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Effects of flexibility and strength interventions on optimal lengths of hamstring muscle-tendon units

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A R T I C L E I N F O

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A B S T R A C T

Objectives: The aim of the present study was to determine the effects of altering both hamstring flexibility and strength on hamstring optimal lengths.
Design: Controlled laboratory study.
Methods: A total of 20 male and 20 female college students (aged 18–24 years) participated in this study and were randomly assigned to either a flexibility intervention group or a strength intervention group. Passive straight leg raise and isokinetic strength test were performed before and after interventions. Paired T-tests were performed to determine hamstring flexibility or strength intervention effects on hamstring optimal lengths.
Results: Male participants in the flexibility intervention group significantly increased range of hip joint flexion ($P = 0.001$) and optimal lengths of semimembranosus and biceps long head ($P \leq 0.026$). Male participants in the strength intervention group significantly increased hamstring strength ($P = 0.001$), the range of hip joint flexion ($P = 0.037$), and optimal lengths of all three bi-articulated hamstring muscles ($P \leq 0.041$). However, female participants did not significantly increase their hamstring optimal lengths in either intervention groups ($P \geq 0.097$) although both groups significantly increased the range of hip joint flexion and strength ($P \leq 0.009$).
Conclusion: Hamstring optimal lengths can be modified through flexibility intervention as well as strength intervention for male participants, but not for female participants in this study. Hamstring optimal lengths should be considered as hamstring flexibility measures in future prospective studies to identify potentially modifiable risk factors for hamstring injury.

Practical implications

- Hamstring optimal lengths can be increased through flexibility or strength interventions at least for male athletes.
- Flexibility and strength interventions may not further increase hamstring optimal lengths after hamstring optimal lengths reach a certain magnitude.
- The length of time for flexibility and strength interventions to show the effects on hamstring optimal lengths may be different for different individuals.
- Hamstring optimal lengths should be considered as a measure of true hamstring flexibility in future prospective studies to identify risk factors of hamstring injury.

1. Introduction

Hamstring muscle strain injury (hamstring injury) is one of the most common injuries in sports related high-speed sprinting such as soccer, American football, and rugby, comprising 11–17% of all injuries.[1] Although most hamstring injuries do not need surgical repair, injured athletes still often need lengthy rehabilitation before returning to sport. The loss of training and competition time varies between 17–73 days.[1] The financial cost of hamstring injuries is a huge burden to sport organizations and society, and rapidly increasing. Hamstring injury also has a high re-injury rate

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of 12–48%.[1] Taken together, there is a continued need for research to develop effective prevention and rehabilitation strategies.

Although significant efforts have been made in the last two decades to identify risk factors for hamstring injuries, modifiable risk factors remain unclear. Various non-modifiable risk factors including previous hamstring injury, age, and ethnicity have been identified. However, the empirical evidence for modifiable risk factors such as flexibility and strength is inconsistent.[1] Several studies have indicated a significant relationship between hamstring flexibility and the risk for primary as well as recurrent hamstring injuries.[2,3] A case-control study with 450 soccer players, however, showed no significant relationship between hamstring flexibility and hamstring injury.[4] Meanwhile, several investigations also support a deficit in hamstring strength as a risk factor for hamstring injury,[5,6] and that hamstring strength training can reduce the risk for hamstring injury.[7] Other study, however, failed to find a correlation between hamstring strength and risk for injury.[3]

Studies using animal models demonstrated that the direct cause of muscle strain injury is muscle strain rather than muscle force.[8,9] Accordingly, muscle optimal length may affect the risk of muscle strain injury since muscle strain is the ratio of muscle elongation to muscle optimal length. Several studies have shown that legs with previous hamstring injury or poor hamstring flexibility had smaller flexion angles corresponding to the maximal knee flexion torque compared to legs without previous hamstring injury or with normal hamstring flexibility.[10,11] A recent study demonstrated that the hamstring muscle-tendon unit lengths at which maximal contraction forces are produced (hamstring optimal lengths) were significantly correlated to hamstring flexibility score and sex, but not to hamstring strength.[12] The follow-up study further demonstrated that peak strains of hamstring muscle-tendon units in sprinting were significantly correlated to hamstring optimal lengths and flexibility score.[13] These studies support hamstring flexibility as a predicator of peak strains in sprinting. However, due to the cross-sectional nature of previous investigations, these studies did not provide any evidence that hamstring optimal lengths could be altered by altering hamstring flexibility. Longitudinal studies are needed to determine if hamstring optimal lengths can be altered through hamstring flexibility and strength interventions.

The purpose of this study was to determine the effects of altering both hamstring flexibility and strength on hamstring optimal lengths for both males and females. We hypothesized that an 8-week hamstring flexibility intervention would significantly increase the range of hip joint flexion and hamstring optimal lengths, but not hamstring strength for both males and females. We also hypothesized that an 8-week hamstring strength intervention would significantly increase hamstring strength and optimal lengths, but not the range of hip joint flexion for both males and females.

2. Methods

Forty college students (aged 18–24 years, 20 males and 20 females) regularly participating in exercise and sport activities such as soccer, basketball, track and field 2–3 times per week volunteered to participate in this study. All participants had no history of hamstring or other lower extremity injury 2 years prior to this study that prevented them from performing the research tasks as required. These participants were randomly assigned to either a flexibility or a strength intervention group (Table 1). Each participant signed a written consent form before any data was collected. The use of human participants was approved by the Institutional Review Board of Beijing Sport University.

Each participant had a pre-intervention test, eight week flexibility or strength intervention depending on experimental group assignment, and a post-intervention test to complete the study. In each of the pre- and post-intervention tests, the participant completed a six minutes warm-up including jogging and jumping. A passive straight leg raise (PSLR) test was then performed to determine the range of hip joint flexion bilaterally. The PSLR test is commonly used as a hamstring flexibility test in which the range of hip joint flexion is used as an estimate of hamstring flexibility.[4,12] Following the PSLR test, an isokinetic concentric strength test was performed to collect knee kinetic and kinematic data bilaterally.

Each participant had three intervention sessions per week for eight weeks with at least 36 h between two consecutive sessions. Each intervention session consisted of a six-minute warm-up and a hamstring flexibility or strength intervention under the direction of a trainer. The warm-up included jogging, and reverse lunge and heel to butt exercises. A flexibility intervention included a series of dynamic and static, and proprioceptive neuromuscular facilitation (PNF) stretches (Table 1, Supplemental Figure 1). A strength intervention included a series of resistant knee flexion exercises and Nordic hamstring curl exercises (Table 1, Supplemental Fig. 2). All trainers and participants received written descriptions and illustrations of required interventions. All trainers were trained and examined to ensure that required exercises were performed appropriately. Participants were instructed to maintain their normal diet and avoid any exercises specifically designed to improve hamstring flexibility or strength in their daily sports activities while participating in the study.

In the PSLR test, the participant's body position with maximal hip flexion without tilting the pelvis in flexibility tests was recorded using a high definition digital photo camera (GC-PX100, JVC, Japan) with its optical axis perpendicular to the sagittal plane of the participant.[12] A total of 16 retro-reflective markers were then placed on participant's critical body landmarks bilaterally, including the anterior superior iliac spine (ASIS), top of the crista iliaca (TCI), lateral and medial femur condyles, lateral and medial malleolus, tibial tuberosity, center of the 2nd and 3rd metatarsals. An additional marker was placed at the intersection of L4-L5. A standing calibration trial was performed and then the marker on the intersection of L4-L5 was removed.[12] The participant was then seated on the IsoMed 2000 strength testing system (D&R Ferstl GmbH, Hemau, Germany) with the hip flexed at 90°. The knee flexion torque-time data were recorded at a sample rate of 100 samples/channel/sec with a knee flexion speed of 10°/sec and a range of motion of 110° for each isokinetic concentric strength test using a dynamometer in the MegaWin 2.4 strength testing system (Mega Electronics Ltd., Kuopio, Finland). Three-dimensional (3-D) trajectories of reflective markers in standing calibration trial and isokinetic strength test were recorded using a videographic system with twelve video cameras (Qualisys, Gothenburg, Sweden) at a sample rate of 100 frames/sec and Qualisys Track Manager software (Qualisys, Gothenburg, Sweden).

To determine the range of hip joint flexion, the video records of body position with maximum hip flexion taken in the PSLR test were digitized using Shixun Motion Analysis System version 4.0 (Beijing Sport University, Beijing, China). The range of hip joint flexion in each PSLR trial was calculated as the angle between the vector from the hip joint center to knee joint center and the vector from the acromion process to hip joint center. The mean range of hip joint flexion from three PSLR trials of each leg was used as the best measure of the range of hip joint flexion of the given leg.

The raw 3-D trajectories of all reflective markers in each hamstring isokinetic strength testing trial were filtered through a low-pass digital filter at a cut off frequency of 10 Hz. The 3-D local coordinates of the L4-L5 marker in a pelvis reference frame were estimated using the 3-D coordinates of markers on the ASISs and TCIs in the standing calibration trail. The 3-D trajectories of the L4-L5 marker in the laboratory reference frame in isokinetic strength

Table 1
Intervention exercises (PNF = Proprioceptive neuromuscular facilitation; NHC = Nordic hamstring curl).

Group	Week	Exercises (30 s rest between sets, 1 min rest between exercise)			
Flexibility intervention	1	Walking knee lift (15 reps x 2 sets)	Sitting toe touch (40 sec/leg x 2 sets)	PNF stretch (50 sec/leg x 3 sets)	Foam roll (40 sec/leg x 3 sets)
	2–4	Lunge walk (15 reps x 2 sets)	Sitting toe touch (50 sec/leg x 3 sets)	PNF stretch (50 sec/leg x 3 sets)	Foam roll (50 sec/leg x sets)
	5–8	Lunge walk (15 reps x 2 sets)	Semi-straddle (60 sec/leg x 2 sets)	PNF stretch (50 sec/leg x 3 sets)	Foam roll (50 sec/leg x sets)
Strength intervention	1	NHC with bend (8 reps x 3 sets)	Prone hamstrings curl (12 reps x 4 sets)	Physio-ball leg curl (8 reps x 3 sets)	Glute bridge (50 sec/leg x 2 sets)
	2–4	NHC with bend (12 reps x 3 sets)	Prone hamstrings curl (14 reps x 3 sets)	Physio-ball leg curl (10 reps x 3 sets)	Glute bridge (50 sec/leg x 2 sets)
	5–8	NHC (12 reps x 3 sets)	Prone hamstrings curl (15 reps x 3 sets)	Physio-ball roll (10 reps/leg x 2 sets)	Glute bridge (60 sec/leg x 2 sets)

Table 2
The relative errors and coefficients of multiple correlations of the optimal length testing procedure.

Reliability measures	Variable	Pre- intervention	Post- intervention
Relative Error (% Femur length)	Semitendinosus optimal length	1.47 ± 1.61	1.31 ± 1.28
	Semimembranosus optimal length	1.76 ± 1.75	1.54 ± 1.44
	Biceps long head optimal length	1.69 ± 1.60	1.69 ± 1.49
Coefficient of Multiple Correlation	Semitendinosus optimal length	0.88	0.89
	Semimembranosus optimal length	0.84	0.85
	Biceps long head optimal length	0.90	0.85

testing trials were then estimated from its 3-D local coordinates and the 3-D trajectories of the markers on the ASISs and TCIs in each strength testing trial.

The moment generated by the hamstring (M_{Ham}) at a given time point during strength testing was reduced as the moment measured by the strength testing system minus the moment of the gravitational force on the shank and foot relative to the knee joint center. The moment of gravitational force was calculated from the mass of shank and foot, and the locations of the center of mass of shank plus foot and knee joint center.[14] The strength testing trial that had the maximal peak knee flexion moment was selected for further data reduction and used in data analysis. The maximal peak knee flexion moment was used as the measure of hamstring strength.[12]

The muscle length of a given hamstring muscle was determined as the distance between the origin and insertion of the muscle, and normalized to femur length defined as the distance between hip and knee joint centers. The 3-D trajectories of the origins and insertions of each hamstring muscle in the laboratory reference frame were calculated from the location and orientation of the corresponding segment reference frames and the 3-D local coordinates of the origins and insertions in the corresponding segment reference frames. The detailed calculations can be found elsewhere[12].

The total force generated by the hamstring muscles (F_{Ham}) at a given time during the strength testing was calculated as

$$F_{Ham} = \frac{M_{Ham}}{P_{BL}R_{BL} + P_{BS}R_{BS} + P_{SM}R_{SM} + P_{ST}R_{ST}}$$

where P_{BL}, P_{BS}, P_{SM}, and P_{ST} were relative physiological cross sectional areas (PCSA) of biceps long head (28.54%), biceps short head (12.88%), semimembranosus (46.46%), and semitendinosus (12.12%), respectively, while R_{BL}, R_{BS}, R_{SM}, and R_{ST} were the moment arms of these four muscles relative to the knee joint center, respectively.[12] The moment arm of each of the four hamstring muscles was calculated as the distance between the knee joint center and the action line of the corresponding muscle in the sagittal plane of the shank. The force generated by an individual hamstring muscle at a given time was calculated as the total force generated by hamstring muscles times the relative PCSA of the given hamstring muscle. The peak force of each individual hamstring muscle was identified for each leg. Muscle-tendon unit optimal length of each individual hamstring muscle was identified as the muscle-tendon unit length corresponding to the peak force generated by the given hamstring muscle.

Between participant coefficients of multiple correlation (CMC) and within participant relative errors in range of hip joint flexion, strengths, and hamstring optimal lengths were calculated to evaluate the reliability of these measures. To test our first hypothesis, the range of hip joint flexion and hamstring strengths and optimal lengths of hamstring flexibility intervention group were compared between pre- and post-intervention tests for each gender using paired T-tests. To test our second hypothesis, the range of hip joint flexion and hamstring strength and optimal lengths of the hamstring strength intervention group were compared between pre- and post-intervention tests for each gender using paired T-tests. All data analyses were performed using Version 18.0 of SPSS computer program package for statistical analyses (SPSS, Chicago, IL, USA). Statistical significance was defined as the type I error rate lower than or equal to 0.05.

3. Results

Two female participants in each of flexibility and strength intervention groups had incomplete data for one leg in pre or post-test. Therefore, 40 and 36 legs were actually used for male and female participants, respectively, in data analyses. The mean within participant errors in estimated hamstring optimal lengths were no greater than 1.76% of femur length while the between participant CMCs of estimated hamstring optimal lengths were no less than 0.84 (Table 2).

The range of hip joint flexion of male participants in the flexibility intervention group was significantly increased in the post-intervention test compared to the pre-intervention test ($P = 0.001$) (Table 3), while hamstring strength of this group was not significantly changed in the post-intervention test ($P = 0.393$) (Table 3). Optimal lengths of the semimembranosus and biceps long head of this group of male participants were also significantly increased in the post-intervention test ($P = 0.011$, $P = 0.026$) (Table 3), while no significant increase in optimal length of the semitendinosus was observed ($P = 0.060$) (Table 3).

Table 3
Training effects on range of hip joint flexion, strength, and optimal lengths.

Sex	Group	Variable	Pre- intervention	Post- intervention	P-value	Cohen's D effect sizes
Male	Flexibility Intervention (n = 40)	Range of hip joint flexion (deg)	96.7 ± 10.3	114.5 ± 12.7	0.001	2.00
	Age = 20.6 ± 1.6 (years)	Hamstring strength (N m)	142.0 ± 40.9	140.5 ± 31.1	0.393	−0.06
	Body Mass = 70.5 ± 5.2 kg	Semitendinosus optimal length (% Femur length)	1.06 ± 0.04	1.08 ± 0.04	0.060	0.37
	Standing Height = 1.79 ± 0.04 m	Semimembranosus optimal length (% Femur length)	1.04 ± 0.04	1.07 ± 0.04	0.011	0.58
		Biceps long head optimal length (% Femur length)	1.04 ± 0.04	1.06 ± 0.05	0.026	0.47
	Strength Intervention (n = 40)	Range of hip joint flexion (deg)	93.6 ± 6.9	97.9 ± 11.6	0.037	0.43
	Age = 20.8 ± 2.0 (years)	Hamstring strength (N m)	108.8 ± 34.3	118.5 ± 35.8	0.001	0.80
	Body Mass = 64.0 ± 3.2 kg	Semitendinosus optimal length (% Femur length)	1.05 ± 0.05	1.07 ± 0.03	0.041	0.42
	Standing Height = 1.74 ± 0.03 m	Semimembranosus optimal length (% Femur length)	1.04 ± 0.04	1.06 ± 0.03	0.003	0.70
		Biceps long head optimal length (% Femur length)	1.02 ± 0.05	1.04 ± 0.03	0.009	0.47
Female	Flexibility Intervention (n = 36)	Range of hip joint flexion (deg)	108.1 ± 16.1	129.4 ± 14.2	0.001	3.15
	Age = 21.6 ± 1.4	Hamstring strength (N m)	77.9 ± 22.4	85.5 ± 27.0	0.009	0.64
	Body Mass = 55.6 ± 5.1 kg	Semitendinosus optimal length (% Femur length)	1.06 ± 0.06	1.07 ± 0.03	0.100	0.32
	Standing Height = 1.65 ± 0.05 m	Semimembranosus optimal length (% Femur length)	1.05 ± 0.05	1.06 ± 0.03	0.107	0.31
		Biceps long head optimal length (% Femur length)	1.02 ± 0.06	1.04 ± 0.03	0.097	0.33
	Strength Intervention (n = 36)	Range of hip joint flexion (deg)	115.6 ± 17.5	127.2 ± 19.2	0.001	1.44
	Age = 20.8 ± 1.5	Hamstring strength (N m)	67.8 ± 18.9	80.3 ± 18.3	0.001	1.19
	Body Mass = 57.1 ± 6.4 kg	Semitendinosus optimal length (% Femur length)	1.08 ± 0.05	1.08 ± 0.04	0.483	−0.01
	Standing Height = 1.63 ± 0.05 m	Semimembranosus optimal length (% Femur length)	1.06 ± 0.05	1.06 ± 0.04	0.387	0.07
		Biceps long head optimal length (% Femur length)	1.05 ± 0.06	1.05 ± 0.05	0.406	0.06

Hamstring strength as well as the range of hip joint flexion of male participants in the strength intervention group was significantly increased in the post-intervention test compared to the pre-intervention test (P = 0.001, P = 0.037) (Table 3). Hamstring optimal lengths of this group of male participants were all significantly increased in the post-intervention test compared to the pre-intervention test (P = 0.041, P = 0.003, P = 0.009) (Table 3).

The range of hip joint flexion as well as hamstring strength of female participants in the flexibility intervention group was significantly increased in the post-intervention test compared to the pre-intervention test (P = 0.001, P = 0.009) (Table 3). No significant changes in hamstring optimal lengths were observed in the post-intervention test (P = 0.100, P = 0.107, P = 0.097) (Table 3).

The hamstring strength as well as the range of hip joint flexion of female participants in the strength intervention group was significantly increased in the post-intervention test compared to the pre-intervention test (P = 0.001, P = 0.001) (Table 3). No significant change in hamstring optimal lengths was observed in the post-intervention test (P = 0.483, P = 0.387, P = 0.406) (Table 3).

4. Discussion

The results of this study partially support our first hypothesis that a hamstring flexibility intervention would increase the range of hip joint flexion and optimal lengths, but not hamstring strength. The results for the male participants support this hypothesis. The range of hip joint flexion and optimal lengths of the semimembranosus and biceps long head of the male participants were significantly increased after the eight weeks of hamstring flexibility intervention, while no significantly change in muscle strength was observed. The results for female participants in the flexibility intervention group, however, did not support our first hypothesis, as their range of hip joint flexion as well as strength was significantly increased after eight weeks of flexibility intervention, but their hamstring optimal lengths were not significantly changed.

The results for male participants in the flexibility intervention group were consistent with the literature. Previous studies have shown that the knee flexion angle corresponding to maximal knee flexion moment decreased as hamstring flexibility score increased,[15,16] suggesting that increasing hamstring flexibility might result in an increase in hamstring optimal lengths. The findings support previous studies using animal models showing that a flexibility intervention increased muscle optimal length due to an increase in the number of sarcomeres in series.[17,18]

The increase in hamstring strength for female participants in the flexibility intervention group was also consistent with the literature. Several studies have shown that flexibility exercises resulted in strength gains for college students.[19,20] The mechanisms how flexibility interventions induced increase in strength, however, are still unclear. Several possibilities have been proposed including increased motor unit recruitment and activation, and increased reflex sensitivity.[19] Stretching of a muscle-tendon unit may also affect neuromuscular transmission. Yamashita et al. demonstrated that Ca^{2+} conductance of the nerve terminal of the neuromuscular junction could be increased by muscle stretching.[21] The male participants in the flexibility intervention group of this study, however, did not significantly increase hamstring strength, a finding inconsistent with the literature. A possible explanation is that the effects of flexibility interventions on strength is limited to individuals with relatively low strength, with male participants in the flexibility intervention group of our study already having relatively high hamstring strength before flexibility intervention. Further study is needed to further confirm the effects of flexibility interventions on strength, and understand the underlying mechanism.

The optimal hamstring lengths of female participants in the flexibility intervention group did not change despite the increase in the range of hip joint flexion after eight weeks. The most likely explanation is that the eight weeks of flexibility intervention did not actually increase flexibility of hamstring muscle-tendon units for the female participants. As pointed out previously, the range of hip joint flexion in PSLR test represents the combined flexibility of the hamstring muscle-tendon units and the hip joint. The increase in the range of hip joint flexion of female participants in the flexibility intervention group was therefore likely due mainly to an increase in hip joint flexibility. Considering that female participants had greater range of hip joint flexion in the pre-intervention test compared to male participants, the correlation between hamstring optimal lengths and the range of hip joint flexion [12] may be limited to a certain range of magnitude of the range of hip joint flexion. Accordingly, it is possible that increasing range of hip joint flexion beyond a certain magnitude may not further increase hamstring optimal lengths.

Our results partially support our second hypothesis that a hamstring strength intervention would significantly increase hamstring strength and optimal lengths, but not flexibility. Both male and female participants in strength intervention group significantly increased both hamstring strength and the range of hip joint flexion, which do not support our second hypothesis in terms of the effects of strengths intervention on the range of hip flexion. Several studies have shown that a strength intervention could increase flexibility measured as range of joint motion in elderly and middle-aged women.[22,23] Our strength interventions include eccentric strength exercises, in which the muscle-tendon unit was passively stretched or actively lengthening at the extreme range of motion.[24] Muscle flexibility could be increased because of increased tensile strength of tendons and ligaments,[22] decreased passive resistive torque,[25] and decreased series elastic component stiffness.[26]

The male participants in the strength intervention group increased hamstring optimal lengths, which support our second hypothesis. A previous study demonstrated that the knee flexion angle corresponding to the maximal knee flexion moment decreased as hamstring strength increased,[27] suggesting that increasing hamstring strength resulted in an increase in optimal lengths of hamstring muscle-tendon units. A study also showed that strength training increased muscle optimal length due to an increase in the number of sarcomeres in series.[28] The female participants in the strength intervention group, however, did not increase hamstring optimal lengths, which do not support our hypothesis and is inconsistent with literature. A possible explanation for this lack of effect is that our strength intervention was not long enough in duration to induce an increase in muscle optimal length. Strength gain is a result of increased muscle activation or muscle hypertrophy, or both.[29] Female participants in the strength intervention group might still have been in an early stage of training, and their increase in hamstring strength might be mainly due to increased muscle activation without significant muscle hypertrophy or increase in the number of sarcomeres in series.[28,30] Another possible explanation is that the effect of strength intervention on hamstring optimal lengths may depend on hamstring optimal lengths before the intervention. Strength intervention may induce an increase in the number of sarcomeres in series when muscle optimal length is within a certain range before the intervention. The optimal lengths of female participants in this study might be beyond this range.

Based on our findings, hamstring optimal length should be considered as a flexibility measure in future prospective studies to identify risk factors of hamstring injury. Previous prospective studies on risk factors of hamstring injury using the range of hip joint flexion as a measure of hamstring flexibility similar to the one used in this study had inconsistent results.[2–4] A likely explanation of this inconsistency is that the range of hip joint flexion is not an appropriate measure of hamstring flexibility. As previous described, hamstring optimal lengths are directly related to hamstring strain while hamstring injury is mainly due to hamstring strain[12,13]. Also, the range of hip joint flexion in PSLR test depends on hamstring flexibility and hip joint flexibility. Our previous and present studies showed that the range of hip joint flexion in PSLR test was not strongly correlated to hamstring optimal lengths,[12] and that hamstring optimal lengths may not change as the range of hip joint flexion changed. Our results also demonstrate that the estimated hamstring optimal lengths are reliable. These findings support the use of hamstring optimal length as a measure of true hamstring flexibility in future prospective studies.

Although the current study evaluated the effects of hamstring flexibility and strength interventions on hamstring optimal lengths, further investigations are needed to confirm the effects of these interventions on peak hamstring strains to provide further evidence supporting the role of these interventions in prevention of hamstring injury. Also, the current study only evaluated immediate effects of hamstring flexibility and strength interventions on hamstring optimal lengths. Additional studies are needed to determine the retention of these intervention effects on hamstring optimal lengths and peak strains after the intervention is stopped. Finally, although the current study provided theoretical support to the roles of flexibility and strength interventions in the prevention of hamstring injury for male individuals, future studies are needed to investigate the effects of our interventions on the biomechanics of the hamstrings to understand prevention of hamstring injury in females.

5. Conclusions

1 Increasing the range of hip joint flexion in PSLR test can increase hamstring optimal lengths for males.
2 Increasing hamstring strength through concentric and eccentric exercises can increase hamstring optimal lengths for males.
3 The flexibility and strength interventions in this study resulted in significant increases in the range of hip joint flexion in PSLR test and strength, but did not lead to increases in hamstring optimal lengths for females.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jsams.2019.09.017.

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