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**Research article**

# Comparing the Effects of Static Stretching Alone and in Combination with Post-Activation Performance Enhancement on Squat Jump Performance at Different Knee Starting Angles

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## Abstract

We aimed to investigate the impact of isolated static stretching (4 sets of 30 seconds) and its combined form with 10 repetitive drop jumps on lower limb performance during squat jumps at different knee joint starting angles (60°, 90°, and 120°). Thirteen participants completed three randomly ordered experimental visits, each including a standardized warm-up and squat jumps at three angles, apart from the intervention or control. Information was gathered through a three-dimensional movement tracking system, electromyography system, and force platform. The electromyography data underwent wavelet analysis to compute the energy values across the four wavelet frequency bands. The average power (Pavg), peak power (Ppeak), peak ground reaction force (GRFpeak), peak center of mass velocity (Vpeak), and force-velocity relationship at peak power (SFv) were extracted from the force and velocity-time data. The results revealed no significant influence of isolated static stretching, or its combined form with drop jumps, on the energy values across the frequency bands of the gastrocnemius, biceps femoris and rectus femoris, or the Pavg or Ppeak ($P > 0.05$). However, at 120°, static stretching reduced the GRFpeak ($P = 0.001$, $d = 0.86$) and SFv ($P < 0.001$, $d = 1.12$), and increased the Vpeak ($P = 0.001$, $d = 0.5$). The GRFpeak, Pavg, Ppeak, and SFv increased with an increase in the joint angle ($P < 0.05$), whereas the Vpeak decreased ($P < 0.05$). These findings suggest that static stretching does not diminish power output during squat jumps at the three angles; however, it alters GRFpeak, Vpeak, and the relative contributions of force and velocity to peak power at 120°, which can be eliminated by post-activation performance enhancement. Moreover, compared to 60° and 90°, 120° was more favorable for power and peak force output.

**Key words:** Electromyography, wavelet analysis, peak power, average power, peak ground reaction force, peak center of mass velocity.

## Introduction

Many authorities in sports science, such as the American College of Sports Medicine and the European College of Sport Science, discourage static stretching (StS) during warm-ups before competitions or training due to its detrimental effects on high-intensity performance (Magnusson and Renström, 2006; Ce et al., 2011). These effects include reductions in force output, explosive performance, and running speed (La Torre et al., 2010; Kay and Blazevich, 2012; Konrad et al., 2021). However, some studies and reviews have reported that StS may not necessarily detrimentally affect athletic performance (Behm et al., 2016, 2021; Blazevich et al., 2018; Samson et al., 2012), pointing out that the research showing a negative impact of StS on performance has certain limitations, such as immediate testing post-StS, excessive stretching duration (Behm et al., 2021), the absence of dynamic activities before and after StS (Behm et al., 2016, 2021). Additionally, given the positive role of StS in mitigating the risk of explosive musculotendinous injuries, especially during changes of direction (Behm et al., 2016, 2023), the inclusion of StS in warm-up protocols is recommended.

Compared to StS, short-duration conditioning contractions (CC) can significantly enhance muscle force output, an effect known as post-activation performance enhancement (PAPE) (Blazevich and Babault, 2019). Evidence exists in both mammalian and human studies that PAPE occurs in skeletal muscle, and it is generally believed to be caused by an increase in the voluntary neural drive to the muscle and increased sensitivity to calcium ions (Ca2+) (Cuenca-Fernández et al., 2017; Blazevich and Babault, 2019; Vargas-Molina et al., 2021). Muscle contractile force is enhanced because of the increased sensitivity of contractile proteins to calcium ions (Ca2+), leading to increased cross-bridge attachment rates (Blazevich and Babault, 2019).

Research on the impact of StS and CC as components of pre-competition preparation on athletic performance is growing. For instance, Kümmel et al. (2017) found that PAPE induced by CC could counteract the decline in triceps surae twitch torque associated with stretching. However, research by Bazett-Jones et al. (2005) suggested that CC could reduce the rate of force development (RFD) in isometric squats performed post-StS. Similar to the effects of StS and PAPE, the joint angles also have a significant impact on performance. Existing research has shown that the angle of the knee joint can affect extensor muscle function. For example, Newman et al. (2003) found that the maximum force generated by the knee joint is angle-dependent. Rousanoglou et al. (2010) revealed that the peak explosive torque of the knee joint throughout the muscle contraction rise phase is closely related to its angle. Additionally, studies have reported interactive effects between the joint angle and StS. Nelson et al. (2001) investigated isometric knee extensions at different knee joint angles and found that the negative impact of pre-exercise StS on performance was especially prominent when the working knee joint angle was close to full extension. La Torre et al. (2010) further noted that pre-exercise StS may

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negatively affect squat jump (SJ) force and power output, especially when the initial knee joint angle is smaller. Despite existing research offering in-depth insights into the effects of StS, PAPE, and joint angle on athletic performance, the results are not always consistent. Thus, the interaction between these factors remains unclear. In particular, there is limited research on the cumulative impact of StS and the interaction of StS and PAPE on power output across different joint angles. Hence, a more comprehensive understanding of how these factors, individually and collectively, influence athletic performance is required. Such studies could further deepen our understanding of the impacts of StS, PAPE, and joint angles, offering practical guidelines for athletes and coaches in pre-competition preparation and selection of optimal takeoff angles.

Our objective was to examine the impact of StS and StS combined with 10 repetitive drop jumps (S-D) on lower limb performance during SJs at various knee joint starting angles. Based on existing evidence, we hypothesize that different joint angles may affect the muscle activity, power, force output, and velocity performance of the lower limbs during SJs. We further predict that as joint angles increase, strength and power will be enhanced, while velocity may decrease. StS may not significantly affect power output, but could potentially reduce strength and increase velocity. Conversely, S-D may counteract these effects.

## Methods

### Experimental design

This study utilized a repeated-measures design using a counterbalanced crossover approach to compare the effects of StS and S-D on the energy values across wavelet frequency bands in the gastrocnemius lateralis (GL), biceps femoris, long head (BFL), rectus femoris (RF), average power (Pavg), peak power (Ppeak), peak ground reaction force (GRFpeak), peak center of mass velocity (Vpeak), and force-velocity ratio corresponding to Ppeak (SFv). Each participant was randomly assigned to three distinct experimental conditions [control group (CG), static stretching group (StSG), or static stretching and drop jump combined group (SDG)]. In each condition, SJs were performed at three initial knee joint angles (60°, 90°, and 120°). To prevent carryover effects, a rest interval of 2 - 7 days was scheduled between the experiments for each participant, during which no form of training was performed. To maintain experimental consistency, each session for every participant was scheduled at the same time of day. Participants were instructed to refrain from heavy workouts and consuming alcohol 48 h before each test session, avoid caffeine intake 8 h prior, and fast for 2 h prior to the experiment.

### Participants

Thirteen male collegiate athletes (age = 24 ± 1.5 years; height = 178.77 ± 4.3 cm; body mass = 70.98 ± 6.73 kg; mean ± SD) willingly took part in this study. To ensure adequate statistical power of 80%, we calculated the required sample size using G* Power 3.1.9.7 software, setting parameters of $\alpha = 0.05$, $\beta = 0.8$ and $r = 0.71$. A minimum of twelve participants was deemed necessary; however, we expanded the sample size to account for potential dropouts or data loss. All participants in basketball underwent a review of their medical histories to ensure that there were no existing neuromuscular diseases. They maintained a regular training regimen of 3 - 4 sessions per week, each lasting 1.5 - 2 h. Prior to their initial laboratory session, participants received comprehensive information about the research methods and potential risks, after which they gave their written consent to participate. The research was conducted in accordance with the Helsinki Declaration and received approval from the ethics committee of Jeonbuk University (JBNU2022-04-008-001).

### Preparation for testing

All evaluations made use of a 3D motion tracking system featuring 13 infrared cameras (Prime 17 W, OptiTrack, Natural Point, Inc., Corvallis, OR, USA), set to a capture rate of 100 Hz. Reflective markers with a 14 mm diameter were strategically positioned on key anatomical points of the participants' lower limbs, amounting to 20 markers in total. Ground reaction forces were recorded using an OR6-6-2000 force platform (Advanced Mechanical Technology, Inc., Watertown, MA, USA) with a 1000 Hz sampling frequency. Electrical activity from the GL, BFL, and RF muscles of the dominant leg was recorded via an electromyography (EMG) setup (Trigno Avanti Sensor, Delsys, Natick, MA, USA), with a sampling rate of 1000 Hz. Each Trigno Avanti Sensor (37 mm × 27 mm × 13 mm, 14 g) included a double-differential EMG sensor with silver bar electrodes (5 mm × 1 mm, inter-electrode distance: 10 mm), a common mode rejection ratio of 80 dB, amplifier gain of 909, and an analog Butterworth filter with a bandwidth of 20–450 Hz. Prior to electrode placement, the hair at the corresponding skin sites was shaved with an abrasive gel, followed by cleansing with alcohol. Synchronized data collection from the motion capture system, force platform, and EMG system was performed with Motive 2.2.0 software (OptiTrack, Natural Point, Inc., Corvallis, OR, USA).

### Test procedure

All participants underwent a 5-minute dynamic warm-up on a power bicycle (Monark 894E Wingate Testing Bike Ergometer, Sweden) at 60 rpm and 1 kp (70 W) resistance. Following the warm-up, a 5-minute rest period was allocated for body temperature and oxygen consumption normalization (Bishop, 2003). SJ tests for the CG and the StS interventions for the StSG were performed after passive rest. SJ tests for the StSG and 10-repetition drop jumps for the SDG were conducted 3 min post-StS interventions. Given the timing effect of PAPE, the SJ tests for the SDG were administered 4 min post-CC (Vargas-Molina et al., 2021).

### Interventions

During StS, the target muscles (triceps surae, hamstrings, and quadriceps) were stretched in a random order. These muscles were chosen based on previous studies showing their impact on SJ performance (Sekir et al., 2009; La Torre et al., 2010). The StS regimen, based on Chen et al. (2023), involved performing four repetitive StS exercises for each muscle group in each leg, with each exercise lasting 30 seconds and separated by 15 seconds of passive rest time, accumulating a total stretching duration of 120 seconds per muscle group. Stretching was calibrated to the threshold of discomfort without crossing into pain. Subsequently, active quadriceps and hamstrings stretches were conducted in an upright stance. For the quadriceps, participants maintained balance by placing one hand against a wall, bending the intended leg at the knee to a 90°. The ipsilateral hand grasped the ankle, gently pulling the heel toward the gluteal area to ensure a proper stretch. Hamstrings stretching was performed by placing one leg on a step with a slightly bent knee and leaning forward from the hips until a stretch was felt. The triceps surae muscles stretch involved participants in a supine position, with an experimenter assisting in dorsiflexing the foot to achieve the desired stretch. For further details on StS movements, see Sekir et al. (2009) and La Torre et al. (2010).

Ten repeated drop jumps were performed as CCs to induce PAPE. The optimal drop height for the participants was predetermined prior to laboratory visitation. A 30-second interval separated each of the 10 executed drop jumps. During each jump, the participants were directed to maximize the jump height expeditiously. The efficacy of this jump protocol was corroborated in a previous study (Kümmel et al., 2017).

### SJ Test

The SJ tests were performed on a force platform with knee joint angles set at 60°, 90°, and 120°, and the angles were confirmed using an electrogoniometer (Biopac Systems Inc., Goleta, CA, USA). Prior to each leap, participants were guided to position their feet close together, place their hands on their waists, and hold the designated knee angle in a squat posture for roughly one second. This setup aimed to eliminate the influence of arm swing, stretch reflex, and elastic muscle elements on jump performance (Gillen et al., 2022). Three maximum-effort SJs were performed at each angle. A 60-second passive rest was allocated between jumps at the same angle, and a 3-minute passive rest between different angles (Gillen et al., 2022). The testing sequence was set at 60°, 90°, and 120° to reduce potential confounding factors that could be attributed to PAPE (Sekir et al., 2009).

### Data processing

Utilizing R 4.3.1 (The R Foundation for Statistical Computing, Vienna, Austria), raw EMG signals were subjected to denoising and decomposition via the application of Maximal Overlap Discrete Wavelet Transform (MODWT) algorithms. Daubechies-4 wavelets were employed to achieve optimal decomposition, resulting in a four-level wavelet domain (Wei et al., 2012). Wave a5 represents the fifth-level approximation component, whereas waves d1 to d4 serve as detailed components for levels one to four, capturing the spectral characteristics of the raw EMG signals across the high- to low-frequency bands (with d1, d2, d3, and d4 representing the high-, mid-high, mid-low, and low-frequency bands, respectively). Threshold estimation was performed using the Median Absolute Deviation (MAD) approach (Jiang and Kuo, 2007). The energy levels for each muscle and wavelet domain were calculated under varying conditions. To eliminate inter-subject baseline variations, frame-wise EMG intensities underwent a process where the mean signal strength was subtracted, and subsequently scaled according to the standard deviation within each wavelet frequency band (Zandiyeh et al., 2022).

We used Visual3D Setup x64 v2022.9.1 (C-Motion, Inc., Germantown, MD, USA) to extract vertical ground reaction forces and peak center of mass velocity. The onset of the action phase was identified as the moment when the force value exceeded a threshold of five standard deviations above the force recorded during the airborne phase, and termination was identified when the force dropped to 20 N (McLellan et al., 2011). Force-time data were smoothed using a 17 Hz bidirectional fourth-order Butterworth low-pass filter (McLellan et al., 2011), whereas velocity-time data were processed through a 6 Hz bidirectional fourth-order Butterworth low-pass filter (Escamilla et al., 1998). After exporting the data, the force and velocity data were normalized to 101 data points. The reliability of the collected force-time data was assessed under each experimental condition. The two datasets with the highest intraclass correlation coefficient (ICC > 0.8) were selected for further analysis (Janicijevic et al., 2021). Power-time curves were generated by integrating the force and velocity (Rice et al., 2017). Based on the force-, velocity-, and power-time data, Ppeak, GRFpeak, and Vpeak were extracted, and Pavg was calculated. Additionally, the force-velocity ratio (SFv), defined as the quotient of force (F) and velocity (V) at Ppeak, was computed (Samozino et al., 2012). This ratio describes the interaction between force and velocity at the maximum power output. The average values for Pavg, Ppeak, GRFpeak, Vpeak, and SFv were obtained from the two selected tests and standardized by dividing them by the pre-test body mass of the participants (Rice et al., 2017). Data calculations were carried out in Microsoft Excel (version 2019; Microsoft Corp., Redmond, WA, USA).

### Statistics analysis

All statistical computations were done via R 4.3.1. Shapiro-Wilk tests were conducted on the energy values for each frequency band of each muscle under each condition. For cases with P-values exceeding 0.05, a repeated-measures two-way ANOVA was employed, and for P-values less than or equal to 0.05, Friedman's test was used. For GRFpeak, Vpeak, Pavg, Ppeak, and SFv, a mixed-effects model with two factors (group × angle) was utilized for significance testing. The optimal model incorporating a random intercept was selected based on likelihood ratio tests ($P < 0.01$). When significant variations were found ($P < 0.05$), we carried out subsequent tests using Bonferroni corrections for numerous comparisons. Prior to applying the mixed-effects model, the normality of the data set was confirmed through the Shapiro-Wilk test ($P > 0.05$). Data are displayed as the average value plus or minus the standard deviation.

## Results

### Electromyography

For all three muscles, neither the group main effect nor the interaction effect was significant in terms of energy values across all frequency bands (P > 0.05). For GL in the CG group, when the initial knee angle was 120°, the energy values of GL-d3 were significantly greater than at 60° (P = 0.029, d = 0.98) and 90° (P = 0.021, d = 0.94) (see Table 1); for other frequency bands, the energy values were not significant (P > 0.05). For BFL, the angle main effect was not significant (P > 0.05) for energy values across all frequency bands. For RF, the angle main effect was significant (P = 0.021); however, the multiple comparisons were not significant (P > 0.05) (see Table 1). Additionally, as the three angles increased, the energy values for GL-d1, GL-d2, GL-d3, and GL-d4 transitioned from increasing to decreasing, while for RF, the opposite was observed.

**Table 1. Important calculations for the energy values of gastrocnemius lateralis (GL) in the mid-low frequency band (d3), as well as rectus femoris (RF) in the high frequency band (d1), are presented for different groups at various knee starting angles (mean ± SD) (n = 13).**

| Parameter | Condition | Knee starting angle (deg) | | | |
|---|---|---|---|---|---|
| | | 60° | 90° | 120° | ANOVA results（A） |
| GL-d3 energy values | CG | 0.98 ± 0.46 | 0.73 ± 0.68[0.43] | 0.46 ± 0.59[0.98] | F = 5.29 P = 0.024 |
| | SDG | 0.96 ± 0.59 | 0.54 ± 0.58[0.72] | 0.47 ± 0.6[0.82] | |
| | StSG | 0.78 ± 0.58 | 0.62 ± 0.52[0.29] | 0.47 ± 0.58[0.53] | |
| RF-d1 energy values | CG | -0.17 ± 0.47 | -0.15 ± 0.53* [0.04] | -0.57 ± 0.34* [0.98] | F = 6.99 P = 0.009 |
| | SDG | -0.18 ± 0.51 | -0.26 ± 0.55[0.16] | -0.4 ± 0.38[0.48] | |
| | StSG | -0.06 ± 0.44 | 0.00 ± 0.49[0.12] | -0.26 ± 0.49[0.43] | |

The effect sizes of 90° and 120° relative to 60° are reported in square brackets. The two-way ANOVA results (A: angle effects, P- and F- value) are shown in the right column. ANOVA, analysis of variance; CG, Control Group; StSG, Static Stretching Group; SDG, Static Stretching and Drop Jump Combined Group. *: A significantly (P < 0.05) different from the 60°

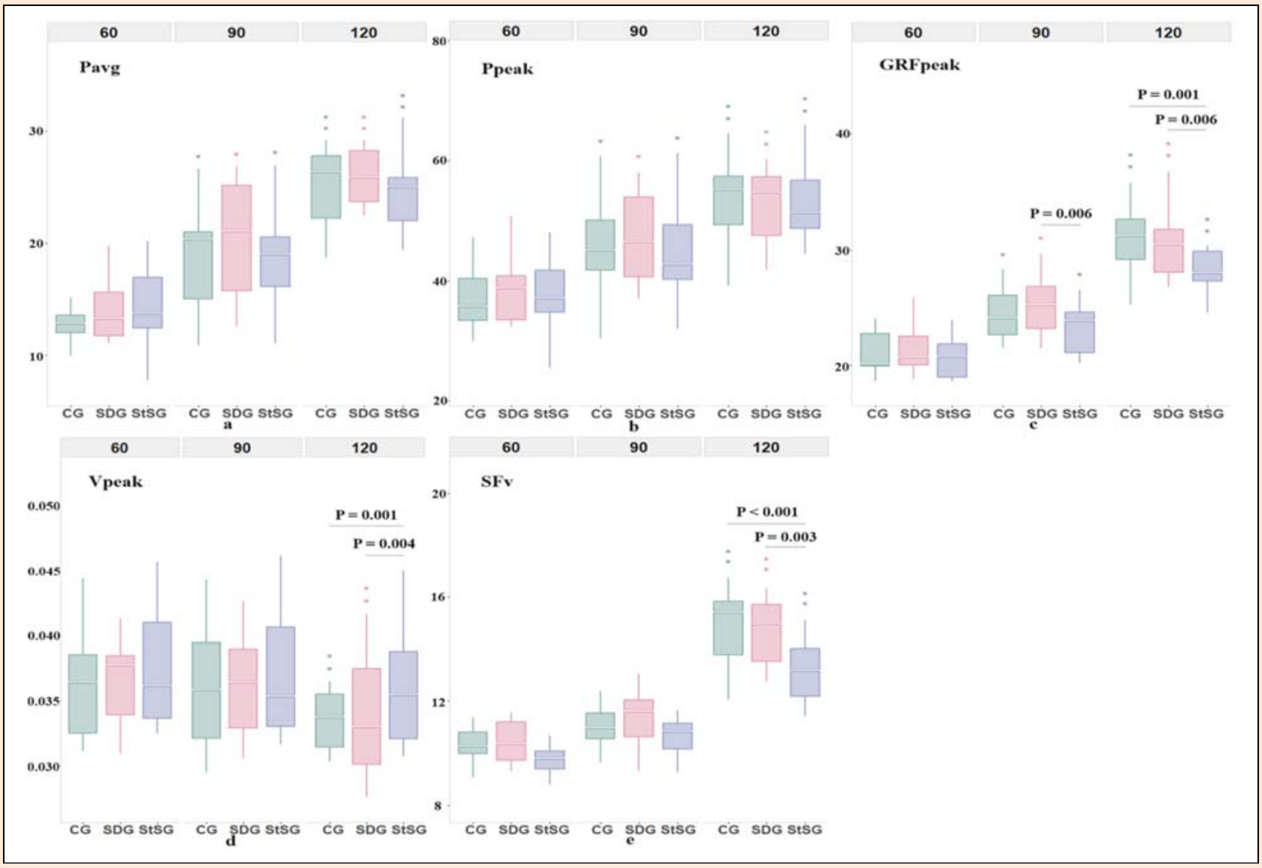


**Figure 1. This illustration presents the average power (Pavg), peak power (Ppeak), peak ground reaction force (GRFpeak), peak center of mass velocity (Vpeak), and force-velocity ratio (SFv) values for the three groups (CG, StSG, and SDG) at three initial knee joint angles (60°, 90°, and 120°).** This figure is subdivided into four panels: (a) Pavg, (b) Ppeak, (c) GRFpeak, (d) Vpeak, and (e) SFv. Each box plot within the figure delineates the following characteristics:

Upper edge (Q3): upper quartile; upper whisker: maximum value plus 1.5 times the interquartile range (IQR); central white line: median; lower edge (Q1): lower quartile; lower whisker: minimum value plus 1.5 times the IQR.

The significance between different angles within the same group is denoted by asterisks; a single asterisk indicates a significant difference between the 120°, 90°, and 60° angles. The two asterisks denote significant differences between 120°, 90°, and 60°. Horizontal lines with associated P-values represent significant differences among the StSG, SDG, and CG. CG, control group; StSG, static stretching group; SDG, combined static stretching and drop-jump group.

**Table 2. Important calculations for average power (Pavg), peak power (Ppeak), peak ground reaction force (GRFpeak), center of mass peak velocity (Vpeak), and force-velocity ratio (SFv) are presented for different groups at various knee starting angles (mean ± SD) (n = 13).**

| Parameter | Condition | Knee starting angle (deg) | | | Condition |
|---|---|---|---|---|---|
| | | 60° | 90° | 120° | |
| Pavg ($W\cdot kg^{-1}$) | CG | 12.73 ± 1.33 | 19.13 ± 5.01‡ | 25.21 ± 3.67‡ | CG |
| | SDG | 14.21 ± 3.21[0.6] | 20.65 ± 4.88‡[0.31] | 25.6 ± 3.68‡[0.11] | SDG |
| | StSG | 14.24 ± 3.48[0.57] | 18.26 ± 5.78‡[0.16] | 24.89 ± 3.24‡[0.09] | StSG |
| Ppeak ($W\cdot kg^{-1}$) | CG | 37.33 ± 5.34 | 46.38 ± 8.23‡ | 53.42 ± 7.05‡ | CG |
| | SDG | 39.14 ± 5.97[0.32] | 47.76 ± 7.14‡[0.18] | 52.9 ± 6.2‡[0.08] | SDG |
| | StSG | 38.36 ± 7.64[0.16] | 45.33 ± 8.98‡[0.12] | 53.13 ± 6.39‡[0.04] | StSG |
| GRFpeak ($N\cdot kg^{-1}$) | CG | 21.04 ± 1.84 | 24.38 ± 2.2‡ | 30.92 ± 2.81‡ | CG |
| | SDG | 21.66 ± 2.15[0.31] | 25.17 ± 2.7‡[0.32] | 30.59 ± 2.78‡[0.12] | SDG |
| | StSG | 20.87 ± 1.75[0.1] | 23.16 ± 2.02‡[0.58] | 28.58 ± 2.63*†‡[0.86] | StSG |
| Vpeak ($m\cdot kg^{-1}\cdot s^{-1}$) | CG | 0.036 ± 0.004 | 0.036 ± 0.004 | 0.034 ± 0.004‡ | CG |
| | SDG | 0.037 ± 0.004[0.18] | 0.037 ± 0.004[0.08] | 0.034 ± 0.004‡[0.05] | SDG |
| | StSG | 0.038 ± 0.005[0.27] | 0.037 ± 0.005[0.22] | 0.036 ± 0.005*†[0.5] | StSG |
| SFv ($N\cdot s\cdot kg^{-1}\cdot m^{-1}$) | CG | 10.27 ± 0.67 | 11.32 ± 1.16 | 15.49 ± 2.35 | CG |
| | SDG | 10.4 ± 0.85[0.17] | 11.53 ± 1.34[0.17] | 14.93 ± 1.97[0.26] | SDG |
| | StSG | 9.91 ± 1.03[0.41] | 10.58 ± 0.83[0.73] | 13.26 ± 1.54*†[1.12] | StSG |

The effect sizes of the intervention and control groups are reported in square brackets. *: A significantly ($P < 0.05$) different from the CG. †: A significantly ($P < 0.05$) different from the SDG. ‡: A significantly ($P < 0.05$) different from the 60°. CG: Control Group, StSG: Static Stretching Group, SDG: Static Stretching and Drop Jump Combined Group

## Pavg, Ppeak, GRFpeak, Vpeak, and SFv

For Pavg, Ppeak, GRFpeak, Vpeak, and SFv (Figure 1 a, b, c, d, and e, respectively), significant baseline effects were observed ($P < 0.01$). No significant group main effects were found for Pavg or Ppeak ($P > 0.05$). Across all groups, Pavg, Ppeak, GRFpeak, and SFv increased with an increase in the joint angle, whereas Vpeak decreased (Table 2).

At a starting knee angle of 90°, the GRFpeak in the StSG was significantly lower than that in the SDG ($P = 0.006$, $d = 0.84$). At 120°, the GRFpeak in the StSG was significantly lower than that in the CG ($P = 0.001$, $d = 0.86$) and SDG ($P = 0.006$, $d = 0.74$). Additionally, the Vpeak in the StSG was significantly higher than that in the CG ($P = 0.001$, $d = 0.5$) and SDG ($P = 0.004$, $d = 0.44$), whereas the SFv in the StSG was significantly lower than that in the CG ($P < 0.001$, $d = 1.22$) and SDG ($P = 0.003$, $d = 0.95$).

Both the Pavg and Ppeak were significantly greater at a starting knee angle of 120° in the CG, SDG, and StSG than at 60° (CG: Pavg, $P < 0.001$, $d = 4.52$; Ppeak, $P < 0.001$, $d = 2.57$; SDG: Pavg, $P < 0.001$, $d = 3.29$; Ppeak, $P < 0.001$, $d = 2.26$; StSG: Pavg, $P < 0.001$, $d = 3.17$; Ppeak, $P < 0.001$, $d = 2.1$) and 90° (CG: Pavg, $P < 0.001$, $d = 1.38$; Ppeak, $P < 0.001$, $d = 0.92$; SDG: Pavg, $P < 0.001$, $d = 1.14$; Ppeak, $P = 0.003$, $d = 0.77$; StSG: Pavg, $P < 0.001$, $d = 1.41$; Ppeak, $P < 0.001$, $d = 1$). At a starting knee angle of 90°, both Pavg and Ppeak were significantly greater than at 60° (CG: Pavg, $P < 0.001$, $d = 1.75$; Ppeak, $P < 0.001$, $d = 1.3$; SDG: Pavg, $P < 0.001$, $d = 1.56$; Ppeak, $P < 0.001$, $d = 1.31$; StSG: Pavg, $P < 0.001$, $d = 0.84$; Ppeak, $P = 0.008$, $d = 0.84$).

At a starting knee angle of 120°, the GRFpeak was significantly greater in the CG, SDG, and StSG than at 60° (CG: $P < 0.001$, $d = 4.16$; SDG: $P < 0.001$, $d = 3.59$; StSG: $P < 0.001$, $d = 3.45$) and 90° (CG: $P < 0.001$, $d = 2.59$; SDG: $P < 0.001$, $d = 1.98$; StSG: $P < 0.001$, $d = 2.31$). Similarly, the SFv was significantly greater at 120° than at 60° (CG: $P < 0.001$, $d = 3.02$; SDG: $P < 0.001$, $d = 2.99$; StSG: $P < 0.001$, $d = 2.56$) and 90° (CG: $P < 0.001$, $d = 2.25$; SDG: $P < 0.001$, $d = 2.02$; StSG: $P < 0.001$, $d = 2.17$). At a starting knee angle of 90°, the GRFpeak was significantly greater than that at 60° (CG: $P < 0.001$, $d = 1.65$; SDG: $P < 0.001$, $d = 1.44$; StSG: $P = 0.001$, $d = 1.22$). In both the CG and SDG, Vpeak was significantly lower at 120° than at 60° (CG: $P < 0.001$, $d = 0.67$; SDG: $P < 0.001$, $d = 0.74$) and 90° (CG: $P < 0.001$, $d = 0.59$; SDG: $P < 0.001$, $d = 0.63$).

## Discussion

The core outcomes of this research can be distilled into three key points: (1) Neither StS nor S-D had a significant impact on the energy values of the different frequency bands for GL, BFL, and RF. However, the initial knee angle elicited opposite effects on the high- and low-frequency energy values of the GL and RF. (2) Neither StS nor S-D significantly affected the Pavg or Ppeak. However, in all groups, both Pavg and Ppeak increased significantly with an increase in the angle with the three examined angles. (3) At 90° and 120°, StS led to a significant reduction in GRFpeak. At 120°, StS caused a significant increase in Vpeak. However, these effects could have been negated by PAPE. Additionally, in all three groups, from 60° to 120°, GRFpeak significantly increased with angle, whereas Vpeak decreased. StS rendered Vpeak insensitive to angle changes, an effect that could also have been counteracted by PAPE. The influence of StS, PAPE, and angle on GRFpeak and Vpeak were likewise mirrored in how F and V proportionally contributed to the corresponding Ppeak.

The findings of this study corroborate, to some extent, previous perspectives indicating that StS and S-D have no significant impact on the EMG amplitude of the GL, BFL, and RF muscles (Kümmel et al., 2017). Unlike previous studies that compared the effects of a 20-second StS regimen and a regimen combining 20 seconds of StS with 10 repetitive squat jumps on EMG amplitude, this study adopted a regimen of 4 sets of 30-second StS exercises with a 15-second interval between sets. This specific regimen was designed to rule out the possibility that shorter-duration StS (< 60 s) may not adversely affect athletic performance (Kay and Blazevich, 2012; Behm et al., 2016). Additionally, the current study employed a more comprehensive time-frequency analysis technique, namely wavelet analysis, which is considered more suitable than the Fast Fourier Transform for analyzing EMG signals during dynamic contractions (Rafiee et al., 2011; Wei et al., 2012; Zandiyeh et al., 2022). In relation to the impact of angle on EMG measurements, previous research has mainly concentrated on variations in EMG amplitude (Jaskólska et al., 2003; Lanza et al., 2019). For the first time, the present study revealed that with SJs, varying takeoff angles have distinct impacts on the energy values across the frequency bands of GL, BFL, and RF. Intriguingly, the angle had opposing effects on the high- and low-frequency energy values for the GL and RF; as the three angles increased, the high-frequency energy values for the GL increased, while the low-frequency values decreased, and the opposite effect was observed with the RF.

Previous studies have yielded inconsistent results regarding the effects of StS and S-D on Pavg and Ppeak. One study's findings indicated that StS exerts no significant influence on SJ power output (Blazevich et al., 2018); whereas another found that StS negatively impacts it (La Torre et al., 2010). The present study is aligned with this perspective. A notable difference was the prior inclusion of a comprehensive dynamic warm-up, which was absent in our protocol. In our study, only a standardized warm-up was performed before the intervention, primarily to neutralize any potential PAPE effects (Turki et al., 2011). Disparities between other studies and our findings could be due to differing interlude durations between the standardized warm-up and StS protocols. For example, in one study, StS was executed immediately following the warm-up, whereas in ours, a five-minute interval was established to offset potential interference from elevated body temperature (Samson et al., 2012).

In terms of the impact of S-D on jump power, prior research indicates that the combination of StS and DJ improves power performance in straight-knee drop jumps (Kümmel et al., 2017). This does not align with our findings, possibly because our evaluation involved SJs, whereas previous studies utilized movements incorporating the stretch-shortening cycle (SSC). Regarding the influence of different takeoff angles on Pavg and Ppeak, La Torre et al. (2010) explored the impact of various knee joint angles (50°, 70°, 90°, and 110°) on SJ peak power. They found that the peak power was the highest at 90°, which diverged from the results of our study. Our findings indicated that as the knee-start angles (60°, 90°, and 120°) increased, the power output also increased significantly. This inconsistency may stem from differing StS protocols; previous research stretched the quadriceps and triceps surae, whereas our study additionally stretched the hamstrings, possibly altering the muscle coordination patterns at various angles.

In this study, divergent results were observed regarding the influence of StS and S-D on GRFpeak compared with prior research. Previous studies have suggested that neither the StS nor S-D had a significant impact on GRFpeak during SJs (Kümmel et al., 2017). However, in our study at knee angles of 90° and 120°, StS led to a notable reduction in GRFpeak, an effect that was neutralized by PAPE. This discrepancy may stem from our experimental design, which extended the stretch not only to the triceps surae, but also to the hamstrings and quadriceps, coupled with a longer stretch duration. These modifications were made for practical applications. Prior research has shown that three sets of 15-second StS did not significantly affect Vpeak during vertical jumping (Knudson et al., 2001). However, in our study, four sets of 30-second StS significantly increased Vpeak at a 120° angle, an increase neutralized by PAPE. These variations may be attributed to differences in the set numbers and durations. Our study also diverges from previous findings on the influence of different jump-start angles on GRFpeak and Vpeak. Earlier studies have shown that in SJs initiated at varying knee angles, GRFpeak decreased, while Vpeak increased with the angle (La Torre et al., 2010). In contrast, our study showed the reverse trend for both GRFpeak and Vpeak. These inconsistencies may be due to variations in the stretching protocols. Finally, an intriguing phenomenon not previously reported was observed: at 120°, StS altered the relative contributions of F and V to Ppeak, an effect nullified by PAPE. This may be because previous studies have primarily focused on the overall F-V relationship rather than the F-V relationship at specific time points.

In this investigation, we found no marked alterations in the frequency band energy values for the GL, BFL, and RF following StS and S-D, which could be due to various factors. First, StS is known to reduce the EMG amplitude, which is thought to be linked to alterations in cortical-spinal excitability due to prolonged stretch-induced sensory stimulation (Trajano et al., 2017). However, the duration and intensity of stretching implemented in this study may have been insufficient to affect the cortical-spinal excitability. Second, many earlier studies relied on the interpolated twitch technique (ITT) for measurement (Fowles et al., 2000; Trajano et al., 2014), a technique that reflects activation level increases dependent on increased discharge rates of fibers rather than on additional motor unit recruitment (Trajano et al., 2017). In contrast, our study employed maximal rapid contractions using SJs, indicating that all motor units were recruited (Desmedt and Godaux, 1978). This methodological divergence may account for the variances between our results and those of prior research. Finally, PAPE did not induce significant alterations in energy values across the muscle frequency bands. This may be attributable to the primary influence of PAPE on intramuscular Ca2+ sensitivity (Blazevich and Babault, 2019), which occurs within muscle fibers (French et al., 2003). As for the BFL, the energy values across its frequency bands showed no marked response to angle changes, likely because the length of the BFL is influenced simultaneously by both the hip and knee joint angles (Gajdosik et al., 1993). Thus, even if the knee joint angle increases, any simultaneous increase in the hip joint angle could lead to negligible changes in the actual length of the BFL. The divergent effects of angular changes on the GL and RF frequency bands can be attributed to two factors. First, the length variations of the GL are smaller than those of the RF at different knee joint angles, thereby affecting muscle activation differently (Close, 1972). Second, the differing proportions of Type I and Type II muscle fibers in the GL and RF result in different activation thresholds and intensities (Schiaffino and Serrano, 2002).

For Pavg and Ppeak, neither StS nor S-D led to significant changes. This may be attributed to the fact that in our study, StS and S-D did not influence the neuromuscular system, which could be a critical factor in dictating reduced performance in exercise (Power et al., 2004). Moreover, shifts in the mechanical attributes of muscle-tendon units may reposition the maximal force-velocity curve towards the right, without necessarily affecting peak force performance (Balnave and Allen, 1996). As the angle increased, both Pavg and Ppeak demonstrated significant increases. This could be due to the alteration in joint angles, leading to corresponding adjustments in the initial muscle length moving toward the optimal length. At this optimal length, the crossbridge overlap is maximized (Millman, 1998). Additionally, changes in the joint angles result in altered lever arms (Worrell et al., 2001), subsequently affecting various power outputs.

At 120°, the significant changes in GRFpeak, Vpeak, and the F-V relationship corresponding to Ppeak induced by StS may be attributable to the noticeable shortening of the primary force-generating muscles compared to other angles (Reese and Bandy, 2017). This change, coupled with the decrease in muscle stiffness caused by StS (Iwata et al., 2019), creates a cumulative effect. This effect modulates the length-dependent changes in Ca2+ sensitivity (Balnave and Allen, 1996) and the rate of force conveyance (Maffiuletti et al., 2016). Ultimately, these factors collectively alter the F-V relationships associated with GRFpeak, Vpeak, and Ppeak. However, PAPE may counteract these effects by increasing the sensitivity of contractile proteins to calcium ions (Ca2+) (Blazevich and Babault, 2019). Compared to other angles, GRFpeak significantly increased, while Vpeak decreased at 120°. Concurrently, the relative contribution of F to Ppeak increased, whereas that of V decreased. This may be because the primary force-generating muscles have a more advantageous initial length and lever arm at this specific angle (Millman, 1998; Worrell et al., 2001). This observation was consistent with previous findings (La Torre et al., 2010).

This study had a limitation. In analyzing the force-velocity relationship, our study only assessed GRFpeak, Vpeak, and the force and velocity indices corresponding to Ppeak. We did not account for the theoretical limits of both force and velocity, thus hindering a comprehensive evaluation of the impact of StS and PAPE on full F-V characteristics. Given this limitation, future studies should explore the effects of StS and PAPE on the theoretical aspects of the force-velocity relationship in greater depth. This would help in understanding the applicability of these interventions across a broader range of force-velocity configurations, thereby advancing both the theoretical framework and practical applications of the research.

## Conclusion

Overall, this study suggests that neither StS nor S-D significantly influence the energy values across the frequency bands of the GF, BFL, or RF, as well as the mean and peak power output. However, at an initial knee joint angle of 120°, StS led to a relative decrease in the GRFpeak and F corresponding to the Ppeak, whereas the Vpeak and V corresponding to Ppeak increased. These effects were effectively ameliorated by PAPE. These findings imply that the incorporation of StS as a preparatory component may not impair performance in power-oriented sports. However, for athletes focused on strength or speed, the StS could impact their specific capabilities, and PAPE may neutralize this effect. Therefore, athletes should carefully assess the possible influences of StS and PAPE on performance before competition. In addition, this study discovered that as the joint angle increased, there was an opposite trend in the high- and low-frequency energy values of the GL and RF. Concurrently, there was a significant enhancement in power and force output, while there was a slight decline in speed performance. This suggests that when determining the starting angle, athletes need to consider the specific demands of the sport (whether the focus is on power, strength, or speed) and their own muscle contraction properties to achieve optimal performance under varying competitive requirements.

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The authors have no conflict of interest to declare. The present study complies with the current laws of the country in which it was performed. The datasets generated and analyzed during the current study are not publicly available, but are available from the corresponding author who was the organizer of the study.

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## Key points

- We investigated and compared the effects of acute static stretching (StS) alone, and in combination with, 10 repetitive drop jumps (S-D) on squat jump performance at different knee joint starting angles (60°, 90°, 120°).
- We designed three experimental groups to explore the efficacy of different intervention methods: a control group, a group solely performing static stretching, and a group combining static stretching with repetitive drop jumps.
- Key performance indicators included energy values across various wavelet frequency bands for the gastrocnemius, biceps femoris, and rectus femoris muscles, as well as average power, peak power, peak ground reaction force, maximum velocity, and the force-velocity ratio corresponding to peak power.
- We recommend incorporating StS as part of warm-up when the goal is to increase range of motion (ROM) while maintaining power output. However, for activities emphasizing pure power or speed output, we suggest combining StS with ten repetitive drop jumps or avoiding StS altogether.
- We advise selecting an appropriate takeoff angle based on the specific requirements of the sport, such as an emphasis on power or speed.

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