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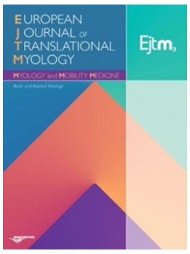

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Acute effects of movement-specific warm-up on force production and neuromuscular activation during maximal isometric squat in resistance-trained men: a pilot study

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Abstract

Warm-up is a fundamental preparatory phase for optimizing performance, yet its acute effects may depend on the specificity of the protocol to the target task. This pilot study compared a General, mobility-based Warm-Up (GWU) with a low-intensity, bodyweight Movement-Specific Warm-Up (MSWU) replicating squat biomechanics on maximal isometric force and neuromuscular activation during isometric squat. Eight resistance-trained men (age 23.5 ± 1.2 years; height 182.9 ± 5.9 cm; body mass 84.3 ± 9.1 kg; 1RM back squat 146 ± 19 kg) completed two randomized, counterbalanced sessions. Each session included a standardized preliminary warm-up, baseline maximal isometric high-bar back squat at 90° knee flexion, and either the GWU or the MSWU, followed by a 2-min rest and reassessment. Peak force and surface EMG of vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), gluteus maximus (GMax), and biceps femoris (BF) were measured. Completion time did not differ between protocols (~6–7 min; $p = 0.806$). Peak force significantly decreased after the GWU (−3.8%; $p = 0.004$; $d = 1.47$) but was maintained following the MSWU (−1.9%; $p = 0.138$; $d = 0.59$). Between-protocol differences in peak force were not significant ($p = 0.186$; $d = 0.52$). No significant changes were observed in normalized GMax activity or total integrated EMG. These results indicate that, for isometric, task-specific performance, a brief movement-specific warm-up better preserves force-generating capacity than a general mobility routine of similar duration, emphasizing the importance of biomechanical specificity in warm-up design.

Key words: preparatory phase, force production, myoelectric activity, surface electromyography, experienced lifters.

Warm-up is a fundamental preparatory phase designed to optimize subsequent training or competition performance, and minimize the risk of injury.[1–4] Active warm-ups, characterized by exercise-induced increases in muscle and core temperature, are widely used for their metabolic, cardiovascular, and neuromuscular benefits, including reduced muscle and joint stiffness, enhanced nerve conduction velocity, improved force-velocity characteristics, and facilitation of Post-Activation Potentiation (PAP).[1,4–7] Typically, active warm-ups comprise a general component, aimed at elevating systemic temperature and readiness,[1] and a specific component that replicates the biomechanics of the subsequent task to enhance task-specific muscle activation.[4,5,8–10]

Despite the well-documented benefits of warm-up on athletic performance and its widespread use, the optimal structure of warm-up routines remains debated.[4,7] Active warm-up can induce both potentiation and fatigue, and its net effect depends on the balance between these opposing influences.[11,12] Some studies report performance benefits following dynamic or movement-specific warm-ups,[6,13] whereas others have shown negligible or even detrimental effects.[10,14] Previous and recent meta-analytic evidence confirms substantial between-study variability in warm-up efficacy, driven by differences in modality (active vs. passive) intensity, duration, and recovery intervals, outcome measures (e.g., Maximal Voluntary Contraction [MVC] and Rate of Force Development [RFD]), and study design.[3,7,15] Additionally, task specificity and participant characteristics (e.g., training status, sex) may further modulate performance responses, underscoring the need for carefully controlled, task-specific investigations.[4,7,16]

Evidence regarding the warm-up effects on resistance exercise performance, particularly maximal strength tasks, is limited and mixed.[6,10,13] For example, Ribeiro *et al.* observed no improvement in repetition-to-fatigue performance for the squat, bench press, or arm curl following a movement-specific warm-up,[10] whereas Abad *et al.* reported greater improvements in 1RM leg-press after a combined warm-up compared with a specific warm-up alone.[13] Barnes *et al.* showed that a movement-specific warm-up enhanced peak power in the high-pull to a greater extent than temperature-related warm-ups.[6] Warm-up-induced changes in neuromuscular activation are also equivocal, several studies report no alterations in EMG activity,[6,17] whereas Sotiropoulos *et al.* found significantly increased vastus lateralis and quadriceps EMG activity after low- to moderate-intensity half-squats.[8] Research on intensity has largely focused on heavy resistance protocols (e.g., ≥85% 1RM or 3RM) designed to elicit PAP and improve subsequent jump performance,[18,19] while findings for light-to-moderate loads (30–65% 1RM) are inconsistent.[20–22] Notably, submaximal explosive half-squats (≤65% 1RM) and low-load gluteal-activation protocols have been shown to acutely enhance countermovement jump performance, suggesting that low-intensity, targeted warm-ups can improve explosive output while minimizing fatigue.[8,23]

However, the acute effects of low-intensity, bodyweight-based movement-specific warm-ups that replicate the biomechanics of a target exercise and engage its primary synergistic muscles remain largely unexplored, particularly for isometric tasks. Such protocols may offer a practical and time-efficient strategy to elicit task-specific neuromechanical readiness in strength and conditioning settings.[23] To address this gap, the present pilot study examined the acute effects of a Movement-Specific Warm-Up (MSWU), composed of low-intensity, bodyweight exercises replicating back squat biomechanics, on maximal isometric force production and Surface Electromyographic (sEMG) activity of key lower-limb muscles in resistance-trained men, compared with a General mobility-based Warm-Up (GWU). We hypothesized that, compared with a general warm-up, the MSWU would better maintain or enhance neuromuscular activation and force output during maximal isometric squat. Given the small sample size and absence of a priori power calculation, this study should be considered preliminary and hypothesis-generating, with findings interpreted cautiously and used primarily to inform future, adequately powered investigations.

Material and Methods

Participants

Eight healthy college resistance-trained men (mean ± SD; age 23.5 ± 1.2 years; height 182.9 ± 5.9 cm; body mass 84.3 ± 9.1 kg) volunteered to participate in the study following signing informed consent forms. The inclusion criteria were: i) male sex, ii) age 20–30 years, iii) regular incorporation of the squat exercise into the participant’s training regimen, iv) back squat performance corresponding to a one-Repetition Maximum (1RM) ≥ 1.5x body mass (back squat 1RM 146 ± 19 kg), and v) a minimum of 36 months of strength training experience (training age 6.4 ± 2.2 years). Participants were excluded if they i) reported chronic musculoskeletal pain, ii) had sustained an acute musculoskeletal injury requiring more than 14 days of treatment within the past 6 months, iii) presented with a diagnosed neuromuscular disorder, or iv) had experienced an infectious disease within 3 weeks prior to testing, v) exhibited inter-trial variability in force production exceeding 10% between the two post-warm-up trials during the maximal isometric high-bar back squat. The study was approved by the Ethics Committee of the Faculty of Physical Education and Sport, Comenius University, Bratislava, Slovakia (Protocol No. 14/2024) and was conducted in accordance with the latest version of the Helsinki Declaration.

Study design

A randomized, cross-over, within-subject design was used to examine the acute effects of two distinct warm-up protocols on force production and neuromuscular activation, assessed using Surface Electromyography (sEMG) during maximal isometric high-bar back squat at a 90° knee joint angle. Each participant completed two trials, corresponding to a GWU and a MSWU, administered in a randomized, counterbalanced order. At the beginning of every session, participants first performed a standardized preliminary general warm-up (~6–7 min), which was identical across both conditions and served solely to elevate body temperature and joint mobility. This warm-up consisted of eight bodyweight exercises (56 total controlled repetitions) targeting the ankle, hip, spine, and shoulder complexes. Following this preliminary warm-up, participants rested for 2 minutes. After the 2-min rest, baseline (PRE) measurements were obtained. First, gluteus maximus (GMax) activity was normalized using maximal voluntary isometric contractions (MVIC) in prone hip extension. Subsequently, participants performed one familiarization trial of the maximal isometric high-bar back squat at approximately 50% of their perceived maximal effort, followed by two maximal isometric squat trials at 90° knee flexion. These two maximal efforts constituted the baseline (PRE) assessment of peak force and sEMG activity. Participants then rested for another 2 minutes before performing the assigned experimental warm-up protocol (GWU or MSWU). In the GWU condition, participants completed eight dynamic stretching and mobility exercises targeting joint range of motion. In the MSWU condition, they performed eight low-intensity, bodyweight exercises designed to replicate squat biomechanics and activate the primary synergistic lower-limb muscles. Following completion of the experimental warm-up, participants rested for 2 minutes and then performed four unloaded bodyweight squats to reacquaint themselves with the testing position. Subsequently, they completed two further maximal isometric squat trials at 90° knee flexion, during which peak force and sEMG activity of the primary lower-limb muscles were recorded. These trials represented the Post-Intervention (POST) assessment for the corresponding warm-up condition. All trials were conducted by the same investigator at the same time of day, with 4–7 days of recovery between sessions. Participants were instructed to maintain their habitual diet, sleep, and hydration routines, and to refrain from any strenuous physical activity or lower-body training for at least 48 hours prior to each testing session.

Procedures

Before data collection, participants attended a supervised familiarization session where they were instructed on the proper execution of both warm-up protocols and the maximal isometric squat procedure. During this session, the adjustable bar of a custom-built metal rack was set to correspond to a 90° knee joint angle, verified using a goniometer. Participants subsequently completed three consecutive practice sessions to ensure technical consistency and minimize potential learning effects. All testing sessions were conducted indoors, at the same time of day, under controlled environmental conditions (temperature: 22–25 °C).

Warm-up protocols

Two distinct warm-up protocols were implemented: a GWU and a MSWU. Each protocol consisted of eight bodyweight exercises performed sequentially, totaling 56 controlled repetitions (4–6 repetitions per exercise when bilateral, or 3–4 repetitions per side when unilateral). All warm-up sessions were supervised and standardized, with each protocol designed to be completed within approximately 6–7 minutes.

The GWU comprised dynamic stretching exercises aimed at enhancing joint mobility across the ankle, hip, spine, and shoulder complexes. The exercises included spinal flexion and extension in the quadruped position (cat-cow), adductor quadruped rock-back, quadruped hip joint control articular rotations, half-kneeling thoracic spine rotations, half-kneeling hip flexor and extensor stretches, half-kneeling ankle dorsi-flexions, standing shoulder external rotations, and the World's Greatest Stretch. The MSWU involved dynamic bodyweight exercises replicating the biomechanics of the back squat and activating the primary synergistic muscle groups. The exercises included quadruped rocking with knees off the ground, single-leg hip thrust, lateral lunge with controlled hip internal and external rotation, modified hip airplane in split stance position, bottom-position split squat with vertical center-of-gravity oscillation, dynamic split squat, half-kneeling lunge with active foot tripod press into the floor, and single-leg lateral step-ups.

Maximal isometric force production

Peak force during maximal isometric high-bar back squat was assessed using a dynamometric force plate (FiTRONiC Diagnostic and Training Systems LTD, Bratislava, Slovakia; Figure 1). Participants stood on the platform integrated into a custom-built metal rack with an adjustable bar fixation. Foot placement was individually standardized, and the knee joint angle was fixed at 90°, verified using a goniometer. Following a familiarization trial at ~50% MVIC, participants completed two maximal efforts both before and after one of the two warm-up protocols. During each trial, they were instructed to push as rapidly and forcefully as possible until peak force was achieved. Each contraction was sustained for $\geq$ 5 s, with standardized verbal encouragement and real-time feedback provided by the examiners. Peak force was defined as the highest value obtained within the force-time curve, and the best of two attempts, separated by 2 min. of rest, was retained for analysis and expressed in Newtons [N].

Neuromuscular activation (electromyography; EMG)

Surface EMG (sEMG) signals during maximal isometric high-bar back squat were recorded using a Trigno Wireless EMG System (Delsys Inc., Delsys Europe, Manchester, UK) connected to a PC running Trigno Discover software (v1.6.4, Delsys Inc.). The Trigno Avanti Sensors (Delsys Inc.) equipped with Inertial Measurements Unit (IMU) were placed over the Vastus Medialis (VM), Vastus Lateralis (VL), Rectus Femoris (RF), Gluteus Maximus (GMax), and Biceps Femoris (BF) of the dominant lower limb. Sensors were positioned on the mid-belly of each muscle parallel to the direction of the muscle fibers, according to the recommendations of the Surface EMG for Non-Invasive Assessment of Muscles (SENIAM) guidelines.[24] Prior to electrode placement, the designated skin site was shaved, gently abraded to reduce impedance, and cleansed with an isopropyl alcohol pad to minimize myoelectrical impedance. To ensure consistent placement across trials, the site of each electrode was marked with a surgical pen.

sEMG signals were recorded and processed using EMGworks® Analysis software (Delsys Inc.) with a fourth-order, zero-lag Butterworth band-pass filter (20–450 Hz) and a 1259 Hz sampling rate. Signals were full-wave rectified and smoothed using a 0.125 s root mean square (RMS) window with 50% overlap (0.0625 s). The primary EMG outcome measures were total integrated electromyographic activity ($iEMG_{SUM}$; μV·s) and normalized EMG activity of the gluteus maximus (GMax; %MVIC). For each trial, iEMG for each muscle was calculated as the time integral of the rectified, smoothed signal over a 1–s window during the isometric effort, and $iEMG_{SUM}$ was obtained as the sum of iEMG values from all recorded muscles, providing a composite measure of overall neuromuscular activation that captures both amplitude and duration of the signal. To normalize EMG data, MVIC of the GMax was assessed during prone hip extension. Following electrode placement, participants lay prone on a treatment table with the knee flexed to 90°, and manual resistance was applied to the distal thigh while they extended the hip against resistance. In accordance with the recommendations of Konrad, two 3–5 s MVICs of the GMax were performed, separated by 60 s of rest.[25] Participants were verbally encouraged to contract the GMax "as forcefully as possible" during each trial. The peak RMS amplitude obtained from the two contractions was used as the reference value for normalization, and EMG activity of the GMax during the high-bar back squat was subsequently expressed as a percentage of this maximal value (%MVIC).

Statistical analysis

All statistical analyses were performed using SPSS (version 23.0, IBM Corp., Armonk, NY, USA), and data visualization was conducted in GraphPad Prism (version 8.0.1; GraphPad Software, San Diego, CA, USA). Data normality was assessed using the Shapiro-Wilk test, with no significant deviations from normality for any variable ($p > 0.05$). Within-protocol differences from pre- to post-warm-up-intervention were assessed using paired-samples t-tests. Between-protocol differences were evaluated by calculating individual change scores for each condition (ΔGWU = POST_GWU − PRE_GWU; ΔMSWU = POST_MSWU − PRE_MSWU) and comparing these change scores using paired-samples t-tests. Data are presented as means ± standard deviations (SD). Effect sizes were calculated using Cohen's d to quantify the magnitude of observed differences and were interpreted as trivial (0–0.2), small (0.2–0.6), moderate (0.6–1.2), large (1.2–2.0), or very large (>2.0).[26] The level of statistical significance was set at $p < 0.05$.

Results

Completion time did not differ significantly between the protocols (GWU: 401.6 ± 53.6 s; MSWU: 394.9 ± 37.8 s; $p = 0.806$). Peak force production during maximal isometric back squat significantly decreased following the GWU (2341 ± 313.71 N to 2252 ± 316.28 N; −3.8%; $p = 0.004$; $d = 1.47$, large), whereas no significant change was observed after the MSWU (2316 ± 293.76 N to 2274 ± 310.31 N; −1.9%; $p = 0.138$; $d = 0.59$, moderate). Between-protocol comparisons revealed no significant differences in peak force ($p = 0.186$; $d = 0.52$, moderate; Figure 2).

No significant changes were observed in normalized gluteus maximus activity after either protocol (GWU: 77.8 ± 28.0% MVIC to 62.0 ± 17.4% MVIC; $p = 0.07$; $d = 0.76$, moderate; MSWU: 74.2 ± 28.5% MVIC to 64.7 ± 16.8% MVIC; $p = 0.18$; $d = 0.53$, moderate), and no significant between-protocol differences were found ($p = 0.495$; $d = 0.26$, small; Figure 3).

Similarly, total integrated EMG ($iEMG_{SUM}$) of all recorded muscles did not differ significantly from pre- to post-measurements in either condition (GWU: 650.1 ± 294.0 µV·s to 582.7 ± 202.9 µV·s; $p = 0.186$; $d = 0.52$, small; MSWU: 710.5 ± 269.2 µV·s to 681.1 ± 216.8 µV·s; $p = 0.568$; $d = 0.21$, small). No significant between-protocol difference was observed ($p = 0.549$; $d = 0.22$, small; Figure 4).

Discussion

This pilot study examined the acute effects of a MSWU compared with a GWU on peak force production and neuromuscular activation during maximal isometric high-bar back squat. The main finding was that the GWU induced a significant decrease in peak force, whereas the MSWU maintained performance. Contrary to our hypothesis, neuromuscular activation, assessed through normalized gluteus maximus EMG activity (GMax; %MVIC) and total integrated EMG ($iEMG_{SUM}$), remained unchanged following both warm-up protocols. These findings indicate that a general, mobility-oriented warm-up may transiently impair maximal isometric force production, while a movement-specific preparation can preserve force-generating capacity without eliciting additional neuromuscular fatigue.

The decline in force observed after the GWU likely reflects the predominance of non-specific mobility and stretching drills that do not replicate squat biomechanics. Static stretching, although effective for improving joint range of motion, can acutely reduce force output by altering musculotendinous properties and neural drive. Kay and Blazevich reported dose-dependent reductions in muscle strength and EMG amplitude following prolonged static stretching (>60 s), attributed to short-term neural inhibition rather than structural changes.[27,28] Hence, the GWU may have insufficiently activated the key synergistic muscles and neuromuscular pathways required for maximal force expression.

In contrast, the MSWU included closed-kinetic-chain, multi-joint exercises that closely replicated squat biomechanics and activated the primary synergistic muscle groups. Such task-specific preparation likely maintained performance through improved motor unit synchronization, intermuscular coordination, and neuromechanical efficiency.[6,8] Within the potentiation-fatigue framework,[11,12] low-load, movement-specific activities may elicit Post-Activation Performance Enhancement (PAPE) through concurrent increases in muscle temperature, intracellular water content, and neuromuscular coordination without inducing substantial metabolic fatigue.[29] This mechanism may explain why the MSWU preserved maximal isometric force, whereas the GWU induced a decrement.

Previous studies have predominantly focused on dynamic performance outcomes, such as Countermovement Jump (CMJ), sprinting, or one-Repetition Maximum (1RM) tests, which tend to benefit more from warm-up-induced potentiation.[8,13,23,30,31] These effects are largely temperature dependent, as elevated muscle temperature enhances cross-bridge cycling, conduction velocity, and enzymatic activity.[32,33] A recent meta-analysis confirmed that increasing muscle temperature within physiological limits (~33.9–39.7°C) significantly enhances rate-dependent contractile properties, including Rate of Force Development (RFD) and power output, whereas maximal force capacity remains largely unaffected.[7] Moreover, Faulkner *et al.* demonstrated that a 15-min standardized cycling warm-up, incorporating moderate-intensity steady work and intermittent maximal sprints, increased intramuscular temperature by approximately 2–2.4 °C at a 2 cm depth (from ~36°C to ~38°C).[34] Accordingly, it is plausible that the relatively short warm-up duration (~6–7 min) in the present study was insufficient to elicit meaningful thermally mediated adaptations. This may also explain why longer general warm-ups (≥20 min) have been associated with improved maximal strength performance,[13] whereas shorter protocols fail to sufficiently elevate muscle temperature.[10] Consistent with this, several investigations have reported enhanced performance following both general and specific active warm-ups, emphasizing that the rise in temperature itself is a critical determinant of performance enhancement, regardless of the modality used.[35–37] However, these thermally induced benefits appear to be task-specific. Increases in temperature enhance high-velocity contractions through improved cross-bridge cycling and faster ATP turnover but exert minimal or inconsistent effects on maximal isometric strength.[5,38] Supporting this, Stewart *et al.* observed no changes in maximal isometric strength following active warm-ups, indicating that elevated temperature primarily facilitates dynamic performance through neuromuscular adjustments in movement coordination rather than increases in maximal force capacity.[5] Similarly, Altamirano *et al.* found no effect of active warm-up on isometric torque, Rate of Torque Development (RTD), or EMG amplitude.[17] Collectively, these findings reinforce that temperature- and activation-related potentiation predominantly benefit dynamic rather than isometric tasks, consistent with our results showing preserved rather than enhanced force following MSWU and a small but significant reduction after GWU (−3.8%; $p = 0.004$). It should be noted, however, that muscle temperature was not directly measured in the present study. This methodological limitation may partly explain the absence of improvement in isometric force across conditions, underscoring the need for future research to directly quantify intramuscular temperature when evaluating warm-up effects. Complementary evidence from Crow *et al.* highlights that low-load, bodyweight-based warm-ups targeting the gluteal musculature can improve CMJ power (+4–7%) without inducing fatigue or requiring external equipment.[23] While such effects may not arise from classical PAP, which is typically associated with near-maximal contractions and mechanisms such as phosphorylation of myosin regulatory light chains,[12,39] they may reflect improved motor cortical excitability or recruitment efficiency following low-level contractions.[40,41] Thus, while low-intensity, movement-specific warm-ups may enhance dynamic performance, under isometric conditions their primary role may be to preserve force capacity rather than augment it.

Electromyographic (EMG) findings further support this interpretation. Neither protocol significantly altered normalized GMax activation or total integrated EMG, suggesting that the observed force changes were not accompanied by detectable modifications in neuromuscular activation. This aligns with prior work showing that warm-up-induced performance effects are not always reflected in EMG amplitude or frequency parameters. Altamirano *et al.* found no changes in EMG amplitude after an active warm-up, suggesting that short-term increases in muscle temperature or activation may not influence neural drive during isometric tasks.[17] Similarly, Barnes *et al.* and Pinfold *et al.* reported no significant alterations in EMG amplitude of the Gluteus Maximus (GMax) or Biceps Femoris (BF) despite improvements in dynamic performance following movement-specific warm-ups.[6,31] However, increases in EMG amplitude have been observed following dynamic, task-specific preparation in ballistic or plyometric contexts. Sotiropoulos *et al.* observed that half-squat warm-ups at low and moderate intensities increased Countermovement Jump (CMJ) height and power output, accompanied by elevated EMG amplitudes of the vastus lateralis and quadriceps (+8.5% and +5%, respectively), indicating enhanced motor unit recruitment and synchronization.[8] Discrepancies among studies likely reflect differences in contraction type, rest duration, and biomechanical specificity between conditioning and performance tasks.[7] Moreover, temperature-induced increases in muscle fiber conduction velocity may elevate EMG frequency without increasing amplitude,[5] a phenomenon that favours dynamic rather than isometric contractions.[7]

Overall, the preservation of performance following the MSWU likely reflects maintained neuromechanical readiness rather than enhanced neural drive, whereas the decline after the GWU may be related to transient alterations in musculotendinous behaviour or suboptimal activation time not captured by surface EMG.

Conclusions

The pilot study showed that, in resistance-trained men, a short movement-specific warm-up replicating squat biomechanics preserved maximal isometric force production, whereas a general, mobility-oriented warm-up led to a small but significant decline. Neither warm-up condition altered gluteus maximus activation or total integrated EMG, suggesting that these performance differences were not driven by changes in neural drive but rather by the biomechanical and coordinative specificity of the warm-up. The preservation of force following movement-specific preparation underscores the functional importance of targeting the precise neuromechanical demands of the subsequent task. Collectively, these findings indicate that individualized, movement-oriented warm-ups may offer superior preparatory benefits over generalized mobility routines by maintaining neuromechanical readiness without inducing fatigue. Future work with larger cohorts, direct intramuscular temperature and conduction velocity measurements, and comparison across contraction modes (isometric vs. dynamic) is warranted to clarify the relative contributions of thermal, neural, and mechanical factors to warm-up efficacy.

List of the abbreviations

MVIC, maximal voluntary isometric contraction
MVC, maximal voluntary contraction
EMG, electromyography
sEMG, surface electromyography
iEMG, integrated electromyography
IMU, inertial measurements unit
PAP, post-activation potentiation
PAPE, post-activation performance enhancement
RFD, rate of force development
GWU, general warm-up
MSWU, movement-specific warm-up
SENIAM, surface EMG for non-invasive assessment of muscles
GMax, gluteus maximus
VM, vastus medialis
VL, vastus lateralis
RF, rectus femoris
BF, biceps femoris
1RM, one-repetition maximum
3RM, three-repetition maximum
RMS, root mean square
CMJ, countermovement jump

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Contributions

Conceptualization, organization and supervision, VO and GB; participants` recruitment, VO, MT; protocol design and implementation, VO, GB, MT; examinations, VO and MT; data acquisition, VO and MT; data analysis, GB, VO, and MT; visualization, GB, manuscript preparation, VO and JES; review, editing and validation, VO, GB and JES. All authors reviewed and edited the manuscript, provided substantial intellectual contributions, and approved the final version for publication. The authors take full responsibility for the content of this work.

Conflict of Interests

The authors declare no financial, personal, or other conflicts of interest.

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Ethics approval

The study was conducted in accordance with the Declaration of Helsinki (1964), as revised in 2013, and approved by the Ethics Committee of the Faculty of Physical Education and Sport, Comenius University, Bratislava, Slovakia (Protocol No. 14/2024). Informed consent was obtained from all subjects involved in the study prior to participation.

Availability of data and materials

All data generated or analysed during this study are included in the article. Further inquiries can be directed to the corresponding author.

Generative AI statement

The authors declare that no Generative AI was used in the creation of this manuscript.

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Figure 1 Peak force and surface electromyographic (EMG) activity during maximal isometric high-bar back squat at 90° knee flexion

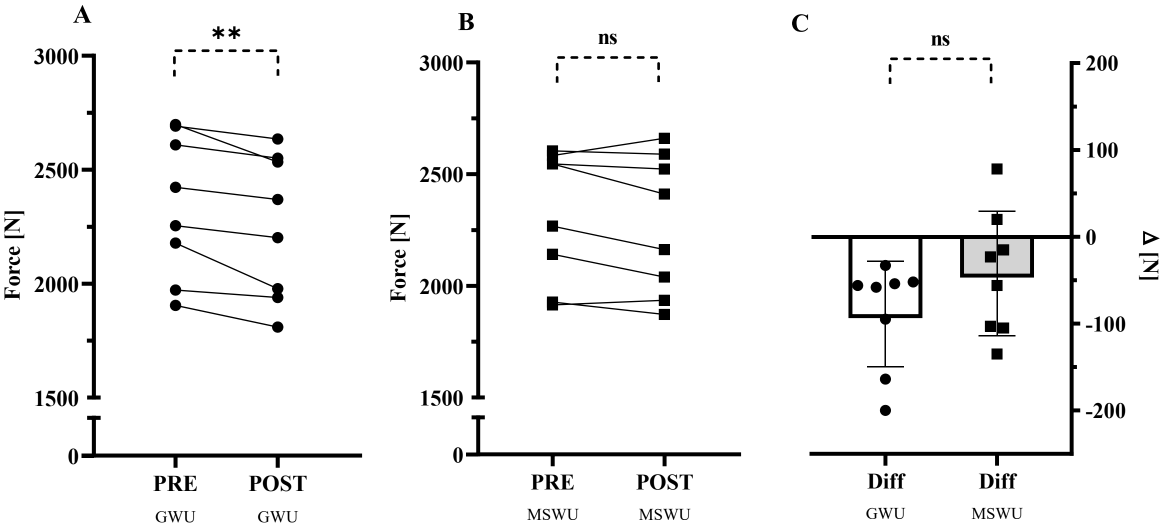

Figure 2 Within- (A, B) and between-protocol (C) differences in peak force production (Force, N) during maximal isometric high-bar back squat before and after general (GWU) and movement-specific (MSWU) warm-ups.

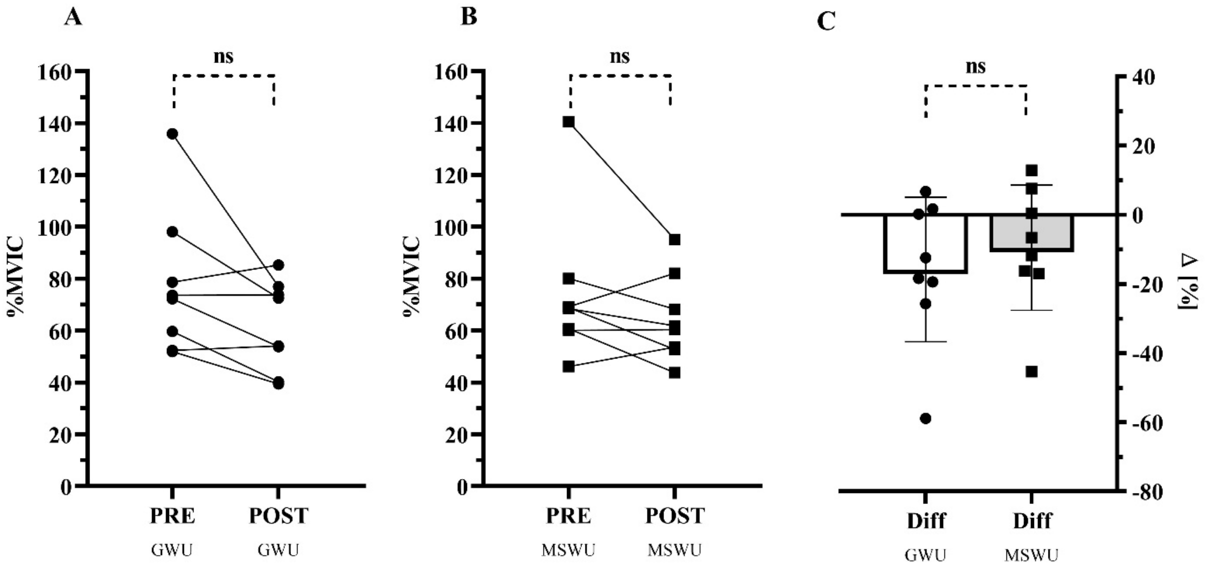

Figure 3 Within- (A, B) and between-protocol (C) differences in normalized GMax activity (%MVIC) recorded during maximal isometric high-bar back squat before and after general (GWU) and movement-specific (MSWU) warm-ups.

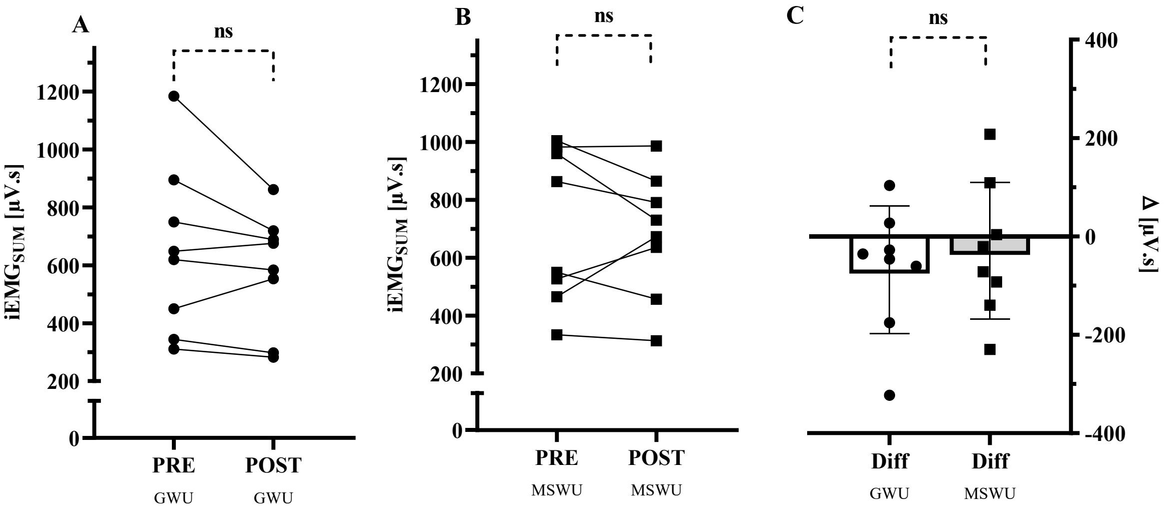

Figure 4 Within- (A, B) and between-protocol (C) differences in total integrated EMG (iEMG$_{SUM}$; μV·s) of all recorded muscles during maximal isometric high-bar back squat before and after general (GWU) and movement-specific (MSWU) warm-ups.