

Isokinetic peak torque and flexibility changes of the hamstring muscles after eccentric training: Trained versus untrained subjects

Amr Almaz Abdel-aziem^{a,*}, Elsadat Saad Soliman^b, Osama Ragaa Abdelraouf^a

^a Department of Biomechanics, Faculty of Physical Therapy, Cairo University, Giza, Egypt

^b Department for Musculoskeletal Disorders and Its Surgery, Faculty of Physical Therapy, Cairo University, Giza, Egypt

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ABSTRACT

Objective: The aim of this study was to examine the effect of eccentric isotonic training on hamstring flexibility and eccentric and concentric isokinetic peak torque in trained and untrained subjects.

Methods: Sixty healthy subjects (mean age: 21.66 ± 2.64) were divided into three equal groups, each with 20 voluntary participants. Two experimental groups (untrained and trained groups) participated in a hamstring eccentric isotonic strengthening program (five days/week) for a six-week period and one control group that was not involved in the training program. The passive knee extension range of motion and hamstring eccentric and concentric isokinetic peak torque were measured at angular velocities 60° and $120^\circ/s$ for all groups before and after the training period.

Results: Two-way analysis of variance showed that there was a significant increase in the hamstring flexibility of the untrained and trained groups ($25.65 \pm 6.32^\circ$, $26.55 \pm 5.99^\circ$, respectively), ($p < 0.05$) without a significant increase in the control group ($31.55 \pm 5.84^\circ$), ($p > 0.05$). Moreover, there was a significant increase in eccentric isokinetic peak torque of both the untrained and trained groups ($127.25 \pm 22.60\text{Nm}$, $139.65 \pm 19.15\text{Nm}$, $125.40 \pm 21.61\text{Nm}$, $130.90 \pm 18.71\text{Nm}$, respectively), ($p < 0.05$) without a significant increase in the control group ($109.15 \pm 20.89\text{Nm}$, $105.70 \pm 21.31\text{Nm}$, respectively), ($p > 0.05$) at both angular velocities. On the other hand, there was no significant increase in the concentric isokinetic peak torque of the three groups ($92.50 \pm 20.50\text{Nm}$, $79.05 \pm 18.95\text{Nm}$, $92.20 \pm 21.96\text{Nm}$, $79.85 \pm 18.97\text{Nm}$, $100.45 \pm 25.78\text{Nm}$, $83.40 \pm 23.73\text{Nm}$, respectively), ($p > 0.05$) at both angular velocities. The change scores in the hamstring flexibility ($06.25 \pm 1.86^\circ$) and eccentric peak torque of the untrained group ($16.60 \pm 4.81\text{Nm}$, $17.45 \pm 5.40\text{Nm}$, respectively) were significantly higher ($p < 0.05$) than those of the trained group ($03.40 \pm 1.14^\circ$, $9.90 \pm 5.14\text{Nm}$, $9.80 \pm 7.57\text{Nm}$, respectively), and the control group ($00.90 \pm 2.10^\circ$, $0.60 \pm 2.93\text{Nm}$, $1.40 \pm 3.53\text{Nm}$, respectively), at both angular velocities. Meanwhile, the change scores of the concentric peak torques of the three groups ($1.15 \pm 1.50\text{Nm}$, $-0.15 \pm 2.16\text{Nm}$, $1.35 \pm 1.63\text{Nm}$, $0.20 \pm 2.95\text{Nm}$, $0.60 \pm 2.28\text{Nm}$, $-0.30 \pm 2.25\text{Nm}$) were statistically insignificant ($p > 0.05$).

Conclusion: After a six-week period of eccentric isotonic training, the hamstring eccentric peak torque and flexibility of trained and untrained groups improved without changes in the concentric peak torque. Moreover, the improvement of untrained subjects was higher than trained subjects. These findings may be helpful in designing the hamstring rehabilitation program.

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* Corresponding author. Department of Biomechanics, Faculty of Physical Therapy, Cairo University, 7 Ahmed Elziat Street, Ben Elsaryat, El Dokki, 12611, Giza, Egypt.

E-mail addresses: amrmalmaz@yahoo.com, amrmalmaz74@gmail.com (A.A. Abdel-aziem).

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Introduction

During the late swing phase of sprinting, there is a rapid change of muscle contraction from eccentric to concentric that has been suggested as the underlying mechanism for hamstring strains. Hamstrings are maximally loaded and lengthened during this phase of rapid contraction mode change.¹ Because hamstring strains commonly occur during the eccentric phase of a muscle

contraction, overloading these muscles with eccentric training could potentially prevent hamstring strains.²

A hamstring strain is a complex injury, so no one single approach can be considered the ideal method for prevention.³ Nonetheless, eccentric-based intervention has been shown to be a hopeful technique in reducing the risk of hamstring strain injuries.^{4–6} Eccentric training is recognized as a powerful stimulus to hypertrophy and increased strength because it promotes greater neural activation compared to isometric and concentric modes of contraction.^{7,8}

Brockett et al² reported that eccentric loading adds sarcomeres in series that shift the length-tension curve, so peak tension is generated at longer muscle lengths. Given the length-dependent nature of muscle damage in hamstring strains near end of range, this structural adaptation optimizes the angle of peak torque to reduce the risk for potential injury.⁹ Static stretch and eccentric training are equally effective in improving hamstring muscles flexibility without a significant difference between both methods,^{10,11} and static stretching increases the concentric torque and flexibility of the hamstring.¹²

Static stretching increased the eccentric and concentric plantar-flexor peak torque in trained and untrained individuals and improved the flexibility of untrained individuals more than trained individuals.¹³ Hamstring injuries appear to occur as a result of weakness at the muscle's lengthened state.¹⁴ So, an inability to increase an athlete's eccentric strength may predispose an athlete

to subsequent injury. Combining eccentric training with a hamstring rehabilitation program may help to reduce the rate of recurrent injury.

Recently, Lovell et al¹⁵ reported that an eccentric hamstring strengthening program increased the strength and electromyographic activities to a similar magnitude irrespective of its schedule before or after football training sessions. However, architectural adaptations to support the strength gains differed according to the timing of the injury prevention program. Moreover, eccentric hamstring exercise increased fascicle length and reduced pennation angle in biceps femoris without significant changes in muscle thickness. So, this type of exercise counteracts multiple hamstring injury risk factors in physically active young adults.¹⁶

To the best of our knowledge, although previous studies have reported that eccentric training increases muscle strength,^{7–9} decreases injury rates, increases flexibility,^{10,11} and improves athletic performance,^{6,17–19} no studies have been performed to compare the effects of eccentric isotonic training on the isokinetic strength profile of the hamstring muscles in trained and untrained subjects. Therefore, this study was conducted to compare the effects of eccentric isotonic training on the hamstring concentric and eccentric peak torque and hamstring flexibility between trained and untrained subjects. The present study hypothesized that the eccentric hamstring training would improve the concentric and eccentric peak torque and flexibility in both trained and untrained subjects.

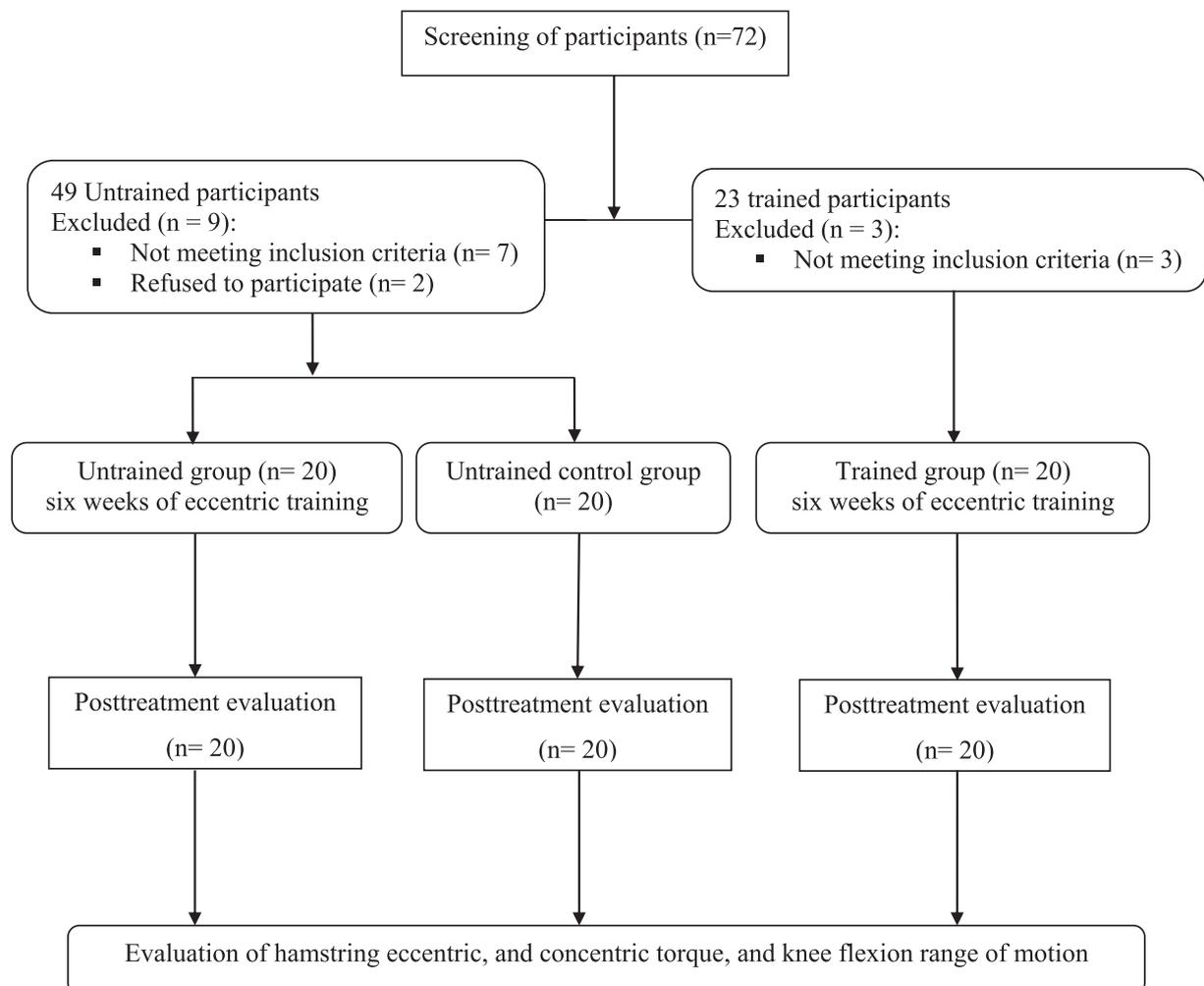


Fig. 1. The participants' flowchart in the present study.



Fig. 2. Eccentric training on a pulley system. Starting position (a) and terminal position (b).

Materials and methods

Participants

Sixty male physical therapy students participated in this study. Initially, 72 students were screened for eligibility, 12 of them were excluded for different reasons. The inclusion criteria were: 1) no physical impairments in either the lower limbs or lower back in the previous year; 2) the tested extremity had to exhibit hamstring tightness with at least a 20° deficit to full knee extension from supine with the hip at 90°; 3) all subjects had to be right-side dominant; and 4) no previous injury to the hamstring muscle. An individual who was engaged in an aerobic activity, such as walking, jogging, running, or swimming, at least three times a week for more than 20 min/session²⁰ and for more than six months²¹ was assigned to the trained group.

The untrained participants were defined as those who had never been involved in any type of regular resistance or aerobic training.²¹ To conceal group allocation, the untrained participants were allocated using a SPSS computer program (version 16.0; SPSS Inc., Chicago, IL, USA) to the two groups: the untrained experimental group or the untrained control group (Fig. 1). The demographic characteristics of the participants are shown in Table 1.

The trained and untrained experimental groups participated in an eccentric isotonic training exercise program for the dominant right leg only. The control group did not perform any form of training exercises. Informed consent for participation in the study were obtained from all subjects at the beginning, and participants received a clear explanation of the study procedures. The study was conducted in accordance with the Declaration of Helsinki and was approved by the ethical committee of the Faculty of Physical Therapy, Cairo University.

Instrumentation

A universal goniometer (Bench-mark Medical, Inc) was used to measure the knee extension range of motion (ROM); it is a highly

Table 1
The participants' demographic characteristics.

	Control group, n = 20	Untrained group, n = 20	Trained group, n = 20	ANOVA ^a p value
Age (year)	21.08 ± 2.39	22.18 ± 2.85	21.73 ± 2.67	0.363
Height (cm)	173.80 ± 4.15	171.50 ± 4.06	174.10 ± 4.79	0.127
Weight (kg)	69.75 ± 4.38	72.30 ± 5.70	70.95 ± 4.88	0.282

Data are presented as mean ± standard deviation.

^a Significance level from ANOVA between the three groups.

reliable tool used to assess the joints ROM.¹⁰ An isokinetic dynamometer (Biodex Multi-Joint System 3, Shirley, NY) was used to measure the eccentric and concentric isokinetic peak torques of the hamstring muscles. The test protocols provided by the manufacturers were strictly followed.

Procedures

Prior to data collection, the Biodex machine was calibrated, and all the procedures were explained and managed by an experienced examiner for all participants. The hamstring muscles' isokinetic peak torque and flexibility (passive knee extension ROM) were evaluated for all groups before and after a six-week period of eccentric isotonic training. Hamstring flexibility assessment was evaluated by using the 90/90 test described by Reese and Bandy.²² The subject did not perform any kind of warm-up before the measurement of hamstring flexibility (Fig. 3).

Eccentric isotonic training was performed by having the subject lay down in a supine position and pull the knee into the chest while hooked up above the ankle joint to a pulley system (Fig. 2a). The subject used his arms to keep the knee-chest position and then slowly and eccentrically resisted the cable as it pulled the knee into extension (Fig. 2b). The force produced by the pulley system equals 40% of the subject's one repetition maximum throughout and resisted by the trainee through five counts to full extension.¹³ The eccentric exercise was repeated six times for a total period of 30 s,⁸ five days/week for a six-week period.



Fig. 3. Measurement of hamstring flexibility.

Table 2

The values of peak torques for the hamstring muscles during eccentric and concentric modes of contraction at angular velocities 60° and 120°/s.

Variables		Control group, n = 20			Untrained group, n = 20			Trained group, n = 20		
		Pre	Post	Change score	Pre	Post	Change score	Pre	Post	Change score
Hamstring eccentric torque (Nm) (M±SD)	60°/s	108.55 ± 21.84	109.15 ± 20.89	0.60 ± 2.93	110.65 ± 19.55	127.25 ± 22.60	16.60 ± 4.81	129.75 ± 21.29	139.65 ± 19.15	9.90 ± 5.14
	120°/s	104.35 ± 22.05	105.70 ± 21.31	1.40 ± 3.53	107.95 ± 19.77	125.40 ± 21.61	17.45 ± 5.40	121.10 ± 21.92	130.90 ± 18.71	9.80 ± 7.57
Hamstring concentric torque (Nm) (M±SD)	60°/s	91.35 ± 20.62	92.50 ± 20.50	1.15 ± 1.50	90.85 ± 21.69	92.20 ± 21.96	1.35 ± 1.63	99.85 ± 25.98	100.45 ± 25.78	0.60 ± 2.28
	120°/s	79.20 ± 18.26	79.05 ± 18.95	-0.15 ± 2.16	79.65 ± 19.18	79.85 ± 18.97	0.20 ± 2.95	83.70 ± 24.89	83.40 ± 23.73	-0.30 ± 2.25

Data are presented as mean ± standard deviation.

All sessions of isokinetic testing were carried out at the same time of the day, more than 3 h after a meal, and the room temperature was maintained at 21 °C. The subject warmed up before the isokinetic torque evaluation.²³ After that, the subjects were positioned in an isokinetic dynamometer according to the recommended prescriptions of Dvir.²⁴

The knee flexor torque was evaluated under eccentric and concentric isokinetic at angular velocities 60° and 120°/s.^{25–28} The ROM for the eccentric/concentric isokinetic evaluations was set to 70° (extension from 20° to 90° and flexion from 90° to 20°). Each test (60° and 120°/s) consisted of a set of five consecutive maximal voluntary eccentric/concentric contractions with 1 min of rest between different velocities.²⁴ The maximum peak torque obtained for the five contractions of knee flexors was calculated at the end of each set.

Statistical analysis

Data were analyzed using a Statistical Package for Social Sciences (Armonk, NY: IBM Corp.) version 20.0. A two-way analysis of variance (ANOVA) was used to assess the isokinetic peak torques within group and between groups. Change scores were also calculated. Finally, one-way ANOVA was used to compare the values of the knee flexion ROM among all groups. A probability of $p < 0.05$ was considered to be statistically significant. Prior to final analysis, data were screened for normality and homogeneity of variance assumptions.

Results

There were no significant differences between the groups regarding their age, weight, and height ($p = 0.363, 0.282, 0.127$, respectively), as shown in Table 1. The pre-values of the trained group were significantly higher than the pre-values of the control and untrained groups at angular velocity 60°/s ($p = 0.007, 0.016$, respectively), without a significant difference between the pre-values of the trained and untrained groups ($p = 0.167$) at angular velocity 120°/s. There was no significant difference between the pre-values of the control and untrained groups at angular velocities 60° and 120°/s ($p = 1.000$).

There were significant improvements in the hamstring eccentric torque of the untrained and trained groups ($p = 0.001$) without a significant increase in the hamstring eccentric torque of the control group ($p = 0.544, 0.402$), respectively, at both angular velocities. The post values of the untrained and trained groups were significantly higher than the post value of the control group ($p = 0.025, 0.001, 0.011, 0.001$, respectively) at both angular velocities, without a significant difference between the post values of the untrained and trained groups ($p = 0.198, 0.654$, respectively). Regarding the change score of the eccentric torque, the untrained group was

significantly higher than the trained and control groups ($p = 0.001$), and the trained group was significantly higher than the control group at both angular velocities ($p = 0.001$), as shown in Table 2.

For the hamstring concentric isokinetic peak torques, there was no significant difference between the pretraining mean values of control, untrained, and trained groups at both angular velocities ($p = 1.000, 0.781, 0.948, 1.000, 0.752, 1.000$, respectively). There were no significant improvements in the concentric torque of the three groups at both angular velocities ($p = 0.134, 0.399, 0.090, 0.349, 0.229, 0.574$, respectively). Moreover, there were no significant differences between the post values of the three groups at both angular velocities ($p = 1.000, 0.829, 1.000, 1.000, 0.763, 1.000$, respectively). There were no significant differences between the change score of concentric torque of the three groups at both angular velocities ($p = 0.414, 0.808$, respectively) (Table 2).

Regarding the knee flexion ROM, there was no significant difference between the pretraining mean values of the three groups ($p = 0.445$). There were significant increases in the hamstring flexibility of the untrained and trained groups ($p = 0.001$), without a significant increase in the control group ($p = 0.070$). The untrained and trained groups post values were significantly higher than the control group values ($p = 0.003, 0.011$, respectively), without a significant difference between the untrained and trained groups ($p = 0.640$). The change score of hamstring flexibility of the untrained group was significantly higher than the trained and control groups ($p = 0.001$), and the trained group was significantly higher than the control group ($p = 0.001$), as shown in Table 3.

Discussion

The hypothesis of this study was partially satisfied as we found that the eccentric isotonic training improved the eccentric isokinetic peak torque of the hamstring muscles at angular velocities 60° and 120°/s. On the other hand, there was no improvement in concentric isokinetic peak torque at both angular velocities. Moreover, there was an improvement in hamstring flexibility in both the trained and untrained groups.

The improvement of the hamstring eccentric torque is supported by the findings of Sato et al,²³ who reported that eccentric training significantly increased the eccentric torque values than before intervention without significant changes in concentric and

Table 3

The values of pre-training and post-training knee flexion ROM (degree).

Variables	Control group, n = 20	Untrained group, n = 20	Trained group, n = 20
Pre knee flexion ROM	32.45 ± 5.59	31.90 ± 7.53	29.95 ± 6.17
Post knee flexion ROM	31.55 ± 5.84	25.65 ± 6.32	26.55 ± 5.99
Change score	00.90 ± 2.10	06.25 ± 1.86	03.40 ± 1.14

Data are presented as mean ± standard deviation.

isometric torques. Moreover, Roig et al.²⁹ reported that eccentric training was more effective than concentric training in increasing the muscle mass and cross-sectional area.

These results are in agreement with Guex et al.,³⁰ who found that eccentric training of the hamstring increased the fascicle length from 4.9% to 9.3%. The concentric peak torque did not change, whereas the eccentric peak torque increased by 12.9%–17.9%, which proved the positive relationship between muscle fiber length and the gain of eccentric torque. This reasoning is supported by the findings of Timmins et al.,³¹ who concluded that eccentric training of the hamstring muscles increases the fascicle length of the biceps femoris long head more than the concentric training in healthy subjects.

The strength gains have a strong correlation with the training modes, i.e., greater concentric strength gains were obtained after concentric training and greater eccentric gains were obtained after eccentric training.³² In the same context, Kaminski et al.²⁵ reported that eccentric isotonic training produced significant improvements in eccentric strength, while concentric isotonic training created no significant eccentric strength gains. Housh et al.³³ also suggested that eccentric isotonic resistance training of the quadriceps musculature produced no significant concentric strength gains at any velocity. However, the results of these studies were derived from healthy untrained individuals, while the current study was conducted on trained and untrained groups. Surprisingly, the change scores in the eccentric peak torque at angular velocities 60° and 120°/s were significantly greater in the untrained group as compared with the trained group.

The improvement in eccentric isokinetic peak torque of the hamstring muscles could be attributed to two main factors: 1) the neural factors, such as increased activation of agonist and/or synergist muscles involved in the muscle action, improved coordination, and reduced coactivation of antagonist muscles, and 2) the hypertrophy of muscle fiber size,³⁴ which leads to an increase in leg girth.² Moreover, eccentric training increases the fascicle length and reduces the pennation angle that decrease the recurrent hamstring injury risk factors in physically active young adults.¹⁵

It should be noted that neural factors affect muscle strength within three weeks (short-term effect). On the other hand, the effect of muscle hypertrophy increases the muscle gains after three weeks (long-term effect).^{35,36} So, both strength mechanisms were influential as the eccentric training was extended for six weeks. In addition, the highest change score of untrained subjects compared to trained subjects could be explained by, to some degree, the neural factors and muscle hypertrophy that were already experienced by trained subjects.

Moreover, the eccentric torque prevalue of trained subjects was significantly higher than the prevalue of untrained subjects at low angular velocity 60°/s, which may explain the greatest change score eccentric torque of untrained subjects compared to trained subjects. However, the same thing did not happen at angular velocity 120°/s. These results may be attributed to the presence of neural inhibition during eccentric compared to concentric contractions, which was evident in sedentary individuals but not in elite athletes, and may suggest that any neural inhibition may be attenuated by training.³⁷ The neural mechanisms that inhibit activation during the maximal eccentric efforts of untrained individuals remains unclear. However, it is thought that the neural mechanisms protect the joint from potentially injurious high levels of force that can be produced during eccentric contractions. Nonetheless, a hamstring's volume was strongly related to knee flexor eccentric strength, suggesting that neural inhibition during eccentric contractions may be muscle specific.³⁸

The significant improvement in the eccentric isokinetic peak torque of the hamstring muscles in untrained subjects after the

intervention is supported by the findings of Cowell et al.,³⁹ who reported that eccentric resistance training is more effective than concentric training for improving muscle strength. Moreover, Guilhem et al.⁴⁰ concluded that eccentric training leads to strength gains, which were higher when tested eccentrically rather than concentrically and higher when trained isotonically rather than isokinetically.

Cook et al.⁴¹ proved that eccentric exercise training can enhance strength gain in already-trained athletes. Also, the results of the current study showed that the eccentric training in the amateur trained group, using a simple pulley system, could produce results similar to those reported by the aforementioned study conducted on professional athletes in terms of strength improvement.

The nonsignificant increase in the concentric torque of the three groups at both angular velocities was consistent with the mode-specificity concept of training that was reported by Carvalho et al.,⁴² who reported that eccentric training of a short duration induces a greater mode-specific stimulus for an increase in strength because it augments eccentric strength more than the concentric training effect on concentric strength. Moreover, muscle strength gains after concentric and eccentric training rely greatly on the muscle action used for both training and testing. Hence, the eccentric training of the current study only produced an increase in the eccentric torque.

The changes in strength revealed more signs of specificity related to velocity and contraction type after eccentric than concentric training.⁸ The higher loads developed during the eccentric contractions could be responsible for the efficiency of eccentric training in increasing eccentric muscle strength without a significant effect in the concentric muscle strength in trained and untrained subjects. The improvement of eccentric torque only (mode-specificity training) in trained and untrained subjects is supported by the findings of Brassine,⁴³ who found that the gains in the eccentric mode were reported after a two-week eccentric training program, and no differences were found in concentric and isometric modes. Moreover, Roig et al.²⁹ and Morrissey et al.⁴⁴ suggested that eccentric training increased more eccentric strength than the concentric training increased concentric strength.

However, during the evaluation procedure of the present study, eccentric torque testing was immediately followed by concentric torque testing. The concentric torque results are not supported by the findings of Svantesson et al.,⁴⁵ who reported that if the eccentric contraction was immediately followed by a concentric contraction, it would increase the values of the concentric contraction. In addition, Wilson et al.⁴⁶ stated that eccentric loading increases the potential energy stored in the muscle that will increase the immediate concentric peak torque production; this controversy can be explained by the mode-specificity training concept.

Many studies have revealed that eccentric training is able to improve muscle flexibility in professional athletes and provide a protective strategy against injury; Nelson and Bandy¹⁰ proved that eccentric training is equal to static stretch in achieving gains in hamstring flexibility and able to shift the optimum angle 7.7° in hamstring muscles for tension generation.³ Moreover, eccentric training increased the optimal length of the hamstring and quadriceps muscles.⁴⁷ Interestingly, these studies were conducted on professional athletes. Yet, the current study supports these findings; however, the improvement has been achieved in untrained and trained subjects who were not professional athletes.

The hamstring flexibility of trained and untrained subjects significantly improved compared to control subjects without a significant difference between the two groups. Nonetheless, the greatest change score of the untrained subjects might be attributed to the lower hamstring flexibility values in the untrained group as

compared to the trained group at the baseline measurement and the aerobic activities that were performed by the trained subjects before the eccentric training. It is well known that aerobic exercises have been advocated as an effective means of enhancing the extensibility of the tissue.⁴⁸

So, the results of the current study revealed that eccentric training is more beneficial for untrained subjects than trained subjects. The greatest change score of the untrained group proved the effectiveness of eccentric training in stimulating gains in muscle eccentric torque of those who were not involved in any training program. However, eccentric training cannot achieve the same level of improvement in the trained group because of their regular aerobic training had already increased their skeletal muscle mass and was associated with improvements in aerobic capacity, cardiovascular function, and metabolic regulation.⁴⁹

Limitations

The study had some limitations. First, the gender in this study was limited to males only, so the appropriateness of generalizing the results is confined to this specific population. Second, all included participants were healthy at the time of testing and had no hamstring injuries. In future research, researchers should investigate subjects who have hamstring injuries. Third, we did not examine the effect of the eccentric isotonic training on the torque-angle relationship because eccentric training changes the peak knee flexion torque angle.⁵⁰ Thus, further study is needed to determine if eccentric training will affect the angle of peak torque during eccentric and concentric contraction, which must be considered during the design of a hamstring-injury prevention program. Finally, the hamstring peak torque was only measured in the open kinetic chain in this study, so caution must be taken when generalizing these results to functional closed-chain activities.

Conclusion

A six-week period of eccentric training improved hamstring flexibility and eccentric torque in both trained and untrained subjects without improvement in the concentric torque. The improvement in the hamstring eccentric torque and flexibility of the untrained group was higher than the trained group. So, incorporating eccentric training in a hamstring rehabilitation program may increase eccentric strength and flexibility and reduce potential hamstring injuries.

Conflicts of interest

The authors have no conflicts of interest relevant to this study.

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References

- Chumanov ES, Schache AG, Heiderscheid BC, Thelen DG. Hamstrings are most susceptible to injury during the late swing phase of sprinting. *Br J Sports Med.* 2012;46:90. <https://doi.org/10.1136/bjsports-2011-090176>. Epub 2011 Jul 4.
- Brockett CL, Morgan DL, Proske U. Human hamstring muscles adapt to eccentric exercise by changing optimum length. *Med Sci Sports Exerc.* 2001;33:783–790.
- Opar DA, Williams MD, Shield AJ. Hamstring strain injuries: factors that lead to injury and re-injury. *Sports Med.* 2012;42:209–226. <https://doi.org/10.2165/11594800-000000000-00000>.
- Petersen J, Thorborg K, Nielsen MB, Budtz-Jorgensen E, Holmich P. Preventive effect of eccentric training on acute hamstring injuries in men's soccer: a cluster-randomized controlled trial. *Am J Sports Med.* 2011;39:2296–2303. <https://doi.org/10.1177/0363546511419277>.
- Nichols AW. Does eccentric training of hamstring muscles reduce acute injuries in soccer? *Clin J Sport Med.* 2013;23:85–86. <https://doi.org/10.1097/JSM.0b013e31827e9f40>.
- Askling C, Karlsson J, Thorstensson A. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scand J Med Sci Sports.* 2003;13:244–250.
- Goldspink G. Molecular mechanisms involved in the determination of muscle fiber mass and phenotype. *Adv Exerc Sport Physiol.* 1999;5:27–39.
- Seger JY, Thorstensson A. Effects of eccentric versus concentric training on thigh muscle strength and EMG. *Int J Sports Med.* 2005;26:45–52. <https://doi.org/10.1055/s-2004-817892>.
- Hather BM, Tesch PA, Buchanan P, et al. Influence of eccentric actions on skeletal muscle adaptations to resistance training. *Acta Physiol Scand.* 1991;143:177–185. <https://doi.org/10.1111/j.1748-1716.1991.tb09219.x>.
- Nelson RT, Bandy WD. Eccentric training and static stretching improve hamstring flexibility of high school males. *J Athl Train.* 2004;39:354–358.
- Nelson RT. A comparison of the immediate effects of eccentric training vs. static stretch on hamstring flexibility in high school and college athletes. *N Am J Sports Phys Ther.* 2006;1:56–61.
- Abdel-aziem AA, Abdelraouf OR. Effect of hamstring static stretch training on knee flexion concentric torque. *Indian J Physiother Occup Ther.* 2011;5:130–133.
- Abdel-aziem AA, Mohammad WS. Plantar-flexor static stretch training effect on eccentric and concentric peak torque—a comparative study of trained versus untrained subjects. *J Hum Kinet.* 2012;34:49–58. <https://doi.org/10.2478/v10078-012-0063-z>.
- Schmitt B, Tim T, McHugh M. Hamstring injury rehabilitation and prevention of reinjury using lengthened static eccentric training: a new concept. *Int J Sports Phys Ther.* 2012;7:333–341.
- Lovell R, Knox M, Weston M, Siegler JC, Brennan S, Marshall PWM. Hamstring injury prevention in soccer: before or after training? *Scand J Med Sci Sports.* 2018;28:658–666. <https://doi.org/10.1111/sms.12925>.
- Breno de AR, Alvares J, Marques VB, Vaz MA, Baroni BM. Four weeks of Nordic hamstring exercise reduce muscle injury risk factors in young adults. *J Strength Cond Res.* 2018;23:1254–1262. <https://doi.org/10.1519/JSC.0000000000001975>.
- Arnason A, Andersen TE, Holme I, Engebretsen L, Bahr R. Prevention of hamstring strains in elite soccer: an intervention study. *Scand J Med Sci Sports.* 2008;18:40–48. <https://doi.org/10.1111/j.1600-0838.2006.00634.x>.
- Arnason A, Sigurdsson SB, Gudmundsson A, Holme I, Engebretsen L, Bahr R. Risk factors for injuries in football. *Am J Sports Med.* 2004;32:5–16. <https://doi.org/10.1177/0363546503258912>.
- Clark R, Bryant A, Culgan JP, Hartley B. The effects of eccentric hamstring strength training on dynamic jumping performance and isokinetic strength parameters: a pilot study on the implications for the prevention of hamstring injuries. *Phys Ther Sport.* 2005;6:67–73. <https://doi.org/10.3233/JES-2012-0466>.
- Seymour RJ, Bacharach DW. The effect of position and speed on ankle plantarflexion in females. *J Orthop Sports Phys Ther.* 1990;12:153–156.
- Arazi H, Asadi A. The Relationship between the selected percentages of one repetition maximum and the number of one the number of repetitions in trained and untrained males. *Facta Universitatis Ser Phys Edu Sport.* 2011;9:25–33.
- Reese NB, Bandy WD. *Joint Range of Motion and Muscle Length Testing.* 2nd ed. Philadelphia: WB Saunders Co; 2002.
- Santos HH, Avila MA, Hanashiro DN, Camargo PR, Salvini TF. The effects of knee extensor eccentric training on functional tests in healthy subjects. *Rev Bras Fisioter.* 2010;14:276–283. <https://doi.org/10.1590/S1413-35552010005000014>.
- Dvir Z. *Isokinetics: Muscle Testing, Interpretation and Clinical Applications.* 2nd ed. New York: Churchill Livingstone; 2004.
- Kaminski TW, Wabbersen CV, Murphy RM. Concentric versus enhanced eccentric hamstring strength training: clinical implications. *J Athl Train.* 1998;33:216–221.
- Sato K, Hosokawa T, Mitsueda S, et al. Effects of eccentric hamstring strength exercise on knee flexor strength. *Br J Sports Med.* 2011;45:372. <https://doi.org/10.1136/bjsm.2011.084038.175>.
- Amiridis IG, Martin A, Morlon B, et al. Coactivation and tension-regulating phenomena during isokinetic knee extension in sedentary and highly skilled humans. *Eur J Appl Physiol Occup Physiol.* 1996;73:149–156.
- Mjolsnes R, Arnason A, Osthagen T, et al. A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. *Scand J Med Sci Sports.* 2004;14:311–317. <https://doi.org/10.1046/j.1600-0838.2003.367.x>.
- Roig M, O'Brien K, Kirk G, et al. The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: a systematic review with meta-analysis. *Br J Sports Med.* 2009;43:556–568. <https://doi.org/10.1136/bjsm.2008.051417>.

30. Guex K, Degache F, Morisod C, Saily M, Millet GP. Hamstring architectural and functional adaptations following long vs. short muscle length eccentric training. *Front Physiol.* 2016;7:340. <https://doi.org/10.3389/fphys.2016.00340.eCollection> 2016.
31. Timmins RG, Ruddy JD, Presland J, et al. Architectural changes of the biceps femoris long head after concentric or eccentric training. *Med Sci Sports Exerc.* 2016;48:499–508. <https://doi.org/10.1249/MSS.0000000000000795>.
32. Tomberlin JP, Basford JR, Schwen EE, et al. Comparative study of isokinetic eccentric and concentric quadriceps training. *J Orthop Sports Phys Ther.* 1991;14:31–36. <https://doi.org/10.2519/jospt.1991.14.1.31>.
33. Housh TJ, Housh DJ, Weir JP, Weir LL. Effects of eccentric-only resistance training and detraining. *Int J Sports Med.* 1996;17:145–148. <https://doi.org/10.2519/jospt.1991.14.1.3110.1055/s-2007-972823>.
34. Holtermann A, Roeleveld K, Vereijken B, et al. Changes in agonist EMG activation level during MVC cannot explain early strength improvement. *Eur J Appl Physiol.* 2005;94:593–601. <https://doi.org/10.1007/s00421-005-1365-9>.
35. Moritani T, deVries HA. Neural factors versus hypertrophy in the time course of muscle strength gain. *Am J Phys Med.* 1979;58:115–130.
36. Hedayatpour N, Falla D. Physiological and neural adaptations to eccentric exercise: mechanisms and considerations for training. *BioMed Res Inter.* 2015;2015, 193741. <https://doi.org/10.1155/2015/193741>.
37. Amiridis IG, Martin A, Morlon B, et al. Co-activation and tension-regulating phenomena during isokinetic knee extension in sedentary and highly skilled humans. *Eur J Appl Physiol.* 1996;73:149–156.
38. Duchateau J, Baudry S. Insights into the neural control of eccentric contractions. *J Appl Physiol.* 2014;116:1418–1425. <https://doi.org/10.1152/jappphysiol.00002.2013>.
39. Cowell JF, Cronin J, Brughelli M. Eccentric muscle actions and how the strength and conditioning specialist might use them for a variety of purposes. *Strength Cond J.* 2012;34:33–48. <https://doi.org/10.1519/SSC.0b013e318253f578>.
40. Guilhem G, Cornu C, Guevel A. Neuromuscular and muscle-tendon system adaptations to isotonic and isokinetic eccentric exercise. *Ann Phys Rehabil Med.* 2010;53:319–341. <https://doi.org/10.1016/j.rehab.2010.04.003>.
41. Cook CJ, Beaven CM, Kilduff LP. Three weeks of eccentric training combined with overspeed exercises enhances power and running speed performance gains in trained athletes. *J Strength Cond Res.* 2013;27:1280–1286. <https://doi.org/10.1519/JSC.0b013e3182679278>.
42. Carvalho A, Caserotti P, Carvalho C, Abade E, Sampaio J. Effect of a short time concentric versus eccentric training program on electromyography activity and peak torque of quadriceps. *J Hum Kinet.* 2014;41:5–13. <https://doi.org/10.2478/hukin-2014-0027>.
43. Brassine E, Mouraux D, Lambert G, Duchateau J. Effect of a short-time eccentric training on the eccentric performance of the quadriceps. *Isokinet Exerc Sci.* 2002;10:23–24.
44. Morrissey MC, Harman EA, Johnson MJ. Resistance training modes: specificity and effectiveness. *Med Sci Sports Exerc.* 1995;27:648–660.
45. Svantesson U, Grimby G, Thomee R. Potentiation of concentric plantar flexion torque followed eccentric and isometric muscle actions. *Acta Physiol Scand.* 1994;152:287–293. <https://doi.org/10.1111/j.1748-1716.1994.tb09808.x>.
46. Wilson GI, Wood CA, Elliot BC. Optimal stiffness of series elastic component in a stretch-shorten cycle activity. *Appl Physiol.* 1991;70:825–833. <https://doi.org/10.1152/jappphysiol.1991.70.2.825>.
47. Brughelli M, Mendiguchia J, Nosaka K, Idoate F, Los Arcos A. Effects of eccentric exercise on optimum length of the knee flexors and extensors during the preseason in professional soccer players. *Phys Ther Sport.* 2010;11:50–55. <https://doi.org/10.1016/j.ptsp.2009.12.002>.
48. Chaouachi A, Castagna C, Chtara M, et al. Effect of warm-ups involving static or dynamic stretching on agility, sprinting, and jumping performance in trained individuals. *J Strength Cond Res.* 2010;24:2001–2011. <https://doi.org/10.1519/JSC.0b013e3181aeb181>.
49. Konopka AR, Harber MP. Skeletal muscle hypertrophy after aerobic exercise training. *Exerc Sport Sci Rev.* 2014;42:53–61. <https://doi.org/10.1249/JES.0000000000000007>.
50. Naclerio F, Larumbe-Zabala E, Monajati A, Goss-Sampson M. Effects of two different injury prevention resistance exercise protocols on the hamstring torque-angle relationship: a randomized controlled trial. *Res Sports Med.* 2015;23:379–393. <https://doi.org/10.1080/15438627.2015.1076418>.