Submitted: 25 March, 2024 Accepted: 14 May, 2024 Published: 30 October, 2024 DOI:10.22514/jomh.2024.170

JOMH Journal of Men's Health

ORIGINAL RESEARCH

Effects of static stretching and its combination with conditioning contractions on lower limb muscle synergy and squat jump performance at two initial knee joint angles

Ming Li[1,2,†], Maolin Dong[1,3,†], Ting Wang[2], Yang Lu[2], Chul-Ho Bum[4,*,†], Sukwon Kim[2,*,†]

[1]College of Education and Sports Sciences, Yangtze University, 434020 Jingzhou, Hubei, China
[2]Department of Physical Education, Jeonbuk National University, 54896 Jeonju, Republic of Korea
[3]College of Wushu, Henan University, 450046 Zhengzhou, Henan, China
[4]Department of Golf Industry, Kyung Hee University, 17104 Yongin, Republic of Korea

***Correspondence**
bch2180@khu.ac.kr
(Chul-Ho Bum);
rockwall@jbnu.ac.kr
(Sukwon Kim)

[†] These authors contributed equally.

Abstract

Static stretching (SS) may reduce maximal muscle force and power output, while short-duration, high-intensity conditioning contractions (CC) have the potential to increase force and power output. However, the precise effects of CC on athletic performance and lower limb muscle coordination after SS are not yet fully understood. This investigation sought to explore the effects of SS (four sets of 30 seconds each) and its combination with CC (10 repetitive drop jumps), denoted as SC, on the synergy patterns of key lower limb muscles and jump performance during squat jumps (SJ) executed at two distinct knee joint starting angles (90° and 120°). Eleven participants were randomly assigned to three experimental conditions, with each condition encompassing three SJs at both angles. A three-dimensional motion capture system, force platform, and electromyography (EMG) system were employed to quantify jump height, extract ground contact time, and perform non-negative matrix factorization. Our findings revealed that at a knee joint starting angle of 120°, both SS and SC altered the weighting of the five major muscles (cosine similarity: SS: r = 0.897; SC: r = 0.767) and augmented the activity strength of the primary synergy (SS: 59.6%; SC: 10.48%). Additionally, SC demonstrably advanced the phase shift (90°: 14%; 120°: 61%). Notably, neither SS nor SC exerted a statistically significant influence on jump height ($p > 0.05$). However, SS significantly increased ground contact time ($p = 0.029$). In conclusion, at a knee joint angle of 120°, both SS and CC were observed to alter lower limb muscle synergy patterns and influence ground contact time. While SS led to an increase in ground contact time, CC effectively countered this rise. These findings suggest that athletes in disciplines demanding rapid movements might benefit from omitting SS in isolation during warm-ups or consider combining SS with CC to optimize performance.

Keywords

Non-negative matrix factorization; Weight matrix; Activity intensity; Ground contact time; Jump height

1. Introduction

Static stretching (SS) has long been considered an effective method for improving joint range of motion [1–4]. As a result, it is commonly employed in pre-exercise preparation to enhance flexibility and reduce the risk of explosive musculotendinous injuries [1, 5]. However, recent research has questioned the impact of SS lasting longer than 60 seconds on athletic performance. Studies have shown that prolonged SS may adversely affect the maximal contraction force and power output of muscles [6–9]. For instance, Behm *et al.* [6] reported in their review that a total SS duration exceeding 60 seconds could lead to a potential strength loss of up to 5.1%. Similarly, Nakamura *et al.* [7] found that SS lasting over 60 seconds significantly reduced the effectiveness of maximum voluntary isometric contractions. The mechanisms by which SS impairs performance are hypothesized to involve both neural and peripheral factors. Neural factors pertain to a reduction in neural drive [10], while peripheral factors are believed to result from changes in the mechanical properties of the muscle-tendon unit itself, specifically decreased stiffness [11], which subsequently impacts athletic performance.

In contrast to the common effect of SS in reducing strength performance, short-term high-intensity conditioning contractions (CC) have been proven to rapidly enhance muscle strength [12–14]. For instance, Kolinger *et al.* [12] found that in male basketball players, isotonic peak torque significantly increased after performing three sets of 3–4 repetitions of submaximal loads (60%, 90% and 90% of one repetition maximum) of barbell squats. Similarly, the study by dos Santos Silva *et al.* [13] demonstrated that performing five consecutive drop jumps prior to an official long jump competition significantly improved the performance of long jump athletes. Current research generally attributes this performance enhancement to an increase in neural activity, which leads to an increase in the motor units controlled by motor neurons, changes in Calcium ion (Ca^{2+}) sensitivity due to increased muscle temperature, and alterations in the angle of muscle fibers [15, 16].

Similar to the effects of SS and CC, joint angles significantly influence sports performance. It is now understood that the angles of knee joints affect the functionality of extensor muscles. In this respect, Garnier *et al.* [17] discovered that at a knee flexion of 110°, the maximal voluntary isometric contraction force and the induced peak twitch torque of the knee extensors were significantly higher than at 20° of knee flexion, with average increases of 42 ± 12% and 47 ± 16%, respectively. Li *et al.* [18] found that the peak force output by the lower limbs during squat jumps varies with changes in knee joint angles. Furthermore, changes in joint angle can interact with SS, impacting muscle performance. In this context, Nelson *et al.* [19] investigated isometric knee extensions across a range of knee angles and reported that static stretching yielded a more pronounced negative impact on performance when the knee is near full extension. La Torre *et al.* [20] further noted that static stretching significantly reduces the development of power and strength during squat jumps, especially when the initial angle of the lower limbs approaches full extension.

The past decade has witnessed a burgeoning interest on the impact of SS and CC on athletic performance. For example, Kümmel *et al.* [9] found that muscle contractions induced by electrical stimulation could offset the decline in power output caused by SS. Meanwhile, Bazett-Jones *et al.* [18] used leg press exercises at 90% of one repetition maximum (3 sets of 3 reps) as a form of CC, and they observed that this approach actually reduced peak force and rate of force development in isometric squats performed after SS. Although previous studies have employed various CC methods to explore their effects on performance post-SS, these methods lack practical application within competitive settings and have yielded inconsistent results. Therefore, it is particularly important to use a CC method that is more applicable in practice to observe its effects on performance after SS. Moreover, there is a relative lack of research on how SS, CC, and changes in joint angles collectively affect the synergy function of lower limb muscles. Given the significance of SS and CC in exercise preparation and the widespread use of knee starting angles of 90° and 120° in various sports [21, 22], this study aimed to explore the effects of SS and its combination with CC (SC) on the main muscle synergies and jump performance during SJ at specific knee joint starting angles. Based on previous research, we hypothesize that SS may influence ground contact time and jump height by altering the contribution, synergy activity intensity, and phase changes of the primary muscles of the lower limbs. Conversely, CC might offset the potential negative impacts of SS by enhancing the contribution and synergy activity intensity of certain muscles and adjusting the phase of synergies. Furthermore, we hypothesize that joint angles may also affect muscle synergy performance, thereby further influencing ground contact time and jump height.

2. Methods

2.1 Experimental design

This study employed a repeated-measures, balanced crossover design to assess the impact of different experimental conditions on the weight matrix, characteristic matrix, as well as ground contact time and jump height for five main muscles (rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), lateral gastrocnemius (LG), and biceps femoris, long head (BFL)). Participants were randomly assigned to three experimental treatments: control, stretching intervention, and combined intervention. Each treatment consisted of SJ tests at two initial knee joint angles (90° and 120°). A washout period of 2 to 7 days, during which no training was conducted, was set between each experiment to avoid carryover effects. To control the influence of circadian rhythm on the results, all experimental sessions for participants were scheduled at the same time of day. Sample size calculation was conducted using G*Power 3.1.9.7 software (Heinrich Heine University Düsseldorf, Düsseldorf, Germany; $\alpha = 0.05$, $\beta = 0.8$), indicating a minimum requirement of nine participants. To enhance statistical power, a total of 11 participants were recruited for the study.

2.2 Participants

This study involved 11 male collegiate athletes (mean age = 23.73 (standard deviation (SD) ± 1.49 years); mean height = 177.91 (±4.11 cm); mean body mass = 69.93 (±6.59 kg)) who voluntarily participated and had no history of neuromuscular diseases in the past 6 months. Their usual training frequency averaged four times per week, each session lasting between 2.5 to 3 hours. Prior to their first visit to the laboratory, all participants were fully informed about the experimental procedures and potential risks and signed a written informed consent form. The experiment required participants to avoid intense physical activities and alcohol consumption 48 hours before the scheduled experimental assessments, abstain from caffeine intake 8 hours prior, and fast 2 hours before the experiment.

2.3 Test procedure

All participants initially completed a 5-minute dynamic warm-up, followed by a 5-minute rest period to regulate body temperature and oxygen consumption. The testing procedure post-warm-up was as follows: the control group (CG) directly proceeded to the SJ tests; the SS group (SSG) rested for 3 minutes after completing the SS intervention, then performed the SJ tests; the SS and CC group (SCG) waited for 3 minutes after completing SS, then carried out CC. Considering the time effect of activation [16], the SCG conducted the SJ tests 4 minutes after the completion of CC.

2.4 Intervention

SS: This study employed the SS protocol described by Chen *et al.* [23], aimed at stretching commonly targeted muscle groups during warm-ups such as the triceps surae, hamstrings, and quadriceps. The stretching regimen involved four stretches for each muscle group on each leg, each lasting 30 seconds with a 15-second rest in between, totaling 120 seconds. Stretching was calibrated to the threshold of discomfort without crossing into pain. The specific stretching maneuvers are as follows: For the quadriceps, participants balanced themselves with one hand on a wall, the leg intended for stretching bent at the knee to 90°, and the same-side hand grasping the ankle to gently pull towards the buttocks to achieve the appropriate stretch. Stretching of the hamstrings was performed by placing one leg on a step, knee slightly bent, and leaning forward from the hips until a stretch was felt. The triceps surae stretch was conducted in a supine position, with an experimenter assisting in dorsiflexion to achieve the desired stretch effect. For specific details and implementation methods of SS, refer to the study of Li *et al.* [18].

CC: For the CC intervention, this study used 10 repetitive drop jumps (DJ), a method validated in previous studies [9, 24]. Each participant's optimal starting ground clearance height was predetermined before their initial laboratory visit. During the experiment, participants were required to complete 10 jumps, maintaining a 30-second interval between each jump. Participants were instructed to perform each jump with maximal effort to achieve optimal jumping performance.

2.5 SJ assessment

SJ tests were conducted on a professional force platform (Advanced Mechanical Technology, Inc., Watertown, MA, USA). Before the test, participants were asked to stand with their feet aligned and hands placed on their hips, then maintain a squat position for about 1 second at the designated knee joint angle to minimize the impact of arm swinging and the muscle stretch-shortening cycle on jump performance. Jump angles (90° and 120°) were accurately measured using an electrogoniometer (TSD130B, Biopac Systems Inc., Goleta, CA, USA). Three maximal intensity SJ tests were conducted at each knee joint angle, with a 60-second interval between each test and a 3-minute interval between tests at different starting angles. To mitigate the influence of potential confounding variables associated with post-activation performance enhancement [15], a standardized testing sequence was employed. This sequence commenced with the 90° knee joint angle assessments, followed by the 120° knee joint angle assessments.

2.6 Data recording

SJ tests were recorded using a three-dimension motion capture system equipped with 13 infrared cameras (Prime 17 W, OptiTrack, Natural Point, Inc., Corvallis, OR, USA), set at a sampling rate of 100 Hz. Participants' lower limbs were affixed with 20 reflective markers, each 14 mm in diameter, to facilitate motion capture. Concurrently, ground reaction force data were collected by the force platform at a frequency of 1000 Hz. Surface electromyography (EMG) data was acquired using a Trigno Avanti Sensor system (Delsys, Natick, MA, USA) at a sampling frequency of 1000 Hz. This system recorded the electrical activity of the five major muscles (RF, VM, VL, LG and BFL) in the dominant leg. The electrodes for the RF were positioned at 40% of the line connecting the superior side of the patella to the anterior superior iliac spine; VM electrodes were placed at a point 25 mm away from the end of the muscle belly at a 50° angle to the line connecting the medial side of the patella and the anterior superior iliac spine; VL electrodes were located at the distal end of the muscle belly, 20 mm along the line at a 20° angle from the lateral side of the patella to the anterior superior iliac spine; LG electrodes were positioned at 85% of the line from the lateral side of the Achilles tendon insertion to the lateral side of the popliteal cavity; and BFL electrodes were located at 80% of the line from the ischial tuberosity to the lateral side of the popliteal cavity. Prior to sensor attachment, the skin was prepared by shaving and disinfecting with an alcohol solution, followed by the application of abrasive gel to ensure stable sensor adhesion. Each Trigno Avanti sensor (size 37 mm × 27 mm × 13 mm, weight 14 g) was equipped with a dual-differential EMG sensor with silver bar electrodes (5 mm × 1 mm, 10 mm inter-electrode distance), a common mode rejection ratio of 80 dB, and an amplifier gain of 909. All equipment data were synchronized using Motive 2.2.0 software (OptiTrack, Natural Point, Inc., Corvallis, OR, USA).

2.7 Data processing

Data on vertical ground reaction force and vertical displacement of the center of mass were analyzed using Visual3D Setup x64 v2022.9.1 software (C-Motion, Inc., Germantown, MD, USA). The start and end of the movement were defined as the moment when the force value exceeded five standard deviations of the flight phase force and the moment when the force dropped to 20 Newtons, respectively. To improve data accuracy, the force-time curve was processed through a 17-Hz bidirectional fourth-order Butterworth low-pass filter, and the displacement-time data were smoothed using a 6-Hz bidirectional fourth-order Butterworth low-pass filter [18]. For each experimental condition, two sets of data with the highest internal consistency coefficient exceeding 0.8 were selected for in-depth analysis, and their 95% confidence intervals were calculated. These selected data were used to calculate ground contact time from the start to the end of the movement and jump height, the latter determined by the difference in height between the center of mass at the jump apex and standing position. To ensure data reliability, the technical measurement error percentage for ground contact time and jump height was calculated to ensure the technical measurement error percentage was less than 10% [25]. For reliable comparison, jump height values were normalized to body mass.

EMG raw data, after processing through a 20–480-Hz band-pass filter (Butterworth, fourth-order), were full-wave rectified and low-pass filtered at 10 Hz to calculate the EMG envelope. Post-processed data were normalized to 101 sampling points and normalized to the maximal EMG activity during the movement. Processed EMG data of the five muscles were grouped according to the experimental design (group × angle) and muscle synergies were extracted using the non-negative matrix factorization (NMF) algorithm [26, 27]. The NMF algorithm assumes that muscle activation patterns are composed of a linear combination of several basic muscle synergy patterns (W), with the activation intensity of each pattern determined by different coefficients (C). W and C matrices were updated over 3000 iterations to minimize the residual error between the original data matrix and the reconstructed data matrix (W × C). To eliminate bias during initial value selection, the model with the highest variance accounted for (VAF) after 20 runs of the NMF algorithm was selected, and the weight and activation coefficient matrices were normalized to ensure each weight was a unit vector. Muscle synergies for each experimental condition were determined based on the principle of explaining at least 90% of the total VAF [26] (see Table 1). All analyses were conducted using R 4.3.2 (R Foundation for Statistical Computing, Vienna, Austria) software.

2.8 Statistical analysis

For each experimental condition, K-means clustering analysis was performed on the data of the same muscle across all participants (a total of five muscles), with the number of clusters set to 1. This analysis aimed to determine the overall synergy (SYN) weight of the first synergy under each condition. Furthermore, the similarity of SYN weights under different conditions was assessed using cosine similarity analysis. During this analysis, the similarity threshold was set at 0.9, indicating that a cosine similarity of 0.9 or higher represents a high degree of similarity between two muscle synergy patterns [28]. The analysis of jump height and ground contact time data employed a two-factor mixed-effects model with random intercepts, where group and angle were factors, to explore intergroup differences. Model selection was based on the likelihood ratio test, with the significance level set at $p < 0.05$. When significant variations were found ($p < 0.05$), subsequent tests were conducted using Bonferroni corrections for multiple comparisons. All data were subjected to Shapiro-Wilk testing prior to significance analysis and conformed to the normal distribution assumption ($p > 0.05$). Statistical data were presented as mean ± standard deviation, and all analyses were performed using R 4.3.2 (R Foundation for Statistical Computing, Vienna, Austria).

3. Results

3.1 The weightings for muscles in muscle synergies

Table 2 presents the cosine similarities of SYN weights across various experimental conditions. Fig. 1a illustrates the weights of the five muscles within the SYN under different conditions. At a knee joint starting angle of 120°, the cosine similarity between CG and SSG was $r = 0.897$. SS resulted in a decrease in the weights of RF, VL and BFL. The most significant decrease was observed in VL, while the weights of VM and LG increased, with VM exhibiting the most notable rise. The cosine similarity between the CG and the SCG was $r = 0.71$. CC caused a reduction in the weights of RF, VL and BFL, with the most prominent decrease occurring in BFL. Conversely, CC led to an increase in the weights of VM and LG, with LG experiencing the strongest rise. The cosine similarity between SCG and SSG was $r = 0.767$. Furthermore, within the SSG, the cosine similarity between the conditions at 90° and 120° was $r = 0.803$. As the initial knee joint angle increased to 120°, the weights of all muscles except VM decreased, with VL exhibiting the most substantial reduction, followed by LG. Within the SCG, the cosine similarity between the 90° and 120° conditions was $r = 0.848$. Similarly, when the angle increased to 120°, the weights of all muscles except LG decreased, with BFL showing the most significant decrease, followed by RF. High cosine similarity values were observed across other group comparisons not explicitly mentioned here.

3.2 Main peak timing and magnitude of activation patterns

Fig. 1b provides detailed information on the characteristic values of SYN under each experimental condition. Table 3 displays the peak timing of muscle synergy activities under different conditions. Following the method used in Lee *et al.* [6], we employed the relative change rate ([pre-intervention − post-intervention]/pre-intervention × 100%) to measure changes in phase shifts and synergy activity intensity before and after the intervention, setting a threshold of 10% for significant changes [7]. Specifically, at knee joint starting angles of 90° and 120°, the phase shift in SCG advanced by 14% and 61%, respectively. With the angle increased to 120°, the phase shift in SCG advanced by 55%. Additionally, Table 3 details the intensity of muscle synergy activities under each condition. Activity intensity was determined by calculating the root mean square during the full width at half maximum, as shown in Fig. 2. At a knee joint starting angle of 90°, the activity intensity in SSG decreased by 0.095, with a relative

TABLE 1. Cumulative percentage of variance explained by the first five synergistic components in different groups at two knee starting angles.

	Knee starting angle (°)									
Condition	90°					120°				
CG	94.5	97.2	98.6	99.3	99.5	91.5	97.1	99.0	99.5	99.6
SSG	92.6	96.6	98.4	98.9	99.2	95.3	97.6	98.6	99.2	99.5
SCG	92.1	97.0	98.3	98.9	99.3	93.9	96.7	98.7	99.3	99.6

CG: Control Group; SSG: Static Stretching Group; SCG: Static Stretching & Drop Jump Combined Group.

TABLE 2. Cosine similarity between the weight vectors of five muscles under different conditions.

Angle	Group	90°			120°		
		CG	SSG	SCG	CG	SSG	SCG
90°							
	CG	1.000					
	SSG	0.944	1.000				
	SCG	0.997	0.932	1.000			
120°							
	CG	0.944	0.905	0.936	1.000		
	SSG	0.927	0.835	0.922	0.897	1.000	
	SCG	0.871	0.803	0.848	0.710	0.767	1.000

CG: Control Group; SSG: Static Stretching Group; SCG: Static Stretching & Drop Jump Combined Group.

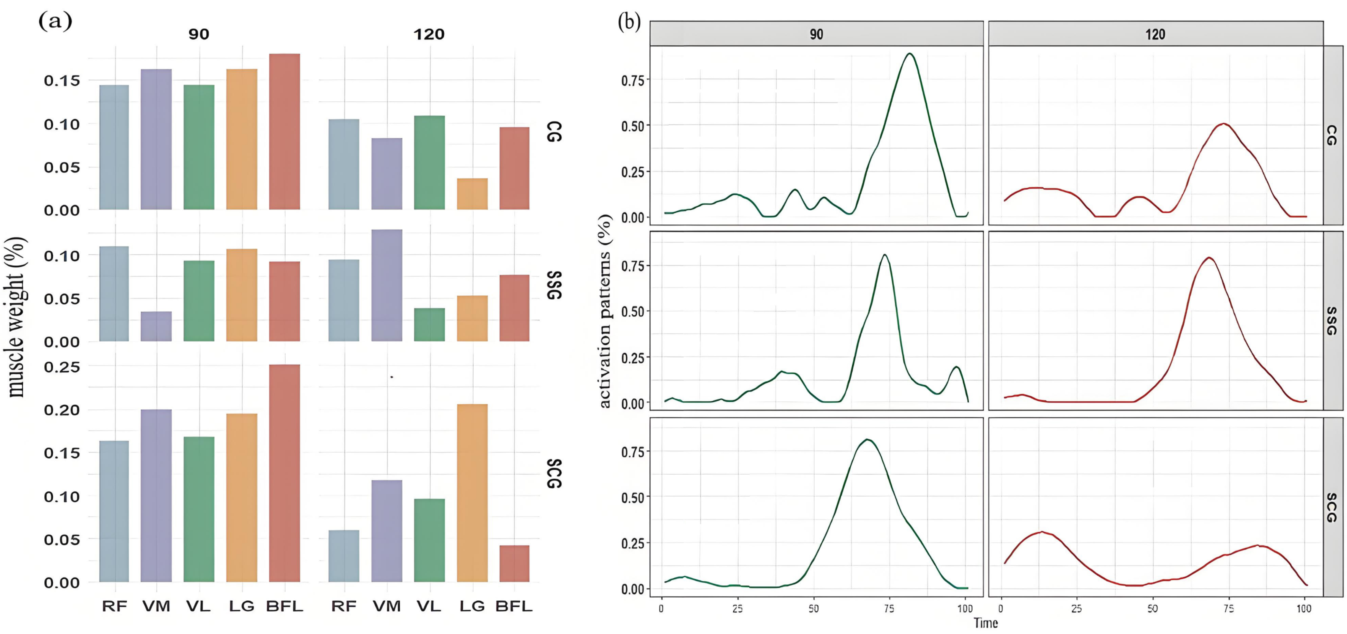

FIGURE 1. Muscle synergies extracted from different conditions. (a) The weightings for muscles in muscle synergies (K-means clustering results). (b) The time-course activation patterns of muscle synergies during a jump cycle. CG: Control Group; SSG: Static Stretching Group; SCG: Static Stretching & Drop Jump Combined Group; RF: rectus femoris; VM: vastus medialis; LG: lateral gastrocnemius; BFL: long head of the biceps femoris; VL: vastus lateralis.

TABLE 3. Time to the peak of muscle synergies and root mean square during full width at half maximum (activity intensity) under different conditions.

		Knee starting angle (°)	
Parameter	Condition	90°	120°
Time to peak			
	CG	82	74
	SSG	73	69
	SCG	68	13
Activity intensity			
	CG	0.692	0.396
	SSG	0.597	0.632
	SCG	0.636	0.438

CG: Control Group; SSG: Static Stretching Group; SCG: Static Stretching & Drop Jump Combined Group.

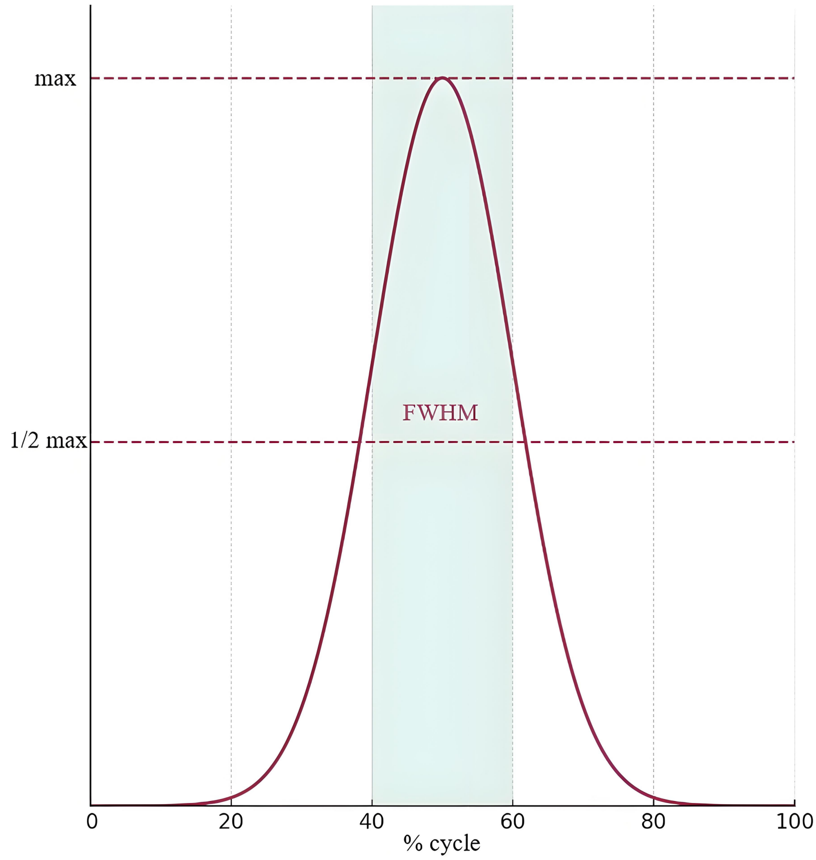

FIGURE 2. Full-width at half-maximum of peak muscle synergy activity. Illustrative Diagram of FWHM in muscle synergy activity.

difference of 13.71%. At 120°, the activity intensity in SSG and SCG increased by 0.236 (59.6%) and 0.042 (10.48%), respectively. In CG and SCG, when the angle increased to 120°, the activity intensity decreased by 0.296 (42.79%) and 0.199 (31.24%), respectively. It is noteworthy that under the 120° SCG condition, we observed two significant peaks. Therefore, we calculated the root mean square values for each cycle within the two full width at half maximum periods and summed these root mean square values to determine the total synergy activity intensity index.

3.3 Ground contact time and jump height

Table 4 displays the means and standard deviations for ground contact time and jump height. Fig. 3a,b illustrates how different factors affect these variables. For ground contact time, analysis revealed statistically significant main effects for group ($p = 0.029$) and angle ($p < 0.001$), with no significant interaction effect. Multiple comparisons revealed that at a knee starting angle of 90°, ground contact time for SSG was significantly higher than for SCG ($p = 0.001$, $d = 0.94$); at 120°, SSG was significantly higher than CG ($p = 0.013$, $d = 0.97$) and SCG ($p = 0.029$, $d = 0.93$). Additionally, for CG, SSG and SCG, ground contact time significantly decreased as the angle increased to 120° (CG: $p < 0.001$, $d = 2.59$; SSG: $p < 0.001$, $d = 2.02$; SCG: $p < 0.001$, $d = 2$). For jump height, the main effect of angle also showed significance ($p < 0.001$), but there were no significant main effects for group or interaction. Multiple comparisons indicated that in CG, SSG and SCG, jump height also significantly decreased as the angle increased to 120° (CG: $p < 0.001$, $d = 0.89$; SSG: $p < 0.001$, $d = 0.59$; SCG: $p = 0.001$, $d = 0.78$).

The upper edge (Q3) represents the upper quartile. The upper whisker extends to the maximum value plus 1.5 times the interquartile range (IQR). The central white line indicates the median. The lower edge (Q1) denotes the lower quartile. The lower whisker reaches the minimum value plus 1.5 times the IQR.

Significance analysis for angle effects showing p-values, F-statistics, and effect size ($\eta_p{}^2$). The significance between different angles within the same group is denoted by asterisks. Horizontal lines with associated p-values represent significant differences among the SSG, SCG and CG. CG represents the control group, SSG stands for the static stretching group, and SCG denotes the group combining static stretching and conditioning contractions.

4. Discussion

This study compared the effects of SS and its combination with CC on the main muscle synergies and jump performance of the dominant leg during SJ at two specific knee joint starting angles. Our findings revealed that at a 120° knee joint starting angle, SS led to reduced weights of RF, VL and BFL, while it increased the weights of VM and LG, and enhanced the activity

TABLE 4. Important calculations for the jump height and ground contact time, are presented for different groups at two knee starting angles (mean ± SD). Significance analysis results (A: group effects, p- and F-value) and partial eta squared (η_p^2) are presented in the right column.

		Knee starting angle (°)		
Parameter	Condition	90°	120°	Results (A)
Jump height ($m \cdot kg^{-1}$)				
	CG	0.00636 ± 0.00106	0.00547 ± 0.00092†	F (2, 20) = 1.97
	SSG	0.00664 ± 0.00119	0.00596 ± 0.00110†	$\eta_p^2 = 0.16$
	SCG	0.00642 ± 0.00082	0.00570 ± 0.00099†	$p > 0.05$
Ground contact time (s)				
	CG	0.367 ± 0.048	0.258 ± 0.036†	F (2, 20) = 11.58
	SSG	0.396 ± 0.054	0.297 ± 0.044*†	$\eta_p^2 = 0.54$
	SCG	0.347 ± 0.053	0.262 ± 0.029†	$p < 0.001$

*CG: Control Group; SSG: Static Stretching Group; SCG: Static Stretching & Drop Jump Combined Group. *: A significantly ($p < 0.05$) different from the CG; †: A significantly ($p < 0.05$) different from the 90°.*

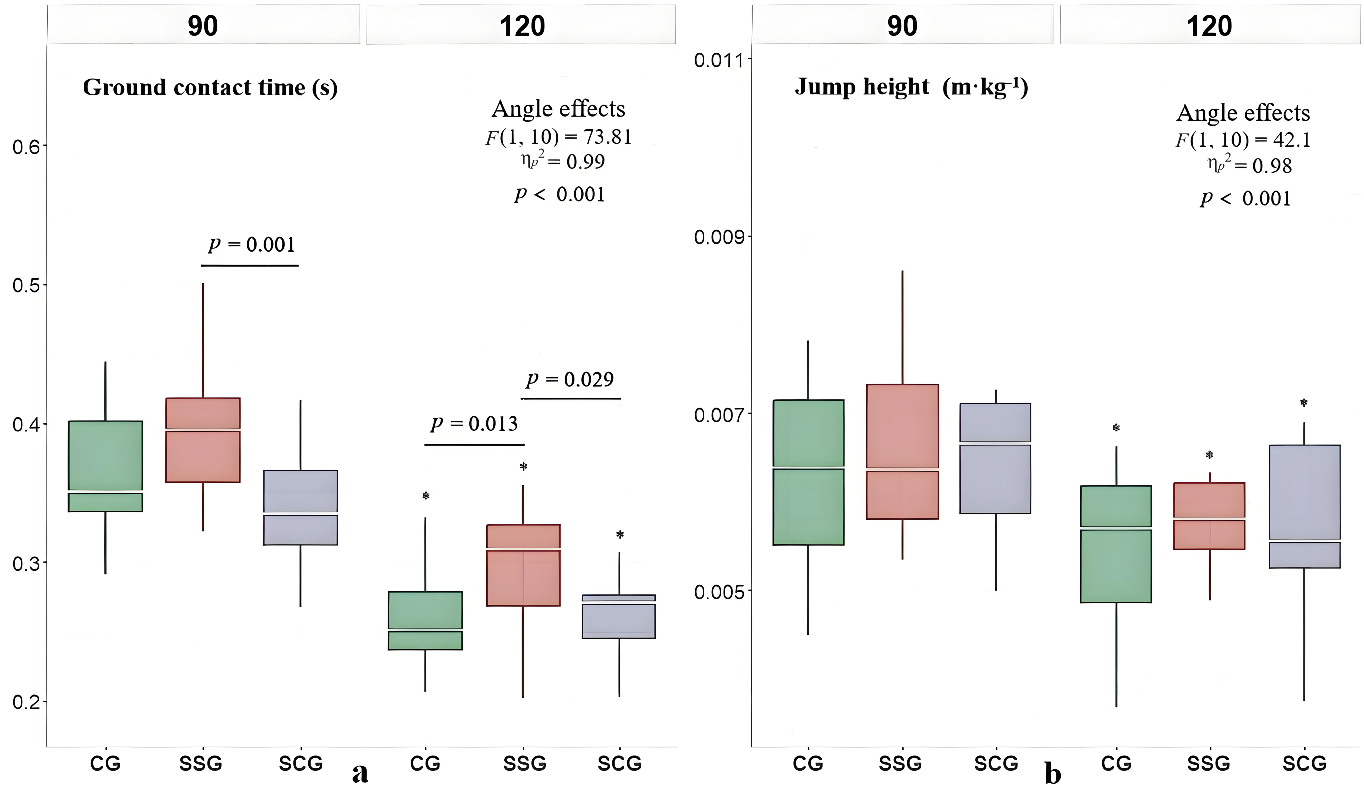

FIGURE 3. Jump performance values for the three groups (CG, SSG and SCG) under two initial knee-joint angles (90° and 120°). (a) ground contact time, (b) jump height. CG: Control Group, SSG: Static Stretching Group, SCG: Static Stretching & Drop Jump Combined Group. * indicates the significance between different angles with the same group.

strength of the target synergy. In contrast, CC augmented the weights of VL and LG, while causing an advanced phase change in the synergy, significantly altering the impact of SS on the weight and characteristic matrices. Moreover, it was observed that in both CG and SCG, compared to the 90° condition, the activity intensity was significantly decreased under the 120° condition. These results might explain why SS and CC did not significantly alter jump height. However, SS demonstrably increased ground contact time, whereas CC effectively counteracted this rise in ground contact time induced by SS.

Previous research has mainly focused on the effects of SS and CC on the activation level of individual muscles [9, 18], with little emphasis placed on understanding how they alter the weights of multiple muscles in synergy. Our study provides hitherto undocumented evidence that at a 120° knee joint starting angle, SS could decrease the weights of RF, VL, and BFL while increasing the weights of VM and LG. Furthermore, CC modified the effects of SS on the weights of these five muscles, particularly enhancing the weights of

LG and VM. These changes may be due to SS altering muscle length [3, 4], affecting motor unit activation and discharge rates [29, 30], thereby changing the distribution of muscle weights. Indeed, the anatomical characteristics of different muscles, such as origin and insertion points, pennation angles, as well as compositional differences [2, 31], may lead to different biomechanical effects of the same stretching action on various muscles. Considering the action profile of DJs, the execution of ten repetitive DJs is likely to preferentially activate the LG muscle [9], thereby significantly increasing its weight, and might have a compensatory effect on other muscles such as BFL [32], consistent with the observed findings. Regarding the changes observed at 120°, the increase in the initial knee joint angle might have altered the initial lengths of the main muscles in the lower limbs [33], thereby affecting the distribution of muscle weights.

Another key finding of this study was that CC led to an advanced phase shift in synergy and increased the activity strength of the target synergy at a 120° knee joint starting angle. In contrast, SS showed different activity intensities at 90° and 120°, which has not been previously reported. The phase advancement and increased activity strength caused by CC may be related to its role in reducing neurotransmitter failure, primarily occurring in larger motor neurons. This effect might improve the efficiency of excitatory synaptic potential transmission at spinal synaptic connections [34], thereby enhancing the conduction of nerve impulses and the recruitment of higher-order motor neurons [35]. At 90°, the decrease in activity strength caused by SS may be related to the overall decrease in the weights of the five muscles. At 120°, certain muscles might be in a more favorable position for motor unit activation and increased discharge rates after SS treatment [29, 30], combined with changes in muscle length and stiffness [3, 4], which may have a cumulative effect with the initial length changes at 120° [33], leading to prolonged muscle activation times. These factors together ultimately result in increased activity strength. In CG and SCG, the decrease in activity strength when the knee joint angle is increased to 120° may be due to reduced muscle activation time caused by a shorter movement path.

In exploring the impact of SS on ground contact time, previous research found that 30 seconds of SS increased ground contact time in DJ [8], similar to the results in this study. However, in order to definitively exclude the potential for even shorter static stretching durations (less than 60 seconds) to exert a negative influence on athletic performance, this study employed a total SS duration of 120 seconds [36]. The possible mechanisms for the SS-induced prolongation of ground contact time include changes in the length and stiffness of the muscle-tendon unit [3, 4], which may cause length-dependent changes in calcium ion sensitivity [37] and slower transmission of force within the muscle [18], thus lengthening ground contact time. In contrast, CC eliminated the effect of SS on ground contact time. This finding aligns with previous research, though some discrepancies exist. For instance, one study showed that after performing 10 repetitive drop jumps, there was no observable change in the ground contact time for the DJ [24]. Conversely, another study found that specific intensities of dynamic activities could counteract the effects of SS on sprinting and T-drill agility test performances [38]. Significantly, both studies employed time-based performance metrics, corroborating the observations of the latter investigation. Notably, our investigation utilized a more concise and efficient warm-up protocol consisting of ten repetitive drop jumps, compared to the comprehensive dynamic warm-up employed in the previous study. Additionally, a potential distinction between our research and the prior study lies in the sequential order of interventions. Our investigation implemented SS interventions before CC interventions, whereas the previous study did not utilize this specific sequence. This alteration in the order of implementation may contribute to the discrepancies observed in our study results compared to existing literature. The potential mechanism by which CC counteracts the effects of SS might be attributed to its ability to expedite muscle activation timing. This aligns with our observation of CC inducing an advanced phase shift within the synergy. Furthermore, a reduction in ground contact time was observed when the knee joint angle was increased to 120°. This phenomenon can likely be explained by a shortened movement path associated with the increased joint angle.

Regarding jump height, previous research indicated that SS reduced the jump height in straight-knee DJ, while CC could counteract this effect [9]. However, our findings diverge from some previous research in that neither SS nor CC exerted a statistically significant influence on jump height during SJ. This discrepancy may be attributable to the distinct types of jumps employed. While our investigation utilized SJ, prior research focused on straight-knee DJ, which place a greater emphasis on ankle joint performance. In the current study, although SS resulted in a reduction in the weights of primary muscles, it concurrently extended the activation time of other muscles. Conversely, CC significantly augmented the contribution of the LG through its activation. This compensatory effect within the synergy might explain the absence of a significant change in jump height. Furthermore, a decrease in jump height was observed when the knee joint angle was increased to 120°, which aligns with previous findings [21]. This might be due to the higher starting angle leading to a shorter movement path, reducing the time window for force generation and thus affecting jump height.

This study has several limitations that should be acknowledged. First, the analysis primarily focused on the first synergy. While this component explained over 90% of the total VAF, some details regarding the contributions of other synergies might have been overlooked. Second, time-domain and frequency-domain analyses of EMG were not included in the present study. This limitation restricts our ability to directly observe the effects of SS and CC on muscle activation amplitude and frequency. Consequently, our understanding of these effects relies heavily on previous research and theoretical frameworks. Third, the study did not directly measure joint range of motion (ROM) or muscle length. Therefore, inferences about changes in muscle mechanical properties can only be drawn based on existing research findings. Finally, while this investigation sheds light on the immediate effects of SS and CC, their long-term impacts remain unclear, limiting our comprehension of the lasting consequences of these training interventions. Considering these limitations, future research should expand the scope of analysis to include more synergy components, a more varied assessment of muscle activation, a broader range of lower limb performance metrics, and track the long-term effects of SS and CC interventions. These measures will help to gain a deeper understanding of the impact of SS and CC on athletic performance and provide more effective guidance for athletic training and rehabilitation.

5. Conclusions

Overall, the findings demonstrate that SS and CC alter the synergy patterns of major muscles in the dominant leg during squat jumps with a starting knee angle of 120°, and these interventions also influence ground contact time. Specifically, SS tends to decrease the contributions of primary target muscles within the synergy. However, SS might induce compensatory actions in muscles less affected by stretching, such as the VM, to maintain the overall activity strength of the synergy. Conversely, CC appears to enhance the contribution of the LG by augmenting its activation, thereby leading to an advancement in the synergy's activation timing. These observations suggest that uneven stretching or localized activation could trigger compensatory actions in certain muscles, potentially increasing their susceptibility to injury. Additionally, neither SS nor CC exerted a statistically significant influence on jump height during SJ. However, SS does prolong ground contact time, while CC appears to counteract this effect. Consequently, for athletes prioritizing jump height, SS might not significantly impact their performance. In contrast, for athletes prioritizing speed, such as sprinters, SS might hinder their performance. It is therefore recommended that athletes seeking to optimize speed refrain from performing SS in isolation before activity. Alternatively, they might consider combining SS with CC to potentially mitigate any adverse effects on performance. Furthermore, an increase in the knee joint starting angle to 120° resulted in a decrease in the overall contribution of the five major muscles, the activity strength of the synergy, and both jump height and ground contact time. This suggests that a 90° starting angle might be a more favorable choice for sports disciplines requiring maximum jump height, while a 120° starting angle could be more suitable for speed-oriented events.

AVAILABILITY OF DATA AND MATERIALS

The data presented in this study are available on reasonable request from the corresponding author.

AUTHOR CONTRIBUTIONS

ML and SK—designed the research study. ML, MLD, TW, YL—performed the research. CHB and SK—provided help and advice on study design. ML and MLD—analyzed the data. ML, MLD, TW, YL, CHB—wrote the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The studies involving human participants were reviewed and approved by the Ethics Committee of Jeonbuk National University (JBNU2022-04-008-002). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

ACKNOWLEDGMENT

The authors extend their sincere appreciation to all study participants for their valuable contribution to this research.

FUNDING

This research received no external funding.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Cai P, Liu L, Li H. Dynamic and static stretching on hamstring flexibility and stiffness: a systematic review and meta-analysis. Heliyon. 2023; 9: e18795.
[2] Nakamura M, Sato S, Murakami Y, Kiyono R, Yahata K, Sanuki F, *et al*. The comparison of different stretching intensities on the range of motion and muscle stiffness of the quadriceps muscles. Frontiers in Physiology. 2021; 11: 628870.
[3] Takeuchi K, Akizuki K, Nakamura M. Acute effects of different intensity and duration of static stretching on the muscle-tendon unit stiffness of the hamstrings. Journal of Sports Science and Medicine. 2022; 21: 528–535.
[4] Zhu Y, Feng Y, Huang F, Li Y, Wang W, Wang X, *et al*. Changes in stiffness of the specific regions of knee extensor mechanism after static stretching. Frontiers in Bioengineering and Biotechnology. 2022; 10: 958242.
[5] Behm DG, Alizadeh S, Daneshjoo A, Konrad A. Potential effects of dynamic stretching on injury incidence of athletes: a narrative review of risk factors. Sports Medicine. 2023; 53: 1359–1373.
[6] Behm DG, Kay AD, Trajano GS, Blazevich AJ. Mechanisms underlying performance impairments following prolonged static stretching without a comprehensive warm-up. European Journal of Applied Physiology. 2021; 121: 67–94.
[7] Nakamura M, Suzuki Y, Yoshida R, Kasahara K, Murakami Y, Hirono T, *et al*. The time-course changes in knee flexion range of motion, muscle strength, and rate of force development after static stretching. Frontiers in Physiology. 2022; 13: 917661.
[8] Fernandes IA, Kawchuk G, Bhambhani Y, Gomes PSC. Does vibration counteract the static stretch-induced deficit on muscle force development? Journal of Science and Medicine in Sport. 2013; 16: 472–476.
[9] Kümmel J, Kramer A, Cronin NJ, Gruber M. Postactivation potentiation can counteract declines in force and power that occur after stretching. Scandinavian Journal of Medicine & Science in Sports. 2017; 27: 1750–1760.
[10] Trajano GS, Blazevich AJ. Static stretching reduces motoneuron excitability: the potential role of neuromodulation. Exercise and Sport Sciences Reviews. 2021; 49: 126–132.
[11] Farrow AC, Blinch J, Harry JR, Palmer TB. Short-term effects of static stretching on hamstring passive stiffness in young and older women. Journal of Musculoskeletal & Neuronal Interactions. 2023; 23: 290–298.
[12] Kolinger D, Stastny P, Pisz A, Krzysztofik M, Wilk M, Tsoukos A, *et al*. High-intensity conditioning activity causes localized postactivation

performance enhancement and nonlocalized performance reduction. Journal of Strength and Conditioning Research. 2024; 38: e1–e7.
[13] Dos Santos Silva D, Boullosa D, Moura Pereira EV, de Jesus Alves MD, de Sousa Fernandes MS, Badicu G, *et al*. Post-activation performance enhancement effect of drop jump on long jump performance during competition. Scientific Reports. 2023; 13: 16993.
[14] Finlay MJ, Bridge CA, Greig M, Page RM. Upper-body post-activation performance enhancement for athletic performance: a systematic review with meta-analysis and recommendations for future research. Sports Medicine. 2022; 52: 847–871.
[15] Chen Y, Su Q, Yang J, Li G, Zhang S, Lv Y, *et al*. Effects of rest interval and training intensity on jumping performance: a systematic review and meta-analysis investigating post-activation performance enhancement. Frontiers in Physiology. 2023; 14: 1202789.
[16] Fischer J, Paternoster FK. Post-activation-performance enhancement: possible contributing factors. Journal of Sports Science and Medicine. 2024; 23: 34–45.
[17] Garnier YM, Lepers R, Canepa P, Martin A, Paizis C. Effect of the knee and hip angles on knee extensor torque: neural, architectural, and mechanical considerations. Frontiers in Physiology. 2022; 12: 789867.
[18] Li M, Meng X, Guan L, Kim Y, Kim S. Comparing the effects of static stretching alone and in combination with post-activation performance enhancement on squat jump performance at different knee starting angles. Journal of Sports Science & Medicine. 2023; 22: 769–777.
[19] Nelson AG, Allen JD, Cornwell A, Kokkonen J. Inhibition of maximal voluntary isometric torque production by acute stretching is joint-angle specific. Research Quarterly for Exercise and Sport. 2001; 72: 68–70.
[20] La Torre A, Castagna C, Gervasoni E, Cè E, Rampichini S, Ferrarin M, *et al*. Acute effects of static stretching on squat jump performance at different knee starting angles. Journal of Strength and Conditioning Research. 2010; 24: 687–694.
[21] Gheller RG, Dal Pupo J, Ache-Dias J, Detanico D, Padulo J, dos Santos SG. Effect of different knee starting angles on intersegmental coordination and performance in vertical jumps. Human Movement Science. 2015; 42: 71–80.
[22] Harland MJ, Steele JR. Biomechanics of the sprint start. Sports Medicine. 1997; 23: 11–20.
[23] Chen CH, Chiu CH, Tseng WC, Wu CY, Su HH, Chang CK, *et al*. Acute effects of combining dynamic stretching and vibration foam rolling warm-up on lower-limb muscle performance and functions in female handball players. Journal of Strength and Conditioning Research. 2023; 37: 1277–1283.
[24] Bergmann J, Kramer A, Gruber M. Repetitive hops induce postactivation potentiation in triceps surae as well as an increase in the jump height of subsequent maximal drop jumps. PLOS ONE. 2013; 8: e77705.
[25] Perini TA, de Oliveira GL, dos Santos Ornellas J, de Oliveira FP. Technical error of measurement in anthropometry. Revista Brasileira de Medicina do Esporte. 2005; 11: 81–85.
[26] Nishida K, Hagio S, Kibushi B, Moritani T, Kouzaki M. Comparison of muscle synergies for running between different foot strike patterns. PLOS ONE. 2017; 12: e0171535.
[27] He J, Liu Y, Li S, Zhou P, Zhang Y. Enhanced dynamic surface EMG decomposition using the non-negative matrix factorization and three-dimensional motor unit localization. IEEE Transactions on Biomedical Engineering. 2024; 71: 596–606.
[28] Cheung VCK, d'Avella A, Tresch MC, Bizzi E. Central and sensory contributions to the activation and organization of muscle synergies during natural motor behaviors. The Journal of Neuroscience. 2005; 25: 6419–6434.
[29] Christova P, Kossev A, Radicheva N. Discharge rate of selected motor units in human biceps brachii at different muscle lengths. Journal of Electromyography and Kinesiology. 1998; 8: 287–294.
[30] Kennedy PM, Cresswell AG. The effect of muscle length on motor-unit recruitment during isometric plantar flexion in humans. Experimental Brain Research. 2001; 137: 58–64.
[31] Neumann DA. Kinesiology of the musculoskeletal system: foundations for rehabilitation. 3rd edn. Elsevier Health Sciences: St. Louis, Missouri. 2016.
[32] Yamagata M, Tateuchi H, Asayama A, Ichihashi N. Influence of lower-limb muscle inactivation on medial and lateral knee contact forces during walking. Medical Engineering & Physics. 2022; 108: 103889.
[33] Reese NB, Bandy WD. Joint range of motion and muscle length testing. 3rd edn. Elsevier: St. Louis, Missouri. 2017.
[34] Hirst GD, Redman SJ, Wong K. Post-tetanic potentiation and facilitation of synaptic potentials evoked in cat spinal motoneurones. The Journal of Physiology. 1981; 321: 97–109.
[35] Tillin NA, Bishop D. Factors modulating post-activation potentiation and its effect on performance of subsequent explosive activities. Sports Medicine. 2009; 39: 147–166.
[36] Arntz F, Markov A, Behm DG, Behrens M, Negra Y, Nakamura M, *et al*. Chronic effects of static stretching exercises on muscle strength and power in healthy individuals across the lifespan: a systematic review with multi-level meta-analysis. Sports Medicine. 2023; 53: 723–745.
[37] Balnave CD, Allen DG. The effect of muscle length on intracellular calcium and force in single fibres from mouse skeletal muscle. Journal of Physiology. 1996; 492: 705–713.
[38] Blazevich AJ, Gill ND, Kvorning T, Kay AD, Goh AG, Hilton B, *et al*. No effect of muscle stretching within a full, dynamic warm-up on athletic performance. Medicine & Science in Sports & Exercise. 2018; 50: 1258–1266.

How to cite this article: Ming Li, Maolin Dong, Ting Wang, Yang Lu, Chul-Ho Bum, Sukwon Kim. Effects of static stretching and its combination with conditioning contractions on lower limb muscle synergy and squat jump performance at two initial knee joint angles. Journal of Men's Health. 2024; 20(10): 101-110. doi: 10.22514/jomh.2024.170.