Original article

Physical principles demonstrate that the biceps femoris muscle relative to the other hamstring muscles exerts the most force: implications for hamstring muscle strain injuries

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Summary

Of the hamstring muscle group the biceps femoris muscle is the most commonly injured muscle in sports requiring interval sprinting. The reason for this observation is unknown.

The objective of this study was to calculate the forces of all three hamstring muscles, relative to each other, during a lengthening contraction to assess for any differences that may help explain the biceps femoris predilection for injury during interval sprinting. To calculate the displacement of each individual hamstring muscle previously performed studies on cadaveric anatomical data and hamstring kinematics during sprinting were used. From these displacement calculations for each individual hamstring muscle physical principles were then used to deduce the proportion of force exerted by each individual hamstring muscle during a lengthening muscle contraction. These deductions demonstrate that the biceps femoris muscle is required to exert proportionally more force in a lengthening muscle contraction relative to the semimembranosus and semitendinosus muscles primarily as a consequence of having to lengthen over a greater distance within the same time frame. It is hypothesized that this property maybe a factor in the known observation of the increased susceptibility of the biceps femoris muscle to injury during repeated sprints where recurrent higher force is required.

KEY WORDS: biceps femoris, force, hamstring, injury, muscle, physics.

Introduction

Hamstring strain injuries are common in sports that require sprinting such as soccer[1], rugby union[2], track and field[3] and Australian football[4]. For hamstring injuries in sprinting sports, the location of the injury is most commonly in the long head of the biceps femoris muscle[3-6]. This contrasts to hamstring injuries in dancers, in whom the semimembranosus muscle is the most common hamstring muscle injured[7].

The reasons for the predominance of biceps femoris muscle injuries in sprinting, compared to the less frequently injured semimembranosus and semitendinosus muscles, is not understood. Postulated theories for this observation for the predominance for biceps femoris muscle injuries in sprinting include unique dual neural innervation of the biceps muscle[8], different hip and knee flexion angles of the biceps femoris muscles compared to the other hamstring muscles[9], hamstring length changes influenced by postural considerations[10], more Type II fibres in the biceps femoris muscle compared to the other hamstring mucles[11]. None of these hypotheses have been substantiated scientifically[12].

A previous study developed an experimental human kinematic model along with a musculoskeletal model to estimate hamstring lengths during treadmill sprinting and demonstrated that the change of length of the biceps femoris muscle was greater than the other two hamstring muscles[13]. This was considered to be, at least in part, a result of the lateral insertion of the biceps femoris[14]. A more recent study demonstrated that the biceps femoris muscle is subjected to more strain (where strain is defined as the ratio of the change in length to the original resting length) than the other two hamstring muscles[15]. The change in length (stretch) of each hamstring muscle is independent of running speed[13], but as running speed increases, the calculated maximal hamstring force increases[16] without any change in maximal hamstring length[16]. The maximum hamstring length occurs during the late swing phase of the gait cycle[13,17], and in jumping[18] and this is considered to result in maximal hamstring muscle work during this lengthening (eccentric) contraction phase[19], which may also be a factor in hamstring muscle injuries[20]. Although these studies have given us valuable information on the kinematics of the hamstring muscles, it is still unclear how these factors relate to the observation that the biceps femoris muscle is more susceptible to injury than the semimembranosus or semitendinosus muscles during sprinting locomotion. This partly arises from an inability to reliably attribute the contributions of individual hamstring muscles to the total force produced by the hamstring muscle unit.

Accordingly, the aim of the current study is to utilise the available anatomical and kinematic analysis of hamstring muscle structure and function to numerically calculate change in length during an eccentric contraction of individual hamstring muscles, and to construct a simulated simplistic model of the human hamstrings. Using these calculations and applying physical principles, the force production of each individual hamstring muscle, relative to the other hamstring muscles, during an eccentric hamstring contraction can be deduced.

Method

This study was performed adhering to the Ethical Standards required by the journal[21].

Numerical values for each individual hamstring muscle length, including the proximal and distal free tendon ends, were derived from a cadaveric study of the human hamstring muscles[22]. The anatomical length data (Tab. 1)[22] was combined with the percentage stretch of individual hamstring muscles beyond their nominal resting length calculated from a previous study (Tab. 2)[13] to calculate a numerical change in length (displacement) during a lengthening (eccentric) contraction. To calculate the total displacement, we used the entire individual hamstring muscle length from proximal bone tendon attachment to distal bone tendon attachment (thereby including the free tendon ends).

To calculate forces on individual hamstring muscles, a model must be employed. In this study we have chosen to represent individual hamstring muscles as springs. A previous study[13] that showed muscular change in length is independent of running speed. This infers that the displacement of the hamstring muscles can be considered constant, but as locomotive speed increases, the number of fibres recruited increases, allowing the muscle to produce more force. If we consider a single speed only, we can assume a constant number of fibres (although not necessarily the same fibres on each contraction) have been recruited for each hamstring muscle, and thus this idealised muscle can be represented as a spring.

Using the laws of elastic spring motion, the force ($\underline{F}$) produced by the hamstring muscles is proportional to displacement (x). It follows that the muscle which displaces least (in the case of the hamstring muscles, the one that lengthens least) is the muscle that exerts the least force (smaller x, smaller F). Defining this as the standard, we can then calculate the force of the other hamstring muscles relative to this least displaced (lengthened) muscle. In this manner, we calculate the relative forces between the three muscles, assuming that each muscle has an identical spring constant.

Finally using the anatomical length data combining with the displacement of each individual hamstring muscle we demonstrate the contraction of hamstring muscles with a simplistic working model scaled both to length and displacement using the object based Interactive Physics™ (Design Simulation Technologies, Canton, Michigan, USA) software.

Table 1. Cadaveric length of hamstring muscles.

Muscle	Proximal Tendon Length (cm)	Muscle Length (cm)	Distal Tendon Length (cm)	Total (cm)
Semimembranosus	11.1	26.4	6.8	44.3
Semitendinosus	1.2	31.6	11.1	43.9
Biceps Femoris	6.5	28.1	9.2	43.8

Muscle length, Proximal Tendon and Distal Tendon Length and Total Length (Ref Woodley and Mercer)[20].

Table 2. Stretch of hamstring muscles.

Muscle	Stretch	Calculated change in length	
Semimembranosus	7.4%	=44.3*0.074	3.28 cm
Semitendinosus	8.1%	=43.9*0.081	3.56 cm
Biceps Femoris	9.5%	=43.8*0.095	4.16 cm

Average stretch of each individual hamstring muscle during a lengthening contraction during treadmill sprinting total (Ref Thelen et al.)[13].

Results

Table 1 shows the cadaveric anatomical hamstring muscle length data from free tendon end proximally to free tendon end distally. Table 2 shows the percentage stretch of each of the hamstring muscles. Combining the results of Table 1 and Table 2 we have calculated the length change (displacement) of each individual hamstring muscle (Tab. 2). This demonstrates the displacement of the semimembranosus muscle is the smallest of the three hamstring muscles. As force is proportional to displacement, and using the calculated force of the semimembranosus as standard, the force of the other hamstring muscles relative to the semimembranosus can be deduced (Tab. 3). As the biceps femoris muscle displaces (lengthens) further than the other two hamstring muscles, it must also produce more force than the other two hamstring muscles in a lengthening contraction. In relation to the semimembranosus muscle the biceps femoris muscle exerts 1.28 times relative more force for an assumed same spring constant.

Hamstring muscle at rest in comparison scaled to length and displacement at full lengthening contraction (Fig. 1).

Table 3. Calculated forces of each hamstring muscle relative to semimembranosus muscle.

Muscle		
Semimembranosus	F(SM)=3.28/3.28	1.0 F(SM)
Semitendinosus	F(ST) =3.55/3.28	1.08 F(SM)
Biceps Femoris	F(BF) = 4.16/3.28	1.27 F(SM)

F=Force, SM=Semimembranosus, ST=Semitendinosus, BF=Biceps Femoris

[Force = Change in Length of muscle divided by the Change in Length of least displaced muscle (Semimembranosus) derived from Table 2]

In a recent study (Ref Ward et al.)[40] where 21 cadavers were dissected the authors measured muscle length that was defined from tendon muscle fibre proximal to distal that did not include free tendon ends the lengths were biceps 34.7 cm ± 3.7, semitendinosus 29.7 cm ± 3.9, semimembranosus 29.3 cm ± 3.4. Thus on these calculations the differentials of the force would be 1.0 SM, 1.11 ST and 1.52 BF. Again if you calculated on the extremes of the standard deviation for semimembranosus and biceps femoris (maximum length SM, minimum length BF) BF calculation is still 1.20 F(SM).

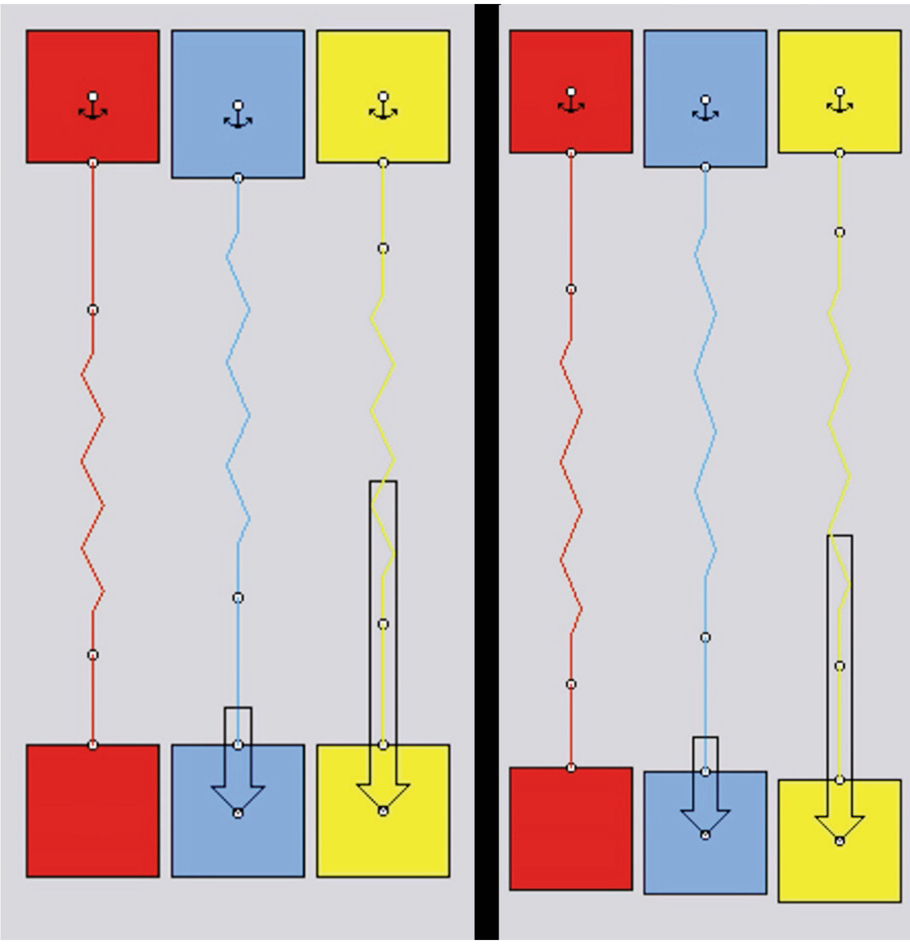

Figure 1. Length and displacement of hamstring muscles during a lengthening contraction.
At rest (Left of Figure) and at full displacement (Right of Figure). Scaled to actual length of each muscle and subsequent displacement during a lengthening contraction.
Red Semimembranosus, Blue Semitendinosus, Yellow Biceps.
Straight lines represent tendon, Bent line represents muscles, Blocks represent bone.

Discussion

The biceps femoris muscle is required to exert more force, relative to the other two hamstring muscles, during a lengthening muscle contraction. It is important to remember that our force calculations arise from change in length data only, and do not attempt to assign spring constant values to the individual hamstring muscles. How this finding contributes to the observation that the biceps femoris is more susceptible to injury in sprinting conditions when compared to the other two hamstring muscles requires some speculation.

Current knowledge demonstrates that: 1) in sports requiring repeated sprinting the biceps femoris muscle is the most common hamstring muscle injured[4-6,12]; 2) the part of contraction (gait) cycle where the maximum hamstring force production occurs is the lengthening (eccentric) phase[16]; 3) hamstring force production increases as running speed increases[16]. The eccentric phase of a sprinting athlete has been considered to be the time of risk for muscle injury[15-17], generally resulting in injury to the biceps femoris muscle of the hamstring. Thus in a sprinting athlete as running speed increases there is a requirement during hamstring lengthening for hamstring increased force production to counter, acting as a brake, the propulsion contraction principally of the hip flexors and quadriceps muscles. The findings of this study demonstrate that the biceps femoris muscle requires proportionally higher force production needed for normal operation (lengthening contraction). Therefore if circumstances exist where overall muscle force production may be impaired it is reasonable to suggest that the biceps femoris muscle would be more affected than the other two hamstring muscles.

Force production in muscles is impaired in fatigued muscles compared to non-fatigued muscles[23]. Observations in sports involving interval sprinting have also demonstrated fatigue as a significant risk factor for hamstring muscle strain injuries, with a predominance of injuries occurring late in both halves of soccer[24,25] and rugby union[2] matches, and in the later stages of Australian football matches[4].

In a similar manner the semitendinosus muscle is required to exert more force, that is, it displaces further, when compared to the semimembranosus muscle, thereby increasing its susceptibility when comparing the properties of these two muscles in sprinting injuries. Again, hamstring injury imaging studies confirm this proposition, with the semitendinosus muscle being the second most common hamstring muscle injured in sports requiring interval sprinting[4-6], with the semimembranosus being the least commonly injured[4-6].

The actual mechanism of muscle injury in the case of a fatigue-associated sprinting injury is not presently known. However, it is not likely to be a simple overstretch which has been proposed for the semimembranosus muscle stretch injury seen in dancers[7]. An alternative theory for mechanism for biceps femoris injury is where there is a failure at the musculotendinous junction (the region of muscle injury in stretch/strain[6,25]) given inadequate force production with the lengthening tendon in effect shearing away from the inadequately contracting (lengthening) muscle.

Muscles acting as springs – movement

The major assumption of this article is that the hamstring muscles have spring like properties thus allowing the use of the laws governing elastic spring motion. A property of springs is that peak lengthening velocity is reached before maximum length, with velocity being zero when the spring reverses direction at its maximum length[26,27]. Human hamstring muscle contraction demonstrates these properties having pek velocity before maximal lengthening occurs and reversing direction after the late swing phase of the gait cycle[13] there by returning to its original length during the concentric muscle phase. Before the lengthening of the muscle (or spring) at the resting position it is assumed that the net force on the tendon attachments (spring ends) is zero. In addition if the tendons stretch, the muscles eccentrically contract (spring elongates) the muscle (spring) exerts a force on the attachments which acts in the direction of returning the spring back to its natural length[27-30]. Thus, it is reasonable to assume that, with respect to movement, muscles can be considered in many respects to act as springs[31].

Activation of muscles – Muscles acting as springs – Independent muscle action

Unlike non biological tissues, muscle springs can produce mechanical energy[30] through muscle activation that is in part neurally mediated. In skeletal muscle, this allows movement energy to be temporarily stored in a tendon and then released to do work on a muscle that is actively lengthened to absorb energy[30]. Although human hamstring muscles act in a unified fashion, almost certainly because of their different architecture the actual timing of each muscle contraction (activation) would vary between the three hamstring muscles and probably contributes to the non-linear muscle action (see below). This probably reflects slightly different functions for the three hamstring muscles. Despite this, there is a turnaround point for all three hamstring muscles – end of the eccentric phase of the contraction – where the muscle begin to shorten and again this property is identical to a spring system.

Laws of spring motion in relation to non-linear muscle action

For the laws of spring motion to be relevant then the spring must work within its elastic limit. When a material breaks or deforms irreversibly it is no longer working within its elastic limit and hence motion will not conform to the laws of spring motion. The original laws of spring motion were devised by Hooke's Law, $F=kx$[26] (where F is the magnitude of the restoring force, x is the displacement, and k is the spring constant). Thus for a given spring constant force is proportional to displacement. However it has been demonstrated that muscle action is non-linear[29,30]. In a recent study on muscle motion (in the ballistic prey capture mechanism in toads) a formula was devised that predicted that the displacement of the muscle spring as function of the change of force[28].

$x=10^{(\Delta F-c_1)/c_2}$

[x= displacement, ΔF = change in force. The shape of the exponential (non-linear) function is described by two constants c1 and c2 with the spring constant of muscle k being the first derivative of the inverse of the above equation][27].

Another recent experiment demonstrates that, for a wide range of muscles over a wide range of species, these constants c1 and c2 remain relatively unchanged[32]. Hence, considering this in non-linear muscle action, by rearranging the equation, force F will be proportional to the log function of the displacement x.

When studies have compared linear motion to non-linear motion of muscles values are not significantly different[33,34]. Most studies that calculate non-linear summation of force in motor units is probably irrelevant in understanding muscle function[35]. Thus we feel justified in our example of classifying force change for hamstrings as being proportional to displacement for non-linear (and linear) muscle contraction.

Muscles acting as springs – Spring constant

The spring constant of each individual hamstring muscle would be affected by muscle density, mass, architecture (pennation), cross-sectional area and the muscles inherent length – tension relationship. Therefore, it is unlikely (and probably impossible) that the (k) spring constant would be identical for each individual hamstring muscle as we have assumed in our study. However a significant dilemma currently exists – it has not been possible to obtain accurate spring constants for the hamstring muscles, thus hampering exact individual hamstring force calculations with the reverse also being true, with an inability to obtain accurate individualised hamstring forces, thus hampering exact spring constant calculations. Thus, we rely on models such has been developed in this study to deduce possible reasons for muscle action and muscle failure, especially in the area of hamstring injuries where the pathogenesis is so poorly understood[12].

Other study weaknesses

In calculating these relative force differentials, various other weaknesses are apparent. Firstly, the anatomical parameters that were used in this study were derived from only 6 elderly embalmed cadavers whose prior history of activity and functionality were unknown[20]. In addition this study did not include error calculations in their measurements and nor could they be calculated from the information provided in this study. This however is the only study to our knowledge that measures in an anatomical method the total muscle length including free tendon ends and thus we chose this study as being the most relevant to calculate our relative forces in the manner outlined in the present study.

Studies on the kinematics of sprinting[13-18] have generally used the principles (a nonlinear optimization algorithm and anatomical constructs that subsequently developed the Open Sim model[36], which does not use any direct measurements of entire hamstring length that includes the free tendon ends. This model calculates the length of the tendon (called the tendon slack length) from the assumed bony model, as the anatomical information is derived from five elderly embalmed cadavers[37,38] that only measured the musculotendon length of the hamstring muscles. Also, in these studies the muscle forces are derived by assuming the muscles have uniform density, based on a study performed over 50 years ago[39]. A recent study on 21 cadavers[40] calculated that the difference in muscle fibre lengths from the anatomical study[37] used to construct the Open Sim model[36] varied by 10-100%. In relation to the hamstring muscles that are used in the current kinematic analysis model, these were considerably shorter than the findings from this recent cadaver study[40]. Thus, the accuracy of the Open Sim model itself has been called into doubt[40]. The likely consequence of this is that calculation of the actual forces of the hamstring muscles presented in all studies must be considered relative to the anatomical model parameters. Two recent studies calculated that the force production in an eccentric contraction was maximal in the semimembranosus muscle, compared to the other two hamstring muscles[15-16]. This finding is not surprising, as the semimembranosus has the shortest fibre length, largest physiological cross-sectional area and largest mass of the three hamstring muscles[22], all features generally considered advantageous with respect to force production[41]. Our study does not conflict with this finding, as we calculate the individual forces of the hamstring muscles relative only to their displacement. Although not part of this study it can also be calculated that, if the semimembranosus exerts the most total force but displaces the least, then this muscle probably has the highest spring constant. In other words, the semimembranosus is the stiffest muscle. This may explain why the semimembranosus is the most likely injured muscle in a simple overstretch injury such as seen in dancers and water skiers[7,42].

For measurements of change in length, we have used the percentage change of length as calculated in a kinematic sprinting study[13]. However, it must be stated that in this study the authors normalized the length of the hamstring muscle to a value that was not defined. Thus, the percentage stretch figures we have used may also not be accurate. In defence of this study[13] the percentage length changes of the three muscles biceps, semimembranosus and semitendinosus were highly consistent at different running speeds (less than 1% difference) and with limited standard deviation (less than on average for all three muscles of 0.2%) and thus considering 14 athletes were tested makes there percentage length changes conclusions valid. In addition other studies have demonstrated that the biceps femoris muscle exhibits a greater change in length[15,16] compared to the other two hamstring muscles. In this way, the principle of the biceps femoris muscle displacing more than the other two hamstring muscles is consistent across relevant studies. This implies that, even though the actual displaced length used in the present investigation may be somewhat incorrect, the principle of the biceps femoris exerting more force in relative terms compared to the other two hamstring muscles will be upheld.

Finally, the present study specifically did not include the short head of the biceps as a separate hamstring muscle in our hamstring modelling: this can be considered another weakness. In terms of evolution and anatomical development, it is considered that the short head of the biceps, with its different innervation, has migrated from originally being a flexor of the hip joint to its current action of assisting the hamstring muscles in extending the leg[43]. It is postulated this has evolved over time to assist in force production for the long head of biceps in the bipedal human animal.

Until further research is completed, only theoretical applications on the value of the findings of this study can be applied. One such application would be that, as the biceps femoris is more susceptible to injury because it exerts more force to complete a longer stretch in the same amount of time than either the semimembranosus or semitendinosus muscles, it seems feasible to suggest that, if these other muscles of the hamstring group could be trained to stretch further during hamstring action then the biceps would require less force to sustain eccentric muscle action. This application might have relevance when the total postural/muscle factors including gluteal muscles and lower lumbar spine can be appropriately assessed and acted upon. Finally, enhancing fatigue resistance by training may also be a fruitful area in preventing hamstring injuries. This has been the basis of some in the field hamstring injury prevention programs[44,45].

Conclusion

As the biceps femoris muscle displaces (stretches) more than either the semimembranosus or semitendinosus muscles during a lengthening muscle contraction, it is required to relatively exert more force. This may be a factor in the known observation of the increased susceptibility of the biceps femoris muscle of the three hamstring muscles to injury where recurrent higher force is required, such as in sports that require repeated sprinting.

References

1. Arnason A, Sigurdsson SB, Gudmundsson A, Holme I, Engebretsen L, Bahr R. Risk Factors for Injuries in Football. Am J Sports Med. 2004;32(1S):5S-16S.
2. Brooks JH, Fuller CW, Kemp SP, Reddin DB. Incidence, Risk and Prevention of Hamsting injury in professional rugby union. Am J Sports Med. 2006 34(8):1297-1306.
3. Askling CM, Tengvar M, Saartok T, Thorstensson A. Acute first-time hamstring strains during high speed running: a longitudinal study using clinical and magnetic resonance imaging findings. Am J Sports Med. 2007;35(2):197-206.
4. Verrall GM, Slavotinek JP, Barnes PG, Fon GT. Diagnostic and Prognostic Value of Clinical Findings in 83 Athletes with Posterior Thigh Injury. Comparison of Clinical Findings with Magnetic Resonance Imaging Documentation of Hamstring Muscle Strain. Am J Sports Med. 2003;31(6):969-973.
5. Connell DA, Schneider-Kolsky ME, Hoving JL, et al. Longitudanal study comparing sonographic and MRI assessment of acute and healing hamstring injuries. AJR. 2004;183(4):975-984.
6. Slavotinek JP, Verrall GM, Fon GT. Hamstring Injury in Athletes: The Association between MR Measurements of the Extent of Muscle Injury and the Amount of Time Lost from Competition. AJR. 2002;179:1621-1628.
7. Askling CM, Tengvar M, Saartok T, Thorstensson A. Acute first-time hamstring strains during slow-speed stretching: clinical, magnetic resonance imaging, and recovery characteristics. Am J Sports Med. 2007;35(2):197-206.
8. Burkett LN. Investigation into hamstring strains: the case of the hybrid muscle. J Sports Med. 1975;3(5):228-231.
9. Chleboun GS, France AR, Crill MT, Braddock HK, Howell JN. In vivo measurement of fascicle length and pennation angle of the human biceps femoris muscle. Cells Tissues Organs. 2001;169(4):401-409.
10. Gajdosik RL, Albert CR, Mitman JJ. Influence of hamstring length on the standing position and flexion range of motion of the pelvic angle, lumbar angle, and thoracic angle. J Orthop Sports Phys Ther. 1994;20(4):213-219.
11. Garrett WE, Mumma M, Lucareche CL. Ultrastructural differences in human skeletal muscle fiber types. Orthop Clin North Am. 1983;14:431-425.
12. Garrett WE. Muscle strain injuries. Am J Sports Med. 1996;24(6):S2-S8.
13. Thelen DG, Chumanov ES, Hoerth DM, et al. Hamstring muscle kinematics during treadmill sprinting. Med Sci Sports Exer. 2005;37(1):108-114.
14. Thelen DG, Chumanov ES, Best TM, Swanson SC, Heiderscheit BC. Simulation of biceps femoris musculotendon mechanics during the swing phase of sprinting. Med Sci Sports Exer. 2005;37(11):1931-1938.
15. Schache AG, Dorn TW, Blanch PD, Brown NA, Pandy MG. Mechanics of the Human Hamstring Muscle during Sprinting. Med Sci Sports Exerc. 2012;44(4):647-658.
16. Chumanov ES, Heiderscheit BC, Thelen DG. The effect of speed and influence of individual muscles on hamstring mechanics during the swing phase of sprinting. J Biomech. 2007;40(16):3555-3562.
17. Padulo J, Powell D, Milia R, Aedigo LP. A paradigm of uphill running. PLoS One. 2013;8(7):e69006.
18. Padulo J, Tiloca A, Powell D, Granatelli G, Bianco A, Paoli A. EMG amplitude of the biceps femoris during jumping compared to landing movements. Springerplus. 2013;9(2)520.
19. Schache AG, Kim HJ, Morgan DL, Pandy MG. Hamstring muscle forces prior to and immediately following an acute sprinting-related muscle strain injury. Gait Posture. 2010;32(1):136-140.
20. Chumanov ES, Heiderscheit BC, Thelen DG. Hamstring Musculotendon Dynamics during Stance and Swing Phases of

High-Speed Running. Med Sci Sports Exerc. 2011;43(3):525-532.

21. Padulo J, Oliva F, Frizziero A, Maffulli N. Muscles, Ligaments and Tendons Journal. Basic principles and recommendations in clinical and field science research. MLTJ. 2013;4:250-252.
22. Woodley SJ, Mercer SR. Hamstring muscles: architecture and innervation. Cells Tissues Organs. 2005;179(3):1251-141.
23. Mair S, Seaber A, Glisson R, Garrett WE. The role of fatigue in susceptibility to acute muscle strain injury. Am J Sports Med. 1996;24(2):137-143.
24. Small K, McNaughton L, Greig M, Lovell R. The effects of multidirectional soccer-specific fatigue on markers of hamstring injury risk. J Sci Med Sport. 2010;13(1):120-125.
25. Garrett WE Jr. Muscle strain injuries: clinical and basic aspects. Medicine and Science in Sports and Exercise. 1990;22:436-443.
26. Hooke R. Micrographia: or some physiological descriptions of minute bodies made by magnifying glasses: with observations and inquiries thereupon. Printed for John Martyn, printer to the Royal Society. 1667.
27. Lindstedt SL, Reich TE, Keim P, et al. Do muscles function as adaptable locomotor springs? J Exp Biol. 2002;205(15):2211-2216.
28. Lappin AK, Monroy JA, Pilarski ED, Zepnewski ED, Pierotti DJ, Nishikawa KC. Storage and Recovery of elastic potential energy powers ballistic prey capture in toads. J Exper Biology. 2006;209:2535-2553.
29. Monroy JA, Gilmore LA, Krebs AK, et al. Elastic properties of muscle during active shortening. Inter Comp Biol. 2006;46:e100.
30. Roberts TJ, Azizi E. Flexible mechanisms: the diverse roles of biological springs in vertebrate movement. J Exper Biology. 2011;214:353-361.
31. Dickinson MH, Farley CT, Full RJ, Koehl MAR, Kram R, Lehman S. How animals move: an integrative view. Science. 2000;288:100-106.
32. Monroy JA, Lappin AK, Nishikawa KC. Elastic Properties of Active Muscle – On the rebound. Exer Sports Science Reviews. 2007;35(4):174-179.
33. Fusi L, Brunello E, Reconditi M, Piazzesi G, Lombardi V. The nonlinear elasticity of the muscle sarcomere and the compliance of myosin motors. J Physiol. 2014;592:1109-1118.
34. Sandercock TG. Non-linear Summation of Force in cat tibialis anterior: A muscle with intrafascicularly terminating fibres. J App Physiol. 2003;94:1955-1963.
35. Sandercock TG. Summation of Motor Unit Force in Passive and Active Muscle. Exer Sports Science Reviews. 2005;33(2):76-83.
36. Delp SL, Anderson FC, Arnold AS, et al. OpenSim: open-source software to create and analyze dynamic simulations of movement. IEEE Trans Biomed Eng. 2007;54(11):1940-1950.
37. Wickiewicz TL, Roy RR, Powell PL, Edgerton VR. Muscle Architecture of the Human Lower Limb. Clin Orthop Relat Res. 1983;(179):275-283.
38. Friederich JA, Brand RA. Muscle fiber architecture in the human lower limb. J Biomech. 1990;23(1):91-95.
39. Mendez J, Keyes A. Density and composition of mammalian muscle. Metabolism. 1960;9:184.
40. Ward SR, Eng CM, Smallwood LH, Lieber RL. Are Current Measurements of Lower Extremity Muscle Architecture Accurate. Clin Orthop Relat Res. 2009;467(4):1074-1082.
41. Lieber RL, Fridén J. Clinical significance of skeletal muscle architecture. Muscle Nerve. 2000;23:1647-1666.
42. Sallay PI, Friedman RL, Coogan PG, Garrett WE. Hamstring muscle injuries among water skiers. Functional outcome and prevention. Am J Sports Med. 1996;24(2):130-136.
43. Martin BF. The origins of the hamstring muscles. J Anat. 1968;102(2):345-352.
44. Small K, McNaughton L, Greig M, Lovell R. Effect of timing of eccentric hamstring strengthening exercises during soccer training: implications for muscle fatigability. Strength Cond Res. 2009;23(4):1077-1083.
45. Verrall GM, Slavotinek JP, Barnes PG. The effect of sports specific training on reducing the incidence of hamstring injuries in professional Australian Rules football players. Br J Sports Med. 2005;39(6):363-368.