



Eccentric Training Effects on Hamstring Strength in Elite Pole Vaulters: A Case Study

Danijela Kuna¹, Ivan Paravac¹, Nikolina Uznik¹

Affiliations: ¹Josip Juraj Strossmayer University, Faculty of Kinesiology Osijek, Osijek, Croatia

Correspondence: D. Kuna. Faculty of Kinesiology Osijek, Drinska 16a, 31000 Osijek, Hrvatska. E-mail: dkuna@kifos.hr

Abstract

Hamstring muscle injuries are among the most frequent injuries in sport and have a significant impact on performance and continuity of the training process. Their occurrence is particularly pronounced in sports involving sprinting and explosive movements, while the recurrence rate within the first year after injury is extremely high. Eccentric training is recognized as a key method in prevention and rehabilitation because it leads to specific adaptations such as increased eccentric strength, lengthening of biceps femoris muscle fascicles, and improved neuromuscular control. This study, conducted as a case study on a homogeneous group of elite pole vaulters, aimed to examine the effects of an eleven-week eccentric program on isometric strength of hamstring muscles at knee flexion angles of 10°, 45° and 90°. The sample included five senior-level athletes, multiple participants in national and international competitions. The training program included Nordic hamstring exercise, Romanian deadlift, single-leg Romanian deadlift, and isolation exercises on machines with emphasis on the eccentric phase of movement. Results showed that although differences between initial and final measurements were not statistically significant ($p > .05$), effect sizes indicated moderate-to-large effects. The greatest increase was recorded at the 10° angle ($r = .78$). These findings are in line with previous research confirming that eccentric training increases muscle strength and reduces injury risk, thus further emphasizing its importance in planning and implementing training programs.

Keywords: *eccentric training, injury prevention, isometric strength, sprint, the hamstring muscles*

Introduction

Hamstring muscle injuries are among the most common sports injuries, particularly in disciplines requiring sprinting, rapid changes of direction, and explosive jumps. Epidemiological data show that hamstring injuries account for 12-16% of all sports injuries in elite sports (Ekstrand et al., 2011; van Dyk et al., 2019), being particularly common in soccer, athletics, and rugby. In soccer, the incidence can reach 1.2 injuries per 1,000 exposure hours (Ekstrand et al., 2016). These injuries are characterized by prolonged recovery, high recurrence rates up to 30% within the first 12 months (Opar et al., 2012), and negative impact on sports performance and training continuity. Prevention and rehabilitation of the hamstring injuries therefore remain major challenges in modern sports training.

The biomechanical role of the hamstring muscles further explains their vulnerability. During the late swing phase in

sprinting, the hamstring muscles are simultaneously maximally stretched and strongly activated in eccentric mode to decelerate the lower leg and prepare the foot for ground contact (Chumanov et al., 2007; Schache et al., 2013). At that moment, forces acting on the muscles can exceed eight times body weight (Bramah et al., 2024), creating conditions for acute strains and ruptures. Additional risk arises from muscle asymmetries, shorter fascicles of the biceps femoris muscle, and reduced eccentric strength, which are factors identified in prospective studies as injury predictors (Timmins et al., 2016). Furthermore, specific knee flexion angles during sprinting and swing phase are crucial for hamstring loading, where the greatest biomechanical load and injury risk occur at positions close to knee extension and an angle of approximately 10° (Kellis & Blazevich, 2022).

Eccentric training in recent decades has been recognized

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as an effective method for reducing hamstring injury risk. Its effectiveness is based on adaptations such as increased eccentric strength, fascicle lengthening, and improved neuromuscular coordination (Franchi et al., 2017). Additionally, eccentric contraction enable generation of greater forces with lower metabolic cost compared to concentric contractions (Roig et al., 2009), making them particularly suitable for high-intensity sports. Specific muscle adaptations, including changes in fascicle architecture and increased isometric strength at different knee angles, are key for maintaining functional stability and reducing injury risk during intensive sprint phases.

The preventive value of eccentric training has been proven in numerous studies. The Nordic Hamstring Exercise (NHE) shows significant reduction in hamstring injury risk and recurrences (Petersen et al., 2011; van Dyk et al., 2019). Systematic reviews and meta-analyses confirm that regular implementation of NHE in training programs reduces injury incidence regardless of competition level (Al Attar et al., 2017). Furthermore, eccentric training contributes to increased strength, sprint speed, and jumping ability (de Keijzer et al., 2022). Despite strong evidence, practice shows that eccentric training is still insufficiently applied or used in insufficient volume and intensity, particularly during the competitive period (Bahr et al., 2015). This emphasizes the need for additional research on optimal protocols, particularly in athlete populations where hamstring injuries are common and can have serious impact on performance.

Therefore, the aim of this study was to examine the effect of an eleven-week eccentric training program on isometric strength of the hamstring muscles at different knee flexion angles (10°, 45° and 90°) in elite athletes specialized in pole vault.

Methods

Participants

Five elite athletes specialized in pole vault participated in the study, with a mean age of 26 years, national-level medals, and experience competing in international competitions. All participants were in the senior category and had no current hamstring injuries at the time of the study. Given the small sample and specificity of participants, the study was designed as a case study. During the preparation process, special attention was directed to eccentric training applied to selected muscle groups, including hamstring muscles.

Variables and Instruments

Isometric strength of the posterior thigh was assessed at three knee flexion positions: 90° (JAK90), 45° (JAK45) and 10° (JAK10). For assessing isometric strength, a K-Pull dynamometer (Kinvent®, Montpellier, France) was used, and a goniometer (Baseline®, Fabrication Enterprises Inc., White Plains, NY, USA) was used for precise adjustment of knee flexion angle. Measurements were performed exclusively on the take-off leg of participants in initial and final testing. For analysis, the maximum achieved force value expressed in kilograms (kg) was used. Intrarater reliability of measurements was high (ICC > .90) for all three flexion angles.

Training Program

Participants regularly performed eccentric exercises targeting hamstring muscles during the eleven-week period. The main component was the Nordic hamstring exercise (NHE) which they performed in three sets of 5-8 repetitions, with

emphasis on controlled forward lowering with ankle fixation by a partner; the eccentric phase lasted less than one second, and load was progressively increased by adding weight or increasing movement amplitude. In addition to NHE, participants performed Romanian deadlift (RDL) in 3-4 sets of 6-10 repetitions, using body weight or additional load of 20-40 kg, where the slow eccentric phase during barbell lowering activated gluteal muscles and trunk stabilization. Single-leg Romanian deadlift was performed in 2-3 sets of 6-8 repetitions per leg, aiming to reduce asymmetries and improve unilateral control. Additionally, eccentric isolation exercises – seated and lying hamstring curl – were performed in exclusively eccentric regime, in 2-3 sets of 8-12 repetitions, where each eccentric phase was shorter than one second; load was increased when the participant could control the movement longer than prescribed time. The program was supplemented with a two-week maximal sprint training, recognized as an important factor in hamstring injury prevention (Gómez-Piqueras et al., 2024). Throughout the entire period, researchers continuously provided demonstrations, corrections, and individual instructions, and exercise intensity was adjusted based on subjective feeling of fatigue and progress assessment.

Research Protocol

Initial testing was conducted in the second week after a training break, on condition that participants arrived rested. All participants performed standardized warm-up including three isometric contractions (50%, 75% and 90% of maximal voluntary contraction). After warm-up, maximal isometric strength was measured at three knee flexion angles (10°, 45° and 90°). Participants were in prone position, and the tested leg was positioned at the desired angle using a goniometer. The dynamometer was attached to the distal part of the lower leg. On verbal command, participants performed maximal isometric contraction lasting 1-2 seconds. Two measurements were taken for each angle, and the better value was included in analysis. Rest between measurements was one minute. After initial testing, an eleven-week eccentric training program was conducted, which included Nordic hamstring exercise, Romanian deadlift, single-leg Romanian deadlift, and eccentric isolation exercises for hamstring muscles. All exercises were performed with eccentric phase shorter than 1 second, with load increase when participant could control movement longer than prescribed time. The program included two weeks of maximal sprint training, recognized as an important factor in hamstring injury prevention. During the program, continuous demonstrations, corrections, and instructions were provided, and intensity was adjusted according to subjective feeling of fatigue and researcher assessment. Final testing was conducted one week before the start of the competitive season, applying the same protocol as at the beginning of the study. The study was conducted in accordance with the Helsinki Declaration and approved by the Ethics Committee of the Faculty of Kinesiology Osijek (CLASS: 029-01/25-01/05, NUMBER: 2158-110-01-25-33).

Statistical Analysis

Statistical analysis included descriptive statistics including mean, standard deviation, minimum and maximum values. To examine differences between initial and final test variables, Wilcoxon test for paired samples was applied due to small sample size and potential deviation from normal distribution.

Effect size was estimated using Cohen's r coefficient, where values of .30, .50 and .80 were interpreted as small, medium, and large effect sizes (Cohen, 1988). Collected data were statistically processed using "IBM SPSS Statistics 20.0". Significance level was set at $p < .05$.

Results

Descriptive indicators of isometric strength at three knee flexion angles (10°, 45° and 90°) are presented in Table

1. In initial measurement, mean values ranged from 31.46 kg (JAK90) to 67.40 kg (JAK10), with relatively low standard deviations, indicating a homogeneous group of participants. In final testing, strength increase was recorded at all angles. The greatest increase was observed for JAK10 (from 67.40 to 79.62 kg), followed by JAK45 (from 53.96 to 58.06 kg), while moderate increase was recorded for JAK90 (from 31.46 to 34.86 kg), with somewhat greater variability of results.

Table 1. Descriptive indicators of initial and final measurement of examined variables

Variable	Measurement	Min	Max	M	SD	Median
JAK90	I	27.8	33.6	31.46	2.3	31.9
	F	22.7	39.6	34.86	6.89	37.3
JAK45	I	43.6	62.8	53.96	7.07	54.2
	F	40.1	69.2	58.06	11.14	60.8
JAK10	I	60.6	73.6	67.4	5.65	65.5
	F	69.2	90.1	79.62	6.84	78.6

Note: M = mean; SD = standard deviation; Max = achieved maximum; Min = achieved minimum; I = initial measurement; F = final measurement; JAK10 = isometric strength at knee angle of 10°, JAK45 = isometric strength at knee angle of 45°, JAK90 = isometric strength at knee angle of 90°

To examine differences between initial and final measurements, Wilcoxon nonparametric test for dependent samples was performed (Table 2). None of the analyzed variables showed statistically significant differences ($p > .05$). However, effect size values indicated moderate to large effects: JAK90 (r

= 0.42), JAK45 (r = 0.54) and JAK10 (r = 0.78). The most pronounced effect was recorded for JAK10, indicating a potentially important practical shift in isometric strength at the 10° angle, although the difference was not statistically confirmed due to small sample size ($N = 5$).

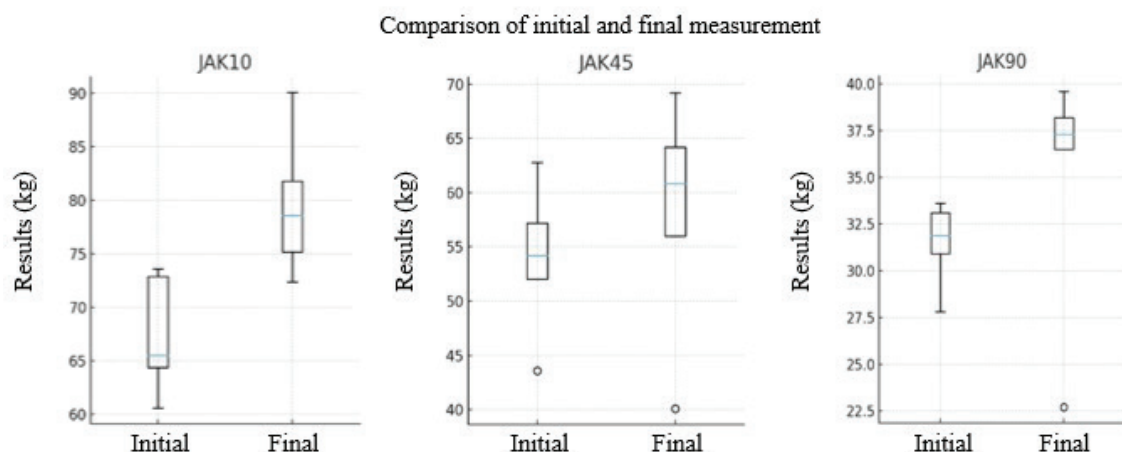
Table 2. Results of Wilcoxon nonparametric test for observed variables

Variable	p	Z	Effect size (r)
JAK90	.345	-.94	0.42
JAK45	.225	-1.21	0.54
JAK10	.80	-1.75	0.78

Note. * $p < 0.05$; ** $p < 0.01$ *

Graphical presentation (Graph 1) enables visual comparison of initial and final values for each observed variable. For variable JAK10, a clear shift of result distribution toward higher values in final measurement is visible, confirming the observed large effect ($r = 0.78$). For variable JAK45, a mild increase in mean values is present, but also greater variability with one lower result in final testing, explaining the absence of statistical significance. For variable

JAK90, results also showed tendency of increase, although greater dispersion of obtained values appeared in final measurement compared to initial measurement. The presented graphical patterns further support the finding that despite lack of statistical significance, changes can be practically relevant, particularly for JAK10.



GRAPH 1. Graphical presentation of differences between initial and final testing of isometric strength at angles of 10°, 45° and 90°

Discussion

Study results show that although no statistically significant difference in isometric knee flexor strength (JAK10, JAK45, JAK90) was determined between initial and final testing, recorded growth trends and effect size values indicate moderate-to-large effects, particularly at the 10° angle. This finding is crucial as it suggests that absence of statistical significance is not necessarily a consequence of lack of real effect, but is more likely the result of small number of participants ($N = 5$), which inherently reduces statistical power and makes detection of differences difficult despite objectively existing adaptations – a phenomenon well known in statistical literature as type II error (Button et al., 2013). Strength increase at all examined angles, albeit non-significant, is consistent with previous research confirming effectiveness of eccentric training in hamstring muscle strength development. Numerous studies in sports kinesiology show that eccentric training programs, including Nordic hamstring exercise and various Romanian deadlift (RDL) variations, consistently result in significant increase in eccentric strength and favorable architectural changes in muscles (Mjølunes et al., 2004; Roig et al., 2009). A meta-analysis including 20 studies with total of 433 participants clearly showed that eccentric training results in on average 35% greater increase in muscle strength compared to concentric contraction, while changes in muscle mass were comparable between both contraction (Roig et al., 2009). These results emphasize that eccentric training is superior for muscle strength development, which is particularly important in sports where high eccentric forces are decisive for performance, such as sprinting and jumping.

The finding of strength increase at small flexion angles (10°) is particularly interesting and important, as this position is biomechanically most loaded precisely in the late swing phase during sprinting and is strongly associated with hamstring injury risk (Chumanov et al., 2007). Previous research has shown that greater eccentric strength and favorable architectural adaptations in muscle, particularly fascicle length, contribute to injury risk reduction (Guex et al., 2016; Maroto-Izquierdo et al., 2023). One prospective cohort study on 152 elite soccer players showed that players with shorter fascicles and lower eccentric strength had significantly higher hamstring injury incidence during the season, directly confirming that increased fascicle length, systematically achieved through eccentric training, represents a key protective mechanism against injuries (Timmins et al., 2016). Although this study did not directly measure fascicle length, significant increase in isometric strength at small angles can be interpreted as an indirect indicator of favorable architectural adaptations in muscle, particularly considering that eccentric training promotes the process of sarcomerogenesis, i.e., addition of new sarcomeres in series within muscle fibers, thereby lengthening the optimal fiber length for force generation (Butterfield & Herzog, 2006). This adaptation not only reduces injury risk but also increases muscle's ability to generate high force in very short time and at great length, which is crucial in sprinting at maximal speeds. In contrast, concentric training primarily promotes transverse hypertrophy but has lesser effect on increasing muscle working range and ability to generate force at high shortening speeds (Franchi et al., 2017).

An important role in these adaptations is played by titin protein, which acts as a molecular spring within the sarcomere and enables muscles to withstand large mechanical stress-

es during eccentric contractions (Hessel et al., 2017). Titin contributes to both passive muscle elasticity and active force transmission during contraction, making it crucial for muscle protection from damage at extreme loads. High-velocity eccentric training – such as downhill sprinting, Nordic hamstring curls, or plyometric jumps with emphasized eccentric phase – is particularly effective for developing this adaptation (Douglas et al., 2017). Clinical applicability of these findings is reflected in prevention and rehabilitation of hamstring injuries. Petersen et al. (2011) in a cluster-randomized controlled trial on male soccer players determined that introducing Nordic hamstring exercise during the season reduces risk of acute hamstring injuries by more than 50%. Meta-analysis by van Dyk et al. (2019) including 8,459 athletes confirmed that including NHE in prevention programs halves injury rate and significantly reduces recurrences. In rehabilitation context, Askling et al. (2014) showed that athletes performing lengthening exercises under load (L-protocol) return to training and competition significantly faster, with lower recurrence rate, confirming the advantage of eccentric approach also in post-injury rehabilitation.

Comparisons of eccentric and concentric methods in terms of sports performance also show benefit of eccentric approach. Wagle et al. (2017) highlighted that protocols with emphasized or supramaximal eccentric loading result in greater gains in maximal strength, rate of force development, and explosive abilities such as sprinting and jumping, compared to classic concentric protocols. Supramaximal eccentric contraction, including eccentric loading above 100% of concentric 1RM, have proven useful not only for injury prevention and rehabilitation but also for enhancing sports performance, because they induce very large forces and mechanical stresses that more faithfully replicate conditions in the field. Similarly, de Keijzer et al. (2022) in a systematic review of flywheel training showed that this form of eccentric overload significantly improves strength, power, and performance in sports tasks.

As main limitations of this study should be noted the small sample of participants ($N = 5$), which inherently reduces statistical power and prevents broader generalization of results, although case studies can provide valuable clinical insights, particularly in athlete populations with high demands and rare available samples (Yin, 2014). Furthermore, only isometric measurements were used, while architectural changes such as fascicle length or changes in neuromuscular activity (EMG) were not monitored, preventing more direct conclusions about structural adaptations. Also, the intervention duration of 11 weeks is relatively short compared to long-term adaptations recorded in longitudinal studies, and introduction of a two-week sprint training, although potentially beneficial, can be a confounding variable affecting results. Future research should include larger samples, longer follow-up periods, and broader spectrum of measurement instruments such as ultrasound sonography for fascicle evaluation and EMG for neuromuscular activity assessment, along with continuous monitoring of injury incidence during the competitive season, to obtain a more comprehensive picture of adaptations. Despite mentioned limitations, results of this study provide clear support for the claim that eccentric training is an essential component of the training process for athletes exposed to high demands of sprinting and jumping, with potential for injury reduction, accelerated rehabilitation, and enhanced sports performance when applied in progressive and individualized manner.

Conclusion

The conducted study indicates that eccentric training leads to functionally significant increase in isometric knee flexor strength, with the most pronounced effect at 10° flexion angle, which is biomechanically critical during the late swing phase of sprinting. Obtained results suggest improvement in eccentric strength, neuromuscular control, and potentially favorable adaptations in muscle structure, indicating practical effectiveness of eccentric training and injury risk reduction. The practical implication for coaches and athletes is that eccentric exercises should be systematically included in preparatory and competitive cycles, with gradual and progressive dosing, and individualized adaptation for athletes of different levels and specific sport demands. Future research should include larger samples, longer follow-up periods, and combination of biomechanical, architectural, and clinical measures to obtain a more comprehensive picture of eccentric training effects.

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