

Opinion

The late swing and early stance of sprinting are most hazardous for hamstring injuries

Yu Liu ^{a,*}, Yuliang Sun ^b, Wenfei Zhu ^b, Jiabin Yu ^c

^a Key Laboratory of Exercise and Health Sciences of the Ministry of Education, Shanghai University of Sport, Shanghai 200438, China

^b School of Physical Education, Shaanxi Normal University, Xi'an 710119, China

^c Research Academy of Grand Health, Faculty of Sport Science, Ningbo University, Ningbo 315211, China

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Hamstring strain injury is one of most prevalent noncontact injuries in sports that involve high-speed running, such as sprinting, soccer, and rugby.¹ In order to optimize prevention strategies and injury rehabilitation, studies have been conducted to understand hamstring function during sprinting.^{2–4} However, differences have long existed in the literature as to the cause of hamstring strain injuries. One of the most controversial topics is the debate over which phase of high-speed running is most associated with hamstring injuries.⁵

Studies of running biomechanics indicate that the hamstrings are active for the entire gait cycle, with peaks in activation during the early stance and the late swing phases.^{6,7} Mann and Sprague³ reported that the highest torques of hip extension and knee flexion occur secondary to a peak value of the ground reaction forces (GRFs) during the initial stance phase. Based on this information, they concluded that the early stance was highly associated with hamstring strains. In contrast, many subsequent researchers held the view that the late swing phase of sprinting is the most hazardous.^{4,6–9} These studies found that the hamstrings contract forcefully while reaching maximum length during the late swing phase. They ignored Mann's argument of high torques as an indicator of hamstring injury risk and preferred the hypothesis that hamstring strains occur during eccentric contractions.¹⁰

However, most previous observers used treadmill sprinting rather than overground sprinting in their studies.^{6,8,9} Although the treadmill is a convenient tool for assessment of running biomechanics, it has been shown that the biomechanics of treadmill running differ significantly from those of overground running, and thus may lead to erroneous conclusions about overground running.^{11,12} Additionally, much of the previous research was aimed at investigating the kinematics of the ham-

string during running alone.^{7–9} Limited attempts have been made to measure the GRFs during overground sprinting and use these data to estimate the hamstring kinetics during stance.^{3,4} To fill this gap, we investigated the loading conditions of the hamstring muscles during maximum-effort overground running.² Our results suggest that the hamstrings are most susceptible to injury during the swing and stance transitions of sprinting.

We used a lower extremity intersegmental dynamics analysis for each body segment.^{2,13} The intersegmental dynamics analysis we used allows for torques at each joint to be separated into 5 categories: gravitational torque (GTT), motion-dependent torque (MDT), external contact torque (EXT), generalized muscle torque (MST), and net joint torque (NET), which is the vector sum of the 4 previous components. Detailed interactions between the active muscle torques and the passive torque components could be quantified, giving us insight into how the hamstrings' function switches during the running cycle.

Using this approach, we reached 3 main conclusions. First, the MST primarily countered the MDT during the swing phase for the knee and hip joints (Fig. 1A). In late swing, the leg was swinging forward due to its inertia, which cause a large hip-flexion MDT and a knee-extension MDT at the same time. Therefore, the hamstrings were active and started to extend the hip and flex the knee joints to counteract these passive effects for the subsequent ground contact (Fig. 1B). Further analysis of the components of the MDT showed that MDT at both joints was caused mainly by torques due to the leg angular acceleration. These passive torques applied stress to the hamstring muscles in the opposite direction of contraction at both joints. To counter this negative effect, the hamstrings encountered enormous loads, approximately 10 times the subjects' average body weight, to control the rapid leg rotation, which created conditions for hamstring injuries. Previous studies reported that the hamstrings stretch to their maximum length and the muscle force reaches its maximal value in this phase.^{6–8} Our results confirmed these findings and showed how they happened. The key contributor to these high torques was the MDT created

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* Corresponding author.

E-mail address: yuliu@sus.edu.cn (Y. Liu)

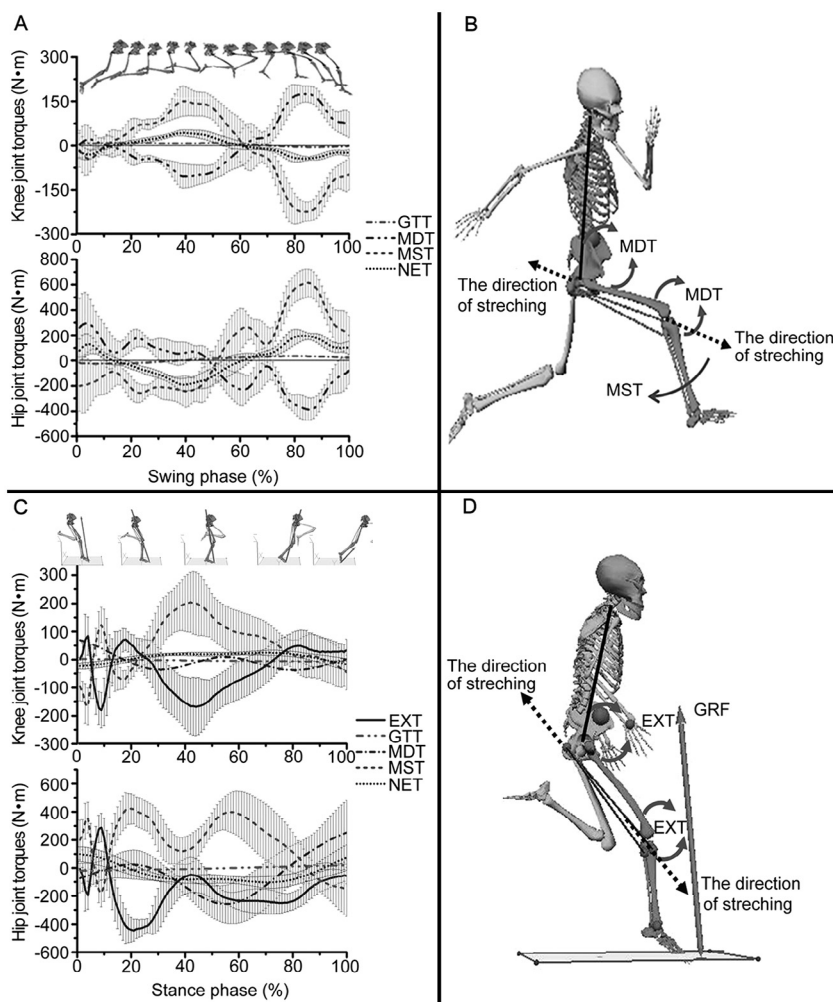


Fig. 1. Averaged time-normalized graphs for joint torques at knee and hip joints during the swing (A) and stance (C) phases of sprinting. The top panels show positions of the lower extremity during the swing (A) and stance (C) phases. Data represent the group mean (lines) with 1SD (shading). (B) Diagram of sprinting during the late swing phase: the inertial loads (MDT) produced by segment motion at the knee and hip joints. (D) Diagram of sprinting during the initial stance phase: the GRF passes anteriorly to the knee and hip joints. EXT = external contact torque; GRF = ground reaction force; GTT = gravitational torque; MDT = motion-dependent torque; MST = muscle torque; NET = net torque. (Positive value indicates extension; negative value indicates flexion.) Adapted with permission.²

mainly due to the leg angular acceleration.² Although there is debate as to whether eccentric muscle strain or muscle stress is the causative factor in muscle strain injuries,^{1,10} it is known that an eccentric contraction occurs when the external force is greater than the muscle contraction force, that is, the eccentric muscle action is induced by an external force. During late swing, the leg angular acceleration led to a tremendous MDT, which caused the hamstring muscles to work eccentrically. This suggests that hamstring strains are associated with high loading caused by the inertial torque MDT.

Second, the dominant passive torque switched to EXT in the transition from late swing to initial stance (Fig. 1C). We noticed that the GRFs passed anteriorly to the knee and hip joints during the initial stance phase, which generates a large extension torque at the knee and a flexion torque at the hip at the same time (Fig. 1D). As with the knee flexors and hip extensors in the late swing phase, the hamstring muscles serve both roles required to counteract the effect of the GRFs. It is likely that the

hamstrings, which encounter at least 8 times the subjects' body weight in the initial stance phase, are susceptible to strain injury in this phase. This conclusion supports Mann's finding.³ Additionally, we discovered that the external GRF passing anteriorly to the knee and hip generate the peak loads on the hamstrings.² As the early stance is a continuation of the late swing, the hamstrings were contracting concentrically after being fully extended. The muscles were suffering from enormous loads caused by 2 different factors (the inertia and the GRFs) throughout this eccentric–concentric transition.

Chumanov et al.⁶ indicated an increased loading for the hamstring muscles during the initial stance phase. However, they did not regard this phase as injurious because negative work (i.e., energy absorbed) during eccentric contraction has been shown to correlate best with muscle injuries in animal models. This is a widely held belief, despite experimental evidence of muscle strains being produced during concentric (shortening) contractions.¹⁴ However, we currently cannot know

for certain if muscle strains are produced by the tremendous external forces during concentric contractions in the early stance of sprinting. In addition, we are aware of the evidence suggesting that loads on their own are not necessarily indicative of injury risk, but accumulated effects of biomechanical loads (i.e., musculotendon strain, velocity, force, power, and work) experienced by the hamstrings may result in hamstring strain injuries. We cannot state conclusively that high loading creates injury. However, we have evidence that the risk factors for hamstring injuries are high in both the late swing and the early stance phase for different loading mechanisms.

Finally, unlike most previous research in which GRFs were not determined,⁷⁻⁹ we took both kinematic and kinetic data into consideration² and examined overground sprinting at maximum effort in elite athletes. The average maximum speed in our study was 9.7 m/s, which approaches typical maximum sprinting speeds and associated enormous GRFs, and is higher than speeds achieved in previous studies.^{4,6} It has been suggested that the hip and knee torques, which are estimated via the inverse dynamics approach, are particularly sensitive to the filter cutoff frequency, and the early portion of the stance phase is the most affected period.^{15,16} Exaggerated fluctuations in the knee joint torques are data-processing artifacts rather than genuine characteristics of the joint kinetics. Therefore, it has been suggested that matched cut-off frequencies be used for both kinematic and kinetic data (i.e., 20–20 Hz) when applying inverse dynamics. Filtering at unmatched cutoff frequencies might affect, to some extent, the results obtained in our lab. However, one should not universally dismiss studies that use unmatched cutoff frequencies. Based on our results, the joint muscle torques counteract the EXT, which was caused by the GRFs during the stance phase. Careful examination of the raw curves of the GRFs reveal that the GRFs switch between passing in front and behind the knee joint during early stance. This phenomenon contributes to the fluctuations of the GRFs and affects the derivation of the joint muscle torque. Therefore, the peak values of the MST in early stance are not all artifacts. In addition, the aim of data filtering is to remove noise and reduce the attenuation of signals as much as possible. Data filtering must be based on the raw signals. To estimate if the filtered data are optimally processed, we need to compare the smoothed curve with the raw data curve. In the current study, we strictly followed the protocol for estimating optimum cutoff frequency.^{17,18} The optimum cutoff frequency is not only a function of the residual between the filtered and unfiltered data but is also a function of the sampling frequency. Matched combinations of cutoff frequencies (i.e., 20–20 Hz) can potentially “over-smooth” the kinetic data, thereby removing crucial peak values of joint torques at the instant of foot strike, which explains why there were no fluctuations when using matched cutoff frequencies.

Schache et al.⁴ studied the mechanics of the hamstring muscles during overground sprinting, using an advanced musculoskeletal model accessed from OpenSim. They estimated the loads acting on individual muscles (semitendinosus, semimembranosus, biceps femoris long head, and biceps femoris short head) based on the joint torques at the knee and hip obtained

from inverse dynamics analysis. However, they did not find peak values during the early stance phase. Peak musculotendon forces for the bi-articular hamstrings would seem to have been underestimated in the early stance phase, and the authors attribute this to the limitations of the inverse dynamics-based static optimization combined with a minimum-stress performance criterion. However, in our opinion, this is a typical case in which over-filtered data were used for an inverse dynamics calculation. Compared with their previous results, which also indicated a peak knee flexion torque during the early stance phase,¹⁹ the peak values might have been attenuated artificially.

To sum up, during both the late swing and the initial stance phase, the large passive torques at the knee and hip joints acted to lengthen the hamstring muscles. The values of the flexion MST at the knee and the extension MST at the hip in those 2 phases were considerable, indicating that the knee flexors and hip extensors play an important role in sprint running, especially during the initial stance phase and the late swing phase. The active muscle torques generated mainly by the hamstrings counteracted the passive effects generated by the inertia of the leg (swing) and the external GRF (stance). Although different causes led to the high loads in the hamstrings in these 2 phases, we might think of these 2 phases as 1 period, the swing–stance transition period, because the motions of the lower-extremity are continuous and the hamstring muscles function to extend the hip and flex the knee throughout the entire phase. As a result, during sprinting or high-speed locomotion, the hamstring muscles may be more susceptible to strain injury during the swing–stance transition than during any other phase in sprint running.

One limitation of our research is that the method for estimating muscle torques across a joint does not reveal an individual muscle’s contributions to the joint torque. In addition, passive structures also contribute to the joint torques at the knee and hip. Because the hamstring muscles are the most injured muscles during sprinting²⁰ and are the only bi-articular muscles that flex the knee and extend the hip, we focused our MST-related discussion on the hamstring musculature. Future studies need to consider the role of other active and passive structures that cross the hip and knee joints.

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Authors’ contributions

YL designed and carried out the study and drafted the manuscript; YS performed the literature review and helped to draft the manuscript; WZ helped to draft and revise the manuscript; JY participated in the design and coordination of the study and helped to draft the manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

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