The quadrant of doom and hamstring injuries: sexy but too easy?

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Headline

The different factors relating to hamstrings injury risk have been well reviewed. They include among others age, previous injuries, ethnicity, strength and strength imbalances, flexibility, muscle architecture, anatomy, training/competitive load (often high-speed running) and fatigue (1-3). Recently, there has been a growing emphasis on two of those factors, namely hamstring strength and fascicle length (4-7). This is related to the fact that these two muscle properties are modifiable factors strongly related to the capacity of the muscle to withstand repeated eccentric contractions during potentially harmful actions such as sprinting. In fact, it has been suggested that players with weak knee flexor eccentric strength (as measured using a Nordbord, Vald Performance, Brisbane, Australia) and short *biceps femoris* long head (BFlh) fascicle length may be at much greater risk of injury than players with strong knee flexors and long fascicle length (6). This has led some authors to present the data in the form of a "quadrant of doom" (1), where the overall risk of an individual to sustain an hamstring injury is shown graphically, while plotted as a function of both hamstring strength and fascicle length. It is therefore understood that athletes should escape from the lower left quadrant (high risk), and enter the top right panel of the graph (lower risk), likely via eccentric biased training (1, 8). The idea behind the quadrant is evidence-based and sensible (1), and the highly practical aspect of those strength and structural measures make the approach very appealing for practitioners. Nonetheless, we wished to comment on two important and still overlooked methodological aspects that deserve more attention to make the most of the utilisation of the quadrant: 1) the possible impact of body mass (BM) on Nordbord performance (9-11) 2) the current limitations of the muscle architecture measurements inferred from static ultrasound images and 3) possible differences in individual muscle properties and their relationships with hamstring ability to withstand active lengthening (12, 19).

The impact of BM on Nordbord performance

The need to consider players' BM when it comes to assessing Norbord performance is straightforward for most practitioners (Figure 1), and is not a new finding in the scientific literature either (9-11). At least three independent studies have now reported moderate-to-large relationships between Norbord performance and BM, and have shown -although correlations don't imply causality- that Nordbord performance likely increases consistently by 3 (11) to 4 (9, 10) N per kg of BM. This is not surprising, for at least two reasons: 1) for most neuromuscular-related types of measures, including hamstring strength (14), muscle mass is generally beneficial for performance (15) and 2) because of the upper body inclination when leaning forward during the Nordic exercise, heavier and/or taller players with a longer lower-leg lever (distance from knee joint axis of rotation to the ankle strap) may apply higher levels of force to the dynamometers. Greater Nordbord performance in heavier players may be in turn interpreted as a greater eccentric knee flexor strength, which may be independent (at least partially) of their true strength. It is however important to note that the beneficial effect of a greater BM on Nordbord performance may be only apparent for the players that are strong enough to perform the exercise in a controlled manner, since more load added to the chest in athletes with weak knee flexors eccentric strength will likely only make them fall faster, with no effect of Nordbord performance. However, and while we agree that the suggested normalization procedure (10) still lacks prospective evidence, until a new solution is provided, scaling Nordbord performance for BM remains the most practical way to account for this likely confounding factor. While we also agree that the value of the slopes reported in those three studies (3 (11) to 4 (9, 10) N per kg of BM) may not be as steep in more homogenous/different players groups (unpublished data from (6)), we still believe that this relationship should be first tested and then accounted for if present (irrespective of its magnitude). Surprisingly, despite this evidence, most researchers have continued to report absolute strength values (N) in their studies (1, 4-6). They have also used a unique absolute eccentric strength threshold value to identify players with increased hamstring injury risk (i.e., 265 N) (16) or to design the quadrant (i.e., 337 N, in Figures 2 and 3 in ref (1)), without taking their own BM into consideration; therefore, this procedure remains prone to approximations. It is also important to note that simply dividing eccentric strength by units of BM (i.e., N/kg) is unlikely optimal either. The various levels of correlations (and slope magnitudes) reported in various player groups differing in age or sports (9, 10) suggest that the relationship between eccentric knee flexor strength and body size (and likely muscle architecture, see next section) is complex, and likely be specific to the group of players considered (i.e., group-based allomet-

Fig. 1. The need for adjusting physical performance for body mass (and likely size) is evident for practitioners when it comes to comparing players of different body dimensions (i.e. >30kg of difference in body mass). Photo C.Gavellle/PSG.

ric scaling parameters (10, 17)). Overall, these data suggest that BM should not be overlooked when monitoring Nordbord performance, which may limit, at least in theory, the usefulness of the "quadrant of doom" as currently presented (1). Further studies are nevertheless required to confirm whether BM-adjusted strength values improve injury risk prediction in elite soccer players.

To further illustrate our point, we used data recently collected in young elite footballers (18) and reproduced a typical "quadrant of doom" (1) using first the suggested absolute strength threshold (i.e., 337 N Figure 2, left panel). While we agree that the value of such a cut-off is often sample-dependent, the point we are trying to make here is likely valid irrespective of the actual value chosen. Following this initial reasoning, player #19 (56 kg, knee-flexor strength: 316 N; BFlh fascicle length: 8.1 cm, bottom left quadrant) was reported to have a higher risk of injury than player #2 (73 kg, 384.5 N; 7.5 cm, lower right quadrant). However, after adjusting players' knee flexors strength to their BM (17), completely different figures were apparent, with risk profiles being drastically different, i.e., player #19's relative strength (compared with body-mass expected performance): +27.1%, player #2: +16.6%. While player #2 remained in the same quadrant, player #19 moved into the lower right quadrant, which likely signified lower injury risk. With this particular player (#19), for example, practitioners (ourselves in this case!) would clearly face a dilemma when assessing his injury risk.

Hamstring muscle properties and their relative susceptibility to injury

The second methodological point that we wished to comment on is related to the other axis (i.e., fascicle length). There are several points that deserve consideration:

a. In fact, players' anthropometrical profile not only impacts on muscle mass, but also on muscle geometry and size, since fascicle length, muscle thickness and pennation are interconnected factors. For example, the fascicle length of a fusiform muscle such as the *semitendinosus* is likely directly related to the length of the femur and in turn, to the player's size (19). This suggests that taller players are likely to present with longer fascicle length, which may have nothing to do with the muscle's ability to withstand active lengthening *per se*. Therefore, as for strength measures, body size likely confounds the relationship between fascicle length and players' actual injury risk. Normalizing fascicle length for muscle length (6, 19) may therefore constitute, at least in theory, a first improvement to the only use of absolute fascicle length (1). In contrast to this reasoning however, normalized measures of fascicle length were pretty similarly related to injury rates in the unique study to date in soccer players (6). It is however worth noting that overall group-based results may not always apply to extreme case scenarios (Figure 1); further studies in players differing largely in size are therefore required to clarify this point.

b. Importantly also, fascicle length measurements of pennate muscles such as the BFlh with a 4.7-cm probe also require a substantial extrapolation (∼60% of the entire length for a 11.8 cm-long fascicle (20)), which can lead to a 3 (20) to 5 (21) % error that is unfortunately greater than the smallest important effect (i.e., 0.2 × between-subject SD (22), estimated to be around 2% in our population (18)). This poor signal/noise ratio shows the limitation of using a single fascicle length measurement on the basis of a single B-mode image to draw the quadrant. To improve precision and in turn, confidence in their assessment, practitioners may therefore need to use i) repeated measures that can decrease the noise by a factor of $\sqrt{n}$ (23) or ii) alternate muscle architecture measurements using MRI (24), diffusion tensor imaging (25) or extended field of view (EFOV) measures (18) for example. This latter mode uses an algorithm that fits series of images, allowing scanning of entire fascicles within one continuous scan. This technique may therefore enable practitioners to avoid any extrapolation of non-visible parts of the muscle and provides improved measurement accuracy (21, 26). Using a scan that follows fascicle orientations along their path (non-linear EFOV) can further account for fascicle curvature and improve the digitization of the fascicle, particularly in the distal regions, resulting in higher reliability compared to single B-mode images or linear EFOV. Interestingly, this method revealed reasonable increases in BFlh fascicle length (∼+0.5 cm i.e. +5%) in elite football players after 6 weeks of eccentric-biased hamstring training (18).

c. Despite the evidence showing the relationship between injuries and fascicle length measured in a relaxed state (1) (i.e., in a resting position as we have also done, Figure 2) it is worth noting that such an assessment is unlikely to accurately represent an individual muscle's ability to withstand an active lengthening. This is particularly true for a muscle group with such a complex and heterogeneous architecture as the hamstring (19, 27), which may likely involve fascicle rotations during contractions (28). In addition, while it is true that fascicle lengthening is related to functional alterations induced by damaging exercises (29), the elastic properties of tendinous tissue may mitigate the extent of fascicle strain (30, 31). Moreover, fascicle length was considered for BFlh only, whilst knee flexor strength measured at the joint level reflects the contribution of all synergists and antagonist muscles. In fact, for the same joint motion, the *semitendinosus* likely displays less relative strain than the other hamstrings probably owing to a greater length, longer fascicles and, possibly, a longer tendon (19). Using kinematics and ground reaction force data integrated with a three-dimensional musculoskeletal computer model, Schache et al. (13) suggested that during sprinting, "the BFlh exhibited the largest peak strain, the *semitendinosus* displayed the greatest lengthening velocity, and the semimembranosus produced the highest peak force, absorbed and generated the most power, and performed the largest amount of positive and negative work". These findings highlight nicely the distinct contributions of each muscle head to lower-limb kinetics during running. Recent studies have also demonstrated that the distribution of force between the heads of the different thigh muscles is often highly variable between individuals (32). The direct consequence of this is that the relative load sustainable by each hamstring head for the same (measured) knee flexor strength may also vary between players (33). Therefore, since the relationship between fascicle length, muscle strength and strain during active lengthening is probably muscle head- and player-dependent, the use of a single measure (i.e., fascicle length) on a single muscle (e.g., BFlh) to assess injury risks remains imperfect, even though a majority of injuries incurred during high speed running occur within the BFlh. Although the single-muscle approach is appealing and particularly adapted to on-field conditions encountered in elite sport, further investigations are required to better understand the individual relationships between the properties of muscle-tendon unit and force-generating capacity of each hamstring muscle. The consideration of these biomechanical features may in turn contribute to a better evaluation of the injury risk of each individual muscle and a greater individualization of prevention programs (12). In fact, assessing the properties of each hamstring muscle should give us more

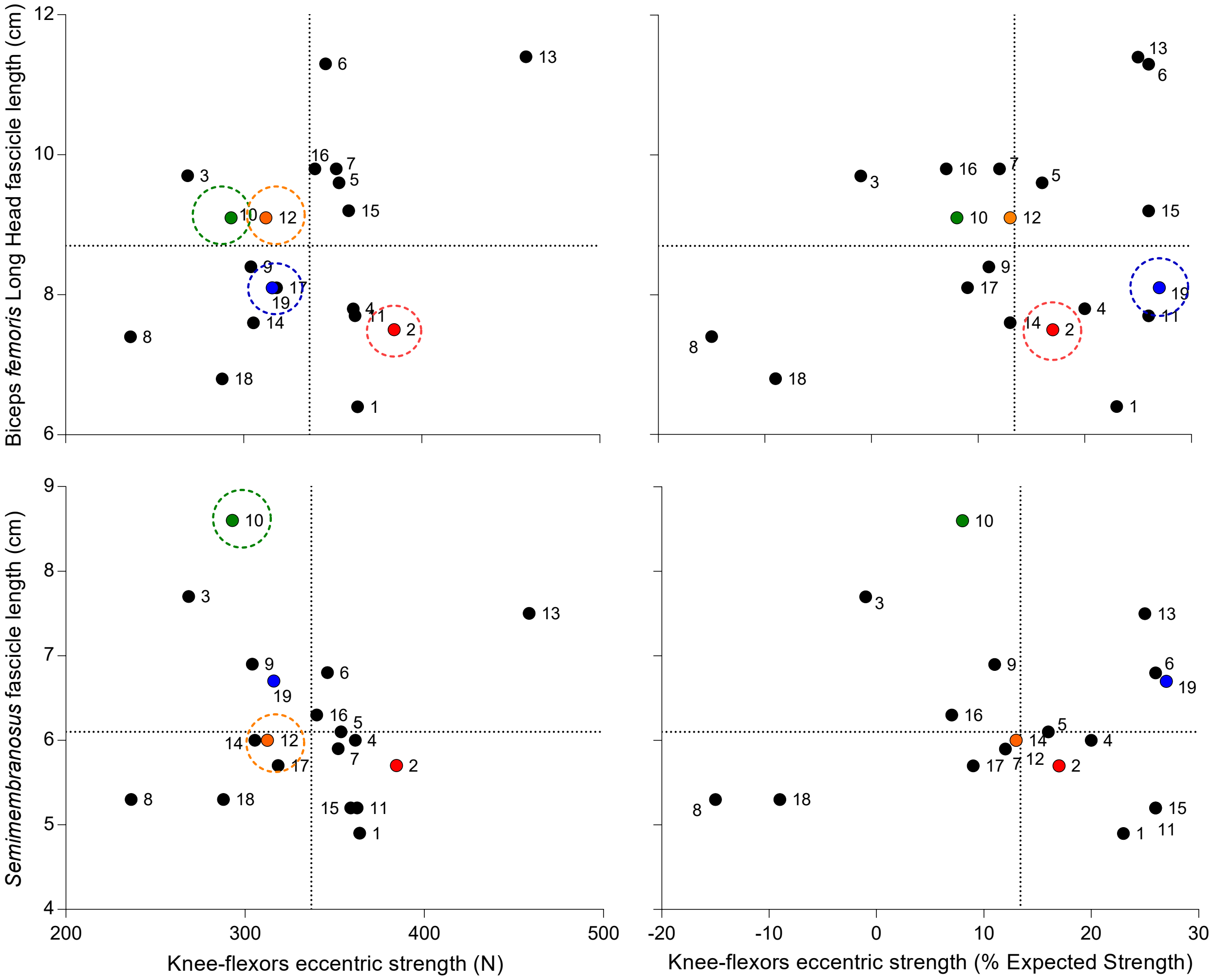

Fig. 2. In-season values of elite U19 soccer players (17.5±0.7 yrs, 175.7±5.0 cm and 64.7±4.9 kg, training 10 hrs a week) for *biceps femoris* long head (upper panels, BFlh, y-axis) and semimembranosus (lower panels, y-axis) fascicle length and eccentric knee flexor strength (Nordbord performance, x-axis) expressed in absolute (left panels) and relative to body mass (right panels). The eccentric knee-flexor strength testing was performed as previously described (10). As between-leg differences were beyond the scope of the current study, the average strength of both legs was used for analysis (10). The data relative to body mass are expressed as the % difference vs. body-mass expected value using the following equation: eccentric strength (N) = 4 × BM (kg) + 26.1 (10). While we agree that the adjustment of Nordbord performance for BM may be optimal using population-specific equations (10), we chose to use this generic equation since this is what most practitioners would use initially, before getting their own equation. We also believe that using a group-specific equation would not change the main message of the present example. Muscle fascicles were imaged using a 42-mm linear probe (2–10 MHz, SL10-2, Supersonic Imagine, Aix-en-Provence, France) coupled with an ultrasound scanner (Aixplorer V11, Supersonic Imagine, Aix-en-Provence, France) (18). Given that the field-of-view of the probe was too narrow to image an entire fascicle, we used an inbuilt panoramic mode of the ultrasound device. This mode uses an algorithm that fits series of images, allowing scanning of entire fascicles within one continuous scan. This technique enabled us to avoid any extrapolation of non-visible parts of the muscle and improved measurement accuracy (21). We used this scan to measure the length of two fascicles per muscle. The two values were then averaged to obtain a representative value for the whole muscle. Reliability assessment in our laboratory (n= 12, test-retest within 24h) showed small and trivial day-to-day variations in BFlh length (typical error: 0.38±0.15 cm, 4.9±2.0%). Dotted lines for strength are based on recommend thresholds (1). Because of the difference in methods used to measure BFlh length in comparison with the literature, the dotted line was based on the median value of the current group (i.e., 8.7 cm).

information and may be, in turn, more useful in preventing injuries.

d. In practice, the above-mentioned differences in muscle properties within the hamstring group are another important limitation to the use of the quadrant as currently presented (Figure 2). In fact, because of the variations in length and structure between the hamstring muscles, a player' position within the quadrant may vary as a function of the muscle considered. For example, player #12 moves from the bottom left (higher risk) to the upper left quadrant (lower risk) when considering the semimembranosus or the BFlh, respectively. Player #10 remains in the same quadrant but moves from a position close to the lower quadrant (semimembranosus) to the highest y-axis position of the group (BFlh). As for absolute vs. relative strength, the fact that players may move from a quadrant to another in relation to the muscle considered represents an important challenge for practitioners seeking a robust means of assessing injury risk.

Additional considerations

Lastly, the "quadrant of doom" being a two-dimensional representation of hamstring injury risk factors only, others extremely important risk factors such as age and previous injury history (6) can't be integrated into the 'picture'. This is another important limitation of the "quadrant of doom" as currently presented.

Conclusion

To conclude, while our intention is definitely not to discard the proposed approach (quadrant) and on-field methodology (easy and quick Nordbord testing and echography measures) that are particularly relevant for practitioners, we wished to highlight some of the limitations that may need to be considered for a better understanding of players' potential injury risk. The example presented in the present paper (Figure 2) suggests the need for considering at least (i) BM when assessing knee-flexors eccentric strength using a Nordbord and (ii) individual muscle-tendon properties when estimating hamstring ability to withstand active lengthening. More specifically, we believe that the effect of these two intrinsic factors should not be overlooked when assessing injury risk using a quadrant (1). Further than a simple analytic question, this should help practitioners to make better decisions and implement injury prevention program for the players at the highest risks.

Practical Applications

- The idea behind the "quadrant of doom" is evidence-based and sensible, and the highly practical aspect of those muscle strength and architecture measures make the approach very appealing for practitioners.
- However, the likely importance of body mass should not be overlooked when monitoring Nordbord performance, which may limit the relevance of the "quadrant of doom" as currently provided with absolute strength values.
- Similarly, since body size may also directly affect muscles length, it's intuitive to normalize the fascicles length used in the "quadrant of doom" for their relative muscle length.
- The measurement of fascicle length with the 2D static image technique likely overestimates fascicle length when compared to extended field of view techniques, thereby affecting the subsequent muscle function and injury risk estimates.
- Since the relationship between fascicle length, muscle strength and strain during active lengthening is probably muscle head- and player-dependent, the use of a single measure (i.e., fascicle length) on a single muscle (e.g., *biceps femoris* long head, BFlh) to assess the overall injury risk of the hamstring group remains prone to approximations.
- The "quadrant of doom" being a two-dimensional representation of hamstring injury risk factors only, others extremely important risk factors such as age and previous injury history can't be integrated into the 'picture'; this can bias the risk evaluation.
- Although sound in theory, whether the above-mentioned theoretical arguments substantially improve the prognostic value of the "quadrant of doom" when it comes to predicting injuries remains to be investigated with real data. More research is still warranted to both improve 1) our understanding and use of Nordbord performance in relation to body mass, and 2) the prognostic value of isolated muscle properties in relation to the overall hamstring group.

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