. Players with a previous hamstring injury within 12 months prior to testing were compared to their uninjured peers using the mean values for maximum and average force of both limbs. Previous hamstring injuries were stratified according to severity based time-loss as mild (1-7 days), moderate (8-28 days), or severe (>28 days). Return to sport was considered once medical clearance was obtained for full participation in all team training and matches. Maximum force was also investigated following return to play in previously injured players.

Cohen *d* was used to assess the magnitude of the effect (effect size, ES) between dominant and non-dominant limbs, injured and non-injured limbs and players, as well as each age-grade in comparison to all others. An ES of 0.2, 0.5, 0.8, or 1.3 was considered small, moderate, large, or very large, respectively. A one-way between-groups analysis of variance was used to compare mean differences between groups based on: age, and severity of previous hamstring injury. Post-hoc Tukey tests were applied for pairwise comparisons. An independent-samples t-test was used to compare means between players with and without a previous hamstring injury. A paired-samples t-test was used to compare means between: dominant and non-dominant limbs, and injured and uninjured limbs. Significance was set at a $p < 0.05$. A linear regression was used to compute the equation representing the relationship between the body mass (independent variable) and maximum force (dependent variable). **Separate regressions were also computed following stratification of players to a subgroup of youth (under 14 to 17 years) or adult (under 21 years to senior) levels.**

Results

Eccentric knee flexor strength scores are outlined in table 1 and table 2. A significant difference in maximum ($p < 0.01$; *d* = 0.7) and average ($p < 0.02$; d = 0.7) strength was recorded between under-14 years and all other age-groups, except under-15 players (p = 0.371). However, no statistically significant (p=0.513) differences were observed when relative force values were analysed ($N \cdot kg^{-1}$). Data on the relative strength ratio comparing metrics for each age group against all other player are outlined in table 3.

On average, relative maximum force was 5.0% (95% CI 3.2 – 6.9) greater in the dominant limb when compared to the non-dominant limb. Similar findings were found for relative average force (5.6%, 95% CI 3.3 – 8.1). Statistically significant differences between dominant and nondominant limbs were found for relative maximum strength and relative average strength in under-17 to senior players ($p < 0.02$, *d* = 0.2).

A moderate-large correlation was found between maximum force and body mass (r = 0.47) **(figure 1**). The linear regression **was found to be statistically significant (r^2=.22, $F(1, 252)$=92.0, p<0.001) and** produced the following equation to describe the relationship between maximum force and body mass: 3.54 x body mass (kg) + 59.897. **A statistically significant linear regression was found among youth players (under 14 to 17 years) (r=.59, r^2=.36, $F(1, 98)$=54.3, p<0.001) with maximum force increasing 4.5N per 1kg increase in body mass. A statistically significant linear regression was also found among adult players (under 21 years to senior level) (r=.16, r^2=.03, $F(1, 152)$=3.9, p=0.049) with maximum force increasing 1.9N per 1kg increase in body mass.**

Comparisons between injured and uninjured players were only completed on players from under-16 years onwards as only one younger player reported a previous hamstring injury. A total of 75 players (22.0%, 95% CI 17.9 – 26.7) reported a previous hamstring injury in the 12 months prior to testing. The proportion of previous hamstring injuries classified as mild, moderate, and severe was 14.0% (95% CI 6.0 – 24.0), 56.0% (95% CI 42.0 – 70.0), and 30.0% (18.0 – 44.0), respectively (table 5). No statistically significant differences for maximum force (p = 0.234), between limb difference (p = 0.431), or percentage between-limb difference (p = 0.779) between previous injured and uninjured players when different periods following return to sport were considered (table 6). Maximum force differed between uninjured limbs and previously injured limbs at <2 months following return to play (p = 0.04; d = 0.6) (table 6).

Statistically significant differences between injured and uninjured players were found for absolute relative maximum (p = 0.01; d = 0.4) and relative average (p = 0.02; d = 0.2) strength in under-21 years players. Statistically significant differences between injured and uninjured players were found for relative maximum strength (p = 0.01, d = 0.7) and relative average strength (p = 0.02, d = 0.7) in under-17. No statistically significant differences were found between injured and uninjured limbs for relative maximum strength (p = 0.46, *d* = 0.3) or relative average strength (p = 0.46, *d* = 0.03). The prevalence of imbalances ≥15% was 1.28-times (95% CI 1.10 – 1.38) greater in players with a previous hamstring injury.

In total, 40.2% (95 CI 31.4 – 48.7) of players had a maximum force between-limb imbalance >10% (table 4). Similarly, 38.5% (95% CI 20.2 – 46.6) of players had average force between-limb imbalances >10%. No statistically significant differences were found between any age groups for maximum (p = 0.09) or average strength (p= 0.16) imbalances. The percentage of uninjured and previously injured players with a >10% maximum force between-limb imbalance was 37.6% (95% CI 32.8 – 42.2) and 41.1% (95% CI 28.6 – 53.7), respectively. Overall, 51.8% (39.3 – 63.3) of limbs with previous hamstring injury were weaker than the uninjured contralateral limb. Furthermore, 23.2% (95% CI 12.5 – 33.9) of limbs with a previous hamstring injury were >10% weaker than the uninjured contralateral limb.

Discussion

This study investigated eccentric knee flexor strength in elite Gaelic football players from underage to senior level. Elite senior Gaelic football players have similar maximum eccentric knee flexor strength (361.0 N, 95% CI 348.4 – 375.8) to elite (366.9 ± 76.9), sub-elite (387.9 ± 96.3), and under-19 (342.8 N ± 81.5) elite rugby union players (Bourne et al., 2015). Similarly, maximum eccentric knee flexor strength in elite Australian football, Australian soccer, and French soccer players have been reported as 371.0 N ± 77.0, 309.5 ± 73.4, and 411.0 N ± 66.0, respectively (Timmins et al., 2015; Buchheit et al., 2016). It also appears that age-matched Gaelic football players demonstrate greater eccentric knee flexor strength than sub-elite cricket players aged 15-years (285.0 N ± 68.0) or 21-years (308.0 N ± 77.0), and French academy soccer players at under-17 (306.0 N ± 68.0), under-19 (301.0 N ± 72.0), and under-21 (299.0 N ± 52.0) age-grades (Chalker et al., 2016; Buchheit et al., 2016). These results suggest that elite Gaelic football players have similar or greater eccentric knee flexor strength profiles when compared other field sport athletes.

Previous research reports increases of 4N in maximum eccentric knee flexor strength per 1kg increase in body mass (Buchheit et al., 2016). Although the current study found a moderate-to-large **correlation** between these variables, **this was not universal across age-groups. Previously the impact of maturation on aerobic capacity among Gaelic football players transitioning across age-groups has been highlighted as being potentially misleading when evaluating performance (Roe and Malone, 2016). Hence, as the association between eccentric knee flexor strength and body mass is moderate-to-large in youth players yet weak in adult players, it is plausible that the timing of increases in strength may coinincide, yet not be attributable, to increases in known maturation-related outcomes such as body mass.** Thus, practitioners should consider age, maturation, and relative strength measures when profiling player characteristics.

In the current study, the mean relative eccentric knee flexor strength for elite Gaelic football players was 4.4 N•kg^{-1} (95% CI 4.2 – 4.5). Such values are greater than reports from elite senior soccer (4.1 ± 0.9 N•kg^{-1}), Australian football (3.2 ± 1.3 N•kg^{-1}), elite rugby union (3.7 ± 0.7 N•kg^{-1}), sub-elite rugby union (4.0 ± 0.9 N•kg^{-1}), elite cricket (3.7 ± 0.9 N•kg^{-1}), and sub-elite cricket (3.7 ± 1.0 N•kg^{-1}) (Opar et al., 2015; Bourne et al., 2015; Chalker et al., 2016; Timmins et al., 2016). These data indicate that relative eccentric knee flexor strength for age-matched players is greater in elite Gaelic football than in other field sports.

The current study also observed that under-21 and senior players, the two older age levels have similar relative strength profiles to their younger peers. Such findings may appear counterintuitive as a greater emphasis on resistance training occurs at the senior level. Although such trends have been described in other field sports, the reasons for this relative decrement are unclear (Bourne et al., 2015; Chalker et al., 2016). As Gaelic football is a contact sport, the development of musculature, including in the upper body, tends to be prioritised in early career players transitioning to senior level. Thus, development of muscle mass in different body regions may contribute to these reductions in relative strength.

However, senior players were 15% weaker, in relative mean force across 3 repetitions, than all other age-groups tested. The use of a ratio to compare metrics between age-groups also reveals that maximum force imbalances were 16% lower among senior players. Thus, practitioners at the elite senior level may be prioritising symmetry and not relative strength.

Eccentric knee flexor strength was superior among limbs with a previous hamstring injury, particularly at 8 weeks following return to sport. This is at odds with research in many field sports, including an isokinetic dynamometer study in collegiate Gaelic football, reporting decrements following return to sport (Croisier et al., 2008; De Vos et al., 2014; van Dyk et al., 2016; O'Sullivan et al., 2008; Opar et al., 2015). However, the current study reported that the likelihood that the injured limb was weaker after return to sport following a hamstring injury was 51%, and that the likelihood that this weakness exceeded 10% was also 23%. Thus, this likely contributes to no statistical relationship being found between previous hamstring injury and maximum eccentric knee flexor strength. Furthermore, this indicates that secondary injury risk management strategies are equally as effective as ineffective with regard to developing comparable strength between limbs.

It remains unclear whether this observation, combined with reduced relative strength in senior players, indicates that eccentric hamstring strength development is mainly prioritised during rehabilitation periods only. The triad of reduced relative strength, greater strength profiles in players with previous hamstring injury, and a known high incidence of hamstring injury in the sport, requires examination of injury risk management practises in elite Gaelic football. This is particularly true when the intense running-demands of elite Gaelic football match-play are considered (Malone et al., 2017).

An important element of return to sport decision making is determining an acceptable level of risk to tolerate (Creighton et al., 2010; Shier, 2015). Although the development of eccentric hamstring strength is an important characteristic to reduce injury risk, identifying objective and clear-cut 'at-risk' thresholds is difficult (Schmitt et al., 2012). Indeed, monitoring development of mechanical properties during performance-oriented training programmes is important for both primary and secondary injury prevention (Mendiguchia et al., 2017). Monitoring strength levels in reference to preinjury levels or uninjured peers, whilst considering pain and mental readiness for full participating in training and match-play, may potentially inform return to sport decisions (van der Horst, 2017). Normative data may inform criteria-based rehabilitation by providing information on desired performance levels (Adern et al., 2015). However, this approach will be high risk if the comparison group (i.e. uninjured player or preinjury level) are not consistantly exposed to adequate training stimuli for developing eccentric hamstring strength.

In addition to reducing hamstring injury incidence by 50% when compared to control groups (0.4 v 0.7 per 1000 hours), the Nordic hamstring programme has been shown to increase eccentric hamstring strength by 14% while increasing electromyographic activity after six weeks (Al Alttar et al., 2016; Delahunt et al., 2014). A 45° hip extension exercise has also been used to develop eccentric hamstring strength and fascicle length (Timmins et al., 2016). Therefore, practitioners with limited time and access to facilities have evidence-based methods for developing eccentrc hamstring strength and managing injury risk.

Examinations of quartiles provides insight into the range in strength between players of the same age, and the overlap of eccentric hamstring strength profiles across age-groups. The similarities within, and between player-groups, has been considered a barrier to identifying those at increased risk of sustaining injury when profiling player characteristics (Bahr, 2016). Indeed, it has been shown that 20% of elite rugby union players with preseason maximum strength imbalances ≥15% sustained an inseason hamstring injury, and players with this characteristic at 2.4-times more risk than those without (Bourne et al., 2015). The current study reveals that 23.2% (95% CI 18.5 – 27.6) fall into this threshold which may contribute to the higher incidence of hamstring injuries seen in the elite Gaelic football than rugby. However, a prospective study needs to be undertaken before such inferences can be made.

Eccentric knee flexor strength varies across the season, with greater gains during preseason reported among previously uninjured players (Opar et al., 2014). Other variables such as age, fascicle length, fatigue, and high-speed running are also known to alter susceptibility to hamstring injuries (Freckleton and Pizzzari, 2012; Timmins et al., 2014; Roe et al., 2016; Timmins et al., 2016; Duhig et al., 2016). The interaction between multiple intrinsic and extrinsic variables influencing the emergence of injury needs to be considered in future research (Bittencourt et al., 2017). For instance, hamstring injury incidence was 2.3-times greater for elite Gaelic football players >30 years when compared to their younger peers (Roe et al., 2016). Future reports of age-related changes in modifable risk factors for hamstring injury may guide development of prevention programmes for sub-groups of players (Gabbe et al., 2006).

Conclusion

The reporting of normative eccentric knee flexor strength values provides unique insights for monitoring a metric known to alter risk of injury. Firstly, senior players had mean strength values 22% greater than all other players. However, when standardised to body mass ($N{\bullet}kg^{-1}$), players at senior level were 15% weaker than younger age-groups. Thus, profiling metrics should be standardised to player characteristics such as body mass. Secondly, players with a history of hamstring injury in the 12 months prior to testing, had relative strength values 9% stronger than uninjured players. We recommend practitioners to monitor strength development following training cycles, although exposure to evidence-based interventions such as Nordic hamstring exercise or hip extension would suffice. Thirdly, 40% of elite Gaelic football players presented had maximum strength imbalances >10% with quartiles revealing overlaps in metrics across the age-groups. As such, sole reliance on developing strength profiles similar to uninjured players may be limited to assess risk of primary or secondary hamstring injuries. Future research is needed to determine if specific eccentric hamstring strength metrics influence injury risk in elite Gaelic football.

References

1. Ardern CL, Glasgow P, Schneiders A, et al. 2016 Consensus statement on return to sport from the First World Congress in Sports Physical Therapy, Bern. Br J Sports Med 2016;50:853–64.

2. Bourne MN, Opar DA, Williams MD, Shield AJ. Eccentric Knee Flexor Strength and Risk of Hamstring Injuries in Rugby Union: A Prospective Study. Am J Sports Med. 2015;43:2663-70.

3. Chalker WJ, Shield AJ, Opar DA, Keogh JW. Comparisons of eccentric knee flexor strength and asymmetries across elite, sub-elite and school level cricket players. PeerJ. 2016 Feb 18;4:e1594. doi: 10.7717/peerj.1594.

4. Creighton DW, Shrier I, Shultz R, et al. Return-to-play in sport: a decision-based model. Clin J Sport Med 2010;20:379–85.

5. Croisier JL, Ganteaume S, Binet J, et al. Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. Am J Sports Med 2008;36:1469–75.

6. De Vos RJ, Reurink G, Goudswaard GJ, et al. Clinical findings just after return to play predict hamstring re-injury, but baseline MRI findings do not. Br J Sports Med 2014;48:1377–84.

7. Freckleton G, Pizzari T. Risk factors for hamstring muscle strain injury in sport: a systematic review and meta-analysis. Br J Sports Med 2013;47:351–8.

8. Gabbe B, Bennell K, Finch C. Why are older Australian football players at greater risk of hamstring injury? Journal of Science and Medicine in Sport 2006;9:327-33.

9. Malone S, Solan B, Collins K, Doran D. The Positional Match Running Performance of Elite Gaelic Football. J Strength Cond Res. 18 December 2015 doi: 10.1519/JSC.0000000000001309

10. Malone S, Solan B, Hughes B, Collins K. Duration specific Running performance in Elite Gaelic Football. J Strength Cond Res. 2017 Apr 25. doi: 10.1519/JSC.0000000000001972.

11. Mendiguchia J, Martinez-Ruiz E, Edouard P, Morin JB, Martinez-Martinez F, Idoate F, Mendez-Villanueva A. A Multifactorial, Criteria-based Progressive Algorithm for Hamstring Injury Treatment. Med Sci Sports Exerc. 2017 Mar 8. doi: 10.1249/MSS.0000000000001241. [Epub ahead of print]

12. O'Sullivan K, O'Ceallaigh B, O'Connell K, Shafat A. The relationship between previous hamstring injury and the concentric isokinetic knee muscle strength of Irish Gaelic footballers. BMC Musculoskelet Disord. 2008;6:9:30.

13. Opar DA, Piatkowski T, Williams MD, Shield AJ. A novel device using the Nordic hamstring exercise to assess eccentric knee flexor strength: a reliability and

retrospective injury study. J Orthop Sports Phys Ther. 2013;43:636-40.

14. Opar DA, Williams MD, Timmins RG, Hickey J, Duhig SJ, Shield AJ. The effect of previous hamstring strain injuries on the change in eccentric hamstring strength during preseason training in elite Australian footballers. Am J Sports Med. 2015;43:377-84.

15. Opar DA, Williams MD, Timmins RG, Hickey J, Duhig SJ, Shield AJ. Eccentric hamstring strength and hamstring injury risk in Australian footballers. Med Sci Sports Exerc. 2015;47:857-65.

16. Reilly B, Akubat I, Lyons M, Collins DK. Match-play demands of elite youth Gaelic football using global positioning system tracking. J Strength Cond Res. 2015;29:989-96.

17. **Roe M, Malone S. Yo-Yo Intermittent Recovery Test Performance in Subelite Gaelic Football Players From Under Thirteen to Senior Age Groups. J Strength Cond Res. 2016;30:3187-93.**

18. Roe M, Malone S, Blake C, Collins K, Gissane C, Büttner F, Murphy JC, Delahunt E. A six stage operational framework for individualising injury risk management in sport. Inj Epidemiol. 2017 Dec; 4: 26.

19. Roe M, Murphy JC, Gissane C, Blake C. Hamstring injuries in elite Gaelic football: an 8-year investigation to identify injury rates, time-loss patterns and players at increased risk. Br J Sports Med 2016; 10 Nov 2016 doi:10.1136/bjsports-2016-096401.

20. Roe M, Murphy JC, Gissane C, Blake C. Lower limb injuries in men's elite Gaelic football: A prospective investigation among division one teams from 2008 to 2015. Journal of Science and Medicine in Sport 2017; 29 Aug 2017 http://dx.doi.org/10.1016/j.jsams.2017.08.023

21. Ruddy J, Pollard C, Timmins R, Williams M, Shield A, Opar D. Running exposure is associated with the risk of hamstring strain injury in elite Australian footballers. Br J Sports Med. 2016 Nov 24. doi: 10.1136/bjsports-2016-096777.

22. Schmitt B, Tim T, McHugh M. Hamstring injury rehabilitation and prevention of reinjury using lengthened state eccentric training: a new concept. Int J Sports Phys Ther. 2012;7:333-41.

23. Shrier I. Strategic assessment of risk and risk tolerance (StARRT) framework for return-to-play decision-making. Br J Sports Med 2015;49:1311–5.

24. Timmins R, Bourne M, Shield AJ, et al., Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study Br J Sports Med 2016;50:1524–35.

25. van der Horst N, Backx FJG, Goedhart E, Huisstede B, et al., Return to play after hamstring injuries in football (soccer): a worldwide Delphi procedure regarding

definition, medical criteria and decision-making. Br J Sports Med 2017;0:1–9.

26. van Dyk N, Bahr R, Burnett AF, Whiteley R, Bakken A, Mosler A, Farooq A, Witvrouw E. A comprehensive strength testing protocol offers no clinical value in predicting risk of hamstring injury: a prospective cohort study of 413 professional football players. Br J Sports Med. 2017 Jul 29. doi: 10.1136/bjsports-2017-097754.

27. van Dyk N, Bahr R, Whiteley R, et al. Hamstring and Quadriceps Isokinetic Strength Deficits are weak Risk Factors for Hamstring Strain Injuries: A 4-Year Cohort Study. Am J Sports Med 2016;44:1789–95.

Table 1 – Eccentric Knee Flexor Strength Profiles in Elite Gaelic Football Players

	Maximum Force (N)	Average Force (N)	Relative Maximum Force ($N \cdot kg^{-1}$)	Relative Average Force ($N \cdot kg^{-1}$)	Maximum Force Imbalance (%)	Average Force Imbalance (%)
All Players	329 (320 - 340)	306 (296 - 316)	4.4 (4.2 - 4.5)	4.0 (3.9 - 4.2)	9.4% (8.5 - 10.3)	8.9% (8.1 - 9.8)
Under 14 Years	236 (211 - 260)*#	212 (201 - 241)*#	4.3 (3.8 – 4.7)	4.0 (3.6 – 4.4)	8.4% (6.4 - 10.9)	7.2% (5.4 - 9.0)
Under 15 Years	276 (258 - 296)	256 (237 - 274)	4.4 (4.1 - 4.6)	4.0 (3.8 - 4.3)	12.6% (9.4 - 16.2)	11.5% (8.2 - 15.3)
Under 16 Years	314 (291 - 342)	290 (268 - 313)	4.6 (4.3 - 4.9)	4.3 (4.1 - 4.6)	9.1% (6.2 - 12.3)	9.2% (6.5 - 11.7)
Under 17 Years	321 (299 - 342)	297 (274 - 321)	4.6 (4.3 - 5.0)	4.3 (4.0 - 4.6)	10.5% (7.6 - 13.8)	9.8% (7.2 - 12.7)
Under 21 Years	351 (331 - 368)	319 (301 - 335)	4.3 (4.1 - 4.5)	3.9 (3.7 - 4.1)	10.4% (9.0 - 12.0)	10.0% (8.6 - 11.5)
Senior	361 (348 - 376)	336 (323 - 350)	4.3 (4.1 - 4.5)	3.5 (3.0 - 4.0)	8.6% (7.6 - 9.8)	8.4% (7.3 - 9.6)

Legend: * indicates p<0.05, # indicates moderate to large effect size (>0.5 – <0.8). All other statistical outputs were insignificant or showed small effect size.

Table 2 – Quartile Ranges Per Eccentric Knee Flexor Strength Metric in Elite Gaelic Football Players

	Under 14 Years			Under 15 Years			Under 16 Years			Under 17 Years			Under 21 Years			Senior		
	25th	50th	75th	25th	50th	75th	25th	50th	75th	25th	50th	75th	25th	50th	75th	25th	50th	75th
Maximum Force	195	236	284	239	275	296	262	298	342	271	322	374	279	356	421	298	360	425
Average Force	184	220	258	214	256	277	247	270	312	244	289	347	256	325	361	269	329	392
Maximum Imbalance	14.3%	7.0%	3.0%	17.5%	9.0%	4.5%	13.5%	7.0%	3.5%	13.5%	9.0%	5.5%	16.5%	8.1%	4.0%	12.0%	7.0%	3.0%
Average Imbalance	11.5%	6.0%	3.0%	19.0%	7.0%	2.5%	14.0%	9.0%	2.5%	13.5%	8.0%	4.0%	14.1%	8.8%	4.5%	12.0%	6.3%	3.3%
Maximum Force Between Limb Difference	32.3	16.5	7.8	47.5	28.0	12.5	44.5	24.0	12.0	42.5	28.0	14.0	56.0	30.5	14.3	47.8	26.0	11.0
Average Force Between Limb Difference	27.3	14.5	8.8	51.0	23.0	7.5	40.0	29.0	7.5	43.0	30.0	11.5	46.8	28.5	14.0	39.0	24.5	11.3
Maximum Relative Force	3.6	4.3	5.2	3.9	4.5	4.8	4.0	4.6	5.3	4.0	4.9	5.3	3.4	4.3	5.2	3.5	4.2	5.1
Average Relative Force	3.4	4.0	4.7	3.6	4.0	4.5	3.8	4.3	4.7	3.6	4.4	4.6	3.2	3.9	4.4	3.2	3.9	4.8

Table 3 – Eccentric Knee Flexor Strength Metrics Per Age Group as a Ratio Relative to All Other Players

	Maximum Force (N)	Maximum Force Between Limb Difference	Average Force Between Limb Difference	Average Force (N)	Relative Maximum Force ($N·kg^{-1}$)	Relative Average Force ($N·kg^{-1}$)	Maximum Force Imbalance (%)	Average Force Imbalance (%)
Under 14 Years	0.73 (0.69 - 0.75)	0.60 (0.56 - 0.62)	0.53 (0.52 - 0.53)	0.73 (0.71 - 0.76)	0.97 (0.92 - 1.00)	1.00 (0.97 - 1.01)	0.82 (0.80 - 0.85)	0.74 (0.71 - 0.76)
Under 15 Years	0.87 (0.86 - 0.88)	1.13 (1.10 - 1.18)	1.12 (1.01 - 1.19)	0.88 (0.86 - 0.88)	1.00 (0.97 – 1.03)	1.00 (0.99 - 1.03)	1.34 (1.28 - 1.38)	1.29 (1.17 - 1.40)
Under 16 Years	1.02 (1.00 - 1.04)	0.88 (0.76 - 0.97)	0.97 (0.86 - 1.03)	1.02 (1.00 - 1.03)	1.05 (1.03 - 1.07)	1.09 (1.08 - 1.13)	0.90 (0.78 - 0.98)	0.98 (0.89 - 1.01)
Under 17 Years	1.04 (1.01 -1.06)	1.13 (1.08 - 1.19)	1.12 (1.06 - 1.20)	1.04 (1.03 - 1.06)	1.05 (1.04 - 1.08)	1.09 (1.08 - 1.10)	1.07 (0.98 - 1.13)	1.06 (1.00 - 1.11)
Under 21 Years	1.16 (1.14 - 1.17)	1.30 (1.20 - 1.43)	1.27 (1.18 - 1.43)	1.14 (1.12 - 1.16)	0.97 (0.95 - 0.99)	0.97 (0.94 - 1.00)	1.06 (0.95 - 1.21)	1.08 (0.99 - 1.24)
Senior	1.21 (1.17 - 1.25)	1.01 (0.89 - 1.15)	1.04 (0.93 - 1.19)	1.22 (1.18 - 1.26)	0.97 (0.95 - 0.99)	0.85 (0.78 - 0.91)	0.84 (0.75 - 0.98)	0.88 (0.80 - 1.02)

Table 4 – Imbalances Associated with Maximum Eccentric Knee Flexor Strength in Elite Gaelic Football Players

	Maximum Force Between-Limb Percentage Imbalance				Maximum Force Between-Limb Force (N) Difference			
	0 to 5% Imbalance	**5 to 10% Imbalance**	**10 to 15% Imbalance**	**>15% Imbalance**	**0 to 5% Imbalance**	**5 to 10% Imbalance**	**10 to 15% Imbalance**	**>15% Imbalance**
All Players	**30.8% (26.1 to 36.1)**	**29.0% (24.3 to 33.7)**	**17.0% (12.9 to 21.1)**	**23.2% (18.5 to 27.6)**	**8.3 (7.3 - 9.4)**	**25.8 (24.1 - 27.5)**	**40.3 (37.4 - 43.3)**	**72.8 (67.3 - 78.6)**
Under 14 Years	34.6% (19.2 to 52.8)	26.9% (11.5 to 42.3)	15.4% (3.8 to 30.8)	23.1% (7.7 to 42.3)	6.2 (4.0 - 7.9)	17.9 (14.3 - 22.0)	24.8 (16.8 - 34.8)	42.8 (37.3 - 48.3)
Under 15 Years	24.2% (12.1 to 39.4)	27.3% (12.1 to 42.4)	9.1% (0.0 to 18.2)	39.4% (24.2 to 57.6)	9.0 (5.5 - 13.6)	22.4 (16.1 - 29.8)	36.0 (28.0 - 41.0)	61.3 (45.9 - 78.2)
Under 16 Years	33.3% (14.3 to 52.3)	23.8% (4.8 to 42.9)	23.8% (9.5 to 42.9)	19.0% (4.8 to 38.1)	8.0 (4.7 - 11.0)	19.2 (15.4 - 23.0)	37.2 (31.6 - 43.8)	68.0 (54.3 - 82.3)
Under 17 Years	24.0% (8.0 to 40.0)	28.0% (12.0 to 44.0)	28.0% (12.0 to 44.0)	20.0% (4.0 to 40.0)	8.8 (6.2 - 11.3)	25.1 (20.4 - 30.7)	38.3 (34.3 - 41.6)	78.4 (65.8 - 93.8)
Under 21 Years	26.1% (17.0 to 36.4)	29.5% (20.5 to 40.9)	15.9% (9.1to 23.9)	28.4% (19.3 to 38.6)	9.0 (23.9 - 30.6)	27.2 (23.9 - 30.6)	40.6 (33.6 - 48.1)	80.7 (70.4 - 91.7)
Senior	35.1% (27.0 to 42.6)	30.4% (23.6 to 37.8)	16.9% (10.8 to 23.0)	17.6% (12.2 to 23.6)	8.3 (6.8 - 9.9)	27.6 (25.2 - 30.3)	44.4 (40.3 - 48.6)	77.5 (70.1 - 85.2)

Table 5 – Eccentric Knee Flexor Strength Between Uninjured and Previously Injured Limbs Based on Severity

	No Hamstring Injury	No Hamstring Injury Senior & U21	Hamstring Injury in Last 12 Months	Mild Injury (1-7 Days)	Moderate Injury (8-28 Days)	Severe Injury (>28 Days)
Sample Size	265	176	76	11	43	23
Maximum Force	325 (315 - 336)	350 (338 - 362)	367 (347 - 387)	375 (275 - 475)	397 (362 - 431)	357 (315 - 400)
Average Force	299 (290 - 309)	321 (309 - 333)	343 (323 - 363)	346 (241 - 450)	375 (340 - 410)	332 (289 - 375)
Maximum Imbalance	9.4% (8.5 - 10.3)	8.8% (7.8 - 9.8)	10.3% (8.4 - 12.1)	7.1% (3.4 - 10.8)	10.8% (7.8 - 13.8)	12.8% (7.9 - 17.7)
Average Imbalance	9.0% (8.1 - 9.8)	8.6% (7.7 - 9.6)	10.0% (8.2 - 11.7)	5.1% (1.0% - 9.2)	10.2% (7.2 - 13.2)	12.4% (7.2 - 17.8)
Maximum Force Difference	27.3 (28.8 - 35.4)	32.8 (28.6 - 37.1)	39.7 (32.9 - 46.5)	21.0 (7.6 - 46.4)	45.0 (33.6 - 56.4)	47.7 (30.0 - 65.5)
Average Force Difference	28.4 (25.5 - 31.4)	29.5 (25.8 - 33.3)	35.8 (29.6 - 41.9)	19.1 (5.7 - 40.8)	40.3 (29.7 - 50.8)	38.0 (29.9 - 46.2)
Reduced Maximum Force on Injured Limb			51.8% (37.5 - 64.3)	80.0% (40.0 - 100)	50.0% (30.8 - 69.2)	60.0% (33.3 - 86.7)

Table 6 – Eccentric Knee Flexor Strength Between Uninjured and Previously Injured Limbs Following Return to Play

Group	Mean Maximum Force Between-Limbs	Difference Between-Limbs	Perentage Difference Between-Limbs	Maximum Force Per Limb
No Previous Hamstring Injury	351 (338 - 364)	33.8 (29.3 - 38.3)	9.8% (8.6 - 11.2)	357 (315 - 400)
<u>Time Following Return to Play</u>				
<2 Months	378 (335 - 421)	33.7 (23.7 - 59.6)	11.9% (7.1 - 18.2)	405 (364 - 445)*#
3-6 Months	413 (342 - 479)	49.1 (20.0 - 78.3)	11.8% (7.4 - 16.9)	399 (349 - 449)
7-12 Months	391 (339 - 447)	46.8 (26.2 - 67.3)	12.3% (8.4 - 16.4)	388 (335 - 442)
12-24 Months	370 (330 - 412)	25.3 (24.7 - 50.7)	10.7% (7.1 - 14.4)	371 (334 - 407)
>24 Months	349 (318 - 381)	29.6 (17.4 - 41.8)	8.5% (5.4 - 11.8)	365 (336 - 395)

Legend: * indicates p<0.05, # indicates moderate to large effect size (>0.5 – <0.8). All other statistical outputs were insignificant or showed small effect size.

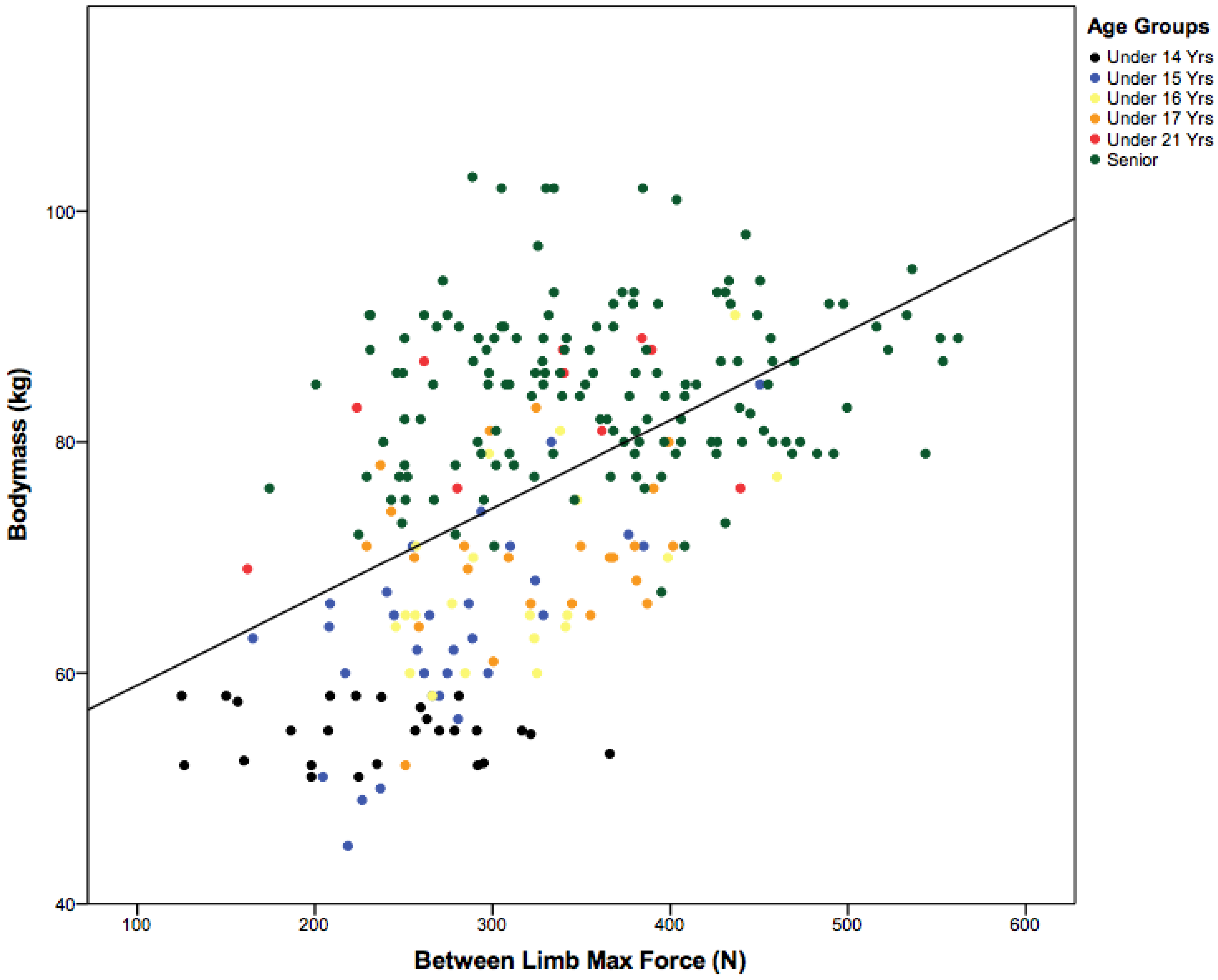
Age Groups
Under 14 Yrs
Under 15 Yrs
Under 16 Yrs
Under 17 Yrs
Under 21 Yrs
Senior
Bodymass (kg)
100
80
60
40
100
200
300
400
500
600
Between Limb Max Force (N)

Fig. 1. Relationship between body mass and maximum eccentric knee flexor strength (between-limbs).