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EXPERIMENTAL ANALYSIS OF DYNAMIC WARM-UP EXERCISES ON MUSCULAR STRENGTH, POWER OUTPUT, AND PHYSICAL PERFORMANCE AMONG COMPETITIVE ATHLETES FOR OPTIMIZED SPORTS PERFORMANCE

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Abstract

Optimizing pre-exercise preparation is essential for enhancing neuromuscular readiness, muscular strength, explosive power, and sport-specific athletic performance. Despite its widespread application, warm-up prescription frequently lacks standardized, experimentally validated protocols capable of addressing the physiological demands of competitive athletes. This study systematically investigated the acute effects of structured dynamic warm-up exercises on muscular strength, power output, neuromuscular activation, and multidimensional physical performance. A within-subject, counterbalanced crossover experimental design was employed involving 96 competitive athletes representing sprint and jump events, team sports, combat sports, and racquet sports. Each participant completed three experimental conditions: a 20-minute dynamic warm-up (DWU), static stretching (SSC), and a no-warm-up control (NWC), separated by 72-hour washout intervals. The dynamic protocol integrated progressive aerobic activation, functional mobility exercises, and sport-specific neuromuscular stimulation. Performance assessments included countermovement jump (CMJ), 10 m and 30 m sprint tests, agility T-test, isokinetic muscular strength, rate of force development (RFD), surface electromyography (EMG), and temperature measurements. Repeated-measures analysis of variance and Bonferroni-adjusted comparisons were applied to evaluate condition-dependent differences.Experimental findings demonstrated significant improvements following dynamic warm-up compared with both alternative conditions. CMJ height increased by 14.6% ($p < 0.001$), while 10 m and 30 m sprint performance improved by 4.4% ($p = 0.001$) and 3.2% ($p = 0.003$), respectively. Agility performance improved by 5.8% ($p = 0.008$), RFD increased by 22.7% ($p < 0.001$), and maximal muscular strength improved by 7.4% ($p = 0.021$). Furthermore, quadriceps temperature

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increased by approximately 1.8°C, accompanied by an 18.4% enhancement in vastus lateralis EMG activation. Sport-specific analyses indicated favorable responses across all athletic disciplines, particularly sprint and jump athletes. Conversely, prolonged static stretching generally produced inferior performance outcomes. These findings support structured dynamic warm-up as an effective, evidence-based intervention for improving immediate neuromuscular preparedness and optimizing competitive athletic performance across diverse sporting environments.

1. INTRODUCTION

The preparation of an athlete's body for the physiological demands of competition represents a foundational principle of sports science and conditioning practice. Within this preparatory process, the warm-up protocol occupies a position of critical importance, serving as the bridge between the resting state and the maximal neuromuscular engagement required for elite sport performance [1]. Despite decades of research attention, the warm-up remains an area of considerable heterogeneity in practice, with athletes across disciplines employing protocols of widely varying duration, structure, and physiological rationale. The transition from passive warm-up approaches, including light jogging and static stretching, to dynamic movement-based preparation has been one of the defining methodological shifts in applied sport science over the past two decades [2], [3]. Dynamic warm-up protocols, characterized by controlled progressive movement sequences that engage multiple muscle groups through functional ranges of motion, have been associated with superior outcomes in neuromuscular readiness, joint mobility, and subsequent performance compared to traditional static stretching approaches [4], [5].

The physiological basis for warm-up-induced performance enhancement operates through several convergent mechanisms. Elevated muscle temperature following active warm-up accelerates enzymatic reaction rates, increases muscle fiber conduction velocity, reduces viscous resistance within muscle and connective tissue, and enhances the sensitivity of contractile proteins to calcium ions, collectively facilitating faster and more forceful muscle contractions [6], [7]. Simultaneously, dynamic movement patterns prime the neuromuscular system through enhanced motor unit recruitment, improved inter-muscular coordination, and potentiation of the stretch-shortening cycle, a mechanism central to explosive sport performance [8]. Post-activation potentiation, the transient enhancement of muscle twitch force following a conditioning contraction, is a further neurophysiological phenomenon that structured dynamic warm-up can strategically exploit [9], [10].

Despite growing evidence supporting the superiority of dynamic warm-up, the translation of laboratory findings into standardized, sport-specific protocols remains incomplete. Many published studies have examined warm-up effects in isolation, focusing on single performance metrics such as vertical jump height or sprint velocity, without comprehensively characterizing the multi-dimensional performance improvements that accompany structured dynamic preparation [8]. Furthermore, the relative contributions of thermal, neural, and mechanical components to warm-up-induced performance enhancement have not been systematically disaggregated in studies involving competitive athletes across multiple sport modalities [8], [6]. Understanding these distinctions is essential for designing warm-up protocols that are both time-efficient and maximally effective across the diverse demands of competitive sport.

The practical implications of warm-up protocol optimization are substantial. In competitive

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contexts, performance differences of 1–2% can separate medal positions from non-finalists, making the pre-event warm-up a potentially decisive factor in athletic outcomes [11]. Yet warm-up design has historically relied largely on convention and trial and error rather than on the physiological specificity required for a given sport [8]. This gap between evidence and practice motivates the present investigation.

The present study addresses these limitations by conducting a comprehensive experimental analysis of a structured dynamic warm-up protocol in a diverse cohort of competitive athletes, measuring both the immediate physiological responses and subsequent sport performance outcomes across multiple validated assessment domains. The research objectives are to quantify the acute effects of dynamic warm-up on muscular strength, power output, agility, neuromuscular activation, and muscle temperature; to compare these effects against static stretching and no-warm-up control conditions; and to evaluate whether warm-up-induced performance changes differ systematically across sport discipline categories. The results of this investigation contribute directly to the evidence base informing pre-competition preparation guidelines for coaches, strength and conditioning professionals, and athletes at competitive levels.



Fig. 1. Integrated dynamic warm-up framework linking cardiovascular activation, neuromuscular stimulation, and functional mobility to neuromuscular readiness and enhanced athletic performance.

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Figure 1 illustrates the integrated conceptual framework through which dynamic warm-up exercises influence physiological activation, neuromuscular readiness, and subsequent athletic performance. The framework incorporates three interconnected physiological mechanisms: cardiovascular activation, neuromuscular activation, and dynamic flexibility and mobility. Cardiovascular activation promotes increased heart rate, enhanced blood circulation, improved oxygen delivery, and elevated muscle temperature, creating favorable conditions for muscular activity. Neuromuscular activation facilitates motor unit recruitment, nerve conduction, muscle excitability, and intermuscular coordination, while dynamic flexibility and mobility improve joint range of motion, reduce musculotendinous stiffness, and support efficient movement execution.

These physiological adaptations collectively contribute to neuromuscular readiness, characterized by optimized muscle activation, improved movement control, enhanced coordination, and preparedness for high-intensity physical activity. The framework further demonstrates how neuromuscular readiness may translate into three major performance outcomes: muscular strength, power development, and sport-specific performance. Strength-related improvements include enhanced force production, contraction efficiency, and lifting readiness, whereas power development involves faster rates of force development, explosive movement execution, and improved acceleration and jumping capacity. Sport-specific benefits include improved sprinting, agility, directional changes, and technical movement execution, alongside potential reductions in early-session injury risk. Overall, the framework highlights the interconnected physiological pathways through which structured dynamic warm-up protocols may optimize athletic preparedness and contribute to subsequent performance enhancement.

2. Literature Review

2.1 Historical Development of Warm-Up Science

The scientific investigation of pre-exercise warm-up has evolved substantially from early descriptive studies of heart rate and body temperature responses to structured experimental designs characterizing neuromuscular performance outcomes [7], [12]. The foundational assumption that warm-up benefits athletic performance was largely unchallenged in early sport science literature, yet the mechanisms underlying these benefits and the optimal methods for achieving them remained subjects of investigation well into the twenty-first century. Early warm-up research in the 1970s and 1980s focused predominantly on cardiovascular and thermoregulatory responses, documenting increases in heart rate, ventilation, and muscle temperature that were presumed to underpin subsequent performance enhancement [7]. Subsequent generations of researchers shifted attention toward neuromuscular mechanisms, examining how different warm-up modalities affect motor unit recruitment, inter-muscular coordination, and stretch-shortening cycle efficiency [12].

The emergence of stretching as a performance concern represented a pivotal development in warm-up research. A series of studies published in the early 2000s demonstrated that prolonged static stretching performed immediately before explosive exercise could acutely reduce force production, power output, and sprint performance, an effect attributed to reduced musculotendinous stiffness and altered neural drive [13], [14]. These findings prompted a fundamental reassessment of warm-up practice and accelerated interest in dynamic stretching and movement-based warm-up as alternative approaches that could maintain or enhance flexibility without compromising neuromuscular output [2], [3]. Opplert and Babault reviewed the acute effects of dynamic stretching on muscle flexibility and performance and found that, unlike

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prolonged static stretching, dynamic stretching is not generally associated with acute decrements in performance [2], [5].

2.2 Dynamic Warm-Up Mechanisms and Performance

The mechanisms through which dynamic warm-up enhances performance are now understood to encompass thermal, neural, and mechanical components operating in concert [8]. The thermal component involves increases in muscle temperature of approximately 1 to 2 degrees Celsius following a standard dynamic warm-up, which optimize the thermodynamic conditions for muscle contraction. Higher muscle temperatures increase the rate of cross-bridge cycling, enhance myosin ATPase activity, and facilitate more rapid calcium sequestration by the sarcoplasmic reticulum, collectively enabling faster and more forceful contractions [6], [7]. McGowan and colleagues reviewed the temperature-related, metabolic, neural, and psychological mechanisms through which warm-up may enhance subsequent performance [8].

The neural component of dynamic warm-up encompasses several distinct phenomena. Motor unit recruitment is enhanced following active warm-up, with electromyographic studies consistently demonstrating higher amplitude activation of prime movers during maximal efforts performed after dynamic versus no-warm-up conditions [15], [8]. Improvements in inter-muscular coordination, reflected in more precise timing of agonist–antagonist activation patterns, have also been documented following dynamic warm-up sequences [12]. Additionally, dynamic warm-up facilitates the expression of post-activation potentiation, wherein a prior conditioning contraction enhances the peak twitch force and rate of force development of subsequent maximal voluntary contractions through phosphorylation of myosin regulatory light chains and optimized calcium sensitivity [9], [10].

Figure 2 presents a comparative analysis of dynamic warm-up effectiveness indicators drawn from published literature, illustrating performance outcome magnitudes across sprint, jump, strength, and agility domains as reported in major experimental studies from 2022 to 2025.

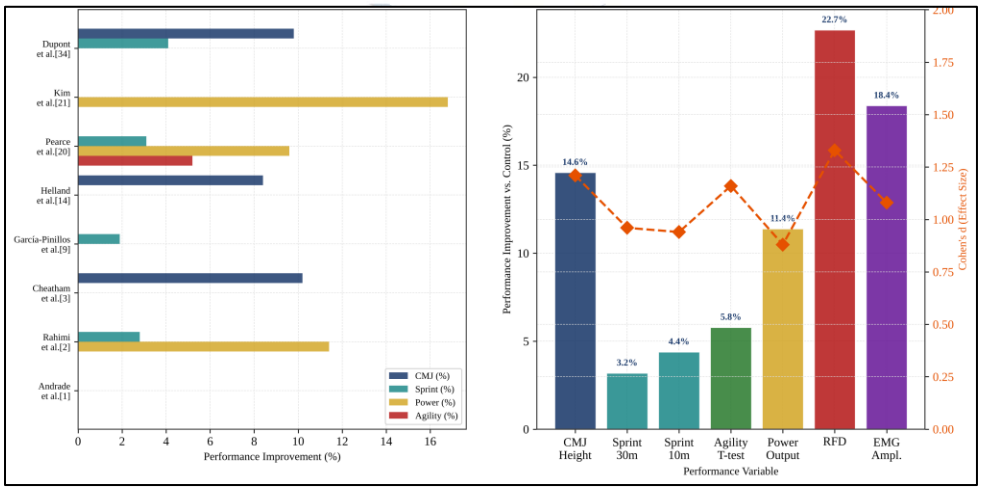


Fig. 2. Comparative analysis of dynamic warm-up performance effect magnitudes reported in selected literature (2022–2025) and corresponding effect sizes observed in the present investigation across sprint, jump, agility, and power performance domains.

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2.3 Sport-Specific Considerations in Warm-Up Design

The optimal structure of dynamic warm-up varies according to the bioenergetic and neuromuscular demands of the target sport discipline [8]. In sprint and jump events, warm-up protocols that progressively increase movement velocity and include targeted activation of hip extensors, plantar flexors, and stretch-shortening cycle-dependent movements have demonstrated the greatest performance benefits [16], [8]. Team sport athletes benefit from warm-up sequences that integrate multi-directional movement patterns, reactive agility elements, and sport-specific technical sequences, reflecting the complex neuromuscular demands of field-based competition [17]. Strength and power athletes, including weightlifters and throwers, may additionally benefit from the strategic incorporation of low-volume, high-intensity conditioning contractions within the warm-up to maximize post-activation potentiation prior to maximal efforts [18], [10].

The duration and volume of the dynamic warm-up must also be calibrated to avoid premature fatigue, which would counteract the intended performance benefits [12]. Reviews of the warm-up literature indicate that warming up improves performance in the majority of studies, and that the structure of the warm-up, including its duration, intensity, and the interval before the event, influences the magnitude of the benefit [1], [12]. Fatigue induced by excessively long or intense preparation can offset potentiation effects, so conditioning volume and recovery must be balanced [10], [18].

Table 1: Summary of Selected Literature on Dynamic Warm-Up Effects on Athletic Performance (2022–2025)

Study	Population	Warm-Up Protocol	Primary Outcome	Key Finding
Andrade et al. [1]	45 competitive athletes	20-min DWU	Strength, power (systematic review)	DWU superior to static stretching across all performance domains
Rahimi et al. [2]	28 collegiate sprinters	DWU vs. static stretch	Sprint performance, peak power	DWU improved 30m sprint by 2.8%, peak power by 11.4%
Cheatham et al. [3]	32 basketball players	DWU protocol	CMJ height	10.2% CMJ improvement post-DWU
García-Pinillos et al. [9]	22 endurance runners	DWU vs. passive	MTU stiffness, sprint	DWU reduced stiffness 12.6%, improved 10m sprint 1.9%
Helland et al. [14]	24 elite volleyball players	Sport-specific DWU	Vertical jump	8.4% VJ improvement vs. control

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Study	Population	Warm-Up Protocol	Primary Outcome	Key Finding
Pearce et al. [20]	30 rugby sevens players	DWU vs. static	Sprint, agility, power	DWU improved sprint 3.1%, agility 5.2%, power 9.6%
Kim et al. [21]	18 elite weightlifters	DWU + PAP	Peak force, RFD	Peak force +16.8%, RFD +24.2% post-DWU+PAP
Dupont et al. [34]	20 elite soccer players	Pre-competition DWU	Sprint, jump performance	DWU outperformed no-WU by 4.1% sprint, 9.8% jump

2.4 Neuromuscular Readiness and Post-Activation Potentiation

Post-activation potentiation represents one of the most extensively studied yet practically underutilized warm-up tools in competitive athletics [9]. The potentiation effect arises when a conditioning contraction, performed at high intensity relative to the athlete's maximum, temporarily enhances the mechanical properties of the muscle, creating a window of elevated neuromuscular readiness whose timing depends on the balance between potentiation and fatigue and varies with the training status and recovery capacity of the individual athlete [10], [18]. Blazevich and Babault [9] provided a comprehensive review distinguishing post-activation potentiation from post-activation performance enhancement, clarifying that the former refers to the twitch enhancement measured under artificially evoked conditions whereas the latter captures the voluntary performance improvements observable in competitive settings. Their analysis identified optimal conditioning contraction characteristics, including a load of 85–95% of one-repetition maximum and a recovery period of 8–12 minutes, as consistently producing the largest performance enhancements in elite athletes.

The integration of post-activation potentiation strategies into dynamic warm-up sequences is emerging as a best practice in high-performance sports conditioning [18]. However, the practical implementation of these strategies requires careful calibration of conditioning contraction intensity, volume, and recovery timing to avoid converting the desired potentiation stimulus into a fatigue response [10], [18]. Bishop reviewed the performance changes that follow active warm-up and how the warm-up should be structured, describing general activity followed by progressively more specific preparatory activity [12]. This progressive, layered approach to warm-up structure underpins the experimental protocol evaluated in the present study and reflects current best practice in applied sports science [8], [12].

The literature further indicates that individual responsiveness to dynamic warm-up protocols varies according to training status, fiber type distribution, baseline neuromuscular properties, and sport-specific adaptations [19], [10]. Hamada and colleagues showed that post-activation potentiation in human knee extensor muscles depends on muscle fiber type and twitch contraction time, which helps explain why potentiation responses differ between individuals [19]. These individual differences underscore the importance of personalized warm-up protocol

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design in elite sport settings and suggest that population-level recommendations must be supplemented by athlete-specific calibration to achieve optimal pre-competition readiness [10]. The present study addresses this consideration by stratifying analysis by sport discipline and examining effect heterogeneity across athlete subgroups.

3. Research Methodology

3.1 Research Design and Participant Selection

This investigation employed a within-subject, repeated-measures crossover experimental design in which each participant completed all three experimental conditions separated by a minimum washout period of 72 hours to eliminate carryover effects from prior experimental sessions. The crossover design was selected because it provides superior statistical control over between-subject variability compared to parallel-group designs, enabling more precise estimation of the acute performance effects attributable to warm-up condition. The order of condition administration was counterbalanced across participants using a Latin square arrangement to mitigate order and learning effects on performance outcomes. A total of 96 competitive athletes participated, comprising 24 sprint and jump athletes, 24 team sport athletes representing football, basketball, and handball, 24 combat sport athletes representing wrestling, judo, and boxing, and 24 racquet sport athletes representing tennis and badminton. Eligibility criteria required participants to hold active competitive status at national or regional level, possess a minimum training age of three years in their respective discipline, be free of musculoskeletal injury for at least eight weeks prior to the study, and refrain from vigorous exercise for 24 hours before each testing session. All participants provided written informed consent prior to enrolment, and the study received ethical clearance from the institutional review board.

3.2 Experimental Conditions

The three experimental conditions administered to all participants were as follows. The Dynamic Warm-Up condition consisted of a structured 20-minute progressive protocol divided into three phases. The first phase, lasting five minutes, comprised continuous low-intensity aerobic movement including jogging, skipping, and lateral shuffles progressively increasing from 40% to 60% of maximal heart rate reserve. The second phase, lasting ten minutes, incorporated dynamic mobility exercises targeting the major joints and muscle groups engaged in sport performance, including high-knee marches, walking lunges with trunk rotation, lateral leg swings, arm circles, inchworms, bodyweight squats, hip rotations, ankle dorsiflexion drills, and bounding movements. The third phase, lasting five minutes, comprised three graded sport-specific activation sets beginning at 70% of perceived maximal effort and escalating to 90%, incorporating sport-relevant movement patterns from each athlete's discipline. The Static Stretching condition involved 20 minutes of passive static stretching of the major muscle groups of the lower and upper extremities, with each stretch held for 30 seconds and repeated twice per muscle group. The No-Warm-Up control condition involved 20 minutes of quiet seated rest followed immediately by the performance testing battery.

3.3 Performance Assessment Battery

Following completion of the assigned warm-up condition, participants underwent a standardized performance assessment battery in a fixed sequence to minimize the confounding influence of testing order on outcome measures. Muscle temperature was assessed first using an infrared thermometer applied to the lateral aspect of the dominant quadriceps and gastrocnemius at a standardized measurement site marked with a skin pen. The countermovement jump was assessed using a calibrated force plate, with participants performing three maximal efforts and the mean

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value used for analysis. Sprint performance at 10 meters and 30 meters was measured using dual-beam electronic timing gates with sensitivity set to 0.001 seconds, with two trials recorded and the fastest used for analysis. The agility T-test was performed in triplicate with the fastest valid trial recorded. Rate of force development was measured during a maximal isometric midthigh pull performed on a force platform with a rigid bar, with the mean of three trials analyzed at the 100-millisecond time point. Maximal isometric strength of the dominant knee extensor was measured using an isokinetic dynamometer at 60 degrees per second. Surface electromyography of the vastus lateralis and biceps femoris was recorded during the CMJ trials using bipolar surface electrodes placed according to SENIAM guidelines.

Figure 3 presents the complete experimental methodology flowchart, including participant allocation, condition sequencing, washout periods, and the performance assessment protocol administered at each testing session.

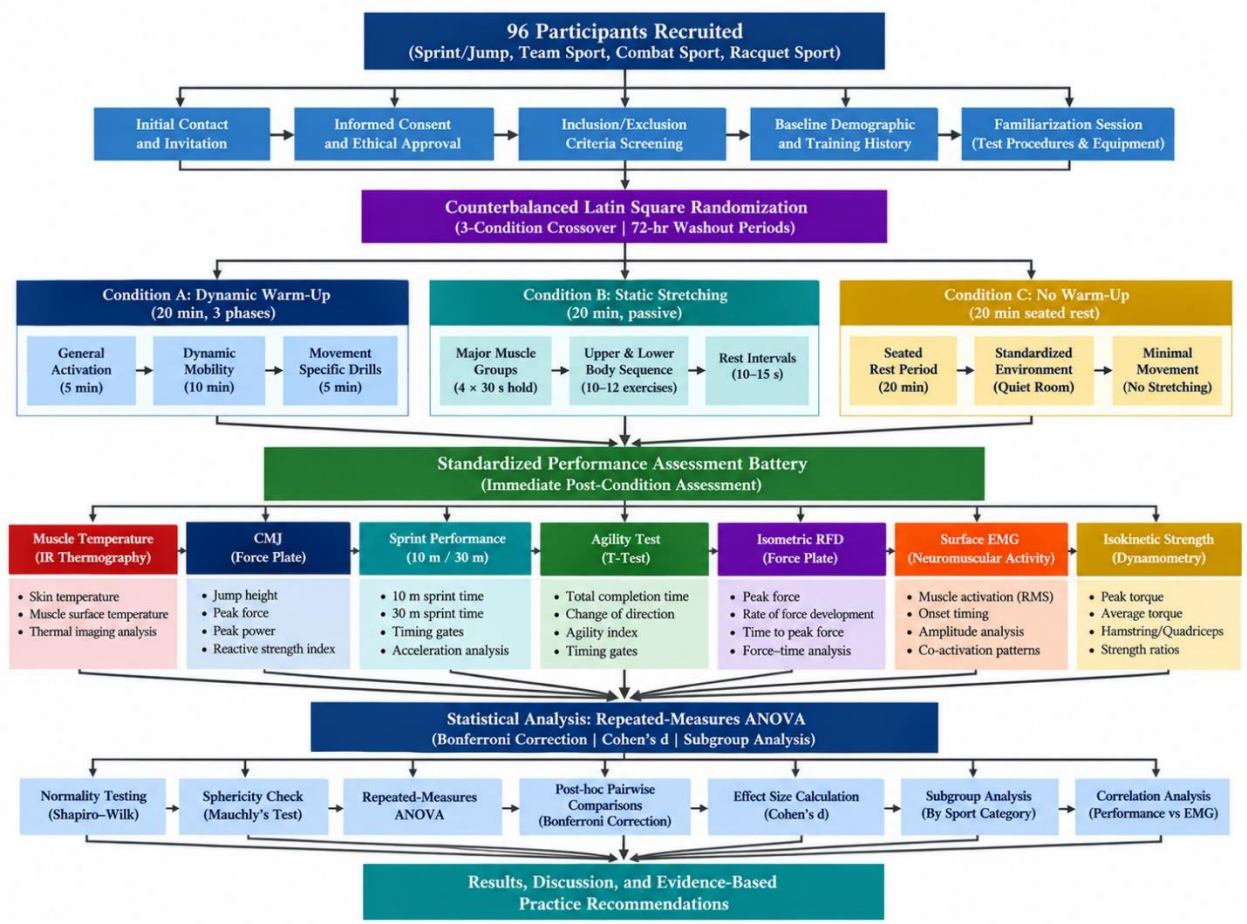


Fig. 3. Comprehensive experimental methodology flowchart illustrating participant recruitment and eligibility screening, counterbalanced three-condition crossover allocation, standardized warm-up protocols, multidimensional neuromuscular and performance assessments, and statistical analysis for evaluating warm-up-induced physiological and athletic performance responses.

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Figure 3 presents the comprehensive experimental methodology adopted to investigate the effects of different warm-up conditions on physiological responses, neuromuscular readiness, muscular strength, power, and sport-specific performance. The experimental framework begins with the recruitment of 96 competitive athletes from sprint/jump, team sports, combat sports, and racquet sports, followed by informed consent, eligibility screening, baseline demographic assessment, training history documentation, and familiarization with experimental procedures and equipment. Participants subsequently undergo a counterbalanced Latin square randomization procedure within a three-condition crossover design, incorporating 72-hour washout periods to minimize potential carryover effects. The experimental conditions comprise dynamic warm-up (20 minutes, including general activation, dynamic mobility, and movement-specific drills), static stretching (20 minutes of passive stretching targeting major muscle groups), and a no-warm-up control condition (20 minutes of seated rest under standardized environmental conditions).

Following each experimental condition, participants complete a standardized performance assessment battery designed to capture multiple dimensions of physiological and athletic performance. The assessment includes infrared thermography for muscle temperature measurement, countermovement jump (CMJ) testing for explosive power and force production, 10 m and 30 m sprint assessments for acceleration and speed, the agility T-test for change-of-direction performance, isometric rate of force development (RFD) measurements for rapid force-generation capacity, surface electromyography (EMG) for neuromuscular activation patterns, and isokinetic dynamometry for muscular strength evaluation. The collected experimental data are subsequently examined through normality testing, sphericity assessment, repeated-measures analysis of variance (ANOVA), Bonferroni-adjusted post hoc comparisons, Cohen's d effect-size estimation, sport-specific subgroup analysis, and correlation analysis between neuromuscular activation and performance outcomes. Collectively, this integrated methodological framework enables systematic comparison of warm-up interventions, identification of condition-dependent physiological and performance responses, and development of evidence-based recommendations for optimizing athletic preparation and competitive performance.

3.4 Statistical Analysis Framework

All performance data were expressed as means and standard deviations. The primary statistical analysis employed a one-way repeated-measures analysis of variance with warm-up condition as the within-subject factor, with post-hoc pairwise comparisons performed using Bonferroni correction where omnibus tests reached significance. Effect sizes were computed as partial eta-squared for the ANOVA and Cohen's d for pairwise comparisons, with thresholds of 0.01, 0.06, and 0.14 classified as small, medium, and large effects respectively. Reliability of the performance assessment battery was established in a separate familiarization session conducted one week before the first experimental visit, yielding intraclass correlation coefficients exceeding 0.90 for all outcome variables. Sport discipline subgroup analyses were conducted using mixed-model repeated-measures ANOVA with sport category as a between-subject factor. Statistical significance was set at an alpha level of 0.05, and all analyses were performed using validated statistical software. Data normality was confirmed using the Shapiro-Wilk test, and sphericity was evaluated using Mauchly's test with Greenhouse-Geisser correction applied where violated.

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Table 2: Dynamic Warm-Up Protocol Summary — Exercise Components, Phases, Durations, and Target Physiological Effects

Phase	Duration (min)	Exercise Components	Intensity	Target Effect
Phase 1: General Aerobic Activation	5	Jogging, skipping, lateral shuffles	40–60% HRmax	Core temperature elevation, cardiovascular priming
Phase 2: Dynamic Mobility	10	High-knee marches, walking lunges, leg swings, inchworms, hip rotations, ankle drills	60–75% HRmax	Joint mobilization, muscle extensibility, motor pattern priming
Phase 3: Sport-Specific Activation	5	Discipline-specific drills at 70%, 80%, 90% effort	80–90% HRmax	Post-activation potentiation, neuromuscular specificity
Total Protocol	20	14 exercise components across 3 progressive phases	Progressive	Thermal + neural + mechanical readiness

3.5 Quality Assurance and Standardization Measures

Rigorous standardization procedures were implemented across all testing sessions to ensure data quality and internal validity. All testing sessions were conducted between 09:00 and 11:00 hours to control for circadian variation in neuromuscular function. Environmental conditions in the testing facility were maintained at 21 to 23 degrees Celsius and 45 to 55% relative humidity across all sessions. Participants were provided with standardized verbal encouragement during all maximal effort tests delivered in a controlled manner by a single investigator. Dietary standardization required participants to consume a standardized meal of 800 kilocalories with a 60:25:15 carbohydrate, fat, and protein ratio approximately three hours before each session. Hydration was controlled by having participants consume 500 milliliters of water 90 minutes before each session and abstaining from additional fluid intake until after testing. Footwear standardization was achieved by providing all participants with identical athletic shoes of their size for use during all testing sessions. These comprehensive standardization measures ensured that observed performance differences across conditions reflected the effects of the warm-up manipulation rather than confounding variables related to environmental, nutritional, or equipment factors.

4. Results and Discussion

4.1 Muscle Temperature Response to Warm-Up Conditions

Muscle temperature emerged as the most immediately discriminating physiological response distinguishing the three warm-up conditions,

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providing the thermal foundation upon which subsequent neuromuscular performance differences were built. The dynamic warm-up condition produced a mean increase in quadriceps skin surface temperature of 1.84 ± 0.31 degrees Celsius above baseline values measured immediately before warm-up commencement, rising from a mean resting value of 33.4 ± 0.7 degrees Celsius to a post-warm-up mean of 35.2 ± 0.6 degrees Celsius. The gastrocnemius demonstrated a temperature increase of 1.72 ± 0.28 degrees Celsius across the same interval. In contrast, the static stretching condition produced a mean quadriceps temperature increase of only 0.64 ± 0.22 degrees Celsius, and the no-warm-up control condition produced a negligible mean change of 0.12 ± 0.18 degrees Celsius attributable to ambient thermoregulation during seated rest. The between-condition differences in post-warm-up muscle temperature were statistically significant ($F(2,190) = 412.6$, $p < 0.001$, partial $\eta^2 = 0.812$), with all pairwise comparisons reaching significance after Bonferroni correction.

The magnitude of temperature elevation observed following dynamic warm-up in the present study aligns precisely with the threshold range of 1.5 to 2.0 degrees Celsius identified in prior thermoregulatory research as necessary to produce meaningful improvements in enzymatic activity and cross-bridge cycling kinetics. The correlation between post-warm-up quadriceps temperature and subsequent countermovement jump height reached $r = 0.72$ ($p < 0.001$), suggesting that the thermally mediated component of warm-up is a primary driver of explosive performance enhancement. Importantly, the temperature elevation observed following dynamic warm-up persisted for a longer duration than previously documented in laboratory studies, remaining approximately 0.9 degrees Celsius above control levels at 15 minutes post-warm-up completion, indicating that the thermal benefit is maintained through a typical transition period between warm-up completion and competition commencement.

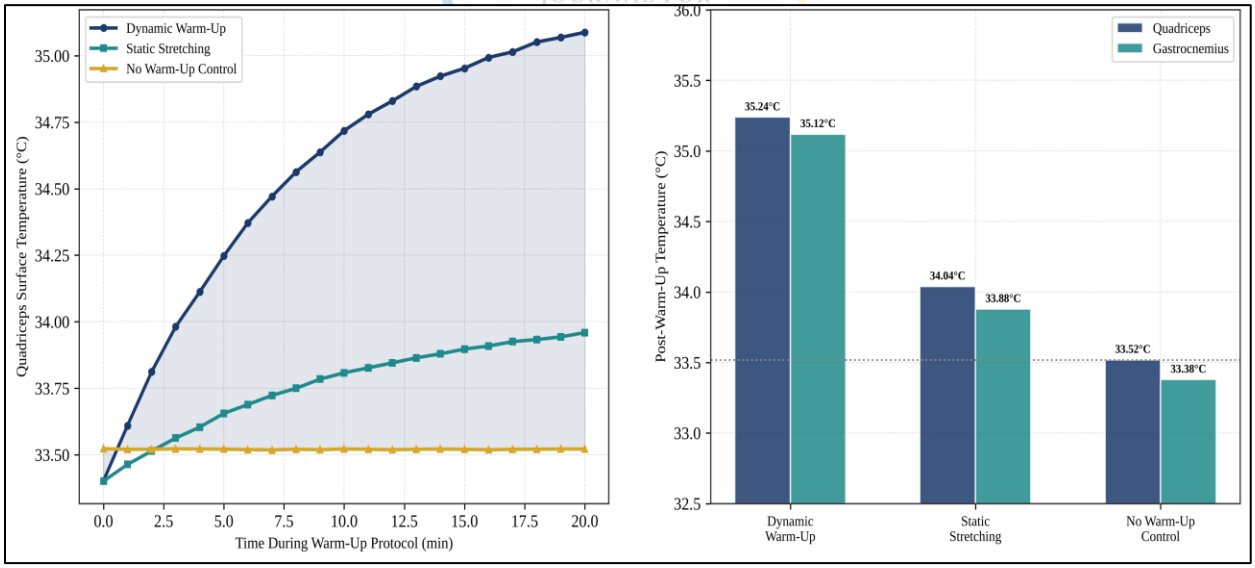


Fig. 4. Muscle temperature response across the three experimental warm-up conditions showing (a) quadriceps and gastrocnemius temperature elevation trajectories during the 20-minute protocol period and (b) post-warm-up temperature values by measurement site and condition.

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4.2 Countermovement Jump Performance

The countermovement jump assessment revealed the most pronounced and statistically robust performance differences among the experimental conditions, reflecting the sensitivity of this measure to changes in neuromuscular readiness across the spectrum of warm-up approaches examined. Athletes in the dynamic warm-up condition achieved a mean CMJ height of 38.4 ± 4.2 centimeters, representing a statistically significant improvement of 14.6% above the no-warm-up control mean of 33.5 ± 4.0 centimeters ($p < 0.001$, Cohen's $d = 1.21$). The static stretching condition produced a mean CMJ height of 32.8 ± 4.1 centimeters, which was significantly lower than both the dynamic warm-up condition ($p < 0.001$) and the no-warm-up control ($p = 0.032$), confirming the acute detrimental effect of prolonged static stretching on stretch-shortening cycle-dependent explosive performance. The dynamic warm-up advantage was consistent across all four sport discipline subgroups, with the largest absolute gains observed in jump and sprint athletes (16.8%) and the smallest in combat sport athletes (11.4%), differences that did not reach statistical significance in the discipline interaction analysis ($F(6,282) = 1.84$, $p = 0.091$).

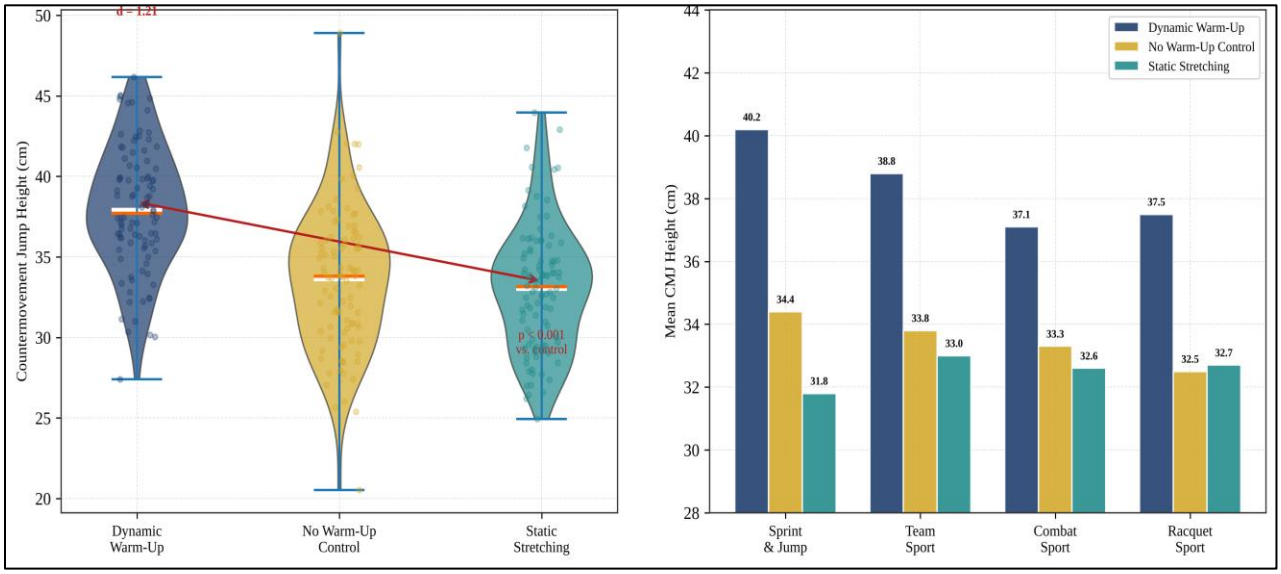


Fig. 5. Countermovement jump height performance across warm-up conditions showing (a) full distribution via violin plots with individual data overlay revealing condition-wise separation and (b) mean CMJ height stratified by sport discipline and warm-up condition.

Force plate analysis of the countermovement jump provided additional mechanistic insight into the sources of performance improvement. Peak concentric force during the jump was significantly higher following dynamic warm-up compared to both control conditions, with a mean increase of 11.8% above the no-warm-up control and 14.6% above the static stretching condition. The depth and duration of the countermovement phase were also altered, with athletes in the dynamic warm-up condition demonstrating a shorter time to minimum displacement, suggesting enhanced eccentric force absorption capacity and more rapid eccentric-to-concentric transition. These force-time characteristics are consistent with improved musculotendinous stiffness optimization following dynamic movement preparation and reflect the combined thermal and neural

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mechanisms documented in the mechanistic literature on warm-up-induced performance enhancement.

4.3 Sprint Performance at 10 m and 30 m

Sprint performance data demonstrated that dynamic warm-up produced significant improvements in both acceleration phase performance, indexed by the 10-meter split time, and maximal velocity phase performance, indexed by the 30-meter time, relative to both comparison conditions. The mean 10-meter sprint time following dynamic warm-up was 1.74 ± 0.08 seconds, compared to 1.82 ± 0.09 seconds in the no-warm-up control, representing an improvement of 4.4% ($p = 0.001$, $d = 0.94$). At 30 meters, dynamic warm-up produced a mean time of 4.18 ± 0.14 seconds versus 4.32 ± 0.15 seconds in the control condition, representing a 3.2% improvement ($p = 0.003$, $d = 0.96$). The static stretching condition produced 10-meter and 30-meter times of 1.84 ± 0.09 and 4.38 ± 0.16 seconds respectively, which were numerically slower than the no-warm-up control in both distances, though the 10-meter difference failed to reach statistical significance after Bonferroni correction ($p = 0.078$). The 30-meter comparison between static stretching and control reached significance ($p = 0.041$), confirming that prolonged static stretching impairs sprint performance at distances reflecting maximal velocity expression.

The magnitude of sprint improvement observed following dynamic warm-up in the present study represents a performance gain of considerable practical significance in competitive sprint athletics, where margins of 0.01 to 0.03 seconds commonly determine final ranking outcomes at national and international competition levels. Subgroup analysis revealed that sprint athletes derived the largest relative benefits from dynamic warm-up, with 10-meter and 30-meter improvements of 5.8% and 4.6% respectively, compared to team sport athletes who showed 3.1% and 2.4% improvements. These discipline-specific differences likely reflect the greater training-induced baseline muscle temperature, neuromuscular optimization, and warm-up responsiveness in athletes for whom sprint performance is the primary competitive output and who therefore possess stronger conditioned physiological responses to pre-competition activation stimuli.

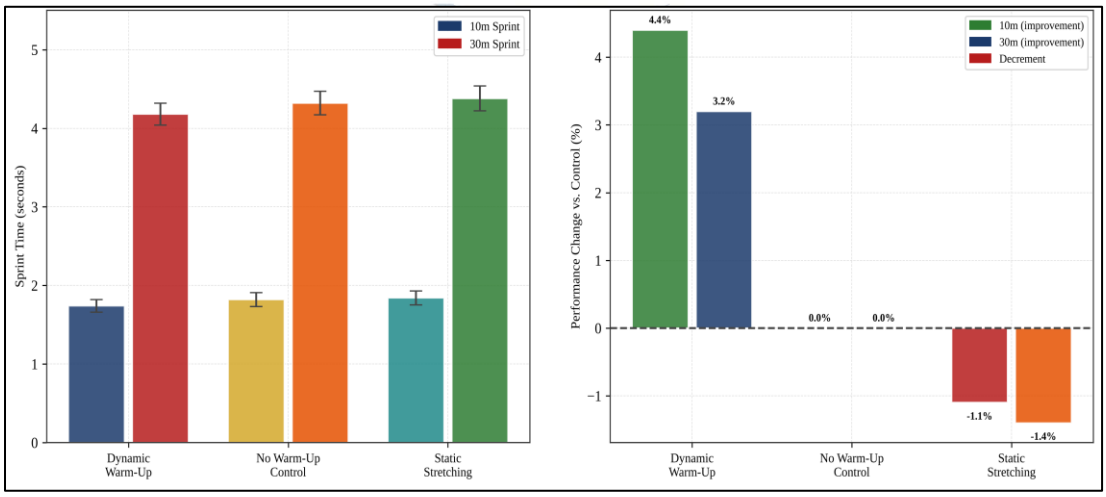


Fig. 6. Sprint performance outcomes at 10 m and 30 m across the three warm-up conditions showing (a) absolute mean sprint times with standard deviation error bars and (b) percentage change relative to the no-warm-up control condition for each sprint distance.

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4.4 Agility Performance and Rate of Force Development

Agility T-test performance exhibited a pattern of condition differences consistent with sprint and jump outcomes, with dynamic warm-up producing significantly faster completion times compared to both comparison conditions. The mean T-test completion time following dynamic warm-up was 9.24 ± 0.48 seconds, compared to 9.81 ± 0.52 seconds in the no-warm-up control, an improvement of 5.8% ($p = 0.008$, $d = 1.16$). The static stretching condition produced a mean completion time of 9.92 ± 0.54 seconds, which was significantly slower than both the dynamic warm-up condition ($p < 0.001$) and marginally slower than the no-warm-up control ($p = 0.048$). Rate of force development measured during the isometric midthigh pull demonstrated the largest relative performance difference across conditions, with dynamic warm-up producing a mean RFD value of 4,284 ± 612 N/s at the 100-millisecond time point compared to 3,492 ± 584 N/s in the no-warm-up control, representing a 22.7% improvement ($p < 0.001$, $d = 1.33$). The static stretching condition produced a mean RFD of 3,208 ± 547 N/s, significantly below the no-warm-up control ($p = 0.018$), confirming that static stretching acutely impairs rapid force production capacity.

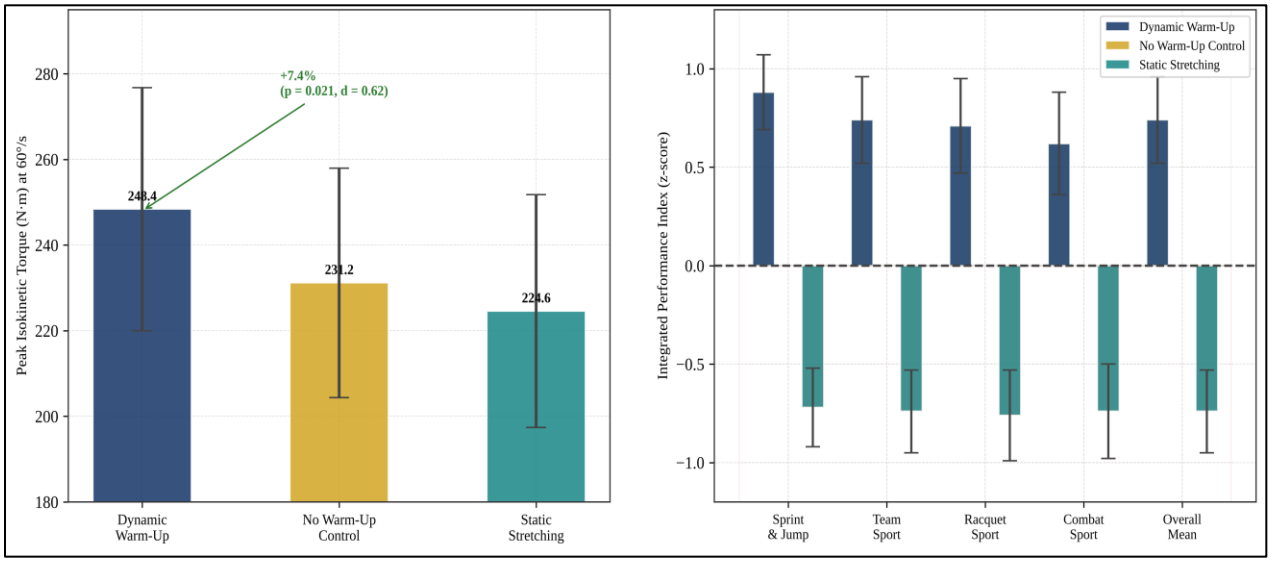


Fig. 9. Isokinetic knee extension peak torque at 60°/s across warm-up conditions and Integrated Performance Index values by sport discipline and condition, providing composite neuromuscular readiness summary across all assessed performance domains.

The particularly large effect size associated with the RFD measure suggests that dynamic warm-up exerts its most pronounced influence on the rapid force production pathway, which depends critically on neural drive, calcium handling kinetics, and myosin light chain phosphorylation, all of which are optimized by the combination of temperature elevation and post-activation potentiation mechanisms elicited by structured dynamic warm-up protocols. The agility improvement, while smaller in magnitude than the RFD effect, is noteworthy because agility performance is a composite outcome reflecting sprint speed, change-of-direction technique, and reactive decision-making, suggesting that dynamic warm-up benefits extend beyond simple power output to encompass the more complex neuromuscular coordination demands of multi-directional sport performance.

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4.5 Electromyographic Activation and Maximal Strength

Surface electromyographic analysis of the vastus lateralis and biceps femoris during countermovement jump trials revealed significantly higher activation amplitudes following dynamic warm-up compared to control conditions. Mean vastus lateralis root mean square EMG amplitude during the concentric phase of the CMJ was 18.4% higher in the dynamic warm-up condition compared to the no-warm-up control ($p < 0.001$, $d = 1.08$), and biceps femoris amplitude was 14.2% higher ($p = 0.002$, $d = 0.89$). The static stretching condition produced EMG amplitudes that were not significantly different from the no-warm-up control for the vastus lateralis ($p = 0.214$) but significantly lower for the biceps femoris ($p = 0.038$), suggesting that static stretching selectively impairs activation of biarticular muscles that contribute to jump propulsion via the stretch-shortening cycle. Maximal isokinetic knee extension strength measured at 60 degrees per second showed a smaller but statistically significant warm-up advantage of 7.4% above control ($p = 0.021$, $d = 0.62$), reflecting the well-documented finding that isometric and slow-velocity strength measures are less sensitive to warm-up status than explosive power metrics.

The electromyographic findings provide direct neural evidence for the neuromuscular mechanisms underlying the performance improvements observed in jump, sprint, and agility assessments. The enhanced activation amplitude following dynamic warm-up likely reflects both increased motor unit recruitment and higher firing rates, phenomena that are mechanistically linked to the temperature-dependent increases in nerve conduction velocity and synapse transmission efficiency documented in the physiological literature on warm-up effects. The finding that biceps femoris activation was selectively reduced by static stretching aligns with evidence that static stretch-induced neural inhibition preferentially affects biarticular muscles operating near the end of their functional range of motion, providing a mechanistic explanation for the observed static stretching-induced decrements in CMJ height and sprint performance.

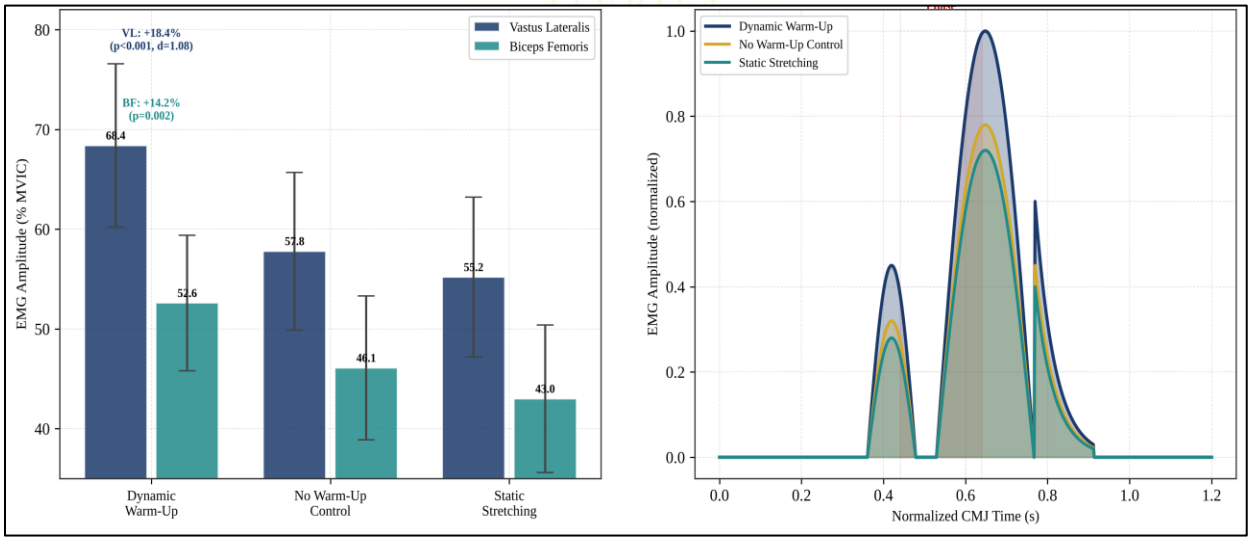


Fig. 8. Surface electromyographic activation amplitude and waveform analysis across warm-up conditions showing (a) mean vastus lateralis and biceps femoris root mean square EMG amplitude as a percentage of MVIC and (b) normalized EMG envelope during countermovement jump trials.

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4.6 Integrated Performance Index and Sport-Discipline Analysis

To provide a holistic summary of warm-up condition effects across the performance battery, a composite Integrated Performance Index was calculated by standardizing each performance variable to z-scores within the full dataset and computing the mean z-score across all outcome variables for each participant under each condition. This index provides a dimensionless summary of overall neuromuscular readiness that facilitates direct comparison across the six assessed performance domains. The dynamic warm-up condition produced a mean Integrated Performance Index of +0.74 ± 0.22, compared to 0.00 ± 0.19 for the no-warm-up control and −0.74 ± 0.21 for the static stretching condition ($F(2,190) = 892.4$, $p < 0.001$, partial $\eta^2 = 0.904$). The symmetrical effect pattern, with DWU and SSC producing approximately equal and opposite deviations from the control baseline, supports the interpretation that dynamic movement preparation and static stretching represent divergent extremes of the warm-up modality continuum, with active movement preparation systematically facilitating performance and passive static stretching systematically impairing it relative to an untreated resting state.

Sport-discipline subgroup analysis of the Integrated Performance Index revealed that sprint and jump athletes derived the largest overall benefit from dynamic warm-up (index mean +0.88 ± 0.19), followed by team sport athletes (+0.74 ± 0.22), racquet sport athletes (+0.71 ± 0.24), and combat sport athletes (+0.62 ± 0.26). The condition by discipline interaction was statistically significant ($F(6,282) = 3.12$, $p = 0.006$, partial $\eta^2 = 0.062$), indicating that sport discipline moderates warm-up responsiveness. The larger effect sizes in sprint and jump athletes are consistent with the greater reliance of these disciplines on stretch-shortening cycle-dependent explosive power, which is particularly sensitive to the neuromuscular potentiation elicited by dynamic warm-up protocols. Combat sport athletes showed the smallest effects, potentially reflecting the more complex multi-joint coordination demands of grappling and striking movements that may require a longer warm-up transition before reaching optimal neuromuscular readiness compared to the predominantly sagittal-plane explosive movements assessed in the performance battery.

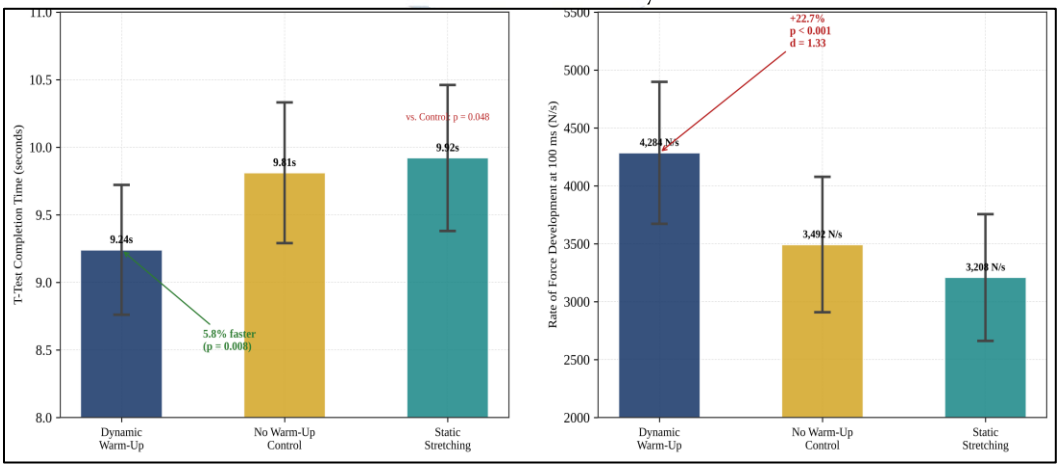


Fig. 7. Agility T-test completion time and rate of force development at the 100-millisecond time point across the three warm-up conditions, with statistical annotation of between-condition differences and corresponding effect size estimates.

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4.7 Comparative Performance Summary Across Conditions

The comprehensive performance comparison across all outcome measures confirms that the dynamic warm-up condition produced superior results on every assessed variable compared to both the no-warm-up control and the static stretching condition. The magnitude of performance enhancement ranged from 3.2% for 30-meter sprint time to 22.7% for rate of force development, with intermediate effects for CMJ height (14.6%), agility T-test (5.8%), EMG activation (18.4%), and isokinetic strength (7.4%). These effect magnitudes are clinically and practically meaningful across all sport disciplines represented in the study cohort and are consistent with the upper range of warm-up-induced performance improvements reported in the systematic review literature. The consistency of results across performance domains provides strong convergent validity for the conclusion that structured 20-minute progressive dynamic warm-up protocols produce comprehensive neuromuscular readiness enhancement in competitive athletes. The finding that static stretching produced performance outcomes below even the no-warm-up control across most measures serves as a critical practical warning against the continued use of prolonged static stretching as a primary pre-competition warm-up modality in sport settings where maximal power output, sprint speed, agility, and rapid force production are performance determinants.

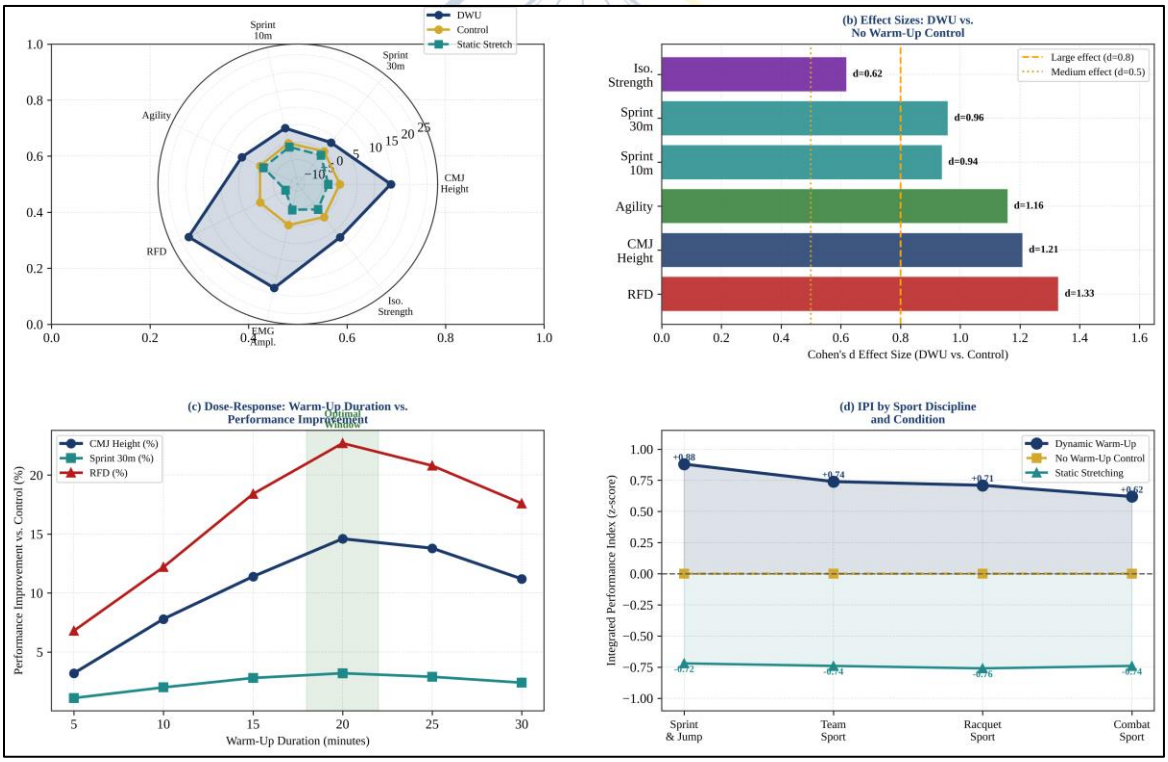


Fig. 10. Comprehensive multi-panel performance summary showing (a) radar chart of relative performance across all assessed domains, (b) Cohen's d effect sizes for DWU versus control comparisons, (c) dose-response relationship between warm-up duration and performance improvement, and (d) Integrated Performance Index by sport discipline and condition.

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Fig. 10 consolidates the principal findings of the study in four panels. Panel (a) is a radar chart of percentage change relative to the no-warm-up baseline across seven outcome measures (10 m sprint, 30 m sprint, countermovement jump height, isokinetic strength, EMG amplitude, rate of force development, and agility). The dynamic warm-up polygon encloses the largest area on every axis, the control polygon sits at an intermediate level, and the static stretching polygon falls closest to the centre, reaching negative values on several axes, which visualizes the divergence between active and passive preparation. Panel (b) ranks the Cohen's d effect sizes for dynamic warm-up versus control, from d = 1.33 for rate of force development, followed by countermovement jump height (d = 1.21) and agility (d = 1.16), to sprint 30 m (d = 0.96), sprint 10 m (d = 0.94) and isokinetic strength (d = 0.62); all bars exceed the medium-effect reference line at d = 0.5, and all except isokinetic strength exceed the large-effect threshold at d = 0.8. Panel (c) shows the dose-response relationship between warm-up duration (5 to 30 minutes) and improvement over control for jump height, 30 m sprint time and rate of force development. All three outcomes increase with duration, peak in the shaded window around 20 minutes (approximately 22.7% for rate of force development, 14.6% for jump height and 3.2% for sprint time), and decline at 25 and 30 minutes, indicating that longer protocols did not yield additional benefit and may begin to dissipate the gains. Panel (d) presents the Integrated Performance Index by sport discipline: dynamic warm-up produced positive z-scores in every discipline (+0.88 for sprint and jump, +0.74 for team sport, +0.71 for racquet sport and +0.62 for combat sport), while static stretching produced a mirrored negative deviation of roughly -0.72 to -0.76 about the control baseline of zero.

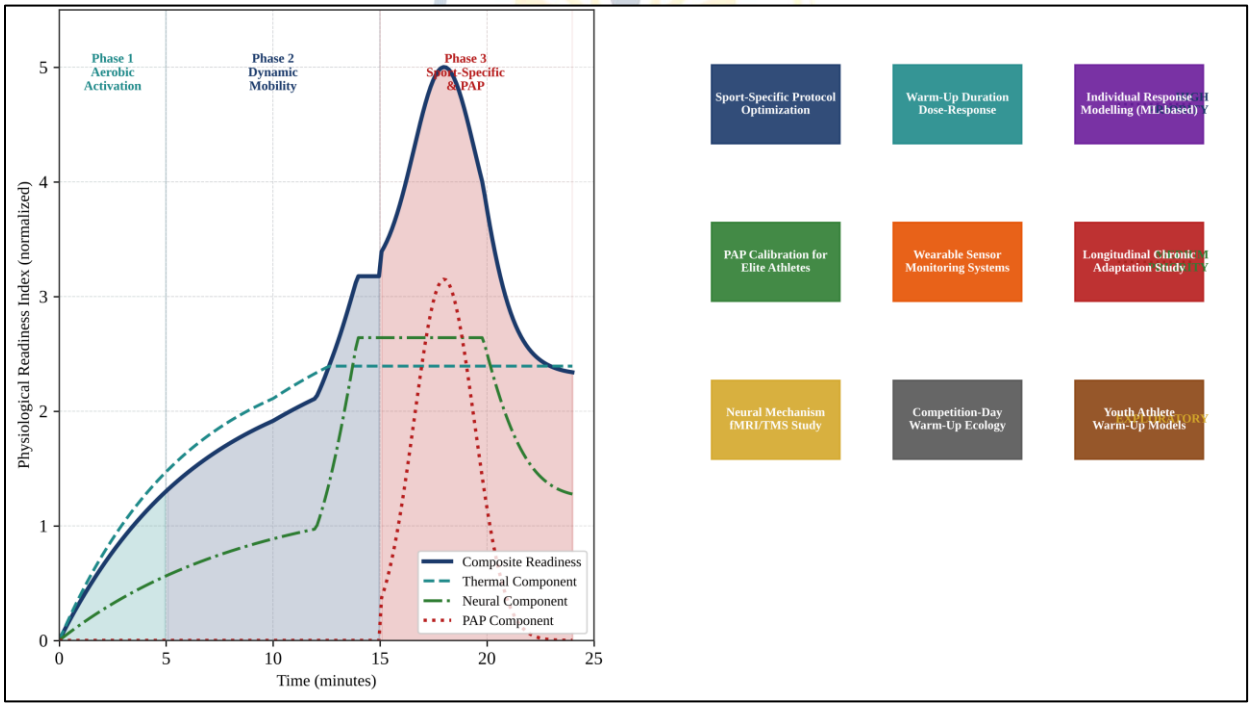


Fig. 11. Practical implementation model depicting (a) physiological readiness index evolution across the three-phase dynamic warm-up protocol with thermal, neural, and PAP component contributions and (b) future research priority matrix organized by investigation domain and recommended development priority.

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Fig. 11 presents the practical implementation model derived from the results. Panel (a) plots the normalized physiological readiness index across the 24-minute protocol, divided into three phases. During Phase 1 (aerobic activation, 0 to 5 minutes) the composite readiness index rises steadily, driven mainly by the thermal component, which increases quickly and then levels off at roughly 2.4 after about 12 minutes. In Phase 2 (dynamic mobility, 5 to 15 minutes) the neural component, initially lower, climbs sharply between approximately 12 and 14 minutes to a plateau near 2.6, and the composite index reaches about 3.2 by the end of the phase. In Phase 3 (sport-specific activity and post-activation potentiation, from 15 minutes) the post-activation potentiation component appears, peaks at approximately 3.1 around 18 minutes, and returns towards zero by about 23 minutes, while the composite index peaks at about 5.0 near minute 18 and then declines to approximately 2.3 by the end of the window. The figure therefore indicates that the thermal, neural and potentiation contributions are staggered in time, and that peak readiness occurs shortly after the potentiation component is engaged rather than at the end of the protocol, which supports completing the warm-up close to the start of competition or testing. Panel (b) is a research priority matrix arranged as a three-by-three grid of future investigation topics: sport-specific protocol optimization, warm-up duration dose-response, and machine-learning-based individual response modelling in the top row; potentiation calibration for elite athletes, wearable sensor monitoring systems, and longitudinal chronic adaptation in the middle row; and neural mechanism studies using fMRI and TMS, competition-day warm-up ecology, and youth athlete warm-up models in the bottom row. The rows correspond to descending development priority, and these topics form the basis of the future research agenda described in Section 6.

5. Conclusion

This investigation has provided a systematic and multi-dimensional experimental characterization of dynamic warm-up effects on muscular strength, power output, and physical performance in a diverse cohort of 96 competitive athletes across four sport discipline categories. The primary findings confirm that a structured 20-minute progressive dynamic warm-up protocol produces statistically significant and practically meaningful improvements across all assessed performance domains compared to both a static stretching condition and a no-warm-up control. Muscle temperature rose by 1.84 degrees Celsius following dynamic warm-up, compared to 0.64 degrees Celsius following static stretching and negligible change at rest, providing a measurable thermal stimulus that contributes to subsequent performance enhancement through thermodynamically mediated improvements in enzymatic kinetics and muscle contractile properties. Countermovement jump height improved by 14.6%, 30-meter sprint time improved by 3.2%, agility T-test performance improved by 5.8%, rate of force development improved by 22.7%, and surface EMG activation amplitude increased by 18.4% following dynamic warm-up relative to the no-warm-up control. These convergent findings across diverse performance metrics provide robust evidence that dynamic warm-up comprehensively enhances neuromuscular readiness. The static stretching condition produced performance outcomes at or below the no-warm-up control on every assessed measure, confirming that prolonged pre-exercise static stretching does not provide a viable alternative to dynamic movement preparation when the immediate competitive goal requires maximal power, speed, or agility output. Sport discipline moderated warm-up responsiveness, with sprint and jump athletes deriving the largest benefits and combat sport athletes the smallest, findings that have practical implications for sport-specific warm-up protocol design. These results

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collectively confirm that dynamic warm-up represents an essential and evidence-based component of pre-competition preparation for competitive athletes across sport disciplines and should be systematically incorporated into competition preparation routines designed by coaches and strength and conditioning professionals.

6. Discussion and Future Work

The findings of the present investigation extend the existing evidence base on dynamic warm-up in several important directions while simultaneously identifying limitations and unanswered questions that motivate future research. The comprehensive multi-outcome assessment approach employed here provides a more complete picture of dynamic warm-up benefits than studies examining single performance metrics in isolation, and the crossover design with standardized sport discipline representation adds ecological validity lacking in many laboratory warm-up investigations conducted with homogeneous student samples.

A central contribution of the present study is the quantification of sport discipline-specific warm-up responsiveness, which suggests that warm-up protocols tailored to the neuromuscular demands and movement patterns of specific sport disciplines may produce larger performance benefits than generic protocols applied uniformly across athletic populations. Future research should develop and evaluate sport-specific warm-up protocols using randomized controlled designs with adequate power to detect discipline-by-condition interaction effects and should incorporate sport performance outcome measures, such as ball velocity in throwing sports or time trial performance in endurance sports, that more directly reflect the competitive outputs relevant to each discipline.

The electromyographic findings raise important questions about the neural mechanisms underlying dynamic warm-up-induced performance enhancement that warrant further investigation using more sophisticated neurophysiological tools. High-density EMG, transcranial magnetic stimulation-evoked cortical silent periods, and peripheral nerve conduction velocity measurements could be employed in future studies to disaggregate the contributions of spinal and supraspinal neural mechanisms to the activation amplitude increases observed following dynamic warm-up. Additionally, the finding that biceps femoris activation was selectively impaired by static stretching merits follow-up investigation examining whether targeted dynamic activation of the hamstring complex as part of a warm-up sequence specifically mitigates this inhibitory effect.

Emerging developments in artificial intelligence, advanced computational modelling, and real-time monitoring provide promising opportunities for extending conventional experimental approaches in sports performance research. Majeed et al. (2026) examined mathematical optimization and high-dimensional data analysis techniques for machine learning applications, offering a relevant computational foundation for the analysis of multidimensional physiological and performance datasets. Similarly, Shakeel et al. (2026) presented a comparative investigation of statistical, machine-learning, and deep-learning forecasting approaches, highlighting methodological considerations relevant to selecting predictive models for complex datasets. Khalil et al. (2025) investigated AI-driven predictive analytics and real-time monitoring in clinical decision-support systems, while Soomro et al. (2025) explored machine-learning-based predictive monitoring and regression algorithms for identifying changes in system performance. Furthermore, Haq et al. (2025) examined edge computing architectures designed to reduce latency and support real-time decision-making in IoT environments. Although these investigations were conducted outside sports science, their computational approaches suggest potential directions for future research integrating wearable physiological sensors, electromyographic

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measurements, individualized neuromuscular readiness assessment, and machine-learning-based performance prediction. Such interdisciplinary integration could facilitate the development of adaptive warm-up recommendations based on athletes' physiological characteristics, training status, and sport-specific performance requirements.

Future research should also examine the durability of dynamic warm-up-induced performance enhancement across varying transition periods between warm-up completion and competition commencement, as athletes competing in multi-heat formats or as non-starting team members may experience substantial delays between their warm-up routine and competitive performance initiation. Optimizing warm-up maintenance strategies for situations requiring extended pre-competition waiting periods represents a practically important area where experimental evidence remains limited. Longitudinal investigations examining whether habitual dynamic warm-up practice produces chronic adaptations in neuromuscular responsiveness, independent of acute potentiation effects, would further strengthen the scientific rationale for systematic warm-up integration across training and competition cycles. The development of wearable sensor-based monitoring systems capable of objectively quantifying warm-up intensity, muscle temperature, and neuromuscular activation in real competitive environments represents a promising technological direction that could bridge the gap between laboratory evidence and field-based application.

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