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ORIGINAL ARTICLE

Effects of eccentric strength training on biceps femoris muscle architecture and knee joint range of movement

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Abstract The aim was to determine whether eccentric strengthening changed the muscle architecture of human biceps femoris and consequently, knee range of motion. Twenty-two subjects were randomly assigned to control and experimental groups. The experimental group completed an eccentric strengthening programme for 8 weeks. Outcome measures included hamstring muscle strength (one repetition maximum), the passive knee extension test (PKE) (knee joint angle at which the onset of passive tension occurs), fascicle length (FL) and pennation angle (PA). One repetition maximum increased by 34% ($P < 0.01$), the PKE test revealed a 5% increase in joint range of motion ($P = 0.01$), FL increased by 34% ($P = 0.01$) and PA did not change ($P = 0.38$). This is the first report of an increase in FL in the biceps femoris following eccentric resistance training. In addition, the results might imply that this fascicle lengthening could lead to an increase in the range of motion of the knee. Clinical implications for rehabilitation and injury prevention are discussed.

Keywords Muscle strength · Range of motion · Sarcomere · Hamstring

Introduction

Hamstring injuries are common in athletes participating in sport (Burkett 1970); for instance, hamstring strains represent 11% of all injuries and one-third of all muscle strains in English professional football (Dadebo et al. 2004). Although there are numerous reasons why these injuries can occur, one reason that has been suggested is a strength imbalance between the quadriceps and the hamstring muscle groups (Burkett 1970). This strength imbalance may result in alterations of the agonist–antagonist muscle coordination during actions, such as kicking. Kicking is thought to require a fast concentric contraction of the quadriceps balanced by an eccentric contraction of the hamstring muscle group at specific angular positions. A weakened hamstring muscle group for example, after surgical intervention, may not be able to counterbalance the tension generated by the quadriceps contraction, which may increase the risk of injury (Brockett et al. 2001). Rehabilitation often includes eccentric strengthening of the hamstring muscles at appropriate angular joint positions, to correct this muscle imbalance. Along with an increase in muscle strength, eccentric resistance training induces structural changes, such as muscle hypertrophy and an increase in fascicle pennation angle (PA) (Aagaard et al. 2001).

Another reason for hamstring injuries to occur is a lack of flexibility of the hamstring muscle (Worrell et al. 1991; McHugh et al. 1999), which can lead to straining or tearing sections of muscle during movements at the end of range of motion, where myofibrils are stretched beyond their end-range (Goldspink et al. 1995). Hamstring stretches are commonly

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prescribed during rehabilitation to increase flexibility/range of motion of the knee and/or hip. The mechanisms by which stretching might increase range of movement include modifying the mechanical or structural properties of the tendon or muscle (Magnusson et al. 1996a, b, c). Structural changes include lengthening of the tendon and/or changes in muscle architecture through lengthening the muscle fascicles. Resistance training is known to elicit changes in muscle architecture. Evidence from animal studies suggests that eccentric resistance training increase muscle fascicle length (FL) by increasing the number of sarcomeres in series (Morgan and Allen 1999) via a process called 'sarcomerogenesis' (Butterfield and Herzog 2006). An increase in fascicular length has recently been shown in the human quadriceps muscle following resistance training of both concentric and eccentric components (Seynnes et al. 2007), or after eccentric resistance training alone (Blazevich et al. 2007). Furthermore, recent studies based on muscle torque–angle relationship Brockett et al. (2001) and Kilgallon et al. (2007) suggest that the shift in optimal angle induced by eccentric training could result from a lengthening of the respective muscle groups, which in turn may result in an increase in range of movement. Conversely, eccentric resistance training is also known to stiffen tendon aponeuroses (Legner and Milner 2008), which would limit the joint range of movement. In addition, as fascicles do not run parallel to their axis in pennate muscles, it is not known whether an increase in FL would necessarily translate into a lengthening of the whole muscle.

To the authors' knowledge, the relevance of training-induced fascicle lengthening upon joint range of movement has never been tested in (a) a young population, where both eccentric training and range of movement are integral to the rehabilitation of hamstring problems and (b) in the hamstring muscle group, where injury can be caused by and also lead to eccentric weakness and decreased flexibility of movement. Thus, the aim of this study was to determine whether the fascicle lengthening resulting from an 8-week eccentric strengthening programme affects the range of motion of the knee joint.

Methods

Ethical approval was gained from the Riverside Research Ethics Committee, and with informed and written consent 22 subjects were recruited voluntarily to the study via advertising and randomly allocated into two equal sized groups using a random number table. Subjects were aged between 20 and 50 years. They were excluded if (a) they performed regular weight training to their lower limbs or (b) they had any pre-existing musculoskeletal injuries or medical conditions limiting their ability to exercise. The following measurements were taken on the dominant leg before and after an 8-week training programme.

One repetition maximum of eccentric hamstring strength

The subject completed 3 min of cycling on an exercise bike to warm up prior to testing. The subject was positioned in prone on a bench of a hamstring leg curl machine (Universal conditioning equipment, Iowa, USA), with the lever arm of the machine positioned under their distal lower leg (Kaminski et al. 1998; Kawakami et al. 1993). Eight submaximal hamstring curls were performed to further warm up the muscle. The subjects were then asked to lift a given weight with their non-dominant leg to their end range of knee flexion, Then, subjects transferred the weight from the non-dominant to the dominant (experimental) leg and lowered it over a 5-s period (i.e. hamstrings muscles contracted eccentrically). The weight was gradually increased until subjects could only lower this weight once over 5 s. This was called the one repetition maximum (1RM). Manual assistance was provided when the load exceeded the maximal concentric force of the non-dominant leg. The weight lifted during this maximum eccentric hamstring contraction was then recorded.

Passive knee extension test

The widespread clinical test, "passive knee extension test (PKE)" (Gajdosik et al. 1993) was used to measure the knee range of motion, up to the onset of passive tension. The angle was measured using an isokinetic machine (Cybex Norm, Cybex International Inc, Ronkonkoma, New York, USA). Subjects were positioned in a supine position with their pelvis secured to the bench with a strap. Using a goniometer, the subject's hip was placed in 90° flexion and maintained in this position by locking the motion arm of the isokinetics machine. The subject was instructed to relax. The knee was passively moved to the point, where the first sign of passive resistance to movement was felt by the examiner (Maitland 1986). The angle at which this was reached was measured and recorded three times and an average calculated.

Ultrasound measurements

The subject was positioned in prone and the knee was extended and relaxed. The ultrasound probe (41 mm, LA424 14 8, Genova, Italy) was placed on the skin overlying the distal part of the biceps femoris and its position was recorded in order to be able to replace the probe in the same position after the 8-week training period was completed. The position of the probe was recorded by measuring the distance from a fixed point on the probe to the posterior margin of the iliotibial band, the greater trochanter and the tibial condyle. Once the probe was appropriately placed and its position recorded, two ultrasound images of the fibres of biceps femoris were taken and stored (Esaote Technos Plus; 13 MHz, Genova, Italy). The images were then analysed digitally off-line (see Fig. 1). FL was measured by manually outlining visible parts of muscle fascicles running between the superficial and deep aponeuroses defining the posterior region of the muscle (Woodley and Mercer 2005). Sections of FL that were not visible on the image were extrapolated as a straight line (Maganaris et al. 1998; Narici et al. 1996), and the summation of measured and extrapolated FL was calculated to obtain total FL. The angle between the line marking the deep aponeurosis and the outlined fascicle was then measured, giving the PA [see Fig. 1; (Gajdosik et al. 1993)].

Strength training

The subjects were asked to warm up by doing a 3-min cycle on an exercise bike. Then using the hamstring curl machine the subjects continued their warm up by completing a set of eight eccentric hamstring curls using 50% of the weight required to lift their 1RM. Having warmed up, the subjects then lowered their 1RM weight over 5 s eccentrically, using the same procedure as the testing protocol. The aim was to increase the number of repetitions that could be performed at the 1RM weight. To this end, subjects attempted to perform additional contractions using the baseline 1RM load, over the specified 5 s duration. Over the training progression, and as subjects reached the target of 5-s contraction time, another repetition was added to increase the training volume. This process was repeated throughout the training duration to match the increase in muscle performance. By the end of the training, subjects aimed to complete three sets of eight repetitions each, at a weight corresponding to the initial 1RM. Training sessions were supervised by the examiner (primary researcher) fortnightly to ensure that the 5 s eccentric contractions target was met and that contractions were performed over the full knee range of motion.

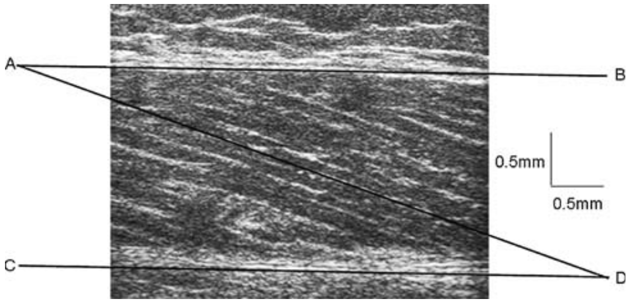

Fig. 1 An ultrasound image of biceps femoris. The *line* (*AB*) represents the position of the superficial aponeurosis. The *line* (*CD*) represents the position of the deep aponeurosis. In order to measure FL and PA, a line of best fit was placed along the length of a fascicle, which joined lines AB and CD. The FL was calculated as the length of this line. The PA was calculated as the angle between lines CD and DA (Chleboun et al. 2001)

After collection of all of these measurements the participants were randomly divided, using a random number table, into a control and an experimental group. The subjects in the experimental group were then enrolled on a strength training programme for their dominant leg. They trained for 8 weeks, three times a week (Kraemer et al. 2002). After an 8-week period, the subjects in both the control and the experimental groups repeated the tests described above.

Data analysis

Any change in FL, PA, 1RM and range of motion of the knee using the PKE test over the 8-week period were expressed as a percentage change. Any differences in the absolute values were tested using independent and paired *t* tests when parametric criteria were reached. Where the data was not normally distributed, Wilcoxon signed-ranks matched pair and Mann–Whitney *U* tests were used. Finally the relationship between change in muscle architecture and change in range of motion were examined using correlation coefficients. Data are expressed as the mean ± standard error of the mean (SE).

Results

At the time of inclusion to the study no differences were found in height ($P = 0.08$), age ($P = 0.10$), PKE angle ($P = 0.15$), FL ($P = 0.68$) or PA ($P = 0.06$) between the control group and the experimental group (see Table 1). There was, however, a statistical difference detected in their weight ($P = 0.03$) and the 1RM ($P = 0.05$), but differences in these parameters do not challenge the validity of the control group.

One repetition maximum hamstring curl

After the 8 week experimental period, the control group did not change their 1RM. However, the experimental group

Table 1 Subject population characteristics (mean ± standard error of the mean)

	Age	Female/ male ratio	Height (cms)	Weight (kg)
Control group	29.6 ± 1.2	9/2	168.0 ± 3.6	64.3 ± 1.2
Experimental group	27 ± 0.8	7/4	175.8 ± 2.0	76.0 ± 4.2

had an average increase of 34.2% in their 1RM strength [$P < 0.01$; 95% confidence interval (95% CI) = 7.5–18.5 kg], which was a mean increase of 13.8 ± 2.3 kg (mean ± standard error of the mean) more than the control group ($P < 0.01$; see Tables 2, 3).

Passive knee extension test

After the 8 week experimental period, there was no change in the PKE test in control group. In contrast, this test indicated that the passive knee range of motion of the experimental group had an average gain of 6.9° ($P = 0.01$; 95% CI = 12–2°), with a mean difference in angle between the two groups of 7.1 ± 0.1° ($P = 0.01$; see Tables 2, 3). The interclass correlation coefficient for this test was 0.89 (95% CI = 1.07–3.05°).

Fascicle length and pennation angle

After the training period, the control group had no significant change in FL; whereas, there was a mean increase of 33.5% in the FL in the experimental group. However, there was no significant difference in FL when comparing the control group to the experimental group ($P = 0.11$). No changes were seen in PA in either the control or the experimental groups (see Tables 2, 3). No correlation was found between change in the FL and the change in the range of motion of the knee ($R = -0.41$, $P = 0.21$). The interclass correlation coefficient for this test was 0.95 (95% CI = 1.07–3.05 mm).

Table 2 A summary of the results of the control group before and after the 8-week experimental period (mean ± standard error of the mean)

	Week 1	Week 8	Paired *t* test (*P*)
1RM (kg)	25.6 ± 4.8	26.5 ± 5.5	0.90
PKE (degrees)	145.4 ± 3.4	143.6 ± 2.8	0.33
FL (mm)	57.3 ± 2.8	66.8 ± 4.0	0.09
PA (degrees)	13.9 ± 0.7	14.8 ± 0.6	0.22

The outcome measures were the *1RM* one repetition maximum, *PKE* passive knee extension test, *FL* fascicle length and *PA* pennation angle

Table 3 A summary of the results of the experimental group before and after the 8-week experimental period (mean ± standard error of the mean)

	Week 1	Week 8	Paired *t* test (*P*)
1RM (kg)	40.4 ± 5.1	54.2 ± 7.0	<0.01
PKE (degrees)	137.5 ± 2.5	144.4 ± 2.5	<0.01
FL (mm)	59.0 ± 3.0	78.8 ± 3.5	<0.01
PA (degrees)	17.1 ± 1.3	16.6 ± 1.1	0.38

The outcome measures were the *1RM* one repetition maximum, *PKE* passive knee extension test, *FL* fascicle length and *PA* pennation angle

Discussion

After an 8-week training period of eccentric strengthening exercise of the hamstring, the experimental group increased their 1RM by 34%. Along side this increase in 1RM there was also an increase in the passive range of motion measured by the PKE test (5%) and a 34% increase in FL with no change in PA.

The mean FL measured in this study (57–79 mm) is in-line, yet slightly smaller, with previous data from embalmed muscles (74–89 mm, Woodley and Mercer 2005) and from in vivo measurements at a similar anatomical position (~66–153 mm, Chleboun et al. 2001). Similarly, our PA measurements (14–17°) were comparable to previous in vivo observations (~10–17°, Chleboun et al. 2001), indicating that the architecture data obtained in the present study are valid and consistent with past literature.

The increase in the PKE test reflects both the length and the flexibility of the hamstrings muscle–tendon unit. Our hypothesis was that eccentric exercise would increase the passive range of motion of the knee joint, as measured through the PKE test, through an increase in the FL in the hamstrings. The increase in FL observed in the present study, suggests the addition of sarcomeres in series within the muscle. Fascicle lengthening through in-series sarcomere addition has been advocated in a few animal (Lynn et al. 1998) and in human (Blazevich et al. 2007; Seynnes et al. 2007) studies following eccentric strength training. The present results extend previous findings by showing for the first time a 34% increase in FL in the human hamstring muscles with this mode of training. Interestingly, this is considerably larger than the increases in FL reported by Blazevich et al. (2007) and Seynnes et al. (2007) who demonstrated a 4.7 and 9.9% increase, respectively. Albeit speculative, these differences may be muscle specific, as both Blazevich et al. (2007) and Seynnes et al. (2007) recorded FL from the quadriceps rather than the hamstring muscle. Possibly, the different function and anatomical location of these muscle groups might induce different adaptations in their muscular and/or tendinous structures. Alternatively, this difference in magnitude of architectural changes may result from differences in training parameters, such as the range of motion or the velocity of contraction. Importantly, our results indicate that fascicle lengthening is accompanied by an increase in passive range of motion, which has not been measured previously.

Although we did not assess this parameter, serial sarcomerogenesis is known to enable the muscle to operate over a greater range of the FL–tension curve, and to induce a right hand shift of the peak of this relationship (Reeves et al. 2004). Consequently, after resistance training the muscle can generate a greater torque at more extended joint positions, where most damage to the hamstring occurs, further preventing muscle fibre tears (Morgan and Allen 1999). This point is of particular importance, as it is believed that protecting against such micro-tears in the muscle may also lead to a protection against gross muscle damage, such as the common hamstring tear (Brockett et al. 2001). Another hypothetical consequence of the increase in FL could be directly ascribed to the increase in range of motion observed in the present study. As stated in the Introduction section, an increase in FL would not necessarily translate into the lengthening of pennate muscles. However, it is noteworthy that aponeuroses do not run continuously between the distal and proximal insertions of the biceps femoris muscle. Although these structures run along a large portion of the muscle (Woodley and Mercer 2005), they are only linked by the muscle fascicles. Hence, a sufficient increase in FL could theoretically extend the inter-aponeuroses distance, lengthening the whole muscle.

Since the muscle is placed in series with the tendons, and since there is no published report of tendon lengthening following resistance training, one could argue that the increase in the PKE test may in fact reflect changes in tendon stiffness, not measured in this study. For instance, an increase in tendon compliance would have caused an increase in the PKE test, even if muscle fascicle did not change. However, strength training has been demonstrated to increase tendon stiffness rather than reduce it (Kubo et al. 2001), suggesting that the influence of tendon stiffness on the observed increase in PKE is unlikely. Rather, since the knee range of motion partly results from a trade-off between muscle length and the stiffness of tendinous structures, the theoretical influence that the present changes in FL might impart upon the PKE test have probably been partially mitigated by an increase in tendon stiffness. This would likely explain the lack of correlation between the changes in FL and knee range of motion in the present experiment. Alternatively our measurements of FL, performed in the distal portion of the biceps femoris, might not reflect the magnitude of the changes in FL in other areas of this muscle, or in the other muscles forming the hamstrings. Finally, despite the acceptable ICC values demonstrated in the present study and elsewhere (Chleboun et al. 2001) we measured a non-significant 18% increase in FL in the control group. The reasons for such an increase remain unclear, and these results possibly denote an inter-day variability higher than that measured during the reliability testing. Nevertheless, even if the adverse conditions leading to an increased variability also affected the results of the experimental group, it should be noted that FL changes in this group were ~100% higher than in the control group. This relative difference hence confirms the validity of the present findings.

The lack of changes observed in PA of the muscle alongside a 34% increase in strength seems counter-intuitive. It is generally accepted that sarcomeres are added in parallel during resistance training, allowing the muscle to generate a higher maximum force (Farthing and Chilibeck 2003; Kawakami et al. 1993; Lieber and Friden 2000). It is also recognised that the number of sarcomeres in parallel is related to PA within the muscle, the latter increasing with training to accommodate newly added sarcomeres (Aagaard et al. 2001). Therefore, the present results suggest that the observed increase in eccentric strength reflects an improvement in the neural factors affecting force exertion capability of the hamstrings (Moritani and deVries 1979; Reeves et al. 2004), or in excitation–contraction coupling (Warren et al. 2001), rather than an addition of sarcomeres in parallel. Another explanation could lie in the fact that any change in PA may be muscle specific, and that significant changes may have been measured in other knee flexor muscles, such as the semitendinosus.

The results of this study have an important clinical relevance. The average 7° increase in passive range of motion found in this study was similar to changes demonstrated after 6 weeks of passive stretching of hamstrings (Nelson and Bandy 2004). This increase combined with an increase in strength of 34% demonstrate that eccentric training may be particularly useful when considering functional rehabilitation of actions, such as kicking. These findings suggest that the clinical interest of this study is that this regime increases eccentric strength and increases knee range of motion when measured with the PKE test. Taken together with the theory that sarcomerogenesis might protect against muscle micro-tears, could this lead to preventing whole muscle tears? This speculation needs further investigation.

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