Effect of an Eccentrically Biased Hamstring Strengthening Home Program on Knee Flexor Strength and the Length-Tension Relationship

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Abstract

Orishimo, KF and McHugh, MP. Effect of an eccentrically biased hamstring strengthening home program on knee flexor strength and the length-tension relationship. *J Strength Cond Res* 29(3): 772–778, 2015—The purposes of this study were to document relative activation intensities of the hamstrings and gluteus maximus during 4 eccentric hamstring strengthening exercises and to assess the effects of a short-term strengthening program comprised of these exercises on knee flexor strength and the length-tension relationship. Twelve healthy subjects participated in this study. Electromyographic (EMG) activities from the biceps femoris, semitendinosus, and gluteus maximus were recorded as subjects performed (a) standing hip extension with elastic resistance, (b) trunk flexion in single limb stance (diver), (c) standing split (glider), and (d) supine sliding bridge (slider). Baseline isometric knee flexor strength was measured at 90, 70, 50, and 30° of flexion at the knee with the subject seated and the hip flexed to 50° from horizontal. After completing the 4-week training program, strength tests were repeated. Repeated-measures analysis of variance were used to compare EMG activity between muscles and to assess angle-specific strength improvements. Hamstring activity exceeded gluteus maximus activity for resisted hip extension, glider, and slider exercises ($p < 0.001$) but not for the diver ($p = 0.087$). Hamstring activation was greatest during the slider and resisted hip extension and lowest during the glider and the diver. Knee flexor strength improved by 9.0% ($p = 0.005$) but was not angle specific (training by angle $p = 0.874$). The short-term home training program effectively targeted the hamstrings and resulted in strength gains that were similar at short and long muscle lengths. These data demonstrate that hamstring strength can be improved using eccentrically biased unilateral exercises without the use of weights or other equipments.

Key Words strength profiles, EMG, eccentric training, unilateral exercises

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Introduction

Hamstring strains are a very common injury in many sports (7,11,28). Recurrence rates for this injury have been reported to be as high as 30% (16,21). Research has suggested that the high incidence of recurrence could be due to continued eccentric hamstring weakness as well as impaired hamstring/quadriceps strength ratios (9,10). In addition to the injured side being weaker, the optimal angle for torque production in injured hamstrings has been shown to occur at a shorter muscle length compared with the uninjured side (6,23). This shift in the angle of peak torque was evident despite the fact that peak torque was not different between involved and noninvolved hamstrings. A shift in the length-tension relationship most likely impairs the hamstring's ability to resist rapid stretching during high-speed athletic maneuvers, making the muscle more susceptible to injury (8,24).

Eccentric hamstring exercises have been shown to increase muscle strength and to cause a shift in the angle of peak torque to a longer muscle length (5,14,20), making them an essential component in effective rehabilitation protocols (12,13,27). In a recent study of the mechanics of hamstring muscles during sprinting, Schache et al. (24) concluded "hamstring injury prevention or rehabilitation programs should preferentially target strengthening exercises that involve eccentric contractions with high loads at longer musculotendon lengths." Additionally, Schmitt et al. (25) have also advocated the use of "lengthened state" eccentric exercise to improve hamstring strength at the end of the range of motion. The lengthened state is achieved by combining maximal or near-maximal hip flexion and knee extension. Thus, the knee flexors are stretched over both the hip and knee articulations. This type of training, however, requires the use of an isokinetic dynamometer, which may not be readily available in most physical therapy clinics. Therefore, identifying which eccentric hamstring exercises produce similar physiologic adaptations while requiring minimal equipment may improve the efficacy of rehabilitation and injury prevention protocols and allow patients to perform these protocols in the home.

In a prospective randomized controlled clinical trial, Askling et al. (3) demonstrated a 45% reduction in the time to return to sport after a hamstring injury using eccentric exercises that required no equipment and used body weight for resistance. Additionally, there were no reinjuries during the 1-year follow-up period in the eccentric training group. Although this eccentrically biased rehabilitation protocol has been shown to result in a faster return to sport and seems to protect against reinjury, the underlying causes of these clinical results are not fully understood. The actual training stimulus (i.e., relative muscle activity levels) for such exercises and the effect of these exercises on strength improvements and the length-tension relationship of the knee flexors has not been established.

The main objectives of this study were (a) to document relative activation intensities of the hamstrings and gluteus maximus during 4 eccentric hamstring strengthening exercises and (b) to assess the effects of a short-term strengthening program comprised of these exercises on knee flexor strength and the length-tension relationship. We hypothesized that this protocol would improve strength and produce a rightward shift in knee flexor length-tension relationship (i.e., increased strength at long muscle lengths). A 4-week training duration was chosen to replicate the typical duration of a hamstring rehabilitation protocol (3,26).

Methods

Experimental Approach to the Problem

This study examined the effect of an eccentric hamstring strengthening home program on the length-tension relationship in healthy active individuals through a pre-post research design. Electromyographic (EMG) analysis of each exercise was first performed to confirm that the hamstrings were being targeted by the exercises included in the training program. Baseline isometric knee flexor strength measurements were then made at 4 knee angles (90, 70, 50, and 30°) with the subject seated in an isokinetic dynamometer with the hip flexed to 50° from the horizontal. The subjects then performed the training program 3 times a week for 4 weeks. After the training period, subjects' isometric knee flexor strength was retested under the same conditions. Repeated-measures analysis of variance (ANOVA) was used to compare EMG activity between muscles and exercises and to assess improvements in isometric strength at each knee angle after training.

Subjects

Twelve healthy uninjured subjects (9 men and 3 women) participated in this study (age: 32 ± 10 years; height: 1.7 ± 0.2 m; weight: 75.4 ± 8.6 kg). For inclusion, subjects had to have been free of injury to their lower extremities at the time of testing, have no lower extremity or hamstring injuries within the past 6 months, and have no knee surgeries within the past year. Before participation, subjects provided written informed consent in accordance with institutional review board regulations.

Procedures

Strength Testing. Baseline isometric strength was assessed with subjects seated in a dynamometer (Biodex, System 2, Shirley, NY, USA) with the hip flexed to 50° from horizontal. Knee flexor strength on the dominant and nondominant leg was measured at 90, 70, 50, and 30° of flexion at the knee (18,19). Hamstring flexibility was also measured as the angle of maximum knee extension tolerated in this position. After the baseline test, subjects were given the training program to be performed 3 times per week for 4 weeks. After completion of the training program, strength and flexibility tests were repeated.

Training Program. The training program consisted of 4 exercises designed to be performed unilaterally. Three exercises have been previously described by Askling et al. (3): (a) standing hip extension, (b) standing trunk flexion (diver), and (c) standing split (glider). The fourth exercise was a sliding supine eccentric bridge (slider). For this exercise, subjects performed a supine single-leg bridge and then lowered their torso to the floor by extending the knee of the supporting leg and sliding the foot forward (Figure 1). A repetition was completed when the subject's body was lowered to the floor and the subject returned to the starting position by sliding both feet into full knee flexion with the torso still on the floor, then assuming the bridge position and lifting 1 leg off the floor. This technique ensured (a) that subjects performed the eccentric phase through the full range of motion and (b) that the subjects performed minimal concentric contraction. The training program was performed 3 times per week for 4 weeks. In the first week, subjects performed 3 sets of 10 repetitions of each exercise. This was progressed to 3 sets of 12 repetitions in the second week and 3 sets of 15 repetitions in the third and fourth weeks. In each training session, the exercise order was standing hip extension, the diver, the glider, and the slider. Each exercise was first performed by 1 leg, then the contralateral leg before moving to the next exercise. All subjects were given a workout log to monitor compliance and to guide the weekly exercise volume progression.

Electromyographic Analysis. Nine of 12 subjects underwent EMG testing. Surface EMG data were acquired as subjects performed 5 repetitions of each of the 4 strength training exercises on each leg using a 16-channel BTS FREEEMG 300 system (CMRR: >110 dB at 50–60 Hz; Input Impedance: >10 GΩ; BTS Bioengineering, Milan, Italy). After shaving, cleaning, and lightly abrading the skin of each subject, muscle activity was sampled at 1000 Hz using disposable Ag/AgCl passive dual electrodes (2.0 cm interelectrode distance) (Noraxon, Scottsdale, AZ, USA).

Electrodes were placed over the biceps femoris (long head), semitendinosus, and gluteus maximus muscles. For the biceps femoris, electrodes were placed 50% of the distance from the iscial tuberosity to the fibular head. For the semitendinosus, electrodes were placed 50% of the distance from the iscial tuberosity to the medial joint line of the knee. For the gluteus maximus, electrodes were placed

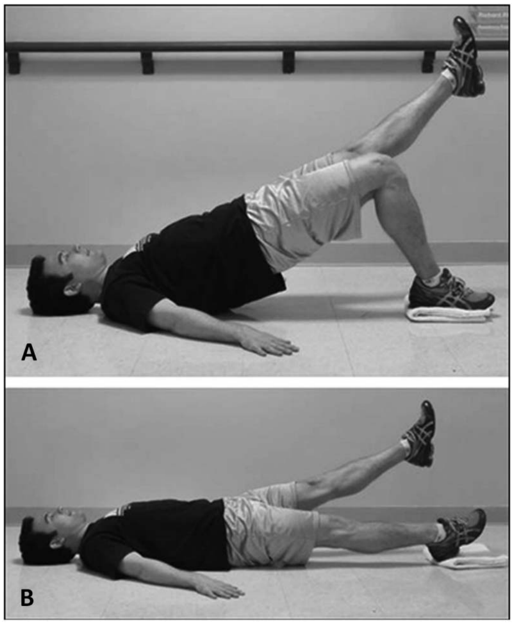

Figure 1. The slider subjects performed: (A) a supine single-leg bridge and then (B) lowered their torso to the floor by extending the knee of the supporting leg and sliding the foot forward until full extension was reached.

in the center of the muscle belly between the lateral border of the sacrum and the greater trochanter. In addition to the EMG electrodes, an electronic goniometer was placed from the lower torso to the greater trochanter to measure sagittal plane hip motion relative to the torso as the subjects performed the exercises. From these measurements, the concentric and eccentric phases of each exercise were defined.

Electromyographic data were high-pass filtered at 10 Hz to eliminate motion artifact and then full-wave rectified and smoothed using a root mean square calculation with a window of 100 milliseconds. The peak EMG activation level for each muscle during both the concentric and eccentric phases of each repetition was then identified. The mean activation level of each muscle from 250 milliseconds before the peak to 250 milliseconds after the peak was calculated and averaged over the 5 repetitions. After processing, the EMG data were normalized to the maximum EMG activities recorded during maximal voluntary isometric contractions (MVIC) of the knee flexors and hip extensors and expressed as a percent.

Maximal Voluntary Isometric Contractions. Subjects performed a 5-second MVIC of the knee flexors in the standing position with the knee flexed to about 60° and the trunk flexed approximately 20°. A 5-second MVIC of the hip extensors was also performed in the standing position with 90° of flexion at the knee and 10° of hip extension. After filtering and smoothing, the normalization values from the MVIC trials were obtained by first identifying the peak activation level and then calculating the average from 250 milliseconds before the peak to 250 milliseconds after the peak.

Statistical Analyses

All statistical analyses were performed using IBM SPSS Statistics (version 21.0; IBM Corp., Armonk, NY, USA). For the muscle activity data, an exercise (resisted hip extension, diver, glider, and slider) by phase (concentric and eccentric) by muscle (biceps femoris, semitendinosus, and gluteus maximus) repeated-measures ANOVA was used to compare EMG activation across exercises and muscles during the eccentric and concentric phases. Univariate ANOVAs and pairwise tests with Bonferroni corrections for multiple comparisons were used as post hoc tests when the ANOVA identified statistically significant differences for the main effects of phase, muscle, or exercise or their interactions. Based on the variability in repeated measures of semitendinosus and biceps femoris EMG activity during isometric contractions (19), it was estimated that there was 80% power to detect an 8% difference in EMG activity between exercises at the $p = 0.05$ level of significance.

For the strength tests, a side (dominant and nondominant) by training (pre to post) by knee angle (90, 70, 50, and 30°) repeated-measures ANOVA was used to assess the effects of limb dominance and the training program on knee flexor strength and the length-tension relationship. Univariate ANOVAs and pairwise tests with Bonferroni corrections for multiple comparisons were used as post hoc tests when the ANOVA identified statistically significant differences for the main effects of side, training, or knee angle or their interactions. A paired *t*-test was also used to compare hamstring flexibility before and after the training period. $p \leq 0.05$ was considered significant for all statistical tests. Based on the variability in measures of isometric hamstring strength repeated 2 weeks apart (17), it was estimated that there was 80% power to detect a 10% difference in isometric hamstring strength following the training protocol at the $p = 0.05$ level of significance.

Results

Electromyography

Electromyographic activities were affected by exercise, phase, and muscle (exercise × phase × muscle interaction: $p < 0.001$, $F = 10.229$, partial $\eta^2 = 0.376$). Muscle activity varied between the concentric and eccentric phases of each exercise for the biceps femoris (exercise × phase interaction, $p < 0.001$, $F = 144.840$, partial $\eta^2 = 0.895$), semitendinosus (exercise × phase interaction, $p < 0.001$, $F = 74.077$, partial $\eta^2 = 0.813$), and gluteus maximus (exercise × phase interaction, $p < 0.001$, $F = 44.152$, partial $\eta^2 = 0.722$). For all 3 muscles, the diver and glider produced greater EMG activity during the concentric phase compared with the eccentric

Table 1. Peak activation levels (%maximal voluntary isometric contraction [*SD*]) for each muscle during the eccentric and concentric phases of the 4 exercises.*

	Biceps femoris		Semitendinosus		Gluteus maximus	
	Eccentric	Concentric	Eccentric	Concentric	Eccentric	Concentric
Resisted hip extension	63.0 (30.7)†	65.0 (35.0)†	81.2 (30.0)†	85.8 (34.6)†	32.9 (17.8)	32.6 (16.7)
Diver	23.7 (11.2)	43.8 (17.2)†‡	33.9 (13.2)	57.4 (17.5)†‡	30.0 (15.1)	43.5 (15.9)‡
Glider	34.4 (28.9)†§	61.5 (26.5)†‡	50.1 (26.7)†	82.3 (33.9)†‡	19.3 (9.7)	45.5 (18.8)‡
Slider	93.0 (27.4)†‡	30.1 (14.8)	108.5 (36.8)†‡	44.4 (18.6)	68.0 (29.6)‡	39.1 (27.7)

*See Results section for details on the differences in muscle activation among the 4 exercises.
†Biceps femoris or semitendiosus activity greater than gluteus maximus ($p \leq 0.05$).
‡Electromyographic activity different between concentric and eccentric phases ($p \leq 0.05$).
§Electromyographic activity different between biceps femoris and semitendinosus ($p \leq 0.05$).

phase ($p < 0.001$, respectively). Conversely, the slider produced higher EMG activities in all muscles during the eccentric phase compared with the concentric phase ($p < 0.001$, respectively) (Table 1).

Activation of the biceps femoris, semitendinosus, and gluteus maximus in the eccentric phase varied among the 4 exercises (exercise × muscle interaction: $p < 0.001$, $F = 6.408$, partial $\eta^2 = 0.274$). Resisted hip extension (main effect

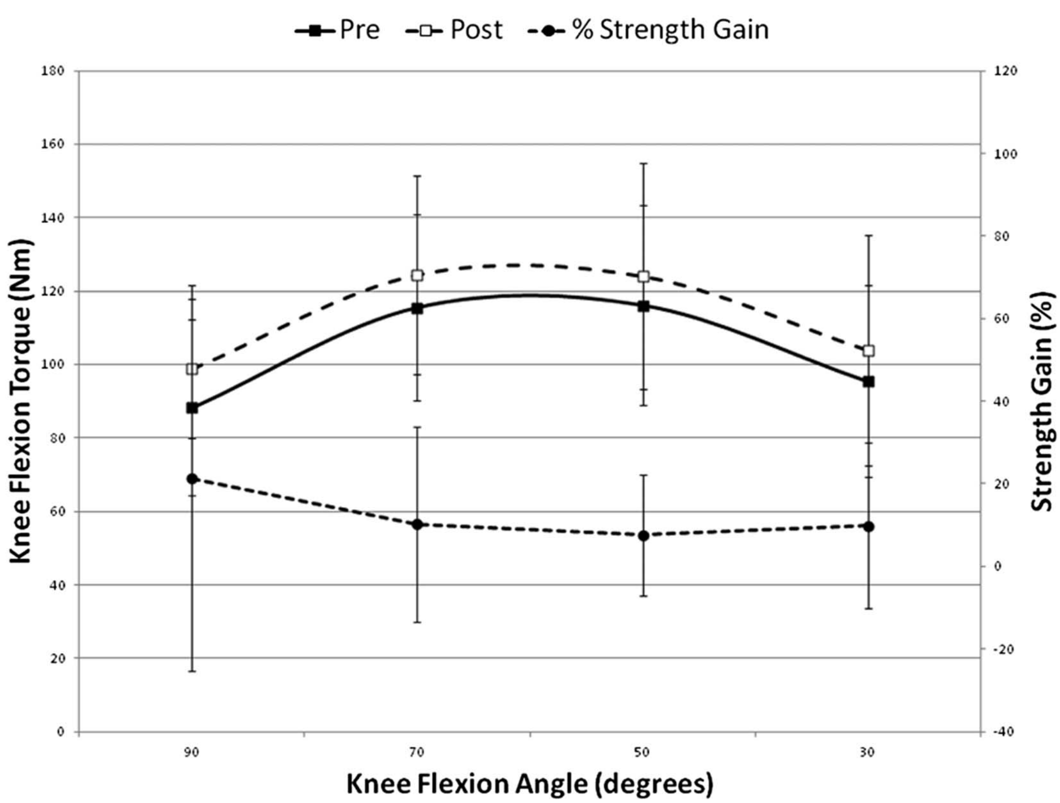

Figure 2. Pre- and post-training knee flexor strength knee flexor strength improved by 9% (main effect of training: $p = 0.005$), but strength gains were similar at short and long muscle lengths (training by angle $p = 0.874$).

of muscle: $p < 0.001$, $F = 20.356$, partial $\eta^2 = 0.545$), the glider ($p < 0.001$, $F = 18.866$, partial $\eta^2 = 0.526$), and the slider ($p = 0.001$, $F = 8.402$, partial $\eta^2 = 0.331$) all recruited the hamstrings to a greater level compared with the gluteus maximus. During resisted hip extension, peak EMG activation for the biceps femoris (63.0% MVIC) and semitendinosus (81.2% MVIC) were similar ($p = 0.133$), and both were greater than that of the gluteus maximus (32.8% MVIC; $p = 0.001$ and $p = 0.001$, respectively). The glider activated the semitendinosus the more than the biceps femoris and gluteus maximus (50.1% vs. 34.4% and 19.3% MVIC $p < 0.001$; biceps femoris and gluteus maximus not different $p = 0.069$). The slider activated the biceps femoris (93.0% MVIC) and the semitendinosus (108.5% MVIC) to similar levels ($p = 0.346$), which both were significantly greater compared with the gluteus maximus (68.0% MVIC, $p = 0.035$ and $p = 0.008$, respectively). Finally, all muscles were activated to similar levels during the diver (biceps femoris: 23.7% MVIC, semitendinosus: 33.9% MVIC and gluteus maximus: 30.0% MVIC) (Table 1).

For both the biceps femoris and the semitendinosus, the slider produced the highest EMG activities, followed by resisted hip extension, the diver, and the glider. Gluteus maximus activity was also highest during the slider and no difference in peak activity was found among the other 3 exercises (Table 1).

Muscle activation during the concentric phase also varied among the 4 exercises (exercise × muscle interaction: $p < 0.001$, $F = 9.749$, partial $\eta^2 = 0.364$). Resisted hip extension (main effect of muscle: $p < 0.001$, $F = 23.369$, partial $\eta^2 = 0.579$), the diver ($p = 0.014$, $F = 4.863$, partial $\eta^2 = 0.223$), and the glider ($p < 0.001$, $F = 11.950$, partial $\eta^2 = 0.413$) all activated the hamstrings to a greater level than the gluteus maximus (Table 1).

Biceps femoris activation during concentric phase of the slider was significantly less compared with resisted hip extension ($p = 0.001$), the diver ($p < 0.001$), and the glider ($p < 0.001$). Similarly, semitendinosus activity was significantly less during the concentric phase of the slider compared with the other exercises ($p \leq 0.05$, respectively) (Table 1).

Strength Testing

Limb dominance did not affect any of the knee flexor strength measurements (main effect of side: $p = 0.801$, $F = 0.066$, partial $\eta^2 = 0.006$). On average, knee flexor strength improved by 9% ($p = 0.033$, $F = 5.939$, partial $\eta^2 = 0.351$), although this improvement was not angle specific (training by angle $p = 0.940$, $F = 0.133$, partial $\eta^2 = 0.012$; Figure 2). Seven lower extremities improved their overall knee flexor strength by 20% or greater (high responders), 5 by 10–20% (moderate responders), and 12 by less than 10% (low responders). Maximum knee extension angle (i.e., hamstring flexibility) was increased by 6 ± 6° (34%) following the training protocol ($p < 0.001$). When entered into the ANOVA as a covariate, neither baseline flexibility ($p = 0.202$, $F = 1.726$, partial $\eta^2 = 0.073$) nor baseline strength ($p = 0.759$, $F = 0.096$, partial $\eta^2 = 0.004$) affected the improvement in knee flexor strength.

Discussion

Our study found that the hamstring strengthening home program targeted the hamstrings to a high level and significantly improved overall knee flexor strength. The strength improvements, however, were not apparent at longer muscle lengths. A possible reason for this could be the fact that the hamstrings were not sufficiently lengthened during the eccentric phases of these exercises to produce a shift in the length-tension relationship. As advocated by Schmitt et al. (25), maximal or near-maximal hip flexion combined with knee extension stretches the knee flexors across both articulations and places the muscle on the descending limb of the length-tension relationship, which can improve strength at the end of the range of motion. The exercises highlighted in this study involve movements, which do not lengthen the hamstrings over both articulations. Lengthening is achieved from movement at either the hip (hip extension, diver, and glider) or the knee (slider) but not at both joints simultaneously.

Additionally, a rightward shift in the length-tension relationship of the hamstrings has only been demonstrated using purely eccentric exercises, for example the Nordic hamstring exercise (5). Although the diver and the glider were part of Askling's eccentric "L-protocol" (3), there was also substantial hamstring activation during the concentric phases of these exercises. For example, the high EMG activity during the concentric phase of the glider occurred at the beginning of the concentric phase to initiate movement from a stretched position. (i.e., to return to the starting position). The slider, by contrast, elicited near-maximal hamstring activation during the eccentric phase with substantially lower activation during the unloaded concentric phase. It is important to note that the muscle force associated with a given EMG amplitude is markedly higher for eccentric contractions vs. concentric contractions (4,15,22). Thus, low activation for eccentric contraction may still provide a training stimulus. However, in terms of the length-tension relationship, the effects of the moderate- to high-intensity concentric contractions during these exercises may counteract the effects of the eccentric phases.

Despite not shifting the length-tension relationship, the exercises examined in this study improved overall strength and flexibility and may enhance core control, all of which have been shown to be instrumental in reducing primary and secondary hamstring strains (1,2,26). Strength exercises that combine elements of balance and flexibility may accelerate an athlete's progression through rehabilitation to the return to sport phase, as opposed to using exercises, which address each element individually. Improvement in these areas may explain the superior clinical results reported by Askling et al. (3) in the training group performing these exercises. It should also be noted that most of the exercises in this training program used only body weight as resistance. Although it is encouraging that a 9% improvement in overall knee flexor strength was achieved using very little equipment, it is possible that greater improvements may be made by adding resistance to some of these exercises. For example, holding dumbbells while performing the diver or wearing a weighted vest during the glider and slider may increase the intensity and lead to increased strength gains.

To the best of our knowledge, only the Nordic hamstring exercise and the stiff-legged deadlift have been shown to produce a shift in the length-tension relationship of the knee flexors (5,14). Although these exercises have been shown to activate the hamstrings to a similar intensity level to the hip extension and slider exercises (29), they are bilateral (i.e., performed on both legs simultaneously), which could allow for 1 side to compensate for the other and to further reinforce side-to-side strength imbalances in patients rehabilitating a hamstring strain. An advantage of the exercises described in this study are that they are performed unilaterally (i.e., performed on 1 leg at a time). This may have the benefits of reducing any lingering side-to-side strength differences and, as most of these exercises require only body weight as the primary source of resistance, the need for any extra equipment.

The implications of this work must be interpreted in light of a few limitations. First, healthy injury-free subjects were used for this study. All subjects were injury free at the time of testing and had no hamstring injuries in the past 6 months. Although this study has shown an increase in overall knee flexor strength in a healthy population, the effect of this protocol on the length-tension relationship in injured subjects is unknown. Brockett et al. (6) showed that the angle of peak torque is shifted to the left (i.e., toward shorter muscle lengths) in previously injured athletes. However, a rightward shift in the length-tension relationship after eccentric training has not been demonstrated in an injured population. Future research is needed to determine the effect of this training protocol, or similar protocols, on the length-tension relationship of the knee flexors in injured subjects. Second, the variability inherent in surface EMG recordings did not make it possible to determine whether small differences in activity between hamstring muscles during each exercise were significant. We were able to show a general hierarchy in terms of overall muscle activation among the 4 exercises.

In conclusion, overall hamstring strength was improved after a 4-week eccentric training program. Three of the 4 exercises (resisted hip extension, glider, and slider) effectively targeted the hamstrings with small contributions from the gluteus maximus. Although this short-term home training program resulted in a small but significant strength improvement, there was no shift in the length-tension relationship to greater strength at longer muscle lengths. Future research is needed to design eccentric exercises, which place the hamstrings in the lengthened state and require little or no equipment.

Practical Applications

The results of this study demonstrate that hamstring strength can be improved using eccentrically biased unilateral exercises without the use of weights or other equipment. This targeted training program, which uses simple exercises and minimal equipment, can be performed in the home or in the gym and is easily adapted to different athletic populations and settings. Despite being effective in increasing the overall strength of the hamstrings over the 4-week training period, this training protocol did not result in a rightward shift in the length-tension relationship. In addition to increased strength, the increased core stability, balance, and flexibility gained from performing these exercises may help to prevent hamstring strains.

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