The Effect of Eccentric Exercise on the Optimum Length of Hamstrings in Collegiate Athletes

by

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ABSTRACT

The purpose of this study was to determine if an eccentric exercise-training regimen in conjunction with an athlete's offseason exercise program can produce a significant shift in optimum length of the hamstrings in athletes of different sports with diverse training protocols. Thirty-one athletes were randomly assigned to an eccentric exercise-training group (EG) or a control group (CG). Over a 7-week period the EG performed two eccentric exercises while the CG performed a stretching protocol over this time in addition to their normal training routine. Isokinetic-testing was performed pre and post intervention to determine optimum length. Significant attrition lead to an inability to report a significant group by time interaction between the EG and CG ($F_{1,13}$= 2.27, p= .156). Examination of simple main effects determined there was a significant shift of optimum length in the EG (t= 2.725, p= .030). No significant changes were seen in the optimum length of the CG or normalized concentric and eccentric peak torque values in both groups. In conclusion, 7 weeks of additional eccentric exercise training shifted the angle of peak torque closer to knee extension in the EG, increasing the optimum length of the hamstrings in Division I football, baseball, and lacrosse athletes.

* Thesis formatting done in accordance with the Author Guidelines of the Scandinavian Journal of Medicine & Science in Sports

Chapter 1

INTRODUCTION

Hamstring strains are one of the most commonly reported soft tissue injuries in sports. Epidemiology studies have reported that hamstring strains account for between 6-29% of all injuries reported in Australian Rules football, rugby union, American football, Major League Baseball, soccer, basketball, cricket and track sprinters (Brooks, Fuller, Kemp, & Reddin, 2006; Croisier, 2004; Feeley et al., 2008; Mendiguchia & Brughelli, 2010; Orchard & Seward, 2002; Posner, Cameron, Wolf, Belmont Jr, & Owens, 2011; Woods et al., 2004). They are debilitating injuries that cause an average loss of play that ranges from 8-25 days (Brooks et al., 2006; Feeley et al., 2008). In addition to the frequency of initial injuries, hamstring strain rehabilitation seems to be characterized by poor healing responses, prolonged symptoms, and high re-injury rates (12-31%) (Croisier, 2004; Woods et al., 2004). Furthermore, the greatest risk of re-injury is within the initial two weeks following return to sport; indicating a need for heightened awareness on the part of the clinician for proper return to play criteria (Orchard & Best, 2002). This high re-injury rate suggests that traditional hamstring prevention and rehabilitation programs are ineffective (Mendiguchia & Brughelli, 2010).

Previous studies have reported that most hamstring strains occur when the hamstrings are acting eccentrically, specifically during the terminal swing phase of sprinting (Feeley et al., 2008; Sugiura, Saito, Sakuraba, Sakuma, & Suzuki, 2008; Woods et al., 2004). After unaccustomed eccentric activation muscles have been shown to have disruptions in structural proteins and an increased inflammatory response as a result of sarcomeres being overstretched (Morgan, 1990) . Several studies have reported that a progressive eccentric-based training program could significantly reduce the incidence of hamstring injuries in sport (Arnason, Andersen, Holme, Engebretsen, & Bahr, 2008; Askling, Karlsson, & Thorstensson, 2003; Brooks et al., 2006; Petersen, Thorborg, Nielsen, Budtz-Jørgensen, & Hölmich, 2011). Although the physiological mechanism as to how a change occurs is not fully understood; one of the proposed explanations as to why eccentric exercise reduces injury rates is that eccentric exercise may cause a shift in peak torque angle (or optimal angle) to longer muscle lengths. This shift in the torque-angle relationship to longer muscle lengths is also referred to as an increase in a muscle's optimum length for contraction. Several previous reports have examined the effect of progressive eccentric exercise on optimum length in the hamstrings (Brughelli M. et al., 2010; Brughelli, Nosaka, & Cronin, 2009; Clark, Bryant, Culgan, & Hartley, 2005; Kilgallon, Donnelly, & Shafat, 2007). Results of these studies suggest that progressive eccentric exercise can produce a positive shift in optimum length of the hamstrings toward greater muscle lengths; allowing the muscle to generate higher forces at longer muscle lengths as well as reducing the risk of sarcomere overstretch and subsequent muscle damage. However, only two of the studies examining optimum length involved trained athletes; one a randomized control trial with professional soccer players (Brughelli M. et al., 2010) the other a case study involving one Australian Rules football player with recurrent hamstring injuries (Brughelli et al., 2009). It is known that hamstring strains plague athletes in various sports with diverse training regimens; however it is unclear whether or not additional emphasis on eccentric training has a universal effect on optimal angle in all athletes.

The purpose of this study was to determine if an eccentric exercise-training regimen in conjunction with an athlete's offseason training program can produce a significant shift in optimum length of the hamstrings in athletes of different sports and training regimens. We hypothesized that a 7-week eccentric exercise program targeted at the hamstring in conjunction with an athlete's offseason training regimen will produce a significant increase in optimum length compared to athletes not performing the additional eccentric exercises.

Chapter 2

METHODS

Participants

Thirty-one student-athletes were recruited from a NCAA Division I university including the sports of men's lacrosse (4), baseball (10), and American football (17). All athletes and strength coaches were informed of the purpose and design before testing and all participants signed a written informed consent agreement (UD IRB approval #224513-2). Any athlete that had a lower extremity injury preventing them from participating in their normal workouts at the time of testing or had sustained a hamstring injury within the previous six months prior were excluded. Any athlete that sustained an injury during testing or the training intervention that prevented them from participating in their normal workouts was excluded. To insure homogeneity of the main dependent variable (optimal angle) between groups a matched-pair design was used to match participants' baseline optimal angle measurements. From these measurements participants were then randomly allocated to either the exercise group (EG) or the control group (CG).

Procedures

A Kinetic Communicator isokinetic dynamometer (KIN-COM 125-AP, Chattanooga Group, Hixson, TN, USA) was used to measure peak torque and torque angle curves in the hamstring muscle group of the dominant leg. Dominance was determined by asking participants what leg they would kick a ball with. A single investigator (DT) conducted all of the isokinetic testing. The participants sat upright in the dynamometer chair with arms folded across their chest and hip joints flexed to 90°. Harness straps were used across the pelvis to limit hip hiking. Knee range of motion was set from 0-90° with the "zero-angle" set at full knee extension (0° extension). It should be noted that because 0° is full knee extension a decrease in optimal angle is a shift in peak torque to longer muscle lengths (increase in optimum length), while an increase in optimal angle indicates a decrease in optimum length (Figure 1). All testing was performed at an angular velocity of 60°/s on the dominant leg as recommended by Brockett et al (2001).

Participants warmed up on a stationary bike for 5 minutes before performing isokinetic testing. They then executed a warm-up set of 3 continuous concentric/eccentric knee curls on the dynamometer at approximately 75% of perceived maximum effort. After the warm-up was completed participants were given 2 minutes rest before the start of testing. Using the interrupted protocol feature on the Kin Com the participants then performed 3 maximum effort concentric/eccentric knee curls with verbal encouragement ("Pull down" for concentric actions and "pull back" for eccentric actions). The subjects were given 15 seconds rest after the concentric action and 30 seconds after the eccentric action. The three repetitions were averaged together and optimal angle was determined by finding the knee angle at which peak torque occurred.

After pre-testing sessions were completed those allocated to the CG were given a general stretching protocol, involving stretches to the low back, gluteal muscles, quadriceps, and gastrocnemius, (see appendix B) to be completed twice a week immediately following their normally scheduled weight room workout. This was done in an attempt to blind the subjects as to which group was the intervention group. Those allocated to the EG began a 7-week hamstring eccentric exercise program in addition to their regularly scheduled weight room workouts. In the initial three weeks participants performed prone hamstring curls emphasizing the eccentric phase of the exercise. These were done using two legs to concentrically curl a participant's predetermined single leg concentric 1 repetition max minus 10 lbs (modified 1RM) and then using one leg to eccentrically lower the weight back to the starting point 8 times on one leg and then 8 times on the other leg (Figures 2a, 2b). Help was given if a subject could no longer concentrically curl the weight. The weekly progression can be seen in Table 1. If a subject performed both sets of 8 repetitions eccentrically without failure (on either leg), with a perceived level of exertion (modified Borg scale) of less than 7, the weight was increased by 10 lb as recommended by Kaminski et al. (1998).

At the conclusion of week 3, Nordic hamstring exercises were introduced into the program for the final four weeks in addition to the prone hamstring curls. Nordic hamstring exercises are an assisted exercise where the participant kneels with arms folded across their chest while a training partner applies pressure to the participant's heels to make sure the feet stay in contact with the ground throughout the exercise. Keeping their torso upright and rigid, the participant then lowers their body slowly against gravity towards the ground using their hamstrings to control their descent (Figure 3a, 3b). This position is held for as long as possible. Once the participant can no longer control the motion they perform a push-up followed by a concentric contraction of the hamstrings to raise themselves back up. The use of Nordic hamstring exercises in the training program progressed as shown in Table 2.

Isokinetic post-testing commenced between 2 and 3 days after the 7-week eccentric exercise intervention concluded.

It should also be noted that, as was the case in Brughelli et al. (2010) study, both groups performed at least one eccentric exercise per week during their normal training in the weight room. While this may reduce the magnitude of a between groups change, Brughelli et al. (2010) still reported a significant difference between groups with a training intervention that placed more emphasis on eccentric training of the hamstrings. In our study, during the first phase of our participants' standard training, they performed single leg Russian dead lifts; while in phase two they performed glute/ham reverses each week. The glute/ham reverese exercise is similar to the Nordic Hamstring exercise, except the action is performed on a Glute Ham Developer (PRO SERIES Glute/Ham Developer #3214, Legend Fitness, Knoxville, TN, USA) machine with more emphasis placed on the concentric aspect of the motion. Subjects that were on the football team also performed additional plyometric exercises once a week such as box jumps/drops during their normal training as well.

Statistical Analysis

Dependent variables (optimum angle, normalized concentric and eccentric torque (Nm/kg)) were compared between groups and across time (pre and post intervention) using a repeated measures analysis of variance (ANOVA) with one within-subjects factor (time, 2 levels), and one between-subjects factor (group, 2 levels). In the case of a significant group by time interaction pairwise comparisons would have been utilized to identify where differences occur. All data are reported as means and standard deviations (SD) and a level of chance occurrence (α) was set a priori ≤ 0.05.

Chapter 3

RESULTS

Of the 31 student-athletes that were baseline tested only 15 completed post-testing. In the EG two were lost to injury (one suffered a hamstring injury before the intervention began, the other a meniscal tear), four dropped from the study because they decided they did not like the intervention exercises, one quit the team, and another was cut. In the CG 3 were lost to injury (one suffered a hamstring strain shortly after the study began, one suffered a serious knee injury, and one had complications with a surgery from 2 years prior), three were cut from team, one quit the team, and one would not report for follow-up. Participants' demographics can be found in Table 3, while comparisons of optimal angle and normalized concentric and eccentric peak torque are located in Table 4.

Attrition resulted in insufficient statistical power (observed power .287) to detect a significant group by time interaction for optimal angle ($F_{1,13}$= 2.27, p= .156) (Figure 4). There was a trend towards significance for the time factor ($F_{1,13}$= 3.783, p= .074) The group effect was not significant ($F_{1,13}$= .698, p= .419). Considering the low power and the graphical support for an interaction (Figure 2) we chose to analyze, using a paired t-test, the simple main effects of time within each group separately. In the CG, the effect of time was not significant (t=.278, p= .790, optimal angle pre= 17.3° (±4.6), optimal angle post= 16.9° (±2.7). In the EG, there was a significant 3.4° decrease in optimal angle (t= 2.725, p= .030, optimal angle pre= 17.5° (±4.2), optimal angle post= 14.1° (±1.6). No significant correlation was found between baseline optimal angle values and normalized concentric and eccentric peak torque values. There was no significant group by time interaction or simple main effects for time in normalized concentric and eccentric peak torque values found in either group.

Chapter 4

DISCUSSION

The present study investigated the effects of progressive eccentric exercise on the optimum length of hamstrings in collegiate student-athletes participating in various sports. It is the only randomized control trial that we know of to examine the effects of progressive eccentric exercise on optimum length in athletes other than soccer players. High amount of attrition lead to our study being underpowered to test the group by time interaction within our planned statistical approach. Considering that the highly trained status of our sample would likely bias this study towards small effects and that the and the control group was also engaged in exercise training, the graphical support for the hypothesized interaction was of particular interest. Whereas the study was underpowered to test the interaction term, greater power was afforded to test the simple main effects of time within each group. Consistent with the hypothesis, simple main effects showed that a progressive eccentric exercise regimen significantly increased the optimum length of the hamstrings in the EG. This finding is consistent with those of previous studies that examined the effect of progressive eccentric exercise on the optimum length of hamstrings (Brughelli M. et al., 2010; Brughelli et al., 2009; Clark et al., 2005; Kilgallon et al., 2007). Our shift of 3.37° is comparable to the 4° shift that Brughelli et al. (2010) found in professional soccer players.

Potential mechanisms for the increase in optimum length include the “popping” sarcomere theory, the serial addition of sarcomeres, changes in the protein connectin, and neural adaptations.

"Popping" Sarcomere Theory

It is well established that repeated eccentric contractions can cause muscle damage (Morgan, 1990; Proske & Morgan, 2001). The cause of damage is thought by some to be due to the inherent instability of the descending limb of the length-tension relation for skeletal muscle (Gregory, Morgan, Allen, & Proske, 2007; Morgan, 1990). In other words when a muscle is lengthened and reaches the descending portion of the length-tension curve, fibers are unable to control tension at any velocity and are susceptible to damage. Morgan and colleagues suggest that this instability provides the basis for the theory of non-uniform lengthening and disruption of sarcomeres on the descending limb (Morgan, 1990). In this theory during eccentric activation some shorter/weaker sarcomeres are stretched beyond the range of actin and myosin myofilament overlap ("pop") and become disrupted (Brockett CL et al., 2001; Morgan, 1990). These disrupted fibers, lying in series with still functional sarcomeres, are no longer able to produce force, which in turn increases the muscle's series compliance (Gregory et al., 2007; Morgan, 1990). This increase in series compliance leads to an increase in the length threshold for tension resulting in the observed shift in optimum length for peak torque (Gregory et al., 2007; Proske & Morgan, 2001). In support of this theory Jones et al. (1997) found that an immediate shift in optimum length after a series of eccentric contractions reversed over the next 5 hours (h). Electron microscope examination immediately after eccentric contractions showed small areas of sarcomere disruption throughout the muscle. When the muscle was examined 5 h later these areas of disruption were no longer present. Indicating that the shift in optimum length reversed when the disrupted sarcomeres recovered their normal structure. While the disruption of sarcomeres may explain the immediate shift in optimum length after repeated eccentric contractions, it seems an unlikely explanation as to why eccentric exercise, especially a progressive protocol involving minimal muscle damage, is able to produce a sustained shift in optimum length.

Sarcomerogenesis

Sarcomerogenesis, or serial addition of sarcomeres within a muscle, is one proposed explanation for the sustained shift in optimum length after eccentric activation (Butterfield, 2010; Friden, 1984; Proske & Morgan, 2001). The serial increase in sarcomere number would increase series compliance and allow individual sarcomeres to work at shorter lengths reducing the risk of sarcomere overstretch during subsequent eccentric activation. This would then allow for larger forces to be generated at longer lengths and increase a muscle's contractile velocity and power; which in turn may help prevent muscle injury when working at longer lengths during functional activities. (Butterfield, 2010; Friden, 1984; Proske & Morgan, 2001).

The mechanism of how additional sarcomeres are generated is not yet completely understood but current evidence suggests that serial remodeling occurs by insertion of new sarcomeres throughout the cell length and at the ends of myofibrils (Boateng & Goldspink, 2008; Goldspink, 1985). While it has been suggested that a mechanical disruption is needed for muscle fibers to adapt (Proske & Morgan, 2001) (fibers lengthened beyond myofilament overlap resulting in necrosis and regeneration) there is evidence that serial sarcomere adaptations may occur without fiber damage and necrosis (Butterfield, 2010). It has been established that immobilizing a foot in extension with the plantarflexor muscles in a shortened position results in loss of sarcomeres in series with no concomitant change in bone length and vice versa if immobilized in a lengthened position (Butterfield, 2010). Friden et al. (1984) found that there was greater variation in sarcomere length as well as a reorganization of sarcomere structure in type II fibers after long-term eccentric exercise without evidence of fiber necrosis. This would suggest that muscle retains a mechanism that allows it to alter muscle architecture without membrane disruption and subsequent fiber regeneration (Butterfield, 2010).

Experiments by Goldspink (Goldspink, 1985) revealed that denervated muscle could still adapt to length changes by adding or removing sarcomeres, suggesting that the detecting mechanism for length change seems to be in each individual fiber. Current evidence suggests that alterations in serial sarcomere number may be accomplished though the process of mechanotransduction, the decoding of mechanical stimuli into a molecular and biochemical response (Boateng & Goldspink, 2008; Butterfield, 2010). It is well established that extracellular signals are transmitted to the sarcomere via activated cytoplasmic kinases/phosphates, indicating any deviation from fiber equilibrium (lengthening during eccentric activation) may evoke signaling pathways in the cell, resulting in alterations in protein synthesis (Boateng & Goldspink, 2008; Butterfield, 2010). This in conjunction with the hypothesis that sarcomere numbers adapt to the length at which muscle tendon experiences peak force could account for the increase in optimum length after eccentric exercise.

Connectin (Titin)

The protein connectin (titin) may potentially play a role in the shift of optimum length as well. Titin is a large structural protein that is anchored into the Z discs and M-band proteins of a sarcomere and is thought to provide the structural blueprint for the length of a sarcomere (Boateng & Goldspink, 2008). Mechanically it functions to help stabilize sarcomeres as well as act as a molecular spring that develops passive tension when sarcomeres are stretched (Ochi, Nakazato, & Ishii, 2007). When analyzed titin shows two major bands, the larger molecular weight band is defined as alpha-connectin or T1 and the lower molecular weight band is defined as beta-connectin or T2 (McBride, Triplettp-McBride, Davie, Abernethy, & Newton, 2003; Ochi et al., 2007).

It has been hypothesized that fibers exposed to large sarcomere strains may express larger titin isoforms to minimize the costly energy loss of unfolding which occurs during high force-slow velocity extension or lengthening of the sarcomere past its yield point (Tskhovrebova, Trinick, Sleep, & Simmons, 1997). If this proves to be true, larger titin isoforms would increase the series elasticity of muscle and improve the stability of the sarcomere structure, increasing the length threshold for tension. McBride et al. (2003) examined titin characteristics in different athletic populations and non-athletes to see if there were any differences. They were unable to make conclusions as to the contribution of titin to strength or power capabilities but they did find that strength and power athletes had significantly higher levels of T1 and lower levels of T2 compared to non-athletes. McGuigan et al. (2003) examined the effects of an 8-week explosive squat jump training program on titin isoforms in trained individuals and found no significant changes. However, they performed their training on a Smith machine with a braking system that minimized eccentric load during the jump training. It is conceivable that since they used trained subjects the braking system did not allow for a strong enough stretch stimulus to evoke a change in titin isoform composition. Another study showed that repeated eccentric exercise had no effect on titin isoform composition in rat gastrocnemius compared to a control group (Ochi et al., 2007). However, this study only examined T2 composition in relation to total connectin [T2/(T1+T2)] in both groups. There is no report on whether the eccentric exercise protocol had an effect on the larger T1 isoform.

In addition to its mechanical properties, titin has also been proposed to play a role in the cellular adaptation of serial sarcomere addition and removal (Boateng & Goldspink, 2008; Butterfield, 2010). It contains multiple binding sites for structural and signaling proteins, as well as an inherent kinase domain (Boateng & Goldspink, 2008). There is evidence that titin kinase may contribute as a stress-dependent modulator of protein synthesis in adult skeletal muscle which Butterfield (2010) suggests would make titin an ideal force and strain feedback control mechanism to regulate sarcomere number and optimal tension at different working lengths.

Neural Adaptations

When rapid changes are observed in function or performance, such as the present change in optimum length after 7 weeks of eccentric exercise, there is potentially a neural adaptation (Guilhem, Cornu, & Guevel, 2010). During eccentric activation, EMG activity of a muscle is lower than the one recorded during a concentric contraction for the same level of force produced; indicating lower motor unit discharge rates or less motor unit recruitment (Guilhem et al., 2010). Further, EMG amplitude and peak torque in the hamstrings have been shown to decrease as the knee approaches full extension during maximal eccentric contractions (Higashihara, Ono, Kubota, & Fukubayashi, 2010). Based on this pattern of activity, it has been suggested that a presynaptic inhibition mechanism exists to protect muscle at longer lengths. (Higashihara et al., 2010). In the quadriceps there is evidence that EMG activity is significantly lower not only during eccentric activation but also during slow concentric contractions compared with fast concentric contractions (Aagaard et al., 2000). Potential explanations for these findings include inhibition of the α motorneuron by type Ib afferent feedback from Golgi tendon organs and changes in Ia and II excitatory input from muscle spindles (Guilhem et al., 2010). Changes in EMG activity indicate however that resistance training can reduce (vastus lateralis and vastus medialis) or completely remove (rectus femoris) motorneuron inhibition in the quadriceps during eccentric activation and slow concentric contractions compared to fast concentric contractions (Aagaard et al., 2000). Parallel to the disinhibition, there was a significant increase maximal quadriceps strength. Current evidence also suggests that eccentric training is significantly more effective at increasing neuromuscular activity than concentric training (Hortobagyi et al., 1996).

In an attempt to better understand the origins of various nervous adaptations, studies have been conducted to determine the effect of eccentric exercise on neural inhibition at the spinal level (Duclay, Martin, Robbe, & Pousson, 2008; Guilhem et al., 2010). The Hoffmann (H)-reflex reflects the presynaptic inhibition of Ia afferent motoneuron synapses and can be used as a tool to evaluate the modulation of the spinal reflex loop (Duclay et al., 2008). Duclay et al. (2008) reported that 7 weeks of eccentric training did not have an effect on resting H-reflex amplitude but did increase H-reflex amplitude in active plantarflexor muscles. This was attributed to significant increases in EMG activity and V-wave (H-wave superimposed on a volitional contraction) amplitude, indicating improved neural drive (increased excitability of α motorneurons) and/or reduced presynaptic inhibition of Ia afferents. It was also noted that a decreased antagonist coactivation could affect the amount of reciprocal inhibition and facilitate the H-reflex. However, there was no change in antagonist coactivation detected in any of their trials which adds to the inconsistent findings on the effects of eccentric training on coactivation levels (Duclay et al., 2008; Guilhem et al., 2010).

Increased EMG activity and reduced presynaptic inhibition after eccentric exercise have been shown to be correlated to increased torque output, but there is no indication that they have a direct effect on changes in optimal angle. It is possible however that decreased inhibition allows for an increased activation (recruitment and/or firing rate) of motor units, at longer muscle lengths during eccentric exercise, resulting in the observed change in optimum angle.

In conclusion, a 7-week eccentric exercise training protocol produced a significant shift of optimum length in the hamstrings of Division I athletes participating in football, baseball, and lacrosse; while those that did not perform additional eccentric exercises did not have a significant shift in optimum length. This shift in optimum length is most likely due to a combination of the mechanical, cellular, and neural adaptations that occur in response to eccentric exercise.

Perspectives

Based on the results of this study and previous studies (Brughelli M. et al., 2010; Brughelli et al., 2009; Clark et al., 2005; Kilgallon et al., 2007), it appears that progressive eccentric training of the hamstrings performed at least twice a week has a positive effect on the torque-angle relationship. In the future larger sample sizes utilizing athletes with longer training periods and periodical isokinetic testing during and after the intervention are needed to determine appropriate training protocols. In addition, the precise mechanism for the shift in optimum length is still not fully understood and the cellular and neural adaptations to eccentric exercise as well as the effect of eccentric exercise on titin composition and signaling all warrant further investigation.

Keywords: Peak-torque angle, training, Nordic Hamstring exercises, isokinetic, optimal angle, length-tension relationship

Table 1 Prone Hamstring Curl Progression

Week	Session(s)	Sets	Reps*
1	2	1(50%)	8
		2(M-1RM)	8
2	2	1(50%)	8
		2(M-1RM)	8
3	2	1(50%)	8
		2(M-1RM)	8
4	1	1(50%)	8
		2(M-1RM)	8
5	1	1(50%)	8
		2(M-1RM)	8
6	1	1(50%)	8
		2(M-1RM)	8
7	1	1(50%)	8
		2(M-1RM)	8

*Reps were performed on both legs
M-1RM= modified 1RM (1RM-10lbs)

Table 2 Nordic Hamstring Exercise Protocol

Week	Sets	Reps
4	2	5
5	2	8
6	3	8
7	3	10

Table 3 Participant Demographics

Group	Age (Yrs)	Mass (kg)	Height (cm)
CG	19.6 (±1.6)	92.2 (±23.1)	181.6 (±7.0)
EG	19.9 (±1.8)	98.6 (±19.9)	187.1 (±5.7)

Table 4 Comparisons of Optimal Angle and Normalized Peak Torque

Variable	Group	Pre	Post
Optimal Angle (°)	CG	17.3 (± 4.6)	16.9 (± 2.7)
	EG	17.5 (± 4.1)	14.1 (± 1.6)*
Con Peak Torque (Nm/kg)	CG	1.4 (± 0.5)	1.7 (± 0.4)
	EG	1.6 (± 0.4)	2.0 (± 0.5)
Ecc Peak Torque (Nm/kg)	CG	1.9 (± 0.6)	2.2 (± 0.3)
	EG	2.0 (± 0.8)	2.5 (± 0.7)

**-Indicates significant change*

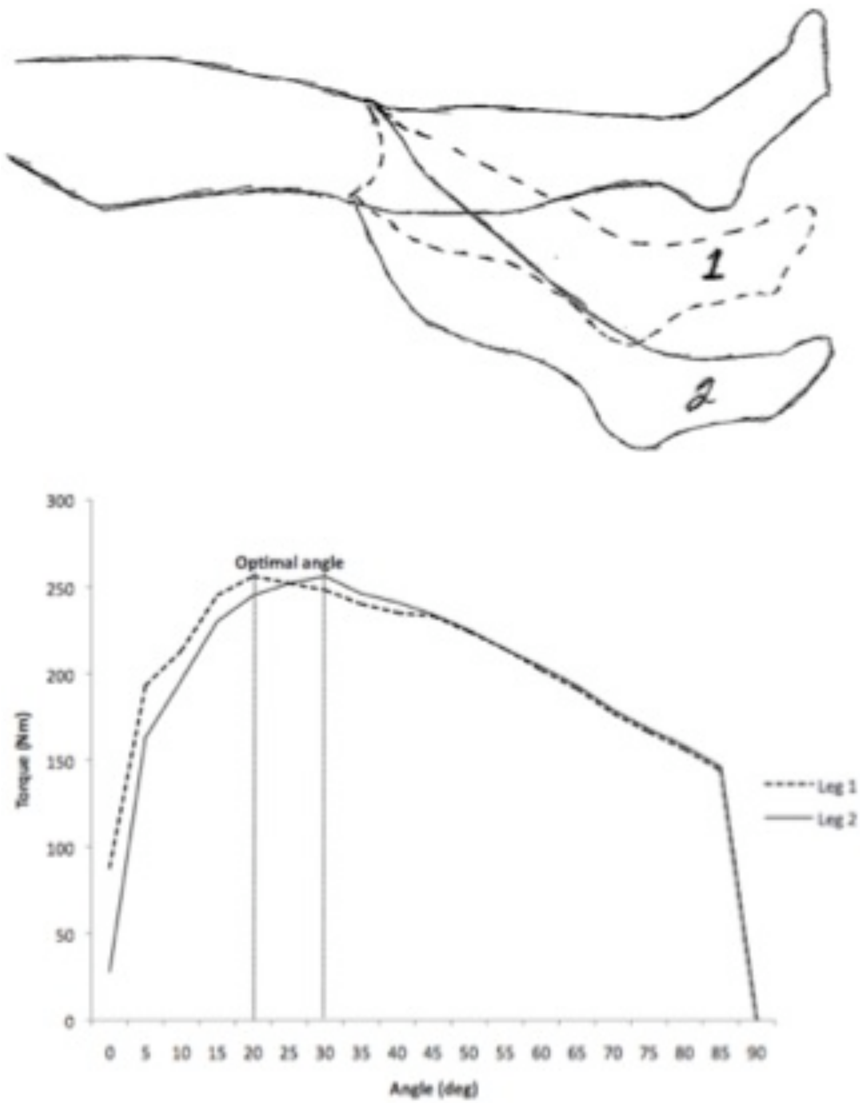

Figure 1 Graphic representation of optimal angle and two isokinetic strength positions

Leg 1 depicts optimal angle of the hamstrings at 20°, while Leg 2 represents optimal angle of the hamstrings at 30°.

Figure 2 Hamstring Curl (concentric/eccentric)

Figure 3 Nordic Hamstring Exercises

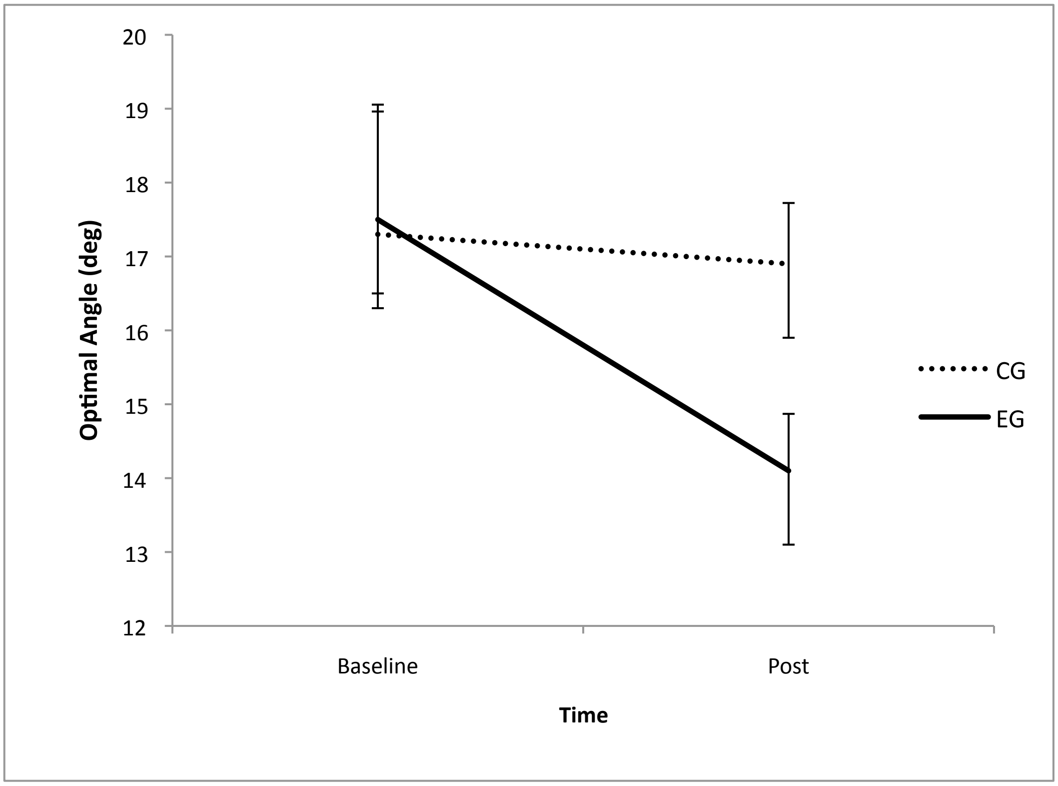

Figure 4 Estimated Marginal Means of Optimal Angle

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Appendix A

INFORMED CONSENT

University of Delaware Human Subjects
Informed Consent Form

RESEARCH STUDY: The Effect of Eccentric Exercise on the Optimum Length (Strength) of Hamstrings in Collegiate Football Players.

INVESTIGATORS: Daniel V. Tocci, BS (graduate student) and Thomas W. Kaminski, PhD (professor) in the Department of Kinesiology and Applied Physiology

INTRODUCTION
You are invited to take part in a research study to gain information that may help reduce hamstring injury in sport. You qualify based on your status as a student-athlete on the University of Delaware's football team and range in age from 18-24 years.

PURPOSE
The purpose of this study is to examine hamstring strength in a group of college athletes, and whether strength changes with specific exercises, and if so for how long the change lasts.

PROCEDURES
You are one of 50 student athletes volunteering to participate in this study during your offseason. With your approval the sports medicine staff (John Smith and Dr. Reisman) will review your medical records and determine if you are eligible to participate in this study. Student athletes with any injury at the time of (or during) the study will be excluded from participating. You will be asked to arrive for testing wearing running shoes and shorts. You will report to the Human Performance Lab at the University of Delaware to complete baseline testing. The baseline and post-training testing sessions of this study will take approximately 15 minutes.

Your age, height, and weight will be recorded. You will then perform a five-minute warm-up on a stationary bicycle followed by a stretching routine for your thigh muscles. When your warm-up is complete you will perform isokinetic testing. The following describes the baseline testing that will be performed:

(A) Baseline Testing

Isokinetic Strength Testing- The first part of the testing will require you to complete a testing session using a device called an isokinetic dynamometer (Figure 1). You will be seated with a strap around your ankle and will be asked to repeatedly bend and straighten your knee. The computer will produce strength values of the thigh muscles being tested.

1-Repetition Max (1RM) Testing – The device used to measure 1RM is the same as a hamstring curl machine that you would see in a gym (Figure 2). This test will require you to perform a hamstring curl at a low weight and then keep increasing the weight by 5 lbs. until you can only perform one repetition and no more.

At the conclusion of the session you will be asked to perform a series of cool-down stretching exercises for the hamstring muscles (Figure 3). Post-test stretching is meant to help alleviate muscle soreness that may develop as a result of the exercises conducted during the test session.

Figure 1.

Figure 2.

Figure 3.

(B) Group Assignment

After you complete the baseline testing you will be randomly placed into one of two groups. One group (Group A) will execute their normal training in the weight room with an additional set of stretching exercises targeted to the hamstrings, while the other group (Group B) performs this same training along with additional exercises targeted at the hamstring muscles for 7 weeks. These additional training sessions will require 10 minutes of time to complete. At the end of 7 weeks (before the start of preseason) both groups will return to the Human

Performance Lab for post-training strength testing. This procedure is the same as described above in (A). Post–training testing will require 15 minutes to complete. During preseason you will not perform any additional exercises other than you normal training in the weight room. You will be asked to report to the human performance lab one last time for isokinetic testing at the conclusion of the preseason.

CONDITIONS OF SUBJECT PARTICIPATION

All of the data will be kept confidential. Your information will be assigned a code number. The list connecting your name to the code number will be kept in a locked file. When the study is completed and the data have been analyzed, that list will be destroyed, but the coded data will be kept indefinitely on a secured electronic file device (in case the results are needed in future analysis). Your name will not be used in conjunction with this study. In the event of physical injury during participation, you will receive first aid. If you require additional medical treatment, you will be responsible for the cost. You will be removed from the study if you experience any injury that interferes with the results or prevents you from completing it. There are no consequences for withdrawing from the study and you can do so at any time.

RISKS AND BENEFITS

Potential risks in this project are minimal. As with any exercise or challenging movements, risks include fatigue, localized muscle soreness, and the potential for strains and sprains of muscles and joints of the lower leg. There is a slight risk to you of suffering bone, muscle, or joint injuries during the testing protocol. In the event of an acute injury, you will receive immediate first aid. Follow-up care will be at your own expense. If you become too fatigued or uncomfortable, you may stop the test at any time.

The results of the study may influence how hamstring strength training routines are developed in the future.

FINANCIAL CONSIDERATIONS

There will be no compensation for participating in this study. There will be no cost to you, the subject, for participating in the study. Transportation is provided on campus to the testing site and all materials will be provided by the researcher.

CONTACTS

Dan Tocci (610) 812-0601 or dtocci@udel.edu & Dr. Thomas W. Kaminski (302) 831-6402 or kaminski@udel.edu Questions regarding the research study can be directed to the above email addresses.

For questions of concerns about the rights to the individuals who agree to participate in the study:

Human Subjects Review Board, University of Delaware (302) 831-2137

ASSURANCE

Participation in this study is completely voluntary. You may stop at any time during the testing without penalty. Refusal or choosing to discontinue participation in this study is the right of the individual, with no loss of benefits to which the subject is otherwise entitled.

CONSENT SIGNATURES

Subject Consent Signature Date

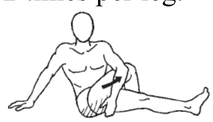
Principal Investigator Signature Date

Signed consent forms will be retained by the researcher for three years after completion of the research.

Appendix B

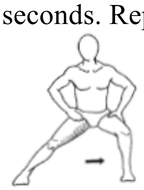
STRETCHING PROTOCOL

IT Band Stretch (Sitting)
Sit on the floor. Bend one knee and cross the leg over the other leg. Turn upper body towards the bent leg. Using the opposite hand slowly pull the knee towards the opposite shoulder until a stretch is felt in the buttocks and along the outside of the hip. Hold 20 to 30 seconds. Repeat 2 times per leg.



Piriformis Stretch (Lying)
Lie on your back with both knees bent. Cross one leg with the foot resting on the other thigh. Put your hands behind the knee of the leg with the foot on the floor. Pull up toward your chest. Hold 20 to 30 seconds. Repeat 2 times/leg.

Hip Adductor Stretch
Stand with feet wide apart. Make sure toes point straight ahead. Bend one knee. Shift weight toward the bent knee until a stretch is felt on the inner thigh of the straight leg. Hold 20 to 30 seconds. Repeat 2 times/leg.

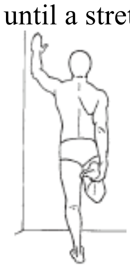


Butterfly Stretch
Sit on the floor with knees bent, soles of feet against each other. Use your forearms to give gentle stretching pressure against inner thigh of each leg. Hold 20 to 30 seconds. Repeat 2 times.

Hip Flexor Stretch
Standing, take a long step forward assuming a lunge position with leg to be stretched straight and in back. It is not necessary to have heel on the floor. Rest hands on hips or front leg, keeping front foot flat on floor. Keep torso upright and back straight. Slowly lower hips forward and downward until a stretch is felt in the front of the thigh. Hold 20 to 30 seconds.

Repeat 2 times/leg.
Variation: A chair may be used to increase the stretch.

Quadriceps Stretch (Standing)
Use a wall or chair for support with the leg to be stretched extended behind you. Knee of opposite leg slightly bent. Hold foot of leg to be stretched with your hand, pulling the heel toward the buttock until a stretch is felt in the front of the thigh. Hold 20 to 30 seconds.



Repeat 2 times/leg.
Quadriceps Stretch (Prone)
Laying on your stomach, bend knee of leg to be stretched. Use your hand or a towel to gently draw your heel toward your buttocks until a stretch is felt in front of the thigh. Do not let lower back arch. Hold 20 to 30 seconds. Repeat 2 times/leg.

Appendix C

SPECIFIC AIMS

Hamstring strains are one of the most commonly reported soft tissue injuries in sports. Epidemiology studies have reported that hamstring strains account for between 6% and 29% of all injuries reported in Australian Rules football, rugby union, American football, Major League Baseball, soccer, basketball, cricket and track sprinters (Brooks, Fuller, Kemp, & Reddin, 2006; Croisier, 2004; Feeley et al., 2008; Garrett, 1996; J. Orchard & Seward, 2002; J. Orchard, 2001; Woods et al., 2004). They are debilitating injuries that cause an average loss of play that ranges from 8-25 days (Brooks et al., 2006; Croisier, 2004; Feeley et al., 2008; Garrett, 1996). In addition to the frequency of initial injuries, hamstring strain rehabilitation seems to be plagued by poor healing responses, prolonged symptoms, and high re-injury rates (12-31%) (Croisier, 2004; Woods et al., 2004). Even more concerning is that the greatest risk of re-injury is in the initial two weeks following return to sport (J. Orchard, 2001). This high re-injury rate suggests that traditional hamstring prevention and rehabilitation programs are ineffective and that a better understanding of the etiology of hamstring injuries is needed(Brockett CL, Morgan DL, & Proske U, 2001).

Non-modifiable risk factors of hamstring injuries that have been identified include the bi-articulate muscular arrangement of the hamstrings (Brooks et al., 2006; Linklater, Hamilton, Carmichael, Orchard, & Wood, 2010; Sugiura, Saito, Sakuraba, Sakuma, & Suzuki, 2008), age (Arnason et al., 2004; Brooks et al., 2006; J. Orchard, 2001; Verrall, Slavotinek, Barnes, Fon, & Spriggins, 2001), and previous history of injury (Bennell et al., 1998; J. Orchard, 2001; Proske, Morgan, Brockett, & Percival, 2004; Verrall et al., 2001). Potential modifiable risk factors include muscle weakness (Croisier, 2004; Jonhagen, Nemeth, & Eriksson, 1994; J. Orchard, 2001), fatigue (Garrett, 1996; Jonhagen et al., 1994; Woods et al., 2004), and hamstring (eccentric) to quadriceps (concentric) strength imbalances (Croisier, 2004; Sugiura et al., 2008). Other risk factors that have been cited include lack of flexibility (Jonhagen et al., 1994; Witvrouw, Danneels, Asselman, D'Have, & Cambier, 2003), neuromuscular trunk deficits (Sherry & Best, 2004), and improper warm-up (Safran, Garrett, Seaber, Glisson, & Ribbeck, 1988) but current evidence for these factors is either limited or conflicting (Arnason et al., 2004; Bahr & Holme, 2003).

Previous studies reported that most hamstring strains occur when the hamstrings are acting eccentrically, specifically during the late swing and early contact phases of sprinting and the deceleration phase of kicking (Jönhagen, Ericson, Nemeth, & Eriksson, 1996; Stanton & Purdham, 1989; Sugiura et al., 2008). Injuries occurring after repetitive eccentric activity during sprinting and kicking may be linked to the fact that repeated bouts of eccentric exercise create small microscopic tears at the muscle fiber level (Armstrong, 1990; Morgan, 1990). Since these microscopic tears have been proposed to provide a starting point from which a major strain could occur, preventing the initial occurrence of the tear may reduce the risk of a strain (Brockett CL et al., 2001; Proske et al., 2004). Studies have suggested that due to sarcomerogenesis, eccentric exercise could be used to create a training effect that protects the hamstrings from future muscle damage(Brockett CL et al., 2001; Clark, Bryant, Culgan, & Hartley, 2005). Brockett et al. (2001) suggests that during the initial bout of eccentric exercise, there is a non-uniform lengthening of sarcomeres, which leads to the damage of sarcomeres by being stretched beyond myofilament overlap. They hypothesize that this damage causes fiber necrosis but eventually leads to the generation of new sarcomeres in a series. The increase of sarcomeres in a series would then result in a positive shift of the muscle's length-tension relationship, or optimum length for contraction. A positive shift in optimum length is translated as a decrease in the optimum angle (peak torque-angle) towards knee extension (Brockett CL et al., 2001; Brockett CL, Morgan DL, & Proske U, 2004).

Currently there are several studies that have examined the effect of progressive eccentric exercise training on optimum length in the hamstrings (Brughelli M. et al., 2010; Brughelli, Nosaka, & Cronin, 2009; Clark et al., 2005; Kilgallon, Donnelly, & Shafat, 2007). Results of these studies suggest that eccentric exercise training can produce a positive shift in optimum length of the hamstrings toward greater muscle lengths. However, only two of the studies examining optimum length used trained athletes, one a randomized control trial involving professional soccer players (Brughelli M. et al., 2010) the other a case study involving one Australian Rules football player with recurrent hamstring injuries (Brughelli et al., 2009). It is known that hamstring strains plague athletes in various sports with diverse training regimens; however it is unclear whether or not additional emphasis on eccentric training has a universal effect on optimal angle in all athletes. The purpose of this study is to determine if a 7-week eccentric exercise-training regimen in conjunction with an athlete's offseason training program can produce a significant shift in optimum length of the hamstrings.

Specific Aim 1: To determine if a 7-week eccentric exercise program in conjunction with an athlete's offseason training regimen can produce a significant shift in optimum length of the hamstrings.

Hypothesis 1: We hypothesize that a 7-week eccentric exercise training program in conjunction with an athlete's offseason training regimen can produce a significant positive shift in optimum length compared to athletes not performing eccentric exercise.

Appendix D

BACKGROUND & SIGNIFICANCE

Muscle strains are a common and debilitating injury found across all sports that involve sprinting and kicking. In high school and collegiate football players muscle strains have been found to comprise between 12% and 24% of all injuries (Dick et al., 2007; Elliott, Zarins, Powell, & Kenyon, 2011; Shankar, Fields, Collins, Dick, & Comstock, 2007). In a NCAA report that spanned 16 football seasons, they found that of the total muscle strains that occurred approximately half occurred in the upper leg (Dick et al., 2007). Muscle strains to the upper thigh were also second (10.3%) behind knee internal derangements for the most severe injuries (10+ days of time loss) during the preseason (Dick et al., 2007). The same researcher also reported upper thigh muscle strains in collegiate men's lacrosse and baseball players during the same time period (Dick et al., 2007; Dick, Romani, Agel, Case, & Marshall, 2007). In men's lacrosse upper leg strains accounted for 7.5% and 11.4% during games and practice respectively (Dick, Romani et al., 2007). Unlike football and lacrosse, baseball players suffered more upper leg strains during games (11%) than practice (8.3%) (Dick et al., 2007). As in football upper thigh strains were some of the most frequent severe injuries suffered. In lacrosse they accounted for 5.6%(games) and 8.3%(practice) of total injuries resulting in 10+ days of time loss (Dick, Romani et al., 2007). In baseball upper leg strains were the second most common injury (7.7%) to result 10+ days of time loss during games (Dick et al., 2007). While the previous studies highlight the prevalence of strains in the upper thigh they do not differentiate which individual muscles were involved.

Currently hamstring injury incidence in the National Football League (NFL) and Major League Baseball (MLB) has been documented in three recent epidemiology studies (Elliott et al., 2011; Feeley et al., 2008; Posner, Cameron, Wolf, Belmont Jr, & Owens, 2011). However, there is little documentation specifically on hamstring injury incidence in collegiate football, baseball, and men's lacrosse. A study examining preseason injuries of one NFL team found that hamstring strains were the second most common injury behind knee sprains, accounting for 11.6% of all injuries (Feeley et al., 2008). A study spanning 7 years examining injury incidence in the MLB found that hamstring strains are the second most common injury in fielders (13.7%) and fourth most common injury in all players (8%) (Posner et al., 2011).

The NFL team from the previously mentioned study had an injury rate of 1.79 per 1000 athlete-exposures (A-E) for practices and 4.07 per 1000 A-E for games (Feeley et al., 2008). A more recent study examining all NFL teams over a full season found an injury rate of .47 per 1000 A-E for practices and 2.7 per 1000 A-E for games. Of the total hamstring injuries 51.3% occurred during the 7-week preseason with an injury rate of .82 per 1000 A-E for practices and 2.92 per 1000 A-E for games (Elliott et al., 2011).

In addition to the frequency of injuries, hamstring strains were found to have an average loss of play of 8.3 days and a re-injury rate of 16.5% in the NFL (Elliott et al., 2011).

This high injury rate coupled with prolonged symptoms and high re-injury rates suggests that traditional hamstring prevention and rehabilitative programs are ineffective and a better understanding of these injuries is necessary.

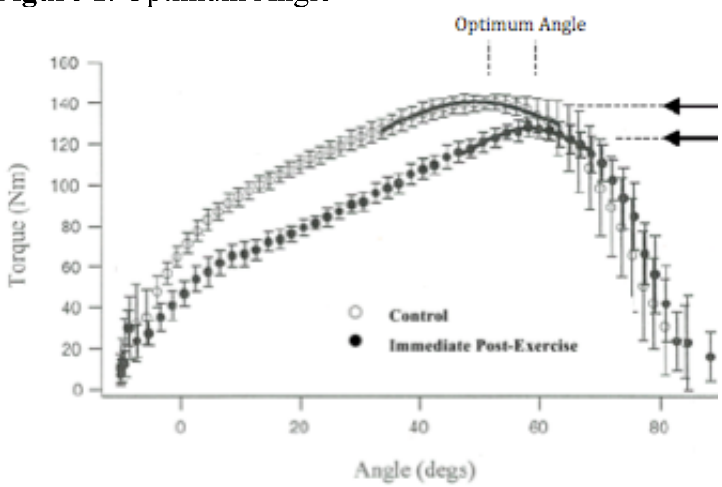
In sports that involve sprinting most hamstring strains occur while the hamstrings are eccentrically contracting during the late swing and early contact phases of sprinting (Arnason et al., 2004; Linklater et al., 2010; Stanton & Purdham, 1989; Sugiura et al., 2008). It has also been noted that because the hamstrings are a bi-articular muscle group it may predispose them to strains during these activities, because this arrangement allows for incredibly high forces to be generated over large muscle length changes (Brockett CL et al., 2001; Linklater et al., 2010; Sugiura et al., 2008). Some other possible causative factors that have been hypothesized include muscle stiffness, muscle weakness, hamstring/quadriceps (H/Q) ratio imbalances, lack of flexibility, neuromuscular trunk deficits and improper warm-up, but the current evidence of these factors is either limited or conflicting and will not be the main focus of this review (Arnason et al., 2004; Bahr & Holme, 2003; Heiderscheit, Sherry, Silder, Chumanov, & Thelen, 2010).

The purpose of this review will be to: 1) define optimum length/angle, 2) determine the effectiveness of eccentric exercise at preventing and treating hamstring strains, and 3) examine how optimum angle is affected by eccentric training and if optimum length can be used to predict hamstring injury.

Defining Optimum Length/Angle

Optimum length is determined using isokinetic testing. An isokinetic dynamometer is used to measure the torque generated by a maximal concentric knee flexion contraction performed at 60°/s (Brockett CL et al., 2001). A "zero angle" is set and angle-torque curves are then generated from these data. (It is important to note whether the knee is in full extension or flexion when setting the “zero angle.” If the “zero angle” is set in full knee extension then a smaller angle represents a longer muscle length when examining knee flexion and vice versa if the angle is set in knee flexion.) The angle-torque curves are used to determine the knee joint angle at which the greatest peak torque is recorded, this is known as the optimum angle (see figure 1) (Brockett CL et al., 2001). The length of the muscle at which it generates peak torque is that muscle’s optimum length for contraction.

Figure 1. Optimum Angle



It has been proposed that muscle strain injuries are thought to occur when activated muscles are lengthened beyond their optimal lengths (Friden & Lieber, 2001). Therefore it has been suggested that hamstring injuries can be reduced if this optimum length can be increased through sarcomerogenesis elicited by strength training, specifically progressive eccentric training (Brockett CL et al., 2001; Brockett CL et al., 2004; Brughelli et al., 2009).

Eccentric Exercise

Based on previous experiments that showed stronger muscles can absorb more energy prior to failure than weaker muscles, strength training has been recommended as a means to prevent muscle strains (Armstrong, 1990; Garrett, 1996; Mjølsnes, Arnason, østhagen, Raastad, & Bahr, 2004). Other studies found that strength gains are mode specific and that the greatest concentric gains are obtained with concentric training and the greatest eccentric gains with eccentric training (Kaminski, Wabbersen, & Murphy, 1998). These findings, coupled with the fact that most hamstring injuries occur during the late swing and early contact phases of sprinting when the hamstrings are absorbing their highest forces (Sugiura et al., 2008), suggest that eccentric exercise would be the most effective strength training intervention for preventing and treating hamstring injuries.

Effectiveness of Eccentric Exercise at Preventing Injury

Several studies have been conducted to determine if an eccentric-based training program could reduce the incidence of hamstring injuries in sport (Arnason, Andersen, Holme, Engebretsen, & Bahr, 2008; Askling, Karlsson, & Thorstensson, 2003; Brooks et al., 2006; Gabbe, Branson, & Bennell, 2006; Petersen, Thorborg, Nielsen, Budtz-Jørgensen, & Hölmich, 2011). Early results suggested eccentric exercise could reduce hamstring injury when compared with a control group in soccer players (Askling et al., 2003). A limitation to this study however was the small sample size which lead to an unusually high hamstring injury rate 20% in the intervention group and 67% in the control group compared to the normally cited frequency (6-29%) (Mendiguchia & Brughelli, 2010).

Two larger cohort studies followed 12 professional rugby teams1 and 24-31 (depending on the season) professional soccer teams (Arnason et al., 2008)40 over multiple seasons to determine the incidence of hamstring injuries. Both studies (Arnason et al., 2008; Brooks et al., 2006) compared eccentric hamstring training using Nordic hamstring exercises in addition to their normal training regimens with other interventions. Both studies found a significant reduction in the incidence of hamstring injuries in the group that incorporated Nordic hamstring exercises into their strengthening program compared to the groups that did not use these exercises. Authors in one study also noted that while numbers did not reach statistical significance those who used the Nordic hamstring exercises seemed to suffer less severe hamstring injuries compared to the other group (Brooks et al., 2006).

Two large scale randomized trials have been conducted to determine the effectiveness of an eccentric exercise program at preventing hamstring injury (Gabbe et al., 2006; Petersen et al., 2011). In one study, preliminary data indicated that eccentric exercise could potentially reduce the incidence of hamstring injury, however, poor compliance and significant attrition especially in the intervention group prevented any definitive conclusions from being made. Researchers state that the players reported DOMS as the primary reason for lack of compliance. This was also seen in one of the previously mentioned cohort studies (Arnason et al., 2008). While none of the teams that followed the prescribed training progression reported problems with delayed onset muscle soreness (DOMS), one team that decided to use a much more aggressive regimen incurred considerable DOMS and eventually dropped out of the study (Arnason et al., 2008). A more recent study had much better compliance, did not suffer significant attrition, and was able to report that eccentric hamstring exercise decreased the rate of overall, new, and recurrent acute hamstring injuries in male professional and amateur soccer players (Petersen et al., 2011).

The current research suggests that a progressive eccentric-exercise based program can be effective at preventing hamstring injury. However, while the large scale cohort studies showed significant reductions in hamstring incidence, the researchers had to rely on reports from team physicians and coaches on injuries and compliance to the training protocol, thus sacrificing some internal validity. More large RCTs, like the ones conducted by Gabbe et al. (2006) and Petersen et al. (2011) are needed in other sports and genders to determine if the results found in these studies are generalizable to other athletic populations.

It should also be noted that DOMS could have a significant effect on player compliance and needs to be taken into consideration before initiating an eccentric-based training program. Several studies suggest that introducing lower intensity eccentric loads at the onset and gradually increasing load and repetition over time can reduce the amount of DOMS encountered, which in turn should increase compliance (Arnason et al., 2008; Brughelli M. et al., 2010; Gabbe et al., 2006; Mjølsnes et al., 2004). Time of season should also be considered; the consensus from most studies suggests that the offseason and preseason are the best times to start a program (Brughelli M. et al., 2010; Gabbe et al., 2006; Mjølsnes et al., 2004). This seems like the best course of action especially since most hamstring injuries occur during this time.

Effectiveness of Eccentric Exercise at Treating Hamstring Injuries

There is evidence to suggest that eccentric exercise can increase optimum length, which in turn may be able to reduce the risk of re-injury in hamstrings. While these results provide promising evidence towards effective treatment of hamstring injury, there are only two studies (Askling et al., 2003; Brughelli et al., 2009) that have been conducted that have tested eccentric exercise on previously injured athletes.

In a study that included 30 players from elite soccer teams, 10 of those players reported sustaining a hamstring injury in the previous season (Askling et al., 2003). Of those 10 players, six were in the intervention group and four were in the control group. A 10-week progressive eccentric exercise program was implemented in the training group followed by a 10-month observational period. Although statistical significance was not calculated, it was noted by the authors that the four players with previous history in the control group all suffered a re-injury while only two of the six players in the training group suffered a re-injury. The other study was a case report that assessed an eccentric-based training program on an Australian Rules football player with recurrent hamstring injuries (Brughelli et al., 2009). The player had suffered two grade II hamstring strains and one grade III strain. Several different traditional rehabilitation programs had been attempted without success. The subject was unable to complete speed or agility exercises because of pain and could not participate in training for an additional three days after exercise due to soreness. An 8-month functional eccentric exercise program divided into 4 phases was implemented. The first 3 phases of the program were completed over a 9-week period. The fourth phase consisted of one or two exercises that were performed every week for the next 23 weeks to maintain gains made in the beginning phases. After nine weeks, the subject reported no muscle soreness after performing his workouts and did not have to skip following workouts. He was able to participate in every game of the following season without re-injury.

Though promising the evidence in these two studies as to the effectiveness of eccentric exercise as a viable treatment for hamstring injury is weak. While, the studies do show an indication that eccentric exercise may be beneficial, no conclusions can be drawn on this subject until larger randomized controlled studies are conducted.

Optimal Angle

Effects of Eccentric Exercise on Optimum Length in Hamstrings

Over the last thirty years, researchers have established that unaccustomed bouts of eccentric exercise damage muscle fibers leading to small microscopic tears. These tears are indicated by delayed onset muscle soreness (DOMS), which is produced by the breakdown products of the damaged fibers (Armstrong, 1990; Brockett CL et al., 2001). After a series of experiments examining the effects of eccentric exercise on muscle, it was proposed that these micro-tears provided a starting point from which a more major tear could occur (Morgan, 1990). In an original study done by Brockett et al. (2001), they proposed that due to a phenomenon now known as sarcomerogenesis eccentric exercise could be used to create a training effect to protect the hamstrings from further muscle damage. They suggested that during the initial bout of eccentric exercise, there is a non-uniform lengthening of sarcomeres, which leads to some sarcomeres being stretched beyond myofilament overlap and becoming damaged. Damaged sarcomeres would then trigger the generation of more sarcomeres in a series. They then hypothesized that the increase of sarcomeres in a series would then result in a shift of the muscle's length-tension relationship, or optimum length for contraction (Brockett CL et al., 2001).

The original study conducted used 10 subjects not involved in regular weight training. They were asked to perform 12 sets of six repetitions of what are known as

Nordic hamstring exercises (NH). These are body weight (BW) exercises that involve the subject kneeling with a partner or apparatus holding their feet while the subject slowly lowers their body in a controlled manner toward a prone position. Subjects were tested immediately after exercise, the results showed a significant shift in average optimum angle of 7.7° toward greater knee extension. Four days post exercise, optimum angle shifted to a mean peak increase of 8.5°. Eight days later, six of the 10 subjects performed a second bout of exercise. The average optimum angle only shifted an additional 1.19° immediately after the second bout of exercise. Ten days later (18 days from first exercise) the last measurement was taken and the average optimum angles remained significantly elevated.

Since this study, other studies have been conducted to evaluate the effects of progressive eccentric strength training programs on optimum length. Two studies (Clark et al., 2005; Kilgallon et al., 2007) using a subject pool of non-athletes found significant shifts in optimum lengths toward greater knee extension after an eccentric exercise-training regimen lasting three (Kilgallon et al., 2007) and four (Clark et al., 2005) weeks. However, only one study followed-up with their subjects and found that while significant shifts of optimum length toward knee extension were present up to 11 days post exercise by day 18 results returned to baseline (Kilgallon et al., 2007). It should be noted that the study reported having a minimum detectable change of 15° in optimum angle to be deemed significant. This is much higher than other studies which found significant changes in optimal angle of 8.5° (Brockett CL et al., 2001) , 6.3° (Clark et al., 2005)and 4° (Brughelli M. et al., 2010). So it is possible that a significant change in optimum angle was still present but undetectable with this study's design. Interestingly in the same study a second group that performed a concentric training regimen was found to have a significant shift in optimum angle away from knee extension suggesting a shortening of the muscle. Results returned to baseline by day 18 just as they had in the eccentric group.

Another study found that a functional eccentric exercise program (eccentric box drops, lunge pushes, forward deceleration steps, and reverse NH) used in conjunction with a traditional training regimen could produce a significant shift in optimum length in elite soccer players compared to their traditional training regimen alone (Brughelli M. et al., 2010). This is a significant study because it is currently the only randomized control trial (RCT) that examined the effects of eccentric exercise on optimum length in the athletic population. Results of all five studies can be seen in Table 1. A case report conducted by Brughelli et al. (2009) has produced the most promising results to date. An 8-month eccentric rehabilitation program was designed for an athlete with recurrent hamstring injuries. By week nine, results showed a shift in optimum angle from 37.3° to 23.9° in the injured leg and a shift of 24.3° to 20.3° in the non-injured leg that remained constant for the next 23 weeks (Brughelli et al., 2009).

While studies like these are promising and suggest that eccentric exercise can shift optimum length toward greater muscle lengths, more RCTs with larger sample sizes and longer training regimens are needed before any conclusions can be made on their effectiveness in the athletic population.

Table 1: Optimum Angle Studies

Author	Intervention	Control	Results
Brughelli (2010)	4 Eccentric exercises targeting hip/knee extensors and knee flexors. 3x/wk + NH eccentric exercise 1x/wk for 4 wks	Regular training regimen including NH eccentric exercise 1x/wk	Significant effect of eccentric exercise on decrease of optimum angle (EG=4°, CG=2.3°, $p<0.05$)
Brughelli (2009)	Functional eccentric exercises broken up into 4 phases. 1-3 performed in offseason, 4 preseason/in-season	----	Significance of eccentric exercise on decrease in optimum angle not reported (Injured leg=13.4°, Non-injured= 4°)
Kilgallon (2007)	Eccentric phase only of 2 hamstring exercises. Total of 7 sessions in 3 wks	No resistance training	Significant effect of eccentric exercise on decrease of optimum angle (21°, $p<0.01$)
Brockett (2001)	One bout of NH eccentric exercise (12 sets x 6 reps)	----	Significant effect of eccentric exercise on decrease of optimum angle post-exercise (Peak day 4 = 8.5°± 1.9°, $p<0.05$)
Clark (2005)	NH eccentric exercise for a total of 9 sessions in 4 wks w/increasing difficulty & volume	----	Significant effect of eccentric exercise on decrease of optimum angle (6.3°, $p<0.05$)

Effectiveness of Optimum Length at Predicting Injury

A retrospective study was conducted to determine if optimum length had any predictive value in determining athletes at risk for hamstring injury (Brockett CL et al., 2004). The study compared the optimum length of previously injured legs to uninjured legs in the same subject as well as a control group consisting of athletes with no previous injury in either leg. Results showed that optimum angle in the injured leg was 12° less (away from knee extension) compared to the uninjured leg. It was also reported that there was no significant difference between the uninjured legs of those with unilateral hamstring pathology and those in the control groups who had no previous hamstring injury. These findings suggest that optimum angle may not be a prediction of injury in previously uninjured subjects and that there are other causative factors involved with initial injury. While there was no significant difference in the uninjured legs between the two groups, they did report that optimum angles in the uninjured group varied between 16 and 34° of knee flexion (Brockett CL et al., 2004).

Large prospective studies are needed to determine if values significantly above a specific optimum angle predispose athletes to a higher risk of injury. It should also be noted that while it is still unknown if optimum length is a factor in predicting initial injury, this study27 reports findings that suggest the high re-injury rates of hamstring strains may be due to the significant reductions in optimum angle after initial injury.

Summary

Optimum length has been shown to be decreased in athletes after initial injury and may be an important factor in predicting re-injury. Furthermore, eccentric exercises like the Nordic hamstring exercises have shown the ability to increase optimum length and decrease both initial injury and re-injury rates. Optimum length studies have almost entirely been conducted mostly in the non-athletic population and only one study has looked at the effect of eccentric exercise on optimum length in athletes. However this was only in professional soccer players and, therefore, more research is warranted to determine if eccentric exercise has an effect on optimum length in athletes from different sport demographics.

Appendix E

PHOTOGRAPHIC RELEASE FORM

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