

Rehabilitation After Hamstring-Strain Injury Emphasizing Eccentric Strengthening at Long Muscle Lengths: Results of Long-Term Follow-Up

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Context: Hamstring-strain injuries have a high recurrence rate. **Objective:** To determine if a protocol emphasizing eccentric strength training with the hamstrings in a lengthened position resulted in a low recurrence rate. **Design:** Longitudinal cohort study. **Setting:** Sports-medicine physical therapy clinic. **Participants:** Fifty athletes with hamstring-strain injury (age 36 ± 16 y; 30 men, 20 women; 3 G1, 43 G2, 4 G3; 25 recurrent injuries) followed a 3-phase rehabilitation protocol emphasizing eccentric strengthening with the hamstrings in a lengthened position. **Main Outcome Measures:** Injury recurrence; isometric hamstring strength at 80°, 60°, 40°, and 20° knee flexion in sitting with the thigh flexed to 40° above the horizontal and the seat back at 90° to the horizontal (strength tested before return to sport). **Results:** Four of the 50 athletes sustained reinjuries between 3 and 12 mo after return to sport (8% recurrence rate). The other 42 athletes had not sustained a reinjury at an average of 24 ± 12 mo after return to sport. Eight noncompliant athletes did not complete the rehabilitation and returned to sport before initiating eccentric strengthening in the lengthened state. All 4 reinjuries occurred in these noncompliant athletes. At time of return to sport, compliant athletes had full restoration of strength while noncompliant athletes had significant hamstring weakness, which was progressively worse at longer muscle lengths (compliance \times side \times angle $P = .006$; involved vs noninvolved at 20°, compliant 7% stronger, noncompliant 43% weaker). **Conclusion:** Compliance with rehabilitation emphasizing eccentric strengthening with the hamstrings in a lengthened position resulted in no reinjuries.

Keywords: length-tension relationship, isokinetic, isometric, knee flexion

Hamstring strains are among the most common injuries in high-speed-running sports and have a 20% to 33% recurrence rate.¹ Brockett et al² showed that athletes who had recurrent hamstring strains had similar strength between their previously injured hamstring and the contralateral uninjured hamstring and had strength similar to that of a control group of athletes who had not previously injured their hamstrings. However, it was apparent that on the injured side, peak knee-flexion torque occurred at a shorter muscle length than the uninjured contralateral side, and also when compared with the hamstrings in the control athletes. This was thought to reflect a chronic shortening of the hamstring muscle fibers and a subsequent leftward shift in the length-tension relationship.

Eccentric strength training has been shown to increase the muscle length at which peak hamstring strength occurs, resulting in a rightward shift in the length-tension relationship.^{3,4} Furthermore, it was previously demonstrated that isolated eccentric strength training was superior to concentric training or isotonic training (concentric and eccentric) for restoration of

strength and hypertrophy after immobilization-induced weakness.⁵

Eccentric hamstring strengthening using the Nordic hamstring exercise has been shown to be effective in preventing new⁶ and recurrent⁷ hamstring strains. However, with respect to preventing injury recurrence, Nordic hamstring training was performed in athletes who had already returned to play. This exercise is difficult to introduce in rehabilitation of hamstring strains because it requires high force production and the movement is difficult to safely control. Furthermore, the exercise must be performed with both legs at the same time, so the uninjured side can compensate for the injured side. In addition, the exercise is not performed at a long muscle length. Thus, isolated unilateral eccentric training in a controlled manner is needed in rehabilitation of hamstring strains. It is notable that while Petersen et al⁸ showed a lower injury rate in players with previous hamstring strains who performed Nordic hamstring training versus players with previous injuries not performing the Nordic hamstring training (7.1 vs 45.8 injuries per 100 player-seasons), the injury rate was still almost twice as high as the injury rate for players performing the Nordic hamstring training who did not have a previous hamstring strain (3.8 injuries per 100 player-seasons). Thus the training did not eliminate the risk associated with a previous hamstring strain.

While eccentric hamstring training is commonly performed on an isokinetic dynamometer, it is typically

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performed in the seated position with the range of motion from approximately 90° knee flexion (short muscle length) to full extension (longer muscle length). However, this position does not place the hamstring near its maximum length, and there is minimal stretch on the muscles at full extension. Considering that hamstring strains often occur in positions of significant stretch, sprinting is a common mechanism for hamstring strains, and the hamstrings work eccentrically at a high intensity in a stretched position while sprinting; during rehabilitation it is important to provide eccentric strengthening with the hamstrings in a maximally stretched position at the knee and the hip simultaneously. This is commonly referred to as the lengthened state in rehabilitation.⁹ This can be achieved on an isokinetic dynamometer by having athletes seated with the trunk upright or slightly flexed forward (eg, flexed 80–90° relative to horizontal) and the thigh flexed toward the chest (eg, flexed 20–40° relative to the horizontal).¹⁰ In this position there is sufficient stretch on the hamstring muscles such that most individuals are unable to reach full knee extension with passive stretch due to passive muscle tension.

The purposes of this study were twofold: to examine if a progressive eccentric strengthening program during hamstring-strain rehabilitation restored isometric knee-flexion strength relative to the contralateral side and restored the angle–torque relationship relative to the contralateral side or shifted it to a longer functional muscle length (rightward shift in the length–tension relationship) and to document the reinjury rate after return to sport. We hypothesized that athletes who completed the rehabilitation program would demonstrate a rightward shift in their angle–torque relationship and have a low rate of injury recurrence.

Materials and Methods

Study Participants

The study group comprised 50 athletes (30 men, 20 women) diagnosed with a unilateral hamstring strain that occurred during sports performance or recreational exercise (age 36 ± 16 y). Subjects were included if they had a mechanism of injury consistent with an acute hamstring strain, tenderness to palpation over 1 of the hamstring muscles, pain with resisted prone knee flexion, pain with passive tension testing using a passive straight-leg-raise test, and any loss of function of daily or sport activity. Exclusion criteria included other lower-extremity injuries producing hamstring pain, complete muscle disruption, avulsion injuries, clinical findings suggesting inguinal or femoral hernia, radiculopathy, history of malignant disease, incomplete healing and rehabilitation of pelvis or lower-extremity fractures, coexisting pelvis or lower-extremity fractures, clinical findings showing nerve entrapment, sacroiliac dysfunction, or any other impairment limiting participation in the rehabilitation program. All athletes were initially seen at a sports-medicine clinic regardless of the time since the injury had occurred.

Twenty-five subjects had had a previous hamstring strain more than 3 months earlier.

Injuries were classified as grade 1, 2, or 3. A grade 1 strain was defined as pain with minimal loss of strength and minimal restriction of motion, a grade 2 strain was defined as tissue damage that compromises the strength of the muscle but does not include complete loss of strength and function, and a grade 3 strain was defined as complete disruption of the muscle–tendon unit and complete loss of function of the muscle. Palpation was used to classify injury location longitudinally as proximal, midsubstance, or distal and mediolaterally as lateral, central, or medial. Activities at the time of injury and injury mechanisms were documented. Level of play was categorized as competitive or recreational. Competitive sport was defined as a sport in which the participants had regular practice or training sessions in addition to games, while recreational sports were defined as any sport or physical activity without regular practices or training sessions. Competitive sport included high school, college, professional, and club-level sports. This differentiation was made because athletes involved in competitive sports may be at greater risk of reinjury due to their greater exposure.

Rehabilitation Protocol

All athletes followed the same rehabilitation protocol (see the Appendix for details) consisting of 3 clearly defined phases, with progression to the next phase being dependent on being pain free with all components of the previous phase. In general the goal of phase 1 was to protect the healing tissue, prevent motion loss, and minimize atrophy and strength loss. The goals of phase 2 were to restore pain-free maximal hamstring contractions throughout the range of motion and improve neuromuscular control of the trunk and pelvis. The goal of phase 3 was to increase hamstring strength at long muscle lengths and return the athlete to sport with minimal risk of reinjury.

With respect to hamstring strength training, phase 1 consisted of pain-free submaximal isometric strengthening at multiple angles progressing from short to intermediate muscle lengths in the seated position. In phase 2 isokinetic eccentric contractions were performed in the seated position at 0.35 rad/s (20°/s), progressing from submaximal to maximal contractions based on athletes' tolerance during contraction. In phase 3 isokinetic eccentric contractions were performed in a lengthened state with the subjects sitting with the test thigh flexed 40° above the horizontal and the seat back at 90° to the horizontal (Figure 1). Eccentric contractions were performed from 90° to 20° knee flexion at 0.35 rad/s (20°/s). Athletes were progressed from submaximal to maximal contractions.

Additional isotonic hamstring- and trunk-strengthening exercises were also prescribed in phases 2 and 3. Assisted Nordic hamstring exercise was introduced in phase 2, as this works the hamstrings in short to intermediate length. In phase 3, plyometric and sport-specific drills were introduced in preparation for return to play. A

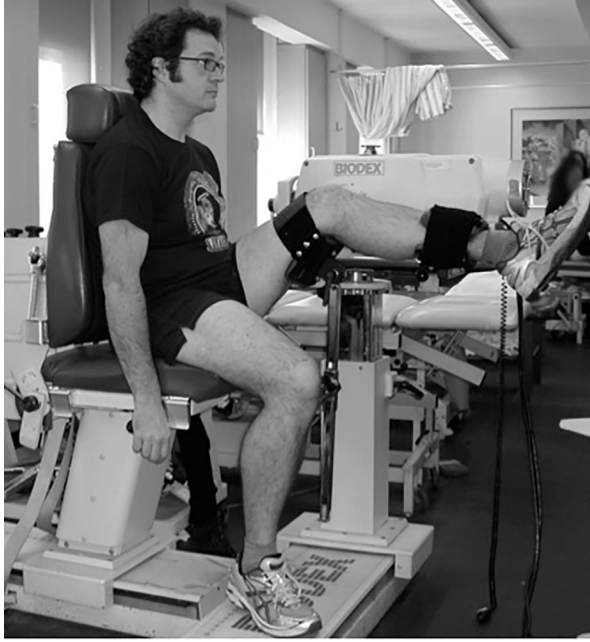


Figure 1 — The setup for isokinetic eccentric hamstring exercise in the lengthened state and isometric knee-flexion-strength testing is shown. The trunk was flexed to 90° to the horizontal and the thigh was flexed to 40° above the horizontal plane. Eccentric exercise was performed from 90° to 20° knee flexion at 0.35 rad/s (20°/s) (a knee flexion of approximately 55° shown in the picture).

home exercise program was given and modified throughout the course of rehabilitation (see Appendix). Criteria for return to play were being pain free with maximal eccentric contractions in the lengthened state and being pain free with sport-specific functional tasks and sprinting. All subjects gave written informed consent, and the protocol was approved by an institutional review board.

Angle–Torque (Length–Tension) Relationship

Before discharge from physical therapy all athletes performed an isometric knee-flexion-strength test in the same seated position in which lengthened-state eccentric contractions were performed. Athletes who chose not to finish the rehabilitation program or had to stop for other reasons were asked to return for isometric strength testing. Strength was assessed bilaterally at 80°, 60°, 40°, and 20° knee flexion to provide a measure of the length–tension relationship. For most subjects in this test setup the knee-flexion angle was 40° when the dynamometer arm was horizontal (parallel to the floor). The limb mass and torque due to passive hamstring tension were subtracted from torque values at each angle to provide a measure of hamstring contractile torque production only. Two maximal contractions were performed at each angle, progressing from short to long muscle lengths. Since the purpose of the study was to determine if lengthened-state eccentric

contractions shifted the length–tension relationship to the right and if this resulted in a low rate of injury recurrence, the results of the isometric testing were not used to determine readiness for return to play. We did not perform the lengthened-state test earlier in the rehabilitation process as we felt that this could potentially create a risk for reinjury.

Reliability for the isometric strength-testing protocol was assessed in 10 healthy volunteers who performed the protocol on 2 separate occasions at least 1 week apart. Measurements were made bilaterally, and the standard error of the measurement (SEM) was computed. These data were used to determine the sample size required to demonstrate a clinically relevant change in the angle–torque relationship. This measurement technique has previously been shown to be effective at demonstrating changes in the length–tension relationship due to passive stretching^{10,11} and in response to exercise-induced muscle damage.¹⁰

Follow-Up Procedure

Athletes were followed for documentation of reinjury after return to play by the study authors who provided medical coverage for their respective teams. If the athlete was not involved with a team covered by an author, he or she was contacted by phone to assess current sport participation and determine if a reinjury had occurred. Athletes were contacted at 3 and 6 months after return to sport and every 6 months thereafter. At the time of long-term follow-up (24 ± 12 mo) only 2 athletes were not still regular participants in their sport (they had failed to make their respective college and professional teams).

Statistical Analyses

Differences in knee-flexion torque between the involved and noninvolved sides across the different muscle lengths tested were assessed using repeated-measures analysis of variance (ANOVA). Since some athletes returned to play before completion of the rehabilitation protocol (see Results section), compliance was added as a between-subjects factor in the ANOVA (compliant vs noncompliant). Effects of previous hamstring injury, level of sport, and location of current injury on strength before return to sport were assessed using mixed-model ANOVA (involved vs uninvolved leg and joint angle were within-subject factors, and previous injury, level of sport, and location of injury were between-subjects factors).

Since the goal of the lengthened-state eccentric strengthening was to increase strength at longer muscle lengths, the sample-size estimate for the study was based on the variance in the difference in torque between the right and left legs of the control group. Based on these data we estimated that with a sample of 50 athletes an involved-to-noninvolved difference of 3.6 Nm for absolute torque could be detected at an alpha level of .05 (adjusted for multiple comparisons) and a beta level of .2 (80% power). Reinjury rates were compared between compliant and noncompliant athletes using Fisher exact tests.

Results

Details of Hamstring Strains

There were 3 grade 1 strains, 43 grade 2 strains, and 4 grade 3 strains. There were 27 proximal injuries (13 lateral, 8 central, 6 medial), 14 midsubstance injuries (3 lateral, 8 central, 3 medial), and 9 distal injuries (6 lateral, 3 medial). The mechanism of injury was sprinting in 38 cases (8 American football, 3 Gaelic football, 2 soccer, 4 softball, 6 track, 7 recreational running, 3 hill running, 2 lacrosse, 2 field hockey, 1 basketball). The 12 nonsprinting injuries occurred in stretching (3), karate (2), plyometrics (3), squash, waterskiing, skiing, weight training. At the time of injury 32 of the athletes were involved in recreational sports or exercise and 18 were involved in competitive sports (2 professional, 2 college, 10 high school, 4 club).

Compliance With Rehabilitation

Of the 50 athletes in the study, 8 chose to return to play before completing all 3 phases of the rehabilitation protocol (noncompliant athletes). Three noncompliant athletes were recreational runners who chose to return to running before completion of rehabilitation as they felt they were at low risk of reinjury (1 sustained a reinjury). One fitness-class participant returned before completion as her priority was to maintain her fitness routine. A recreational softball player and a high school football player returned to play understanding the increased risk but wanting to complete their competitive seasons (both sustained reinjuries). A Gaelic football player had to return to college before completing the rehabilitation and did not have the facilities to continue while at college. He sustained a reinjury when returning to Gaelic football at the end of the semester, after which he chose not to return to school until completing the rehabilitation. A high school soccer player went off to college before completing rehabilitation and chose not to pursue rehabilitation there.

Since 1 noncompliant athlete returned to rehabilitation after sustaining a reinjury and completed the full protocol, results are reported for 8 noncompliant athletes and 43 compliant athletes. Isometric strength tests were performed before return to play on all 8 athletes who failed to complete the full rehabilitation protocol. Three of these 8 athletes had completed phase 1 (male high school football player, female high school soccer player, female recreational runner) but had not started isokinetic eccentric strengthening. Five athletes had completed phase 2 but had not started lengthened-state eccentric strengthening (male softball player, male and female recreational runner, male Gaelic football player, female fitness-class participant). The average number of physical therapy treatments was 11 ± 7 for the 8 noncompliant athletes and 17 ± 7 for the compliant athletes ($P = .09$). Time from initial treatment to discharge was 11 ± 10 weeks for the compliant athletes and 11 ± 8 for the noncompliant athletes ($P = .98$). Visits per week were 2.4

± 1.4 for compliant athletes and 1.4 ± 0.8 for noncompliant athletes ($P = .07$).

Hamstring Strength and the Length–Tension Relationship (Angle–Torque)

For all athletes, hamstring strength was not different between the involved and noninvolved sides at each angle at the time of return to sport (side effect $P = .35$). Peak torque occurred at intermediate lengths (angle effect $P < .001$) in both the involved and noninvolved sides (side by angle $P = .41$). However, when strength results were compared between compliant and noncompliant athletes, clear differences were apparent. Noncompliant athletes had marked weakness on the involved side that was more apparent at longer muscle lengths, while compliant athletes had no apparent hamstring weakness (compliance \times side \times angle $P = .006$; Figure 2). Strength deficit for the noncompliant athletes averaged $-29.2\% \pm 15.1\%$ across all angles compared with $1\% \pm 20\%$ for compliant athletes. More important, strength deficits were progressively greater at longer muscle lengths in the noncompliant athletes (angle effect $P < .001$), while the opposite effect was apparent in the compliant athletes (compliance \times angle $P < .001$; Figure 3). In compliant athletes, hamstring strength was slightly lower on the involved side at short muscle lengths but slightly higher on the involved side at long muscle lengths (angle effect $P < .01$; Figure 3).

To assess whether the lengthened-state eccentric training resulted in a rightward shift in the length–tension curve independent of overall hamstring-strength, knee-flexion torques for the involved and noninvolved sides were expressed as a percentage of the torque at the angle of peak torque (Figure 4). At the shortest muscle length (80°) torque was 90.7% of peak torque on the involved side and 91.6% on the noninvolved side; at the longest muscle length (20°) it was 72.8% on the involved side versus 68.9% on the noninvolved (side \times angle $P < .05$).

For the compliant athletes, hamstring strength at discharge throughout the range of motion was not different between athletes with previous hamstring strains and those with no previous strain (side \times angle \times previous injury $P = .64$). Similarly, strength-testing results were not different between athletes with proximal, midsubstance, or distal injuries (side \times angle \times longitudinal location $P = .66$) or between athletes with lateral, central, or medial injuries (side \times angle \times longitudinal location $P = .67$). Female athletes were significantly weaker than male athletes ($P < .001$), but the effect of compliance on angle-specific effects and the effect of compliance on side-to-side weakness was not different between male and female athletes ($P = .49$ and $P = .31$, respectively). Athletes 30 years old or older were weaker than those under 30 years ($P < .001$), but the effect of compliance on angle-specific effects and the effect of compliance on side-to-side weakness was not significantly affected by age ($P = .07$ and $P = .58$, respectively).

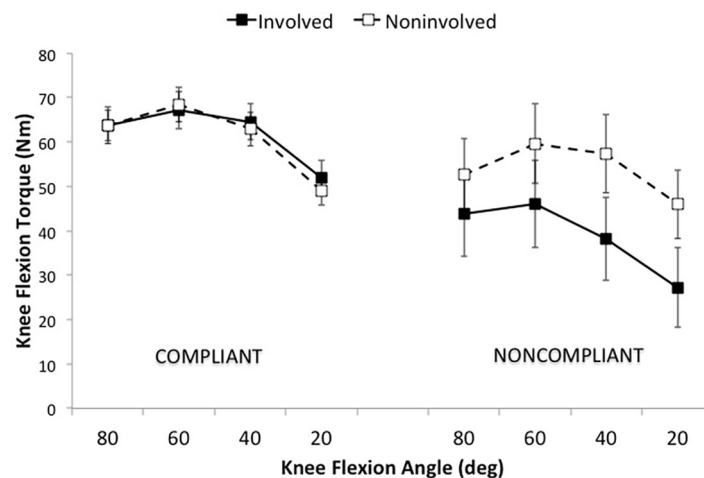


Figure 2 — Isometric knee-flexion torque for the involved and noninvolved sides of compliant and noncompliant athletes. Weakness on the involved side for noncompliant athletes versus symmetrical strength for compliant athletes (compliance \times side $P = .001$). Weakness for noncompliant athletes more evident at longer muscle lengths, with no such effect for compliant athletes (compliance \times side \times angle $P = .006$). Mean \pm SE displayed.

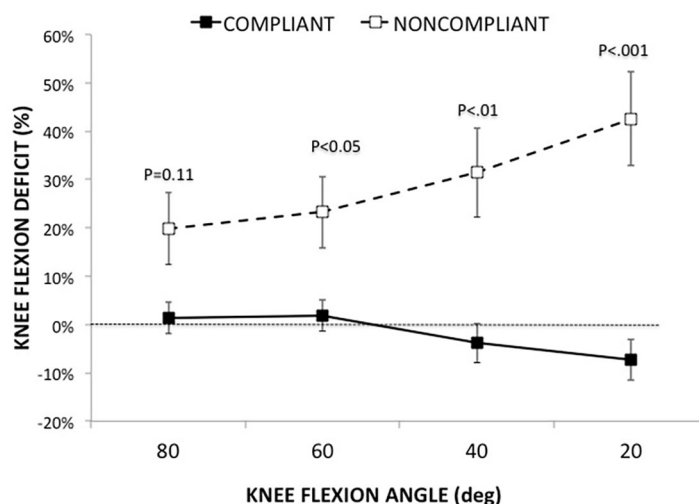


Figure 3 — Isometric knee-flexion-strength deficits at short (80°) to long (20°) muscle lengths for compliant and noncompliant athletes. Significant strength deficits apparent in noncompliant athletes but not in compliant athletes (compliance effect $P < .0001$), with differences in deficits between compliant and noncompliant athletes more evident at longer muscle lengths (compliance \times angle $P < .0001$). P values indicate significance of the difference in strength deficits between compliant and noncompliant athletes. Mean \pm SE displayed.

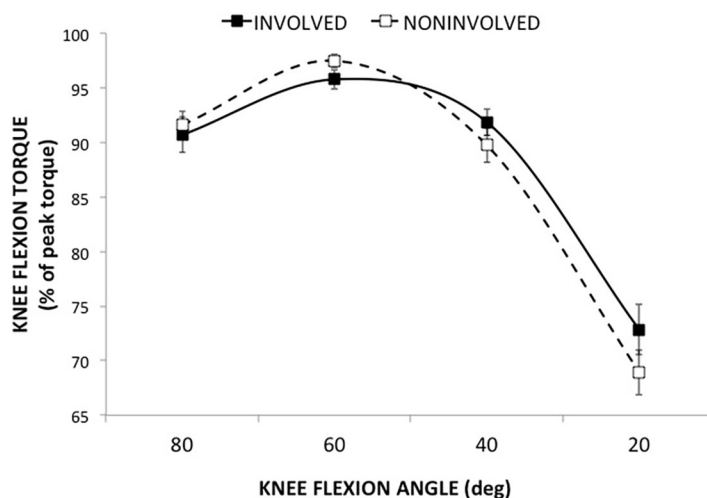


Figure 4 — Knee-flexion strength at each knee-flexion angle for the compliant athletes expressed as a percentage of the peak torque for each athlete. Since peak torque occurred at different angles for different subjects, the group average percentage of peak torque at any given angle is less than 100%. There is an apparent rightward shift of the angle-torque relationship (length-tension curve) on the involved versus noninvolved side (angle \times side $P < .05$).

The SEM for repeated strength measures at 20° of knee flexion in the control group was 7 Nm (11.4% of mean absolute torque value) and 7.6% for the test–retest difference in relative torque at 20°. At other angles SEM was comparable to, or lower than, the SEM at 20°. Based on these control-group data a sample size of 50 was chosen to have sufficient power to detect an estimated 3.6-Nm difference in knee-flexion torque between the involved and noninvolved sides at 20°. The actual torque difference in the compliant athletes (Figure 2) was 2.8 ± 11.5 Nm, which did not reach statistical significance ($P = .44$, adjusted for multiple comparisons). However, while strength was not significantly greater on the involved versus noninvolved side at 20° after eccentric training in the lengthened state, there was evidence of a rightward shift in the length–tension curve (Figure 4).

Injury Recurrence

Four of the 50 athletes sustained reinjuries 3, 4, 6, and 12 months after return to sport (8% recurrence rate). The other 42 athletes had not sustained a reinjury at an average of 24 ± 12 months after return to sport. All 4 reinjuries occurred in noncompliant athletes. There were no injury recurrences in the compliant athletes at an average of 23 ± 13 months after return to sport ($22 > 2$ y, 11 between 1 and 2 y, 10 between 6 mo and 1 y). The recurrence rate was significantly lower ($P < .01$) for compliant athletes (0%) than noncompliant athletes (50%). The reinjuries occurred in high school football (15-y-old male, grade 1), Gaelic football (18-y-old male, grade 1), softball (56-y-old male, grade 3), and hill running (50-y-old female, grade 1). The high school football player was in stage 1 of the rehabilitation strengthening program when he stopped rehabilitation and returned to sport, while the other 3 reinjured athletes were in the second stage of strengthening when they returned to sport.

Of the 8 noncompliant athletes, 4 had had a hamstring strain before this study; 3 of these 4 athletes sustained a reinjury in the current study.

Discussion

In a recent study of the mechanics of hamstring muscles during sprinting, Schache et al⁸ concluded that “hamstring injury prevention or rehabilitation programs should preferentially target strengthening exercises that involve eccentric contractions with high loads at longer musculotendon lengths.”^(p657) Schmitt et al¹ proposed a rehabilitation program with an emphasis on isolated eccentric training to address strengthening in a longer musculotendon length. In the current study such a rehabilitation program was shown to be effective at restoring hamstring strength, particularly at long muscle lengths, and preventing injury recurrence. The athletes who completed rehabilitation were followed for an average of 23 months after return to play with no reinjuries. The only reinjuries occurred in 4 of the 8 athletes who did not complete the rehabilitation program. The noncompliant

athletes attended physical therapy less frequently and therefore advanced less quickly with the protocol. These athletes may not have been sufficiently patient to allow for symptom-free progression. Sixteen compliant athletes had returned to high-speed competitive sports with a predominance of sprinting and cutting (football, soccer, lacrosse, Gaelic football, tennis, field hockey). Of the 27 recreational athletes who had not sustained a reinjury, 14 were involved in high-speed sprinting or stretching sports (football, soccer, softball, skiing, water skiing, basketball, squash, martial arts), while 13 were involved in less-dynamic sports and recreational activities (running/jogging, weightlifting/plyometrics). Thus, the study population was exposed to significant risk of reinjury, and several reinjuries would have been expected based on reported reinjury rates of 20% to 33% for athletes in high-speed sprinting-type sports.^{7,12–14}

While previous studies have used isokinetic testing in the standard seated position to describe the length–tension relationship of the knee flexors, there are important limitations to this approach. First, the standard seated position does not adequately bring the knee flexors close to their end range of motion (full knee extension in the seated position does not place a lot of stretch on the hamstring muscle group). Hence in the current study we chose to position subjects such that there was significant stretch on the hamstrings. This ensured that function was assessed close to the true end of range of motion. Isometric testing is preferable to isokinetic testing for ensuring accurate correction of joint torques for the effects of limb mass and passive muscle tension. The software function for gravity correction due to limb mass typically involves a single measure of torque with the limb relaxed at a specific angle. This approach does not account for the changing contribution of passive muscle tension at different joint angles. When the hamstrings are in a position of significant stretch, such as at 20° knee flexion with the thigh flexed as in the current study, more than 50% of the measured torque may be due to the combination of limb mass and passive tension. To construct a valid length–tension relationship it is important to remove this torque to provide a true measure of the contractile torque production. This is best achieved using isometric testing. It is surprising that details of the limb mass and passive torque correction were not provided in the studies using isokinetic testing to examine the hamstring length–tension relationship.^{3,15} This approach has been described in studies using isometric testing to examine the length–tension relationship in the knee flexors.^{10,16} In addition, examining torque throughout the range of motion is preferable to examining a single angle of peak torque, as it is important to know how effective a muscle group is at producing torque at short versus long muscle lengths. In the test setup used in this study it is possible that pelvic tilt at longer muscle lengths occurred to avoid excessive stretch on the hamstrings in subjects who had difficulty reaching 20° knee flexion. This is a possible limitation in this measurement technique.

Athletes who did not complete the rehabilitation program had decreased strength that was more apparent in the lengthened state. This is consistent with the findings of Brockett et al,³ who found that athletes with recurrent hamstring strains achieved peak isokinetic knee-flexion torque at shorter muscle lengths on the involved side. For the compliant athletes the eccentric training in the lengthened state restored strength throughout the range of motion and provided a small rightward shift in the length-tension curve. Since the rightward shift in the length-tension relationship with eccentric training has been shown to be temporary in uninjured subjects¹⁷ it is probably more important clinically to eliminate weakness in the lengthened state. The lack of reinjuries in the compliant athletes indicates that the elimination of weakness in the lengthened state is protective.

The mechanism by which eccentric training alters the length-tension, or angle-torque, relationship is thought to be longitudinal addition of sarcomeres.^{3,17-19} In an animal model, Lynn et al¹⁸ confirmed longitudinal additional of sarcomeres with decline running (large eccentric component) versus incline running (reduced eccentric component) and demonstrated an associated rightward shift in the length-tension relationship in decline-trained versus inclined-trained animals. In support of the protocol used in this study, Butterfield and Herzog¹⁹ demonstrated in an animal model that the longitudinal addition of sarcomeres is greater when the eccentric contractions are initiated at longer muscle lengths. Others have shown that eccentric exercise of the hamstrings^{3,17} or quadriceps^{7,20} results in a rightward shift in the angle-torque relationship in healthy humans. In fact, this adaptation has been observed within 1 week³ or 2 weeks²⁰ of a single bout of eccentric exercise; this emphasizes the rapid plasticity of myofibrils. This effect is reversed with detraining.¹⁷

It is possible that the low reinjury rate in the current study was due to improved trunk stability. While the emphasis in rehabilitation was on eccentric hamstring strengthening it is important to note that the rehabilitation program also involved trunk-stability strengthening exercises, as well as sport-specific activities. Sherry and Best²¹ previously showed, in a randomized trial, that rehabilitation with an emphasis on trunk stabilization resulted in an earlier return to sport and a lower recurrence rate than a standard stretching and strengthening program. Only 1 of 13 athletes in the trunk-stabilization group sustained a reinjury in the first year after return to sports, while 7 of 11 in the comparison group sustained reinjuries. While these results point to the effectiveness of addressing proximal control in hamstring rehabilitation, the most striking finding was the complete inadequacy of the standard treatment. The small sample size for the trunk-stabilization group makes it difficult to generalize, but a reinjury rate of 8% (1 of 13) would be impressive if established in a larger sample. A zero-of-43 reinjury rate for compliant athletes in the current study is similarly encouraging. Askling et al²² recently demonstrated that an eccentrically biased rehabilitation program resulted in a more rapid return to sport than a conventional program. However, in the first year after

return to play only 1 reinjury occurred in the conventional group with no reinjuries in the eccentric group. The lack of reinjuries regardless of treatment regimen points to the effectiveness of the discharge criteria, not the rehabilitation protocol. In addition, these studies^{20,22} did not include a strength test before return to sport, making it difficult to conclude whether the low recurrence rate was a result of adequate strength or other strict discharge criteria. In the current study it was clear that when athletes returned to play with weakness at long muscle lengths, risk of reinjury was dramatically increased.

The primary limitation of the current study is that there was no comparison group performing a different type of rehabilitation. Thus the effectiveness of the rehabilitation program cannot be wholly attributed to lengthened-state eccentric training. Two previous randomized trials compared an eccentrically biased rehabilitation program with conventional rehabilitation.^{22,23} There were zero reinjuries in 65 athletes in the eccentric groups (0%) and 3 reinjuries in 66 athletes in the comparison groups (5%) within 1 year after return to sport. The overall low reinjury rates in both groups might be attributable to strict criteria for return to play. The real benefit of the eccentric component was a more rapid return to sport in both studies.^{22,23} Two other randomized trials comparing trunk-stabilization training with more conventional rehabilitation^{21,24} reported 2 reinjuries in 27 athletes in the trunk-stabilization groups (7%) within 1 year after return to sport and 9 reinjuries in 24 athletes in the comparison groups (38%). Thus the overall low reinjury rate in this study (8%) and the 0% reinjury rate for compliant athletes compares favorably with reinjury rates in randomized trials. The fact that in the current study the noncompliant athletes had hamstring weakness, particularly in the lengthened state, emphasizes the need for lengthened-state eccentric training. Weakness at long muscle lengths after hamstring-strain injury is consistent with the findings of Brockett et al,² where peak knee-flexion torque occurred at a short muscle length in athletes with recurrent hamstring strains. Furthermore, Timmins et al²⁵ demonstrated that biceps femoris fascicle lengths were shortened in hamstrings that had previously sustained a strain injury. In the current study, increased strength in the lengthened state on the involved side in compliant athletes and the absence of any subsequent injury recurrences demonstrates the effectiveness of the rehabilitation program. While these conclusions cannot exclusively be attributed to lengthened-state eccentric training, that was the primary difference between what the compliant athletes did in rehabilitation compared with the noncompliant athletes. Therefore it is logical to conclude that the lack of reinjury in the compliant athletes was likely due to the addition of lengthened-state eccentric training.

Perspective

Rehabilitation with an emphasis on eccentric strength training with the hamstrings in a maximally stretched position restored strength and resulted in zero recurrent

injuries at an average of 2 years after return to play. Athletes who did not perform lengthened-state eccentric training returned to sport with significant weakness, particularly at long muscle lengths, and had a high recurrence rate (50%).

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Appendix: Rehabilitation Guidelines

Phase 1

Goals

- Protect healing tissue.
- Minimize atrophy and strength loss.
- Prevent motion loss.

Protection

- Avoid excessive active or passive lengthening of the hamstrings.
- Avoid antalgic gait pattern.

Ice

- 2–3 times daily

Therapeutic Exercise (3 d/wk, Isometric Exercise Performed Daily at Home)

- Stationary bike (10–20 min)
- Submaximal isometric at 3 angles (100°, 45°, 20°), 3 sets of 12 repetitions with 3-second hold
- Single-leg balance 30" to 90", adding unstable surface as tolerated
- Balance Board 30" to 90"
- Soft-tissue mobilization (STM)/instrument-assisted STM
- Ultrasound 1.0 MHz 1.2 W/cm² at 50% duty cycle
- Progressive hip strengthening consisting of side-lying hip abduction, prone hip extension, straight-leg raise 3 sets of 12
- Pain-free isotonic knee flexion in seated using cable column 3 sets of 12
- Sciatic nerve flossing in seated (extend knee, dorsi-flex foot, flex spine, the reverse steps)
- Ice with sensory electrical stimulation using pre-modulated current 10 to 15 minutes

Criteria for Progression to Next Phase

- Normal walking stride without pain
- Pain-free isometric contraction against submaximal (50–70%) resistance during prone knee flexion (90°) manual strength test

Phase 2

Goals

- Regain pain-free hamstring strength, progressing through full range.
- Develop neuromuscular control of trunk and pelvis with progressive increase in movement speed, preparing for functional movements.

Protection

- Avoid end-range lengthening of hamstrings if painful.

Ice

- Postexercise, 10 to 15 min

Therapeutic Exercise (Performed 3 d/wk)

- Stationary bike 10 to 15 min
- Treadmill at moderate to high intensity (progressive increasing intervals), pain-free speed and stride
- Isokinetic eccentrics in nonlengthened state using Biodex isokinetic dynamometer at 0.5 rad/s (20°/s)
- Single-limb-balance windmill touches without weight, 3 sets of 12
- Single-leg stance with perturbation (eg, ball toss, reaches)
- Supine hamstring curls on Swiss ball, sets of 12
- STM/instrument-assisted STM
- Nordic hamstring lowers, 3 sets of 8 to 12 reps, with therapist stabilizing at ankles
- Shuttle jumps, 3 sets of 12
- Prone leg drops (therapist holds bent knee in hip extension and drops leg with patient attempting to “catch” leg before it touches table), 10 to 15 repetitions
- Lateral and retro band walks 60 to 120 feet, rest as needed
- Sciatic nerve flossing as in phase 1

Criteria for Progression to Next Phase

- Full strength (5/5) without pain during prone knee flexion (90°) manual strength test
- Pain-free forward and backward jog, moderate intensity
- Pain-free maximal eccentric in shortened state

Phase 3

Goals

- Symptom-free (eg, pain and tightness) during all activities.
- Improve neuromuscular control of trunk and pelvis.
- Integrate postural control into sport-specific movements.

Protection

- Train within symptom-free intensity.

Ice

- Postexercise, 10 to 15 minutes, as needed

Therapeutic Exercise (Performed 3 d/wk)

- Treadmill moderate to high intensity as tolerated
- Hamstring dynamic stretching in standing, kicking leg straight up (eg, Rockette-style kick)
- Isokinetic eccentric training at end range of motion, begin with 3 sets of 10 reps and progress to 15 reps performed at 0.35 rad/s (20°/s)

- STM/instrument-assisted STM
- Plyometric jump training (double-leg hops progressing to single-leg hops, progressing to single-leg hops in multiple directions)
- 5- to 10-yard accelerations/decelerations
- Single-limb-balance windmill touches with weight on unstable surface 3, sets of 12
- Sport-specific drills that incorporate postural control and progressive speed

Criteria for Return to Sport

- Lengthened-state eccentric training pain free at 0.35 rad/s (20°/s) throughout available range of motion while resisting with maximal effort
- Replication of sport-specific movements at competition speed without symptoms