Neuromusculoskeletal Models Provide Insights into the Mechanisms and Rehabilitation of Hamstring Strains

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THELEN, D.G., E.S. CHUMANOV, M.A. SHERRY, and B.C. HEIDERSCHEIT. Neuromusculoskeletal models provide insights into the mechanisms and rehabilitation of hamstring strains. *Exerc. Sport Sci. Rev.*, Vol. 34, No. 3, pp. 135–141, 2006. *Neuromusculoskeletal models are used to investigate hamstring mechanics during sprinting. We show that peak hamstring stretch occurs during late swing phase and is invariant with speed, but does depend on tendon compliance and the action of other muscles in the lumbopelvic region. The insights gained are relevant for improving the scientific basis of hamstring strain injury prevention and rehabilitation programs.* **Key Words:** muscle injury, tendon compliance, stretch shortening cycle, forward dynamics, computer simulation, biomechanics, motion analysis, sprinting

INTRODUCTION

Acute hamstring strains are a common injury in sports involving sprinting. Strain injuries are characterized by observable disruption of the musculotendon junction (7), with postinjury remodeling involving both scar tissue formation and muscle regeneration (6). The injury can cause an athlete to miss a few days to a few weeks of sport. More problematic is the high recurrence rate, with approximately one of three athletes reinjuring within a year of returning to sport (9). These observations highlight the prevalence of hamstring strain injuries and the challenge in preventing the initial injury and subsequent reinjury.

The residual effects of a prior hamstring strain may be identifiable, and the associated risk for reinjury reducible using new approaches. For example, Proske *et al.* (10) identified a shift in the isokinetic knee strength profile in previously injured limbs, an effect that may be amendable via lengthening contraction training. Sherry and Best (11) have shown that a rehabilitation program focused on early movement and neuromuscular control dramatically reduced hamstring reinjury rates compared with a traditional stretching and strengthening approach. Although these are promising observations, the underlying mechanisms are not completely understood.

We have used a neuromusculoskeletal model of sprinting to analyze potential hamstring injury mechanisms. The model describes the relationship among muscle excitations, activation dynamics, musculotendon contraction mechanics, and segmental accelerations (13,15). Thus, the model has allowed us to relate mechanics at the muscle level to the movement produced at the whole body level. In this article, we review the use of a neuromusculoskeletal model to investigate the effects of sprinting speed, musculotendon properties, and coordination on hamstring mechanics during sprinting. The insights gained are relevant for improving the scientific basis of injury prevention and rehabilitation programs.

HAMSTRING INJURY REHABILITATION

Hamstring strain injuries most commonly occur in the biceps femoris long head and exhibit a strong tendency to recur. For example, imaging analysis of 170 recently injured athletes found that approximately 80% of hamstring strain injuries involved the biceps femoris (7). Furthermore, a review of 858 hamstring strains in Australian footballers showed the rate of recurrence was 12.6% during the first week of return to sport and 8.1% for the second week. The cumulative

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risk for reinjury for the 22-wk season was 30.6% (9). The high reinjury rate may be due to the use of inappropriate criteria for determining suitability for return to sport or, alternatively, that traditional rehabilitation methods are insufficient for reducing risk for reinjury.

Rehabilitation protocols for acute muscle strains have traditionally emphasized hamstring stretching and strengthening exercises. Sherry and Best (11) prospectively compared such an approach with a progressive agility and trunk stabilization (PATS) rehabilitation program. PATS included exercises that emphasized early movement and coordination of the pelvis and trunk muscles (Fig. 1). In the first 2 wk after returning to sport, none of the 13 athletes participating in the PATS program experienced a reinjury, compared with 6 (54.5%) of 11 athletes that performed isolated hamstring stretching and strengthening exercises. A significant reduction in reinjury rate was still evident in PATS participants even after 1 yr of returning to sport. However, the study was unable to relate reinjury risk to common clinical measures such as strength, flexibility, speed, and vertical jump height.

Although Sherry and Best (11) have shown a promising clinical outcome, it remains unclear which neuromuscular factors are responsible for the reduced reinjury risk in the PATS group. One hypothesis is that improved neuromuscular control of the lumbopelvic region allows the hamstrings to function at safe lengths and loads during athletic movement, thereby reducing injury risk (11). An alternative explanation is that the use of early submaximal loading limits the residual adverse effects of scar tissue formed early in the remodeling process.

Recent observations by Proske *et al.* (10) suggest residual effects may indeed be present in a previously injured muscle. They studied isokinetic ($60° \cdot s^{-1}$) knee flexion exercises performed by nine athletes who had experienced multiple unilateral hamstring strains within the past 5 yrs. At the time of testing, all athletes were injury-free for at least 1 month and participating in sport. Interestingly, there were no strength deficits in the previously injured limbs. However, peak isokinetic torque was generated at an average 12° greater knee flexion angle in the previously injured limb compared with the uninjured limb. The authors attributed the difference to a shorter optimal musculotendon length for active tension in the previously injured muscle. Such a shift can be a training effect, for example, repeated performance of concentric strengthening exercises in rehabilitation. Alternatively, the shift can reflect the presence of residual scar tissue at the musculotendon junction (6). Scar tissue is stiffer than the contractile tissue it replaces and, thus, may alter the mechanical environment seen by the muscle fibers. Specifically, a decrease in series compliance would shift peak force development to shorter musculotendon lengths as observed. Proske *et al.* (10) have also shown, at least in healthy control subjects, that the performance of controlled lengthening contraction exercises can facilitate a shift in peak force development to longer musculotendon lengths. Their initial data suggest that the incorporation of such exercises into training may reduce hamstring injury rates.

Although there are promising new approaches for improving the prevention and rehabilitation of hamstring strains, questions remain regarding the underlying mechanisms. Fundamentally, a strain injury is the result of exceeding the local mechanical limits of the muscle tissue. Thus, it is relevant to investigate the mechanical behavior of the hamstrings during potentially injurious tasks. In this article, we review the use of a neuromusculoskeletal model

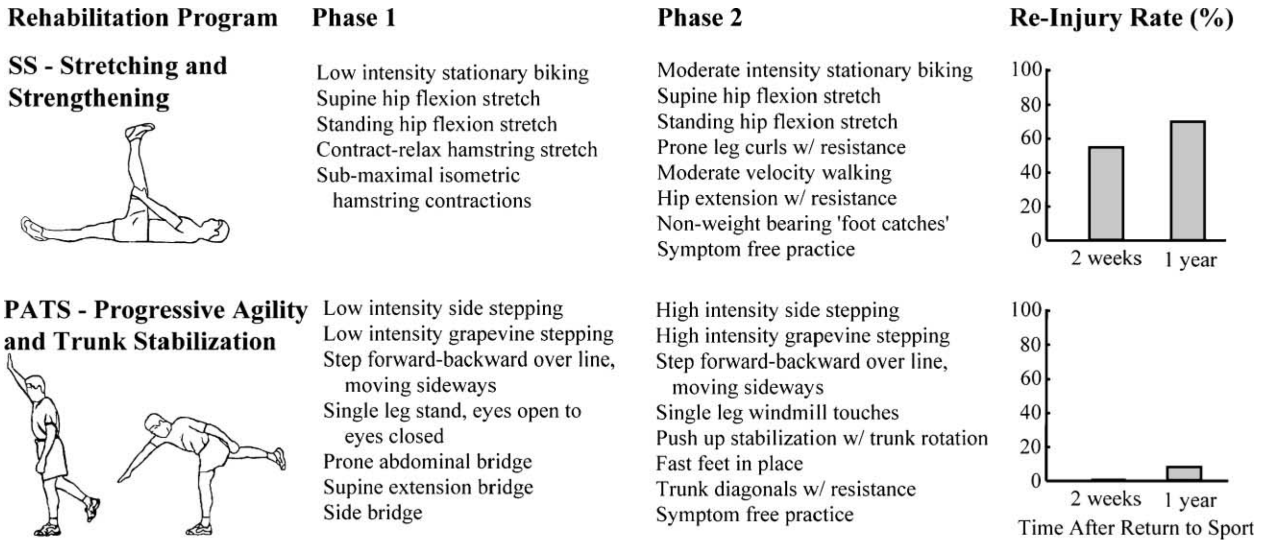

Figure 1. Sherry and Best (11) compared the effectiveness of two rehabilitation programs in reducing reinjury rates in athletes who sustained an acute hamstring strain. A SS group ($N = 11$) performed static stretching, isolated progressive hamstring strengthening, and graduated return to activity. A PATS group ($N = 13$) performed agility exercises beginning with movements primarily in the frontal and transverse planes, then progressing to movements in the sagittal plane. Exercises requiring muscle activity to maintain the spine and pelvis in a desired posture (bridges) were also performed. For each rehabilitation program, athletes progressed from phase 1 to phase 2 when they could walk with a normal gait pattern and do a high-knee march in place without pain. Compared with the SS group, there was a statistically significant reduction in injury recurrence in the PATS group at 2 wk and at 1 yr after return to sport. PATS indicates progressive agility and trunk stabilization; SS, stretching and strengthening.

to estimate the stretch, loading, and work done by muscles during sprinting. These analyses are used to address the following specific questions: When during the sprinting gait cycle are the hamstrings susceptible to injury? How does speed affect hamstring mechanics and potentially contribute to injury risk? How can changes in musculotendon properties affect injury potential? Can the coordination of individual trunk muscles influence hamstring mechanics?

HAMSTRING INJURY MECHANISMS

Despite the frequency of hamstring strains during sprinting, it remains uncertain when in the gait cycle the muscle is injured. It has been suggested that injuries may occur during late swing, when the hip is flexed and the knee is extended. However, others have speculated that the potentially large loads associated with ground contact may cause injury. Animal models clearly show that muscle injury is associated with excessive fiber stretch during a lengthening contraction (8). Thus, we have used a model of sprinting to quantify the stretch of the biarticular hamstrings throughout the gait cycle (14). This information, coupled with EMG measurements, was used to assess when the hamstrings were undergoing an active lengthening contraction and why the biceps femoris long head may be more susceptible to injury.

A generic model of the pelvis and lower extremity was first created, which included a description of the musculotendon paths of the semimembranosus, semitendinosus, and biceps femoris long head muscles (Fig. 2A). The model incorporated important differences between the individual hamstring moment arms at the hip and knee (14). Whole-body kinematics were collected while subjects (N = 14) sprinted on a high-speed treadmill at speeds ranging from 80% to 100% of maximum. The model was scaled to each subject using subject-specific measures of segment lengths. Joint angles were computed to fit the scaled model to the measured marker kinematics. This process provided quantitative estimates of musculotendon stretch for each of the hamstring muscles throughout the gait cycle (Fig. 2B).

We found that peak hamstring stretch occurs during the late swing phase of sprinting before foot contact (14). Electromyography data indicate that the hamstrings are active at this same phase of the gait cycle (13). Thus, the hamstrings are undergoing an active lengthening contraction during late swing, creating the potential conditions for a strain injury to occur. The magnitude of peak stretch was significantly greater for the biceps femoris long head (stretched 9.5% beyond length in an upright posture) than the semimembranosus (7.4%) and semitendinosus (8.1%) muscles. Differences in the knee flexion moment arms between the medial and lateral hamstrings accounted for the intermuscle variations in peak musculotendon stretch. Specifically, because the knee is slightly flexed during late swing, the smaller knee flexion moment arm of the lateral hamstrings (biceps femoris) results in this muscle undergoing greater stretch relative to upright. We concluded that intermuscle differences in hamstring muscle geometry might be a contributing factor to the greater propensity for biceps femoris injury.

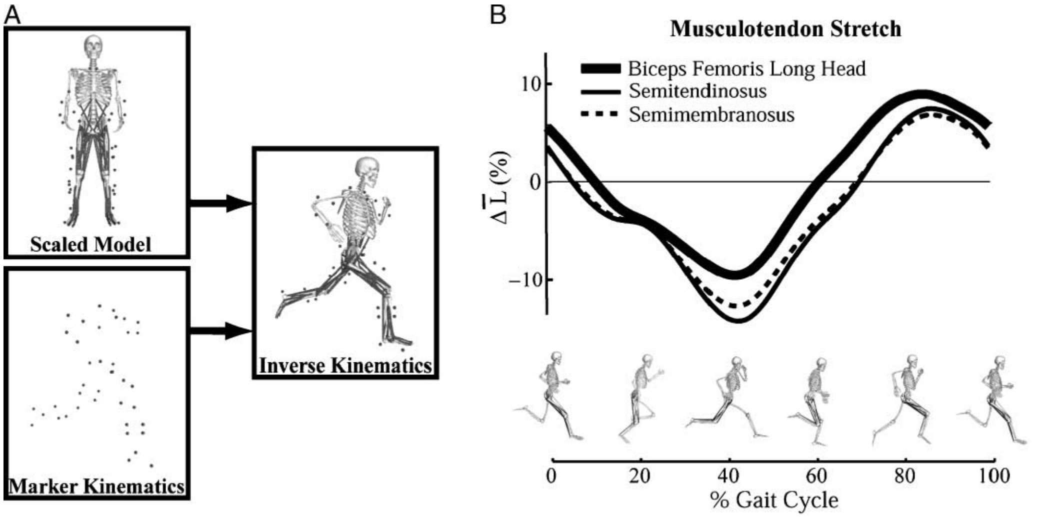

Figure 2. A. Subject-specific models were obtained by scaling segment lengths of a generic musculoskeletal model based on anatomical marker positions recorded of a subject in a standing posture. An inverse kinematics routine was then used to determine the segment joint angles that best align the scaled model with the measured marker kinematics of the subject sprinting on a treadmill. B. Shown are the ensemble-averaged (N = 14 subjects) estimates of musculotendon stretch, normalized to upright musculotendon lengths, for each of the biarticular hamstrings throughout the sprinting gait cycle. Peak stretch is reached during late swing phase when both feet were off the ground. The lateral hamstrings (biceps femoris) are stretched significantly more than the medial hamstrings because of differences in the knee flexion moment arms between muscles (14).

Although providing interesting information, it is difficult to directly assess when an injury occurs based on the kinematic analysis of injury-free running trials. Through unexpected circumstances, we recently completed an analysis of whole-body kinematics obtained at the time of an acute hamstring strain injury (5). A male athlete injured his right biceps femoris while running at 5.36 $m\cdot s^{-1}$ on an inclined (15%) treadmill. We used statistical techniques to identify when individual marker trajectories deviated from a periodic pattern, indicating the earliest mechanical response to injury. This information, combined with estimates of neuromuscular latencies and electromechanical delay, was used to identify a 130-ms portion of the late swing phase of the gait cycle when the injury most likely occurred. Maximum stretch of the biceps femoris and peak hip extension and knee flexion moments also occurred within the suspected period of injury. We concluded that the biceps femoris was likely injured as a result of a lengthening contraction during the late swing phase of the running gait cycle.

SPEED EFFECTS ON HAMSTRING MECHANICS

Hamstring injuries are commonly associated with high-speed sprinting. Therefore, an assessment of how hamstring mechanics vary with speed is relevant to understanding injury mechanisms. We have used a neuromusculoskeletal model to investigate the influence of speed on the stretch, loading, and work done by the hamstrings during the late swing phase of sprinting (13). Musculotendon mechanics were represented by a Hill-type model in which a contractile element is in parallel and series with elastic elements. The series elastic element was assumed to represent the compliance of the tendon and aponeurosis. The input to each muscle was an idealized excitation level that can vary between 0 and 1 (full excitation). The forces developed by the musculotendon actuators acted on the skeleton via the linked-segment equations of motion. Therefore, the neuromusculoskeletal model related the muscle excitations, muscle forces, and the segmental accelerations generated in the system.

A computed muscle control algorithm (12) was used to determine the excitation patterns of 26 lower extremity muscles that drove the lower extremity to track measured hip and knee motion of sprinting athletes (Fig. 3A). Validation of the model was assessed by comparing estimated and measured joint angles and muscle activation patterns. Subject-specific joint angles were tracked closely, with less than 2° of average error in hip and knee angles (13). The timing of computed muscle excitations closely matched measured EMG activities (Fig. 3B).

The simulations show that the hamstrings undergo a stretch shortening cycle during the latter half of swing phase. Biceps femoris muscle excitations increase rapidly between 70% and 80% of the gait cycle, continuing through the end of swing phase. Maximal hamstring loading is reached slightly before peak musculotendon stretch of the musculotendon unit (Fig. 3B). As a result, the hamstrings are doing a substantial amount of negative work (integral of negative musculotendon power) between 70% and 90% of the sprinting gait cycle.

Peak hamstring musculotendon stretch was found to be invariant across the range of speeds (80–100% of maximum) considered (Fig. 4). However, the negative musculotendon work done by the hamstrings increased considerably with speed. The hamstrings likely function to absorb and redistribute the kinetic energy of the swing limb before foot contact. Because kinetic energy increases in proportion to the velocity

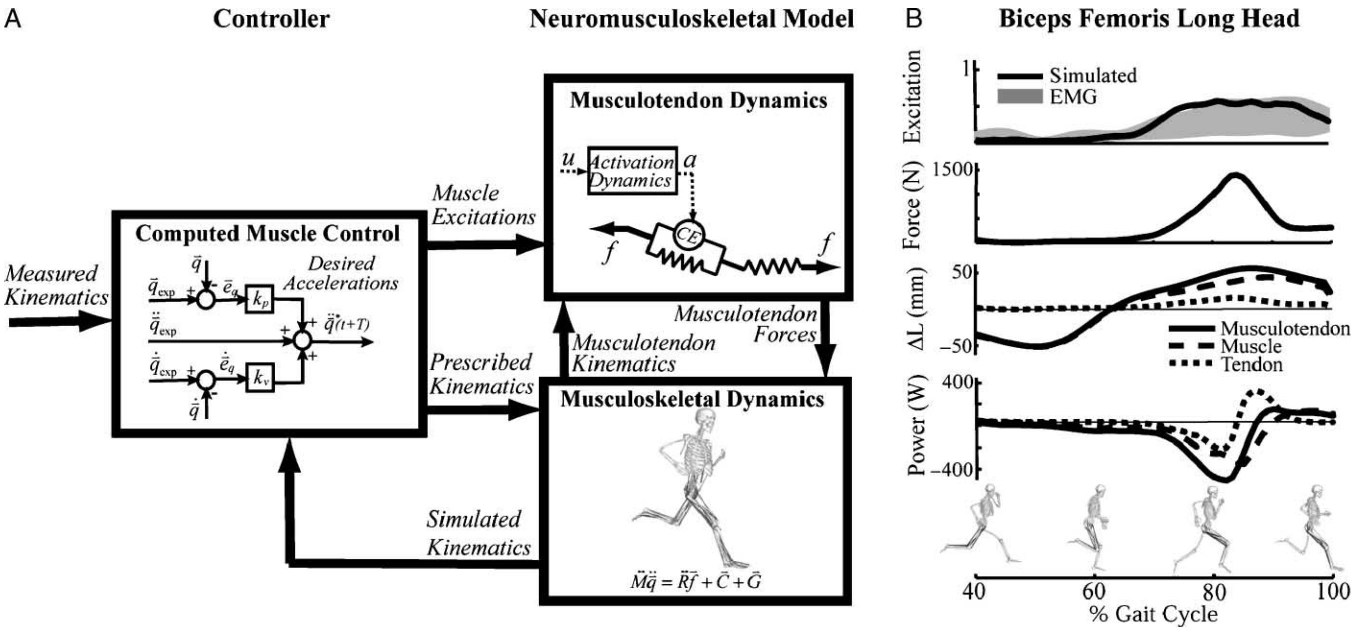

Figure 3. A. A computed muscle control algorithm was used to determine muscle excitations that, when inputted to the neuromusculoskeletal model, produced simulated kinematics that closely replicated measured kinematics. At each time step of the simulation, the controller determined muscle excitations that would produce the desired accelerations while minimizing a cost function to resolve muscle redundancy (12). With the muscle excitations as input, the set of activation, musculotendon, and musculoskeletal dynamic equations were integrated forward to simulate the kinematics that the muscle actions produce. B. Timing of the simulated biceps femoris excitations are consistent with measured EMG patterns (mean ± 1 SD of five subjects). The simulation provides estimates of force, stretch, and power development of the muscle, tendon, and musculotendon components (13).

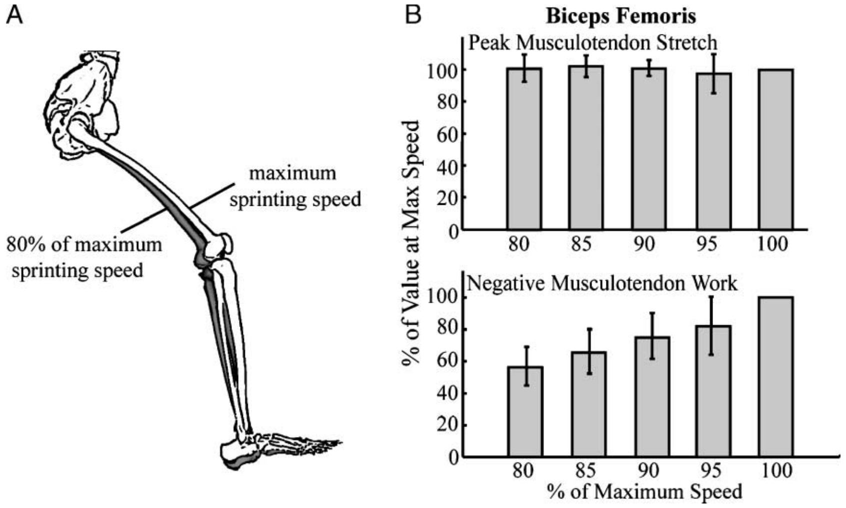

Figure 4. A. Shown is the lower extremity posture at the time of peak hamstring musculotendon stretch. Slightly greater hip and knee flexion occurs at a maximal sprinting speed compared with a submaximal speed. B. However, the additional hamstring stretch due to hip flexion is offset by shortening due to knee flexion, resulting in a peak stretch that is invariant with speed. In contrast to the kinematic quantities, the negative musculotendon work increases substantially with sprinting speed.

squared, the negative work done by the hamstrings increases at a rate that exceeds the percentage change in speed.

These observations demonstrate that maximum muscle stretch may be reached at lower sprinting speeds than the maximum energy absorption capabilities of the muscle. Stretch and negative work requirements may couple together at high speeds to contribute to injury risk. For example, the cumulative negative work done over repeated maximal stretch-shortening contractions may predispose a muscle to injury (2). Alternatively, injury can result from stride-to-stride variability in the peak stretch imposed, with an excessive stretch in a single stride leading to the onset of injury. It should be noted that our analyses of muscle loading and work were limited to the swing phase of sprinting, when the hamstrings are undergoing an active lengthening contraction and seem susceptible to injury. However, similar analysis of stance phase is warranted to characterize the net loading and work done by the hamstrings during sprinting.

EFFECT OF TENDON COMPLIANCE ON HAMSTRING MECHANICS

It is important to recognize that the motion of the musculotendon unit is not necessarily representative of the behavior of individual muscle fibers where the injury occurs. For example, Griffiths (4) showed that a stretch imposed on a contracting musculotendon is often taken up by the tendon, allowing the muscle fibers to maintain an isometric length or even continue to shorten. Griffiths proposed that tendon compliance acts as a mechanical buffer that reduces the stretch of muscle fibers and protects against injury. Therefore, changes in musculotendon properties can affect fiber stretch and, hence, contribute to injury risk. For example, residual postinjury scar tissue at the musculotendon junction can alter the mechanical environment of the muscle fibers. Also, it has been shown in an animal model that series compliance seems to decrease with repeated maximal stretch–shortening contractions (2). A time-dependent decrease in tendon compliance would conceivably alter the stretch and the loading of the fibers during repetitive athletic movement such as sprinting.

We used a sensitivity study to investigate how the stretch and negative work seen at the fiber level depends on the compliance of the in-series tendon component during sprinting (13). A nominal muscle-actuated simulation of the swing phase of sprinting was first created (Fig. 3A). We then varied the tendon compliance of the biceps femoris long head and reconducted the simulation with an altered muscle excitation pattern that retained the overall musculotendon behavior, albeit with altered musculotendon mechanics. A decrease in tendon compliance, within a normal physiological range, necessitated a substantial increase in muscle fiber stretch and negative musculotendon work (Fig. 5). This illustrates that with a reduction in tendon compliance, an increased risk for injury can occur unless the running posture adapts to allow the musculotendon complex to operate at shorter lengths.

INFLUENCE OF MUSCLE COORDINATION ON HAMSTRING MECHANICS

An intriguing aspect of the promising rehabilitation outcomes demonstrated by Sherry and Best (11) involves the potential benefit of trunk stabilization exercises. In particular, the authors suggest that the ability to control the lumbopelvic region during higher-speed skilled movements may prevent hamstring reinjury. Neuromusculoskeletal models provide a tool by which to quantitatively assess how individual muscles influence hamstring mechanics and, hence, injury potential.

The approach taken was to first generate a simulation of the double-float phase of sprinting, the last part of the gait cycle when peak hamstring stretch occurs. The simulation generated included 58 force trajectories for individual muscles crossing the lower trunk, hip, knee, and ankle. We then perturbed the muscle force trajectories one at a time by a small amount (1 N) and resimulated the movement for each perturbation. The change in hamstring musculotendon

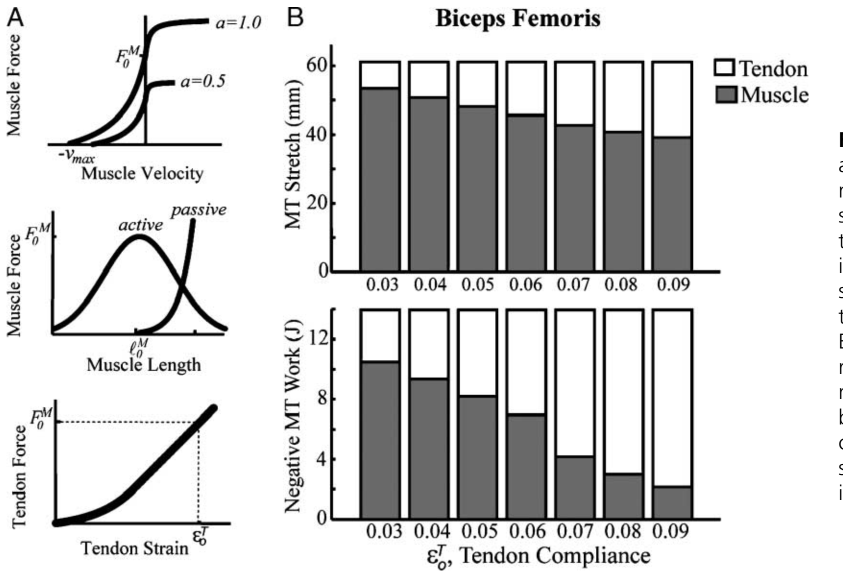

Figure 5. A. Force-length–velocity properties of muscle and force-strain properties of tendon were used to describe musculotendon contraction dynamics. The tendon force-strain curve was parameterized by ε_0^T, defined as the tendon strain resulting from the application of maximum isometric force (F_0^M). Simulations of the swing phase of sprinting were performed with a range of ε_0^T to estimate the effect of tendon compliance on fiber stretch and work. B. A decrease in tendon compliance, within physiologically reported ranges, substantially increases the stretch and negative work attributable to the muscle component of the biceps femoris (13). This illustrates that decreased series compliance because of the performance of repeated stretch-shortening contractions (2) or as a result of post-injury scarring (6) could contribute to increased injury risk.

stretch because of each perturbation was ascertained. The change in stretch was then scaled by the average muscle force over double float, resulting in an estimate of the influence of each muscle on hamstring stretch.

Our analysis suggests that the contralateral hip flexors (*i.e.*, iliopsoas) have as large an influence on hamstring stretch as the hamstrings themselves (Fig. 6). This occurs because the iliopsoas can directly induce an increase in anterior pelvic tilt, which in turn necessitates greater hamstring stretch. Other proximal muscles acting on the pelvis such as the abdominal obliques and erector spinae also substantially influence hamstring stretch. The more distal muscles acting about the knee and/or ankle had much less influence on hamstring mechanics. This analysis illustrates a mechanism by which neuromuscular control of trunk and pelvis muscles can affect hamstring strain injury risk.

FUTURE DIRECTIONS AND RESEARCH

The development and use of neuromusculoskeletal models inherently depends on experimental data both to formulate appropriate scientific questions and to validate model-based estimates. Given the high rate of injury recurrence, there is a need for a better description of the structure and function of the remodeled musculotendon complex after injury. In this regard, magnetic resonance imaging may be a useful tool for characterizing the extent of scar tissue in remodeled muscle. Furthermore, new ultrasound approaches for measuring contraction mechanics can be used to characterize mechanical strains near a prior injury site, at least under controlled circumstances in which these *in vivo* measurements can be performed (3). These data would be important for understanding remodeling factors that might influence reinjury risk. The eventual coupling of imaging-based measurements with controlled intervention studies may provide new understanding of the effects of specific exercises on muscle function and mechanics.

There is a complimentary need for further refinement of the neuromusculoskeletal models to characterize localized mechanics around the musculotendon junction where the injury occurs. Hill-type musculotendon models inherently assume a uniform mechanical strain distribution along the muscle fiber, which may not be the case when injury occurs. For example, it has been suggested that strain injury may be preceded by disruption of individual sarcomeres, leading to large local mechanical strains, which propagate to the musculotendon junction (10). The substantial change in stiffness between fibers and tendon can then contribute to the fibers tearing at the junction. The development and incorporation of more refined soft tissue models are needed to

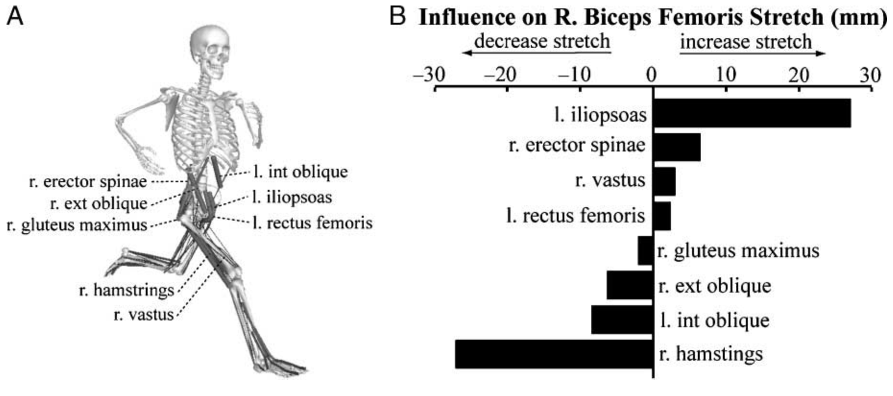

Figure 6. A. A nominal simulation of the double-float phase of sprinting was generated. Individual muscle force trajectories were then perturbed (by 1 N throughout double float) and the simulation regenerated. Perturbation-induced changes in hamstring stretch were determined and then scaled by the associated average muscle force to quantify the muscle's influence. B. Shown are the muscles that exhibited the greatest influence on biceps femoris musculotendon stretch. A positive influence means the muscle acts to increase stretch. This analysis shows that the contralateral iliopsoas, abdominal obliques, and ipsilateral low back muscles all substantially influence hamstring stretch via their actions on the pelvis and, thus, illustrates a mechanism by which trunk muscles may affect injury risk (11).

provide a more detailed description of this injury mechanism and can also provide a means for assessing how remodeling can alter localized strain patterns. The recent development of finite element models of muscle that account for important architecture effects may facilitate such analyses (1).

Quantifying the role of neuromuscular coordination in preventing injury or reinjury remains a challenging endeavor. Trunk stabilization exercises are widely cited as providing such benefits for a range of pathologies, although the specific manner in which the benefits are achieved remains tenuous. In this article, we showed that lumbo-pelvic muscles could indeed influence lower extremity muscle mechanics. However, complimentary experimental approaches are still needed to investigate how training truly facilitates improved coordination of these muscles during athletic movements. An understanding of the changes in coordination can then be coupled with simulations of movement to interpret the mechanical ramifications.

CONCLUSIONS

Hamstring strains are a common and recurrent injury among sprinting athletes. The effective prevention and rehabilitation of such injuries remains challenging. In this article, we have shown that neuromusculoskeletal models enhance the fundamental understanding of factors that affect both injury and rehabilitation mechanisms. The continued development and use of such models, together with controlled experimental observations, are important for scientifically establishing effective injury prevention and rehabilitation programs.

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References

1. Blemker, S.S., and S.L. Delp. Three-dimensional representation of complex muscle architectures and geometries. *Ann. Biomed. Eng.* 33: 661–673, 2005.
2. Butterfield, T.A., and W. Herzog. Quantification of muscle fiber strain during in-vivo repetitive stretch-shortening cycles. *J. Appl. Physiol.* 99:593–602, 2005.
3. Fukunaga, T., Y. Kawakami, K. Kubo, and H. Kanehisa. Muscle and tendon interaction during human movements. *Exerc. Sport Sci. Rev.* 30:106–110, 2002.
4. Griffiths, R.I. Shortening of muscle fibres during stretch of the active cat medial gastrocnemius muscle: the role of tendon compliance. *J. Physiol.* 436:219–236, 1991.
5. Heiderscheit, B.C., D.M. Hoerth, E.S. Chumanov, S.C. Swanson, B.J. Thelen, and D.G. Thelen. Identifying the time of occurrence of a hamstring strain injuring during treadmill running: a case study. *Clin. Biomech. (Bristol, Avon)* 20:1072–1078, 2005.
6. Kaariainen, M., T. Jarvinen, M. Jarvinen, J. Rantanen, and H. Kalimo. Relation between myofibers and connective tissue during muscle injury repair. *Scand. J. Med. Sci. Sports* 10:332–337, 2000.
7. Koulouris, G., and D. Connell. Evaluation of the hamstring muscle complex following acute injury. *Skeletal. Radiol.* 32:582–589, 2003.
8. Lieber, R.L., and J. Friden. Mechanisms of muscle injury gleaned from animal models. *Am. J. Phys. Med. Rehabil.* 81:S70–S79, 2002.
9. Orchard, J., and T.M. Best. The management of muscle strain injuries: an early return versus the risk of recurrence. *Clin. J. Sport Med.* 12:3–5, 2002.
10. Proske, U., D.L. Morgan, L. Brockett, and P. Percival. Identifying athletes at risk of hamstring strains and how to protect them. *Clin. Exp. Pharmacol. Physiol.* 31:546–550, 2004.
11. Sherry, M., and T. Best. A comparison of two rehabilitation programs in the treatment of acute hamstring strains. *J. Orthop. Sports Phys. Ther.* 34:116–125, 2004.
12. Thelen, D.G., F.C. Anderson, and S.L. Delp. Generating dynamic simulations of movement using computed muscle control. *J. Biomech.* 13:321–328, 2003.
13. Thelen, D.G., E.S. Chumanov, T.M. Best, S.C. Swanson, and B.C. Heiderscheit. Simulation of biceps femoris musculotendon mechanics during the swing phase of sprinting. *Med. Sci. Sports* 37: 1931–1938, 2005.
14. Thelen, D.G., E.S. Chumanov, D.M. Hoerth, T.M. Best, S.C. Swanson, L. Li, M. Young, and B.C. Heiderscheit. Hamstring muscle kinematics during treadmill sprinting. *Med. Sci. Sports* 37:108–114, 2005.
15. Zajac, F.E., and M. Winters. Modeling musculoskeletal movement systems: joint and body segmental dynamics, musculoskeletal actuation, and neuro-muscular control. In: *Multiple Muscle Systems—Biomechanics and Movement Organization*, edited by J.M. Winters and SL.-Y. Woo. New York: Springer-Verlag, 1990, pp. 121–148.