Preventing hamstring injuries - Part 2: There is possibly an isometric action of the hamstrings in high-speed running and it does matter.

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Introduction

We thank Shield and Murphy (1) for promoting discussion on our articles (2 3), hereby providing us an opportunity to clarify and elaborate on our arguments and hopefully forward the field of hamstring injury prevention. Most prominently, Shield and Murphy state that recommendations to employ an isometric hamstring training approach instead of an eccentric one is premature and they state that we presented no evidence from human studies showing that hamstring fascicles behave isometrically in running. Here we will respond to both points as well as several other points.

Evidence for eccentric vs isometric hamstring fascicle action during running

Based on a) the quasi-isometric muscle fascicle functioning found in several other muscles during high-intensity movements and b) direct measurements of hamstring fascicle functioning during running in animals, we argued that there is possibly a predominantly isometric rather than an eccentric hamstring fascicle action during the swing phase of running as found by two modelling studies (2). We discussed that one assumption made in these modelling studies is the degree of stiffness of the tendinous tissues, with a too high stiffness of the tendinous tissues leading to an overestimation of hamstring fascicle lengthening, which could (partially) explain the discrepancy with the findings of animal studies (2). Indeed, Bohm and colleagues (4) recently found quasi-isometric (minor elongation) vastus lateralis fascicle behaviour during the stance phase of running as determined with ultrasound (5), while a modelling study predicted substantial active fascicle lengthening, probably due to a too stiff tendon in the modelling study (5). These findings strengthen our suggestion that models do not always correctly predict fascicle behaviour. We would like to point out that the possible underestimation of stretch in the tendinous tissues and hence overestimation of fascicle stretch as a result of potential differences in real and modelled tendon stiffness is not the sole possible error in the models. In our review (2) we also discussed other potential sources of error such as muscle slack, but Shield and Murphy (1) did not specifically discuss these other potential sources of error, even though they may also have a substantial influence on fascicle behaviour. Nevertheless, Shield and Murhpy state they remain open-minded on hamstring functioning during running, but also state that the likely existence of error does not prove that the hamstring fascicles behave isometrically during running. We agree with this notion and would like to underscore that the potential errors made in the models are also not the only reason for proposing an isometric hamstring fascicle action.

A substantial part of our argument on the predominantly isometric hamstring fascicle action is based on the findings of animal studies, where it is possible to directly measure muscle fascicle lengths using sonomicrometry (small ultrasonic crystals implemented in the fascicle) (2). These studies do therefore not rely on the assumptions of the previously discussed models. Shield and Murphy (1) did however not discuss the findings of these studies in their paper. An important question –and perhaps the reason why Shield and Murhpy did not discuss these findings- is whether the results of these animal studies can be generalized to humans. To answer this question, we can compare 'direct' measures of muscle fascicle behaviour between animals and humans.

Fascicle behaviour of the gastrocnemius, soleus and vastus lateralis has been investigated during running and drop jumping in various animals (with sonomicrometry) and in humans (with ultrasound) and generally agree well. For the gastrocnemius muscle, both animal (6) and human (7) studies for example report active fascicle lengthening during an energy-dissipating drop jump after initial lengthening occurred in the tendinous tissues. Similarly, during the stance phase of level running, the gastrocnemius and soleus fascicles remain quasi-isometric or shorten in both animal (8, 9) and human (10, 11) studies. For the more proximally located vastus lateralis, a study among humans recently found a quasi-isometric fascicle action (only minor lengthening) during the stance phase of running and passive lengthening during the initial flight phase (5). Studies among animals observed more variable results during the stance phase (but not swing phase), depending on the animal under investigation and type of gait (i.e., galloping or trotting). For example, a study among rats reported active lengthening during the initial stance phase in trotting, followed by quasi-isometric behaviour and passive lengthening during the initial flight phase (12), while a study among goats reported active lengthening during the initial stance phase followed by shortening and passive lengthening during the initial swing phase (13). Therefore, the results of animal and human studies agree less well for vastus lateralis behavior during the stance phase, primarily because vastus lateralis functioning differs between different animals. However, the results agree well during the swing phase. Further, the results for biceps fascicle behaviour are relatively consistent among animal studies (2, 13), which increases our confidence that the predominantly isometric hamstring fascicle functioning during the swing phase of running found in these studies (Figure. 1) is similar in humans. Although the limitations of animal studies should also be considered (e.g., no running at maximum speed), these findings collectively suggest that animal studies can provide valid insights into human fascicle functioning. Combined with the potential errors made in modelling studies, and predominantly isometric-elastic muscle fascicle functioning found in other high-intensity movements, we therefore consider it more likely that the hamstring fascicles

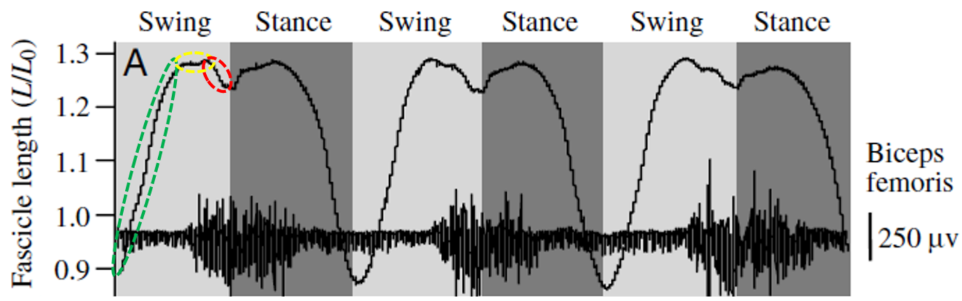

Fig. 1. Biceps femoris long head fascicle length and muscle activity during three strides of trotting at 2.0 m/s in an individual goat. First there is passive lengthening (green circle), and when the muscle is activated the fascicle remains isometric (yellow circle) and even slightly shortens (red circle) before ground contact. These findings show that there is no active fascicle lengthening (i.e., eccentric action) during the swing phase. Adapted from Gillis, et al. (13) with permission.

function predominantly isometric rather than eccentric during the swing phase of running.

Mechanisms of hamstring injuries

In our review paper (2), we hypothesized that an eccentric fascicle action may still be the cause of an injury, with an eccentric action possibly occurring as a result of an inability of the fascicles to remain isometric due to too high forces (14, 15) or poor lumbo-pelvic control (16). Based on our argument that hamstring injuries may still be a result of an eccentric action, Shield and Murphy (1) contended that increasing 'damage resistance' with eccentric training would therefore be appropriate to reduce injury risk. We agree that eccentric training generally may lead to more 'damage resistance' than isometric or concentric training and is therefore useful for this purpose. However, preventing damage at the first place, for example by isometric training or improving intermuscular coordination should perhaps be the primary goal.

With regard to the first possible mechanism of hamstring injuries (too high forces), we would like to clarify that an inability of the muscle fibers to remain isometric when the forces acting on the muscle-tendon unit become too high occurred at approximately 10-12 times body weight in the drop jump experiments (14, 15). However, the forces acting on the hamstrings during running are considerably smaller with approximately 5.3 times body weight at maximum speed (17). If the maximum force production of the hamstrings is smaller than the calf muscles, this could indicate that an inability of the fascicles to remain isometric could occur during maximum sprinting. However, it could also indicate that an inability of the hamstring fascicles to remain isometric may only occur with poor coordination or under fatigue (for example as a result of rapid increases in high-speed running load (18)), which reduces the force producing capability of the fascicles. Indeed, several studies found associations between fatigue or poor fatigue-resistance (hamstring strength-endurance) and injuries (19-22). Preventing damage could therefore also involve improving hamstring strength-endurance (e.g., using specific contextual movements), hereby improving the ability of the fascicles to function near optimum length despite fatigue (2, 3, 23). Nevertheless, training programs should attempt to improve both 'damage prevention' and 'damage resistance'.

Contraction type specific training effects

Based on our discussion on the inconsistent effects of contraction type on alterations in fascicle lengths(3), Shield and Murphy (1) state that 9 of 10 published eccentric training studies have shown hamstring fascicles to lengthen, while a quasi-isometric exercise (i.e., the Razor curl) resulted in no significant increase in hamstring fascicle length. We agree that eccentric training is more likely to induce increases in fascicle lengths compared to other contraction types, but as discussed in our review (3), increases in fascicle lengths can also be achieved with other contraction types, depending on the intensities, velocities and muscle-tendon unit lengths used. Therefore, this adaptation should not be viewed as something that can solely be achieved with eccentric training and future research should for example also investigate the effects of isometric-elastic (impact) training on fascicle lengths.

We argued that contraction intensity may be the primary (but not exclusive) stimulus for some improvements seen with eccentric training and that isometric training could therefore also be highly effective when performed at a high contraction intensity (3). In response to this, Shield and Murphy (1) state that this argument ignores the force-velocity relationship of

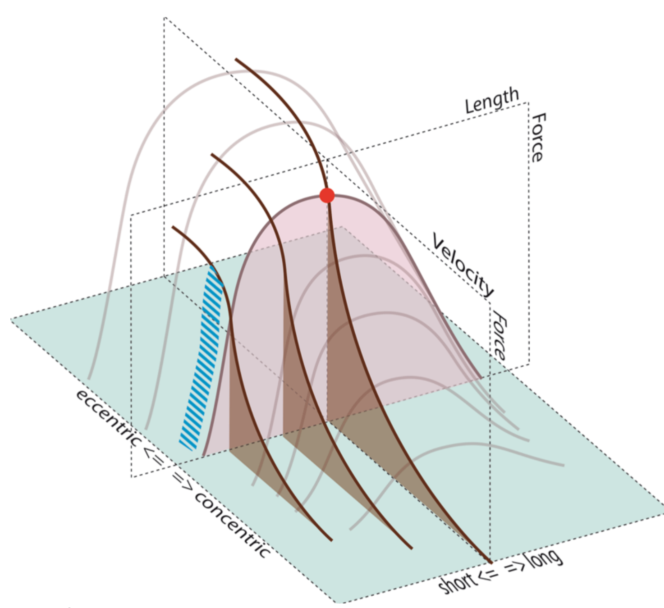

Fig. 2. Three-dimensional plot of the active force-length-velocity relationship at maximum activation based on Winter (29). Although eccentric actions can result in higher forces compared to isometric or concentric actions, force is also depends on the length of the muscle. For example, the red dot represents the theoretical force production during a high-intensity isometric exercise when the muscle functions around its optimum length, while the blue dashed line represents the theoretical force production during an eccentric-only exercise performed at a short length and slow velocity. Further, a lower activation due to selective inhibition during eccentric actions can also result in a lower eccentric force compared to concentric actions.

skeletal muscles as isometric contractions simply cannot be performed at the forces observed in maximal eccentric-only or eccentrically-biased resistance training. However, here Shield and Murphy ignore the effects of length (i.e., the force-length-velocity relationship) and activation. Specifically, isometric contractions can result in higher forces as eccentric-only actions when the isometric contraction is performed around the optimum length while the eccentric action is performed slowly and at short or long muscle lengths (Figure 2). In support of this, preliminary data from an English Premier League football club show that the external forces measured at the ankle are higher during the single-leg Roman chair (especially when using impact loads) compared to the Nordic curl, although more research is required to investigate the (internal) muscle forces. Finally, several studies found selective neuromuscular inhibition in previously injured hamstrings during eccentric actions (in particular at long muscle-tendon unit lengths), but not concentric actions and this inhibition has also been suggested to explain the greater decreases in eccentric strength compared to concentric strength observed in some studies (24-28). This selective inhibition can alter the force-velocity relationship in such a way that concentric force production is higher than eccentric force production (25), although not all studies have observed this. Nevertheless, these aspects show that the relation between mechanical load and contraction mode is more complex then only the force-velocity relationship and eccentric exercises do therefore not necessarily result in higher muscle forces than isometric exercises. Finally, eccentric overload is not always achieved in practice as some exercises require a concentric muscle action to get back to the starting position, hereby limiting the exercise to the concentric maximum strength, unless an external device or other individual assists with the concentric action or unless the concentric part is performed with two legs and the eccentric action with one leg (e.g., Romanian deadlift with bilateral concentric and unilateral eccentric action).

Specificity of exercises

If the hamstrings indeed function predominantly isometric during the swing phase of running (2), then high-intensity isometric exercises with the muscle functioning around optimum length arguably more specifically replicate this functioning than slow eccentric exercises performed at either very short or very long muscle-tendon unit lengths (3). Shield and Murphy however argue that some of the exercises we proposed also not specifically replicate running in terms of movement patterns, velocities and posture. We agree that most of our proposed exercises do not exactly replicate running. However, to create quantitative or qualitative overload, some specificity has to be sacrificed. The question is what degree of specificity is required to achieve sufficient overload, while simultaneously maintaining enough positive transfer. We believe the isometric exercises proposed can generate sufficient overload, while simultaneously maintaining enough positive transfer to positively impact performance or injury risk, although further research is required to substantiate this notion. For example, with regard to intermuscular coordination, the Roman chair likely highly activates both the hamstrings and gluteus maximus, which partially replicates the combined hip extension role of these muscles during running, while a strong activation of both muscles may be lacking in some knee dominant eccentric exercises as the hamstrings will likely produce most force, with substantially lower force production in the gluteus maximus. This may therefore not optimally train intermuscular coordination.

Muscle soreness and training

Muscle soreness is typically higher following eccentric than isometric training. Shield and Murphy (1) argue that muscle soreness will be most problematic in elite sport and that soreness due to eccentric training will be limited after 2-6 weeks due to the repeated bout effect. However, muscle soreness has in several studies been a reason for amateur sport athletes to drop out of an eccentric training program (3), suggesting that this is also an important consideration for amateur athletes, although we acknowledge that this can partly be overcome by lower volume protocols. Further, although we agree that careful planning can partly overcome the issue of muscle soreness, these problems are even less or absent with isometric training. For example, isometric training has by some sports teams (e.g., English Premier League, Wales and Japan national rugby teams) successfully been incorporated the same day after the game or the next day after the game and it is therefore not required to wait until 3 days post-match as with eccentric training.

Example of an isometric and motor control biased training program

Here we provide an example of how an isometric and motor control biased training program has been implemented in the training program at elite level (national team level).

In a typical (professional) rugby set up, the following rule has been used for hamstring exercises: they need to be planned at the end of a day with no or limited (high-speed) running performed during the next day (3). For players who have no special issues with the hamstrings (e.g., current injuries, recent injury history), two 15-20 minute sessions per week should suffice. A single session typically contains one heavy single-leg Roman chair hold of 2-3 holds on each leg with a maximum of 3 sets. Additionally, one or two exercises with impact loading or rotation (biceps femoris or semitendinosus/semimembranosus oriented exercises) are added, using 3 sets with 4-8 repetitions depending on the exercises. If required, some stretching of the activated muscle can be added. As exposure to high-speed running is crucial for injury prevention as well as performance enhancement, high-speed running is typically specifically trained twice a week, with limited volume, but with strong focus on good technical execution. The amount of high-speed running is increased over the season and varied within a week to optimally prepare the athletes for the competition load and prevent spikes in their high-speed running workload. For more information and practical examples of an isometric and motor control biased approach, see Van Hooren & Bosch (3).

Conclusion

Although no direct measurements of hamstring fascicle lengths during running are available in humans, direct measurements in animals show a predominantly isometric hamstring fascicle functioning. Comparisons of human and animal fascicle behaviour in other muscles generally agree well, suggesting that the findings of animal hamstring fascicle functioning can provide information on human hamstring fascicle functioning. Combined with the potential errors made in modelling studies, and predominantly isometric-elastic muscle functioning found in other high-intensity movements, we therefore consider it more likely that the hamstrings fascicles function predominantly isometric during the swing phase of running than eccentric.

Especially for non-elite athletes, the scientific evidence for eccentric training for hamstring injury prevention is stronger than isometric and motor control based hamstring training, simply because the effect of isometric and motor control based hamstring training on hamstring injuries has not yet been investigated. Nevertheless, from this perspective, eccentric training should indeed not be (completely) replaced by an isometric & motor control biased training program. However, research can sometimes be lagging far behind best practice, and although practice should attempt to follow evidence-based guidelines as much as possible, unless there are specific reasons to assume a training method is ineffective, has negative effects or is effective for different reasons (e.g., placebo effect), best practice 'evidence' should not be abandoned simply because it has not yet been investigated as *"absence of evidence is not evidence of absence"* (30). Best practice 'evidence' shows that programs without a specific emphasize on eccentric exercises such as the Nordic curl can be very successful in injury prevention, suggesting that other approaches that have simply not yet been investigated can also be highly effective. For example, the Japan rugby team has reported no single hamstring injury (and actually no soft tissue injury at all) during 5 months of training in preparation for the world championships using an isometric and motor control biased approach. Further, it has recently been shown that isometric training with the single-leg Roman chair was more effective at improving hamstring strength-endurance than the Nordic curl in previously injured Gaelic football players (31). Although the evidence from this study is not as strong as the randomized controlled trials that directly investigated the effect of Nordic curl training on hamstring injuries, it demonstrates the potential usefulness of isometric hamstring exercises. Therefore, we suggest that isometric exercises and training of intermuscular coordination in contextual patterns in combination with well-planned exposure to high-speed running should (also) be considered as valuable, if not indispensable for hamstring injury prevention and performance enhancement.

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