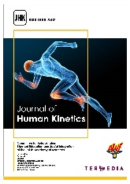

Journal of Human Kinetics volume xx/xxxx, x–x DOI: 10.5114/jhk/220315

Section III – Sports and Physical Activity

Acute Effects of Static Stretching and Its Combination with Menthol Gel on Squat Jump Performance at Two Initial Knee Joint Angles

by

Yi Peng [1], Ming Li [2,3], Hao Li [2], Xinpeng Gao [4,]*

This study investigated the effects of static stretching (SS) and its combination with menthol gel on lower limb muscle activation, synergistic patterns, and squat jump (SJ) performance at two knee starting angles (90° and 120°). Twelve participants completed a randomized crossover protocol across three sessions, each involving SJ trials under different intervention conditions. Data were collected via a 3D motion capture system, EMG, and a force plate. EMG data were analyzed using principal component analysis and amplitude calculations, while jump height, ground contact time, peak ground reaction force (GRF_{peak}), and the rate of force development (RFD) were derived from kinematic and kinetic data. Results showed no significant changes in average EMG amplitude with SS or menthol gel ($p > 0.05$). However, SS at 120° significantly altered muscle synergy ($p < 0.001$, $d = 2.02$), increased jump height ($p = 0.002$, $d = 0.59$), and reduced ground contact time ($p = 0.005$, $d = 1.15$), GRF_{peak} ($p < 0.001$, $d = 1.59$), and the RFD ($p < 0.001$, $d = 1.47$). Menthol gel offset these changes. Additionally, joint angle influenced all performance metrics ($p < 0.05$). These findings suggest that while SS can enhance jump height at certain joint angles, it may hinder explosive force output, and combining it with menthol gel can mitigate such drawbacks.

Keywords: *electromyography; ground contact time; jump height; rate of force development; peak ground reaction force*

Introduction

Stretching is a common practice in both exercise preparation and recovery. By lengthening muscles and connective tissues, it can enhance joint range of motion (ROM) and reduce the risk of musculotendinous unit injuries during explosive movements (Behm et al., 2023). Among the various stretching techniques, static stretching (SS) has garnered significant attention due to its potential effects on subsequent athletic performance. Previous studies have generally suggested that SS may have a negative impact on subsequent strength and power performance (Bouvier et al., 2017; Çabuk et al., 2025; Li et al., 2023), leading authoritative sports organizations to recommend avoiding prolonged SS before tasks that demand strength and power. However, recent research indicates that SS might not necessarily impair jumping or sprinting performance and even proposes incorporating SS into warm-up routines (Warneke and Lohmann, 2024). Although the findings remain inconclusive, the reported benefits of SS, such as improving joint flexibility, expanding pain-free ROM, enhancing directional change ability, and reducing musculotendinous injury risk, are more pronounced compared to other stretching methods (Siebert et al., 2022). Therefore, further investigation into the effects of SS on athletic performance is essential to provide more definitive evidence.

[1] *Department of Physical Education, Putian University, Putian, China.*
[2] *College of Education and Sports Sciences, Yangtze University, Jingzhou, China.*
[3] *Postdoctoral Research Station, Chengdu Sport University, Chengdu, China.*
[4] *School of Physical Education, Yulin University, Yulin, China.*
* Correspondence: gxp202055390@yeah.net

Menthol, a naturally occurring cyclic terpene alcohol (Patel et al., 2007), is extracted from plants of the genus Mentha. Through topical application, it activates the transient receptor potential melastatin 8 (TRPM8) channel to produce a cooling sensation and may enhance local cutaneous blood flow. As a TRPM8 channel agonist, menthol modulates sensory nerve excitability and mediates vasodilation via nitric oxide release (Sun et al., 2014). Additionally, menthol may further induce vasodilation through activation of the RhoA/ROCK signaling pathway (Craighead et al., 2017), optimizing blood perfusion and metabolic efficiency in muscle tissue. These mechanisms suggest that menthol could indirectly enhance endurance and muscle strength performance by improving neuromuscular recruitment and accelerating aerobic oxidation processes (Gavel et al., 2024). Although existing studies have not identified significant acute effects of menthol in single applications (Topp et al., 2011), its underlying physiological actions provide a theoretical basis for exploring its combination with static stretching and other interventions.

In addition to the effects of SS and menthol gel, joint angles also play a crucial role in athletic performance. For example, Rousanoglou et al. (2010) found that peak explosive torque during muscle contraction was strongly influenced by the joint angle, while Li et al. (2023) reported a positive correlation between lower limb power and knee joint angles ranging from 60° to 120°. These findings underscore the importance of joint angle configuration in performance outcomes. Furthermore, the joint angle may interact with SS, affecting its influence on muscle function. Regarding menthol, studies suggest that it may mitigate SS-induced performance declines by modulating muscle receptor excitability, promoting nitric oxide release, and improving neuromuscular efficiency (Craighead et al., 2017; Sun et al., 2014). However, how joint angles influence these interactions remains unclear.

Given the frequent use of 90° and 120° knee joint angles in sports settings (Fan et al., 2025; Gheller et al., 2015; Harland and Steele, 1997), this study aimed to examine the effects of SS and its combination with menthol gel on squat jump (SJ) performance at these two angles. This investigation sought not only to address potential limitations of SS during the warm-up, but also to clarify the interplay among SS, menthol application, and the joint angle. We hypothesized that SS might influence muscle synergy, jump height, ground contact time, peak ground reaction force (GRF_{peak}), and the rate of force development (RFD), with these effects potentially modulated by the joint angle and mitigated by menthol gel.

Methods

Experimental Design

This study employed a randomized crossover design to compare differences in primary outcome variables under various conditions, including average EMG amplitude, the cumulative explained variance percentage, load vectors, jump height, ground contact time, GRF_{peak}, and the RFD across five muscles: the gastrocnemius lateralis (GL), the biceps femoris long head (BFL), the rectus femoris (RF), the vastus lateralis (VL), and the vastus medialis (VM). Prior to the experiment, each participant completed a familiarization session, during which they practiced the SJ at both selected knee angles. In the second session, participants were randomly assigned to complete three interventions on separate days: control (C), static stretching (SS), and static stretching combined with menthol gel (SM). Under each condition, SJ tests were performed at two initial knee angles (90° and 120°). To minimize carryover effects, a washout period of 2–7 days was provided between sessions, during which participants refrained from all forms of training. All testing sessions for each participant were conducted at the same time of the day. Participants were also instructed to avoid strenuous exercise and alcohol consumption for 48 h prior to testing, abstain from caffeine- and theophylline-containing beverages within 8 h, and refrain from eating for 3 h before each session.

Participants

Twelve male university athletes voluntarily participated in this study. The participants had a mean age of 22 years (± 1.3 years), body height of 179.57 cm (± 5.1 cm), and body mass of 69.28 kg (± 7.63 kg) (mean ± standard deviation). An a priori power analysis was conducted using G*Power 3.1.9.7 software (α = 0.05, effect size f = 0.71, based on prior data) to determine the required sample size. The analysis indicated that a total of 12 participants was sufficient to achieve adequate statistical power for the study design. The inclusion criteria for all recruited participants were as follows: 1. no significant movement restrictions or muscle weakness, as determined by observation and a brief assessment conducted by an experienced physical therapist; and 2. no lower-limb pain before testing. The exclusion criteria were as follows: 1. any recent musculoskeletal injuries or conditions that could affect the study's performance measures; and 2. use of medications that might influence muscle performance or recovery. Additionally, all participants maintained a regular training regimen consisting of at least three training sessions per week, each lasting approximately two hours. Participants visited the laboratory on four occasions. During their first visit, they were provided with detailed information about the study's methodology and potential risks, they also signed informed consent forms. This study strictly adhered to the principles outlined in the 2013 revision of the Declaration of Helsinki and received approval from the Ethics Committee of the Chengdu Sport University, Chengdu, China (protocol code: 2025-95; approval date: 20 January 2025). All experimental protocols were thoroughly reviewed to ensure compliance with ethical standards and to adequately protect the rights and welfare of the participants.

Preparation for Testing

This study utilized a three-dimensional motion capture system equipped with thirteen Prime 17W infrared cameras (OptiTrack, Natural Point, Inc., Corvallis, OR, USA), capturing motion data at a frequency of 100 Hz. Twenty reflective markers, each 14 mm in diameter, were placed on key anatomical points of the participants' lower limbs, aligning with a pre-constructed model. Ground reaction forces were recorded using an OR6-6-2000 force plate produced by Advanced Mechanical Technology, Inc. (Watertown, MA, USA), with a sampling rate of 1000 Hz. Concurrently, EMG data of the GL, BFL, RF, VL, and VM muscles on the dominant leg of participants were collected at a frequency of 1000 Hz using Trigno Avanti sensors (Delsys, Natick, MA, USA). Electrode placement followed the SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles) guidelines, using anatomical landmarks to ensure consistency across participants. Each Trigno Avanti Sensor, measuring 37 mm × 27 mm × 13 mm and weighing 14 g, was equipped with dual differential EMG sensors featuring silver bar electrodes (5 mm × 1 mm, 10 mm inter-electrode distance), achieving a common mode rejection ratio of 80 dB and an amplifier gain of 909. Before affixing the EMG electrodes, the skin surface was prepared by removing hair with a disposable sterile manual razor and disinfected with a medical alcohol swab. The synchronized collection of kinematic data, dynamic data, and EMG signals was facilitated using Motive 2.2.0 software (OptiTrack, Natural Point, Inc., Corvallis, OR, USA).

Test Procedure

In this study, all participants initially performed a standardized warm-up cycling for 5 min on a Monark 894E ergometer (Sweden) at 60 rpm and a resistance of 70 W. This was followed by a 5-min passive rest to allow the body's metabolic activities to return to a normal state. SJ tests under the control condition were conducted after the warm-up, while SJ tests under SS and SM conditions were performed 3 min post-SS. The menthol gel application in the group performing SM was done approximately 27 min before the SJ tests (Craighead et al., 2017).

Interventions

In this study, the triceps surae, hamstring, and quadriceps muscle groups were selected for SS due to their high incidence of strain during physical activities (Orchard et al., 2020) and their significant influence on SJ performance. The stretching exercises were bilateral and randomly assigned, following the protocol designed by Chen et al. (2023). Specifically, the stretching amplitude was determined during the participants' initial visit to the laboratory. The intensity was set to elicit mild discomfort without causing pain, and the corresponding joint angles of the hip, the knee, and the ankle at this intensity were recorded. These recorded angles were then used as the basis for controlling the stretching intensity in subsequent trials. The stretching procedures were performed as follows: quadriceps stretching was conducted in an upright stance, with participants maintaining balance by placing one hand against a wall, bending the intended leg at the knee to approximately 90°, and grasping the ankle with the ipsilateral hand to gently pull the heel toward the gluteal area. Hamstrings stretching involved placing one leg on a step with a slightly bent knee and leaning forward from the hips until a stretch was felt in the posterior thigh. Triceps surae stretching was performed in a supine position, with the experimenter assisting by dorsiflexing the foot to achieve the desired stretch. Each muscle group on each leg was stretched four times, holding each stretch for 30 s with a 15-s rest interval in between (i.e., 4 × 30 s, with 15-s rest intervals), totaling 120 s of stretching per muscle group. This stretching protocol has been shown to provide improvements in ROM lasting up to 30 min (Li et al., 2024). For additional information on the stretching protocol, readers are referred to Chen et al. (2023) and Li et al. (2023).

The application dose of menthol gel was calculated based on the total skin surface area using the formula proposed by Yu et al. (2010) for the body surface area (BSA): $BSA = 71.3989 \times H^{0.437} \times W^{0.4040}$. The cutaneous surface areas of the target muscles, i.e., the triceps surae, hamstrings, and quadriceps femoris, were estimated to represent 3.5%, 4.5%, and 5.1% of the total BSA, respectively (Yu et al., 2010). Menthol gel was applied at a density of 0.5 mL per 100 cm^2 of the skin surface (Topp et al., 2011). Specifically, prior to the warm-up protocols, a gloved technician applied menthol gel containing 4% menthol to the skin overlying the target musculature in a randomized sequence.

SJ Test

Participants performed SJs at two randomized knee joint angles (90° and 120°) on a force plate, with knee angles confirmed using a goniometer (Biopac Systems Inc., Goleta, CA, USA). All measurements were conducted by the same experienced researcher, and consistency was further monitored through real-time visual feedback. At the same angle, participants performed three maximal jumps, with a 1-min rest interval in between, while a 3-min rest interval was set between SJs performed at different angles (Li et al., 2023). The standard starting posture for the SJ was based on the study by Gillen et al. (2022). Specifically, participants stood on the force plate, bent their knees and hips into a static squat position, and placed their hands on their hips. They maintained the specified knee joint angle for 1 s before performing a maximal vertical jump without a countermovement (Gu et al., 2026).

Data Processing

Extraction of centroid displacement-time and force-time data was accomplished using Visual3D Setup x64 v2023.10.1 software (C-Motion, Inc., Germantown, MD, USA). The start of the movement was defined as the point where force exceeded five standard deviations of the force during the flight phase, and the end of the movement was determined when force dropped to 20 N (Zhang et al., 2025). Force-time data were smoothed using a 17-Hz bidirectional fourth-order Butterworth low-pass filter, while displacement-time data were processed with a 6-Hz bidirectional fourth-order Butterworth low-pass filter (Li et al., 2023). EMG data, after being filtered through a 20–480-Hz bandpass Butterworth fourth-order filter, underwent two different processes: the first included calculating the root mean square, then dividing each RMS value by the RMS value corresponding to the peak muscular activity observed during the action to normalize, and finally averaging these normalized values to obtain the average amplitude of EMG; the second process consisted of full-wave rectification of the data followed by 10-Hz low-pass filtering, used for calculating the EMG signal envelope. The normalized data were linearly interpolated into 101 sampling points. The processed EMG data (five muscles) were grouped according to the experimental design (group × angle) and subjected to principal component analysis separately (Deluzio and Astephen, 2007).

Jump height (difference in center-of-mass height between standing and apex), ground contact time (time from movement onset to force-plate clearance), peak ground reaction force (GRF_{peak}), and the rate of force development ($RFD = \Delta Force/\Delta Time$) were computed from the force-time data. Reliability of ground contact time and GRF_{peak} across the experimental conditions was assessed using the intraclass correlation coefficient ($ICC_{3,3}$; two-way mixed-effects, average measurement) and the coefficient of variation (CV%), with ICC ≥ 0.80 and CV ≤ 10% deemed acceptable (Li et al., 2026). All three trials were then averaged and normalized to body mass to ensure comparability. EMG data processing was performed in R (v4.3.2, R Foundation for Statistical Computing, Vienna, Austria), and all other calculations were conducted in Microsoft Excel (2019, Microsoft Corp., Redmond, WA, USA).

Statistical Analysis

Data were reported as mean ± standard deviation and statistical analysis was conducted in the R 4.3.0 environment. Before principal component analysis (PCA), EMG data were normalized and averaged. PCA was used to extract spatial synergies among muscles, with the cumulative percentage of variance explained by the first five principal components as shown in Table 1. The loading vector of the first principal component, which accounted for the highest rate of explained variance, was subjected to repeated measures ANOVA, a method of which effectiveness and validity have been widely verified (Deluzio and Astephen, 2007). A two-factor mixed effect model (group × angle) was used to analyze data other than loading vectors, with normality of the data tested (Shapiro-Wilk test) ($p > 0.05$) before conducting significance analysis. The optimal model including random intercepts was chosen through a likelihood ratio test ($p < 0.01$). Post hoc analysis was conducted where main effects or interaction effects were significant ($p < 0.05$), with Bonferroni correction applied for multiple comparisons. To evaluate the effect size between different conditions, Cohen's d was calculated [(Mean1 − Mean2)/SD pooled].

Results

In terms of EMG average amplitude, the main effects of the experimental group, the joint angle, and their interaction were not significant ($p > 0.05$) for BFL, RF, VL, and VM muscles. For GL's EMG (GLEMG) average amplitude, both the main effect of the group and the interaction effect were not significant ($p > 0.05$). The main effect of the angle was significant ($p = 0.003$), with multiple comparisons showing that the EMG average amplitude significantly increased when the initial knee angle increased to 120° under both C and SM conditions (C: $p = 0.003$, $d = 1.22$; SM: $p = 0.002$, $d = 1.31$). The mean and standard deviation of GLEMG average amplitude is listed in Table 1.

For the load vector of the first synergy component, the main effects of the group, the angle, and their interaction were all significant ($p < 0.001$). Multiple comparisons revealed significant differences between SS and C conditions ($p < 0.001$, $d = 2.02$) and the SM condition ($p < 0.001$, $d = 2.12$) when the angle was 120°. Under C and SM conditions, significant changes in the load vector were observed when the angle increased to 120° (C: $p < 0.001$, $d = 1.16$; SM: $p < 0.001$, $d = 1.16$).

Table 2 presents the mean and standard deviation of jump height (Figure 1a). The main effects of the group, the angle, and their interaction on jump height were all significant ($p < 0.05$). Multiple comparisons revealed that when the angle was 120°, the SS group significantly exceeded the C group ($p = 0.002$, $d = 0.59$) and the SM group ($p = 0.002$, $d = 0.62$). Under C, SS, and SM conditions, jump height significantly decreased when the initial knee angle increased to 120° (C: $p < 0.001$, $d = 0.88$; SS: $p = 0.008$, $d = 0.4$; SM: $p < 0.001$, $d = 1.02$).

For ground contact time (Table 2 and Figure 1b), the main effects of the group, the angle, and their interaction were all significant ($p < 0.05$). Multiple comparisons showed that when the angle was 120°, ground contact time under the SS condition was significantly greater than under C ($p = 0.005$, $d = 1.15$) and SM ($p = 0.04$, $d = 0.95$) conditions. Under C, SS, and SM conditions, ground contact time decreased significantly when the angle increased to 120° (C: $p < 0.001$, $d = 2.61$; SS: $p < 0.001$, $d = 1.91$; SM: $p < 0.001$, $d = 2.7$).

For GRF_{peak} (Table 2 and Figure 1c), the main effects of the group, the angle, and their interaction were all significant ($p < 0.05$). Multiple comparisons revealed that when the angle was 120°, GRF_{peak} under the SS condition was significantly lower than under C ($p < 0.001$, $d = 1.59$) and SM ($p = 0.002$, $d = 1.19$) conditions. GRF_{peak} significantly increased when the angle increased to 120° (C: $p < 0.001$, $d = 2.86$; SS: $p < 0.001$, $d = 2.9$; SM: $p < 0.001$, $d = 2.58$).

For the RFD (Table 2 and Figure 1d), the group main effect, the angle main effect, and the interaction effect were all significant ($p < 0.05$). Multiple comparisons showed that at the angle of 120°, the RFD was significantly lower under the SS condition compared to C ($p < 0.001$, $d = 1.47$) and SM ($p = 0.006$, $d = 1.07$) conditions. As the angle increased to 120°, the RFD increased significantly (C: $p < 0.001$, $d = 2.52$; SS: $p < 0.001$, $d = 2.34$; SM: $p < 0.001$, $d = 2.21$).

Table 1. Cumulative percent variance explained by the first five synergies for different groups at two initial knee angles.

	Knee starting angle (°)									
Condition	**90°**					**120°**				
C	**51.3**	**70.3**	**80.2**	**88.7**	**92.4**	**58.4**	**78.5**	**88.5**	**94.9**	**96.5**
SS	**48.3**	**68.8**	**82.3**	**89.1**	**92.6**	**54.9**	**70.3**	**80.3**	**86.4**	**91.4**
SM	**53.2**	**67.9**	**79.1**	**88.3**	**92**	**50**	**69.7**	**83**	**92**	**94.7**

C: control condition, SS: static stretching condition, SM: static stretching combined with menthol gel condition

Table 2. Statistical comparison of key variables across conditions under two initial knee joint angles.

		Knee starting angle (°)	
Variable	Condition	90°	120°
GLEMG average amplitude (%)	C	13.39 ± 2.7	18.36 ± 5.08†
	SS	15.12 ± 3.98[0.51]	16.87 ± 3.12[0.35]
	SM	13.49 ± 2.09[0.04]	18.71 ± 5.24†[0.07]
jump height (cm·kg^{-1})	C	0.62 ± 0.11	0.53 ± 0.09†
	SS	0.64 ± 0.12[0.22]	0.6 ± 0.12*†[0.59]
	SM	0.62 ± 0.08[0.03]	0.53 ± 0.08†[0.00]
ground contact time (ms·kg^{-1})	C	5.26 ± 0.65	3.64 ± 0.59†
	SS	5.75 ± 0.72[0.72]	4.39 ± 0.71*†[1.15]
	SM	5.32 ± 0.63[0.09]	3.83 ± 0.46†[0.35]
GRF_{peak} (N·kg^{-1})	C	24.2 ± 2.19	30.96 ± 2.53†
	SS	22.62 ± 1.62[0.82]	27.51 ± 1.75*†[1.59]
	SM	24.22 ± 1.86[0.01]	30.21 ± 2.71†[0.28]
RFD (N·kg^{-1}·s^{-1})	C	96.41 ± 31.51	226.8 ± 65.88†
	SS	79.94 ± 23.2[0.6]	149.2 ± 34.75*†[1.47]
	SM	94.28 ± 29.06[0.07]	204.5 ± 64.33†[0.34]

*The effect sizes of the intervention and control groups are reported in square brackets. *: significantly ($p < 0.05$) different from the control condition; †: significantly ($p < 0.05$) different from the 90° condition. GLEMG: gastrocnemius lateralis' electromyogram; GRF_{peak}: peak ground reaction force; RFD: rate of force development; C: control condition; SS: static stretching condition; SM: static stretching combined with menthol gel condition*

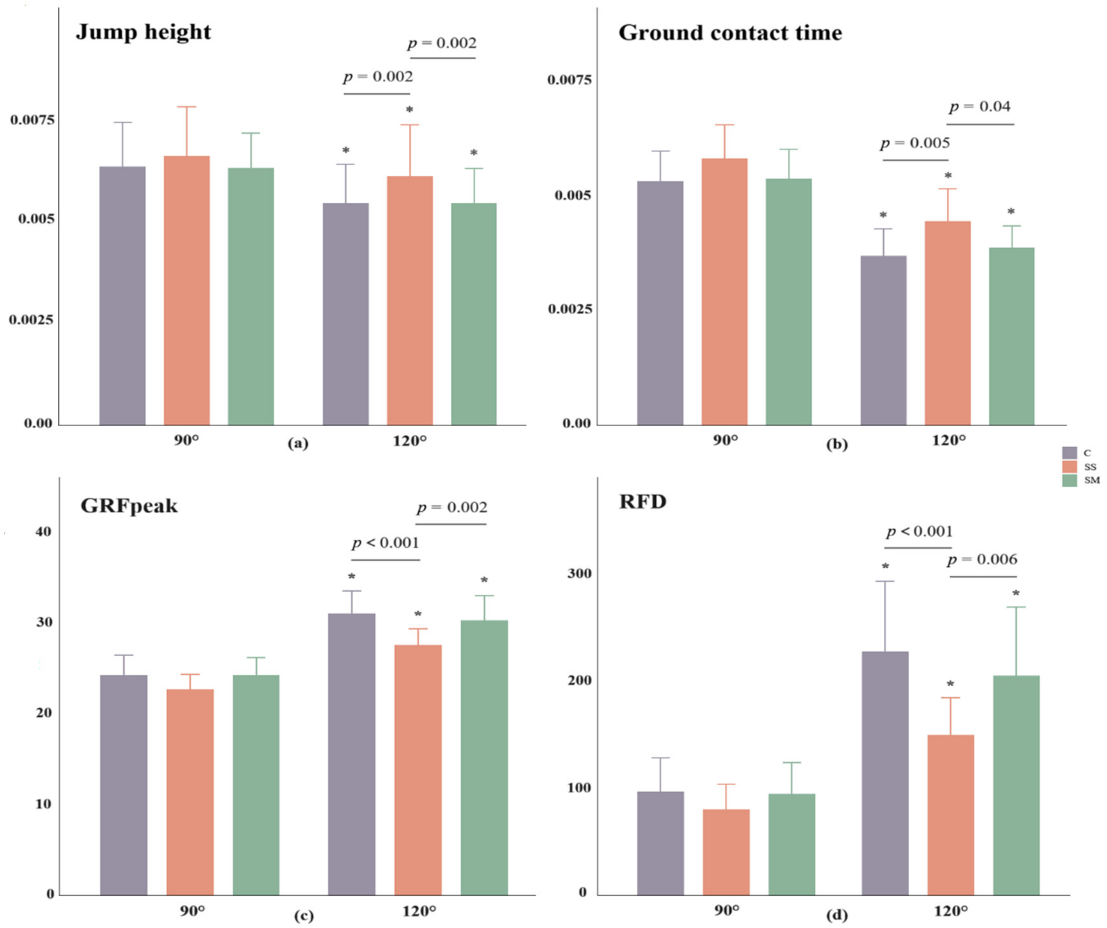

Figure 1. Average values and standard deviations for jump height, ground contact time, peak ground reaction force (GRF_{peak}), and the rate of force development (RFD) across three condition (control [C], static stretching [SS], and static stretching combined with menthol gel [SM]) at two knee joint starting angles (90° and 120°). Panel (a): jump height, (b) ground contact time, (c) GRF_{peak}, and (d) RFD. Differences between angles within each condition are marked by asterisks, while significant discrepancies between C, SS, and SM conditions are highlighted with horizontal lines and corresponding *p*-values.

Discussion

This study focused on the effects of SS and its combination with menthol gel on athletic performance, with key findings showing that SS and menthol gel did not significantly impact the electrical activity of the five considered muscles, but at 120°, SS significantly altered the synergy patterns of these muscles, an effect that was effectively nullified by the application of menthol gel. Additionally, under both the C and SM conditions, an increase in the joint angle not only enhanced GL activation, but also changed muscle synergy patterns. Additionally, at 120°, SS led to increased jump height and ground contact time, effects that were counteracted by the use of menthol gel. Furthermore, the increase in the angle to 120° resulted in a reduction in both jump height and ground contact time. Lastly, SS reduced

GRF_{peak} and the RFD at 120°, effects that were eliminated with the application of menthol gel. Moreover, the increase in the angle to 120° showed an upward trend in both GRF_{peak} and the RFD.

Regarding the effects of SS on muscle activation, previous studies have reported inconsistent findings. Opplert et al. (2020) found that SS altered corticospinal excitability without affecting muscle activation levels. In contrast, a review by Behm et al. (2021) suggested that SS-induced impairment in athletic performance might result from reduced voluntary activation. Our findings align with those of Opplert et al. (2020). Unlike their study, which focused solely on plantar flexor muscles, our research expanded to a broader range of muscles to examine the consistency of SS effects across different muscle groups. The discrepancy with Behm et al.'s (2021) conclusions may be attributed to differences in the experimental design, particularly the absence of dynamic warm-ups and the longer stretching duration in previous studies. The lack of significant impact of menthol gel on muscle activation contrasts with Tokunaga et al.'s (2017) findings, where menthol significantly increased the root mean square EMG activity of the VL and VM muscles during low-load contractions at 35% of maximum voluntary contraction. This discrepancy may be attributed to the lower load levels used in previous studies compared to the dynamic, maximal-effort activities employed in the present study. The lack of significant changes in muscle activation following the interventions may stem from the limitations of surface electromyography (Farina et al., 2004), which may not detect subtle changes in corticospinal excitability induced by stretching or menthol. Discomfort caused by stretching or cutaneous sensations from menthol could potentially modulate corticospinal excitability levels (Chung and Wang, 2011; Trajano et al., 2017; Veldman et al., 2014), but such effects may require more specialized assessments, such as the Hoffman reflex, for detection (Opplert et al., 2020). In this study, increased muscle activation levels were observed at larger joint angles under both the C and SM conditions, which is consistent with previous findings on the influence of knee joint angles on muscular electrophysiological activity (Arampatzis et al., 2006). Unlike previous studies that primarily employed isometric contraction tests, this study utilized dynamic testing. Dynamic contractions, being common in most sports, might more closely reflect actual movement states (Zabaloy et al., 2025). The observed changes in gastrocnemius muscle activity could stem from adjustments in muscle fiber length due to changes in joint angles, thereby affecting the activation of motor units in the gastrocnemius (Arampatzis et al., 2006; Kennedy and Cresswell, 2001). Prior research has mainly focused on the effects of SS or menthol on the activation levels of individual muscles (Li et al., 2023; Opplert et al., 2020; Tokunaga et al., 2017; Trajano et al., 2017), with less attention on how they influence the cooperative work of multiple muscles. This study is the first to find that at a knee joint initial angle of 120°, SS can change the synergy patterns of five major muscles, while the application of menthol could eliminate this change. This effect may originate from discomfort caused by SS and skin sensory stimulation induced by menthol (Ohta et al., 2009; Tokunaga et al., 2017; Trajano et al., 2017), which could alter corticospinal excitability and, consequently, affect muscle synergy patterns (Trajano et al., 2017; Veldman et al., 2014). Although not directly reflected in muscle activation levels, this might manifest in the power frequency (Opplert et al., 2020). Particularly, these differences occur at a knee joint angle of 120°, because at this angle, the initial lengths of the main force-producing muscles are shorter, and the reduced muscle stiffness caused by SS (Zhu et al., 2022) jointly affects muscle synergy patterns.

The impact of SS on jump height observed in this study is consistent with the findings of de Souza et al. (2016) who found that 90 s of SS could enhance jump height. Unlike the previous study that focused solely on the hamstrings, this study targeted the quadriceps, the triceps surae, and the hamstrings, reflecting the common muscles stretched during actual warm-up activities. The reason for this outcome could be that SS expanded the window for force generation, thereby increasing the impulse and, in turn, enhancing jumping height. This aligns with the observed changes in GRF_{Peak} and time-related variables. As for the effect of menthol on jump height, our findings align with those of Rites et al. (2024) who observed a decrease in jump height among soccer players following inhalation of menthol. This phenomenon may occur because menthol improves the efficiency of synaptic signal processing (Tsuzuki et al., 2004), shortening the effective window for force generation and thus reducing jump height. Additionally, this study noted a decrease in jump height as the initial angle increased to 120°, which is consistent with earlier research (Gheller et al., 2015). This could be due to the larger starting angle shortening the movement path, reducing the time available for force production, and thus lowering jump height.

The findings on ground contact time by Behm and Kibele (2007), which demonstrated that a total of 2 min of SS increased ground contact time in drop jumps, align with the outcomes of this study. However, differing from prior research that utilized the drop jump, this study opted for the SJ as the testing action to eliminate the potential influence of elastic energy and the stretch reflex. The elongation of ground contact time induced by SS might be attributed to alterations in the length and stiffness of the muscle-tendon unit (Zhu et al., 2022), which could lead to length-dependent adjustments in calcium ion sensitivity and a decrease in the speed of force transmission within the muscle (Balnave and Allen, 1996; Maffiuletti et al., 2016), thereby prolonging the duration of ground contact time. Previous studies indicated that menthol had no significant effect on ground contact time in SJs (Rites et al., 2024), diverging from the results obtained in this study. Such discrepancies may arise from prior research solely involving menthol intervention, whereas the current study included both menthol and stretching. The combined usage might have exerted additional impacts (Yano et al., 1991). Furthermore, a reduction in ground contact time was observed as the angle increased to 120°, likely due to a shortened movement path.

Previous research has indicated that SS reduces GRF_{peak} during vertical jumps (Li et al., 2023), which is consistent with the findings of this study. Additionally, another study reported that menthol application enhanced maximal isometric lifting performance (Over et al., 2023), aligning with our observation that menthol increased GRF_{peak}. At 120°, both SS and menthol influenced GRF_{peak}. This may be attributed to the combined effects of a reduced initial length of the primary force-generating muscles and decreased muscle stiffness induced by SS (Zhu et al., 2022). Menthol, by enhancing cutaneous sensation, may have facilitated greater muscle fiber recruitment (Over et al., 2023), thereby counteracting the negative effects of SS. Furthermore, the increase in GRF_{peak} as the angle increased to 120° might be attributed to the primary force-generating muscles being at a relatively optimal length. At this length, the cross-bridge overlap is maximized (Huxley, 1969), and the lever arm also changes with the angle, collectively promoting an increase in GRF_{peak}.

The research by Warneke and Lohmann (2024) indicated that SS had no significant effect on the subsequent RFD, which differs from our findings. Our study observed that when the initial knee joint angle was set to 120°, SS significantly reduced the RFD. The difference from previous studies may be due to the different knee joint angles used in this study, with this variation potentially interacting with SS to produce a combined effect. The study by Rites et al. (2024) found that menthol increased the RFD during SJs by 17.66%, which is consistent with our results. The difference lies in the previous study's use of a single menthol intervention, whereas our research applied a mixed intervention approach. This result might be due to the menthol increasing GRF_{peak} while shortening the time to peak, thereby enhancing the RFD. Additionally, the increase in the RFD as the angle increased to 120° could also stem from the increase in GRF_{peak} and the shortened peak time, which is consistent with the changes observed in our experimental data.

Although this study has made progress in revealing the effects of SS and menthol on sports performance, there are some limitations: 1) while an analysis of muscular synergy was conducted, the specific characteristics of each principal component were not thoroughly explored, limiting our comprehensive understanding of the intervention effects; 2) frequency domain analysis of EMG was not performed, preventing direct observation of the specific impacts of SS and menthol on power frequency. Thus, interpretations rely on existing research and theoretical inferences; 3) an independent menthol intervention group was not set up. Although this does not affect the results, it limits the understanding of the sole effects of menthol. Therefore, future research should include a detailed analysis of the characteristics of each principal component, incorporate EMG frequency domain analysis, and consider establishing an independent menthol intervention group to deepen the understanding of the impacts of SS and menthol on neuromuscular and sports performance.

Conclusions

Overall, SS and its combination with menthol gel had minimal effects on the activation levels of the five tested muscles. However, at a 120° knee joint starting angle, SS altered muscle synergy patterns, which were reversed by menthol gel. At this angle, SS also increased jump height and ground contact time, while it decreased GRF_{peak} and the RFD. These effects were similarly counteracted by menthol gel. These findings suggest that, for male collegiate athletes, SS may enhance performance in activities focused on height or distance, while it may impair performance in strength- or speed-oriented tasks unless combined with menthol gel. Additionally, as the joint angle increased to 120°, jump height and ground contact time decreased, whereas GRF_{peak} and RFD increased. This indicates that, within this population, a 90° starting angle may be more suitable for height- or distance-based activities, while 120° may be preferable for strength or speed tasks.

Author Contributions: Conceptualization: Y.P., M.L., H.L. and X.G.; methodology: Y.P. and M.L.; data curation: M.L.; formal analysis: M.L.; investigation: M.L.; writing—original draft preparation: Y.P. and M.L.; writing—review and editing: Y.P., H.L. and X.G.; supervision: H.L. and X.G.; project administration: X.G.; final approval of the article: H.L. and X.G. All authors have read and agreed to the published version of the manuscript.

ORCID iD:

Yi Peng: https://orcid.org/0009-0000-2420-978X

Ming Li: https://orcid.org/0009-0002-3553-6932

Hao Li: https://orcid.org/0009-0007-1132-2370

Xinpeng Gao: https://orcid.org/0009-0008-0988-8241

Funding Information: This research was funded by the Startup Fund for Advanced Talents of Putian University, China (grant number 2024056).

Institutional Review Board Statement: This study was conducted in accordance with the principles of the Declaration of Helsinki and approved by the Ethics Committee of the Chengdu Sport University, Chengdu, China (protocol code: 2025-95; approval date: 20 January 2025).

Informed Consent: Informed consent was obtained from all participants included in the study.

Conflicts of Interest: The authors declare no conflict of interest.

Acknowledgements: The authors would like to thank all participants for their time, effort, and cooperation in this study.

Received: 07 June 2025

Accepted: 03 April 2026

References

Arampatzis, A., Karamanidis, K., Stafilidis, S., Morey-Klapsing, G., DeMonte, G., and Brüggemann, G.-P. (2006). Effect of different ankle- and knee-joint positions on gastrocnemius medialis fascicle length and EMG activity during isometric plantar flexion. *Journal of Biomechanics*, *39*(10), 1891–1902. https://doi.org/10.1016/j.jbiomech.2005.05.010

Balnave, C. D., and Allen, D. G. (1996). The effect of muscle length on intracellular calcium and force in single fibres from mouse skeletal muscle. *Journal of Physiology*, *492*(3), 705–713. https://doi.org/10.1113/jphysicalol.1996.sp021339

Behm, D. G., Alizadeh, S., Daneshjoo, A., and Konrad, A. (2023). Potential effects of dynamic stretching on injury incidence of athletes: A narrative review of risk factors. *Sports Medicine*, *53*(7), 1359–1373. https://doi.org/10.1007/s40279-023-01847-8

Behm, D. G., Kay, A. D., Trajano, G. S., and Blazevich, A. J. (2021). Mechanisms underlying performance impairments following prolonged static stretching without a comprehensive warm-up. *European Journal of Applied Physiology*, *121*(1), 67–94. https://doi.org/10.1007/s00421-020-04538-8

Behm, D. G., and Kibele, A. (2007). Effects of differing intensities of static stretching on jump performance. *European Journal of Applied Physiology*, *101*(5), 587–594. https://doi.org/10.1007/s00421-007-0533-5

Bouvier, T., Opplert, J., Cometti, C., and Babault, N. (2017). Acute effects of static stretching on muscle-tendon mechanics of quadriceps and plantar flexor muscles. *European Journal of Applied Physiology*, *117*(7), 1309–1315. https://doi.org/10.1007/s00421-017-3618-9

Çabuk, R., Demirarar, O., Arslan, H., Cin, M., Özçaldıran, B., and Karsten, B. (2025). Counteracting Static Stretching-Induced Anaerobic Performance Impairment: The Role of Caffeine. *Journal of Human Kinetics*, Advance online publication. https://doi.org/10.5114/jhk/207251

Chen, C.-H., Chiu, C.-H., Tseng, W.-C., Wu, C.-Y., Su, H.-H., Chang, C.-K., and Ye, X. (2023). 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*, *37*(6), 1277–1283. https://doi.org/10.1519/JSC.0000000000003998

Chung, M.-K., and Wang, S. (2011). Cold suppresses agonist-induced activation of TRPV1. *Journal of Dental Research*, *90*(9), 1098–1102. https://doi.org/10.1177/0022034511412074

Craighead, D. H., McCartney, N. B., Tumlinson, J. H., and Alexander, L. M. (2017). Mechanisms and time course of menthol-induced cutaneous vasodilation. *Microvascular Research*, *110*, 43–47. https://doi.org/10.1016/j.mvr.2016.11.008

de Souza, L. M. L., Paz, G. A., Eloi, I. L., Dias, R., de Freitas Maia, M., Miranda, H., and Lima, V. P. (2016). Vertical jump performance after passive static stretching of knee flexors muscles. *Apunts. Medicina de l'Esport*, *51*(192), 131–136. https://doi.org/10.1016/j.apunts.2016.05.005

Deluzio, K. J., and Astephen, J. L. (2007). Biomechanical features of gait waveform data associated with knee osteoarthritis. *Gait and Posture*, *25*(1), 86–93. https://doi.org/10.1016/j.gaitpost.2006.01.007

Fan, P., Wang, T., Kim, Y., Zhao, Z., and Kim, S. (2025). Acute Optimization of Squat Jump Performance in Trained Collegiate Sprinters through Knee Angle-Specific Isometric Training. *Journal of Human Kinetics*, Advance online publication. https://doi.org/10.5114/jhk/208832

Farina, D., Merletti, R., and Enoka, R. M. (2004). The extraction of neural strategies from the surface EMG. *Journal of Applied Physiology*, *96*(4), 1486–1495. https://doi.org/10.1152/japplphysiol.01070.2003

Gavel, E. H., Barreto, G., Hawke, K. V., Stellingwerff, T., James, L. J., Saunders, B., and Logan-Sprenger, H. M. (2024). How Cool is That? The Effects of Menthol Mouth Rinsing on Exercise Capacity and Performance: A Systematic Review and Meta-analysis. *Sports Medicine - Open*, *10*(1), 18. https://doi.org/10.1186/s40798-024-00679-8

Gheller, R. G., Dal Pupo, J., Ache-Dias, J., Detanico, D., Padulo, J., and dos Santos, S. G. (2015). Effect of different knee starting angles on intersegmental coordination and performance in vertical jumps. *Human Movement Science*, *42*, 71–80. https://doi.org/10.1016/j.humov.2015.04.010

Gillen, Z. M., Shoemaker, M. E., McKay, B. D., Bohannon, N. A., Gibson, S. M., and Cramer, J. T. (2022). Influences of the Stretch-Shortening Cycle and Arm Swing on Vertical Jump Performance in Children and Adolescents. *Journal of Strength and Conditioning Research*, *36*(5), 1245–1256. https://doi.org/10.1519/JSC.0000000000003647

Gu, Z., Chen, Z., Liao, K., Bishop, C., Gao, C., Zhong, F., Deng, S., Wang, X., Wei, J., & Li, Y. (2026). A Novel Approach to Improving Squat Jump Performance: The Pre-Loaded Squat Jumps. *Journal of Human Kinetics*, *100*, 27–37. https://doi.org/10.5114/jhk/200809

Harland, M. J., and Steele, J. R. (1997). Biomechanics of the Sprint Start. *Sports Medicine*, *23*(1), 11–20. https://doi.org/10.2165/00007256-199723010-00002

Huxley, H. E. (1969). The Mechanism of Muscular Contraction: Recent structural studies suggest a revealing model for cross-bridge action at variable filament spacing. *Science*, *164*(3886), 1356–1366. https://doi.org/10.1126/science.164.3886.1356

Kennedy, P. M., and Cresswell, A. G. (2001). The effect of muscle length on motor-unit recruitment during isometric plantar flexion in humans. *Experimental Brain Research*, *137*(1), 58–64. https://doi.org/10.1007/s002210000623

Li, M., Kim, Y., and Kim, S. (2024). Optimizing acute static stretching protocols: Balancing range of motion and strength performance. *Current Sports Medicine Reports*, *23*(11), 363–365. https://doi.org/10.1249/JSR.0000000000001204

Li, M., Meng, X., Guan, L., Kim, Y., and Kim, S. (2023). 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 and Medicine*, *22*(4), 769. https://doi.org/10.52082/jssm.2023.769

Li, M., Zhu, Y., & Peng, Y. (2026). The Relationship Between Lower-Limb Explosive Strength and Climbing Speed in Elite Speed Climbers: A Comprehensive Analysis Based on Muscle Morphology and Electromyography. *International Journal of Sports Physiology and Performance*, *21*(3), 456–462. https://doi.org/10.1123/ijspp.2025-0329

Maffiuletti, N. A., Aagaard, P., Blazevich, A. J., Folland, J., Tillin, N., and Duchateau, J. (2016). Rate of force development: Physiological and methodological considerations. *European Journal of Applied Physiology*, *116*(6), 1091–1116. https://doi.org/10.1007/s00421-016-3346-6

Ohta, T., Imagawa, T., and Ito, S. (2009). Involvement of transient receptor potential vanilloid subtype 1 in analgesic action of methylsalicylate. *Molecular Pharmacology*, *75*(2), 307–317. https://doi.org/10.1124/mol.108.051292

Opplert, J., Paizis, C., Papitsa, A., Blazevich, A. J., Cometti, C., and Babault, N. (2020). Static stretch and dynamic muscle activity induce acute similar increase in corticospinal excitability. *PLoS One*, *15*(3), e0230388. https://doi.org/10.1371/journal.pone.0230388

Orchard, J. W., Jomaa, M. C., Orchard, J. J., Rae, K., Hoffman, D. T., Reddin, T., and Driscoll, T. (2020). Fifteen-week window for recurrent muscle strains in football: A prospective cohort of 3600 muscle strains over 23 years in professional Australian rules football. *British Journal of Sports Medicine*, *54*(18), 1103–1107. https://doi.org/10.1136/bjsports-2019-100755

Over, D. M., Arjomandkhah, N., Beaumont, J. D., Goodall, S., and Barwood, M. J. (2023). Skin application of menthol enhances maximal isometric lifting performance. *Journal of Strength and Conditioning Research*, *37*(3), 564. https://doi.org/10.1519/JSC.0000000000004305

Patel, T., Ishiuji, Y., and Yosipovitch, G. (2007). Menthol: A refreshing look at this ancient compound. *Journal of the American Academy of Dermatology*, *57*(5), 873–878. https://doi.org/10.1016/j.jaad.2007.04.008

Rites, A. A., Merino-Muñoz, P., Ribeiro, F., Miarka, B., Salermo, V., Gomes, D. V., Brito, C. J., and Aedo-Muñoz, E. (2024). Effects of peppermint oil inhalation on vertical jump performance in elite young professional soccer players: A double-blinded randomized crossover study. *Heliyon*, *10*(2), e24360. https://doi.org/10.1016/j.heliyon.2024.e24360

Rousanoglou, E. N., Herzog, W., and Boudolos, K. D. (2010). Moment-Angle Relations in the Initial Time of Contraction. *International Journal of Sports Medicine*, *31*(09), 651–655. https://doi.org/10.1055/s-0030-1255114

Siebert, T., Donath, L., Borsdorf, M., and Stutzig, N. (2022). Effect of Static Stretching, Dynamic Stretching, and Myofascial Foam Rolling on Range of Motion During Hip Flexion: A Randomized Crossover Trial. *Journal of Strength and Conditioning Research*, *36*(3), 680–685. https://doi.org/10.1519/JSC.0000000000003517

Sun, J., Yang, T., Wang, P., Ma, S., Zhu, Z., Pu, Y., Li, L., Zhao, Y., Xiong, S., Liu, D., and Zhu, Z. (2014). Activation of cold-sensing transient receptor potential melastatin subtype 8 antagonizes vasoconstriction and hypertension through attenuating RhoA/rho kinase pathway. *Hypertension*, *63*(6), 1354–1363. https://doi.org/10.1161/hypertensionaha.113.02573

Tokunaga, T., Sugawara, H., Tadano, C., and Muro, M. (2017). Effect of stimulation of cold receptors with menthol on EMG activity of quadriceps muscle during low load contraction. *Somatosensory and Motor Research*, *34*(2), 85–91. https://doi.org/10.1080/08990220.2017.1299004

Topp, R., Winchester, L., Mink, A. M., Kaufman, J. S., and Jacks, D. E. (2011). Comparison of the effects of ice and 3.5% menthol gel on blood flow and muscle strength of the lower arm. *Journal of Sport Rehabilitation*, *20*(3), 355–366. https://doi.org/10.1123/jsr.20.3.355

Trajano, G. S., Nosaka, K., and Blazevich, A. J. (2017). Neurophysiological Mechanisms Underpinning Stretch-Induced Force Loss. *Sports Medicine*, *47*(8), 1531–1541. https://doi.org/10.1007/s40279-017-0682-6

Tsuzuki, K., Xing, H., Ling, J., and Gu, J. G. (2004). Menthol-induced Ca^{2+} release from presynaptic Ca2+ stores potentiates sensory synaptic transmission. *Journal of Neuroscience*, *24*(3), 762–771. https://doi.org/10.1523/jneurosci.4658-03.2004

Veldman, M. P., Maffiuletti, N. A., Hallett, M., Zijdewind, I., and Hortobágyi, T. (2014). Direct and crossed effects of somatosensory stimulation on neuronal excitability and motor performance in humans. *Neuroscience and Biobehavioral Reviews*, *47*, 22–35. https://doi.org/10.1016/j.neubiorev.2014.07.013

Warneke, K., and Lohmann, L. H. (2024). Revisiting the stretch-induced force deficit: A systematic review with multilevel meta-analysis of acute effects. *Journal of Sport and Health Science*, *13*(6), 805–819. https://doi.org/10.1016/j.jshs.2024.05.002

Yano, T., Kanetake, T., Saita, M., and Noda, K. (1991). Effects of 1-menthol and dl-camphor on the penetration and hydrolysis of methyl salicylate in hairless mouse skin. *Journal of Pharmacobio-Dynamics*, *14*(12), 663–669. https://doi.org/10.1248/bpb1978.14.663

Yu, C.-Y., Lin, C.-H., and Yang, Y.-H. (2010). Human body surface area database and estimation formula. *Burns*, *36*(5), 616–629.

Zabaloy, S., Healy, R., Pereira, L. A., Tondelli, E., Tomaghelli, L., Aparicio, J., Vega, F., Medrano, J., Giráldez, J., Comyns, T., Freitas, T. T., & Loturco, I. (2025). A Randomized Controlled Trial of Unresisted vs. Heavy Resisted Sprint Training Programs: Effects on Strength, Jump, Unresisted and Resisted Sprint Performance in Youth Rugby Union Players. *Journal of Human Kinetics*, *95*, 199–214. https://doi.org/10.5114/jhk/200121

Zhang, X., Zhu, C., Ou, Z., Wu, L., and Li, M. (2025). The relationship between lower-limb asymmetry and speed-climbing time: The role of muscle thickness and neural activation. *International Journal of Sports Physiology and Performance*, *20*(8), 1161–1167. https://doi.org/10.1123/ijspp.2025-0052

Zhu, Y., Feng, Y., Huang, F., Li, Y., Wang, W., Wang, X., Cao, X., and Zhang, Z. (2022). Changes in stiffness of the specific regions of knee extensor mechanism after static stretching. *Frontiers in Bioengineering and Biotechnology*, *10*, 958242. https://doi.org/10.3389/fbioe.2022.958242