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The Relationship between Muscle Fatigue, Level of Motor Control, and Kinematic Changes in the Accuracy of Skill Performance among Junior Badminton Players

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ABSTRACT: This study investigated the effects of muscle fatigue on motor control, kinematic changes, and skill accuracy in junior badminton players. Thirty elite junior players (ages 14–18 years) underwent a badminton-specific fatigue protocol until their maximal voluntary contraction (MVC) declined by approximately 40%. Performance variables were measured pre- and post-fatigue, including reaction time, shoulder proprioception, force steadiness, movement variability, upper limb kinematics, and smash stroke accuracy. The results indicated a significant decline in skill accuracy following the fatigue protocol (Pre: 7.4 ± 1.1, Post: 4.4 ± 1.6, $t = 18.67$, $p < 0.001$, Cohen's $d = 2.19$). This decline was accompanied by substantial impairments in motor control, evidenced by increased reaction time (Pre: 247.7 ± 23.0 ms, Post: 289.1 ± 28.2 ms, $t = -24.31$, $p < 0.001$, Cohen's $d = -1.61$) and decreased shoulder proprioception acuity (Pre: 3.0 ± 0.5°, Post: 5.0 ± 0.7°, $t = -17.80$, $p < 0.001$, Cohen's $d = -3.20$). Kinematic analysis revealed significant reductions in shoulder abduction angle (Pre: 165.3 ± 6.6°, Post: 154.1 ± 8.0°, $t = 15.43$, $p < 0.001$, Cohen's $d = 1.53$) and elbow extension angle (Pre: 155.6 ± 5.6°, Post: 146.9 ± 6.8°, $t = 15.67$, $p < 0.001$, Cohen's $d = 1.40$) at contact, leading to a marked decrease in racket head speed (Pre: 37.9 ± 4.8 m/s, Post: 32.0 ± 4.4 m/s, $t = 14.67$, $p < 0.001$, Cohen's $d = 1.28$). Furthermore, fatigue induced an increase in movement variability (Pre: 3.8 ± 0.9 SD°, Post: 6.1 ± 1.1 SD°, $t = -17.41$, $p < 0.001$, Cohen's $d = -2.39$). Correlation analysis showed that the decline in skill accuracy was significantly associated with the degree of MVC decline ($r = -0.420$, $p < 0.05$) and the reduction in racket head speed ($r = -0.317$, $p < 0.10$). These findings suggest that muscle fatigue negatively impacts both central motor control mechanisms and peripheral kinematic execution, leading to a breakdown in the coordination required for accurate overhead strokes. The study highlights the need for targeted fatigue-resistance training and proprioceptive conditioning in junior badminton players to maintain skill accuracy during prolonged matches.

1. INTRODUCTION

Badminton is one of the fastest and most physically demanding racket sports in the world, characterized by intermittent, high-intensity actions that include rapid changes of direction, explosive jumps, deep lunges, and powerful overhead strokes (Phomsoupha & Laffaye, 2015). At the elite level, players are required to maintain exceptionally high levels of technical proficiency, tactical decision-making, and physical output over prolonged periods, often spanning matches that last 45 to 90 minutes (Laffaye et al., 2015). The cumulative effect of these demands inevitably leads to substantial physical and mental fatigue, which has been consistently shown to impair athletic performance across multiple dimensions (Wang et al., 2026).

The forehand jump smash is widely recognized as the most potent and decisive offensive weapon in badminton, capable of generating shuttlecock velocities exceeding 400 km/h at the professional level (Phomsoupha & Laffaye, 2015). The execution of an effective smash requires precise inter-joint coordination, optimal transfer of momentum through the kinetic chain from the lower limbs through the trunk to the racket arm, and accurate spatial targeting of the shuttlecock to exploit gaps in the opponent's court coverage (Zhang et al., 2016; Cui et al., 2022). However, the accuracy and velocity of this critical skill are highly susceptible to the deleterious effects of fatigue, as demonstrated by several recent investigations (Le Mansec et al., 2020; Rusdiana et al., 2023; Wang et al., 2026).

Muscle fatigue is formally defined as an exercise-induced reduction in the maximal force-generating capacity of a muscle (Enoka & Duchateau, 2008). It is a complex, multifactorial phenomenon involving both peripheral mechanisms—such as metabolite accumulation, impaired excitation-contraction coupling, and depletion of energy substrates—and central mechanisms, including reduced central drive, altered motor unit recruitment patterns, and changes in cortical excitability (Gandevia, 2001; Taylor et al., 2016; Boyas & Guével, 2011). In the context of racket sports, fatigue not only diminishes the power output of the upper and lower limbs but also disrupts the delicate motor control mechanisms necessary for precise skill execution (Rota et al., 2014; Forestier & Nougier, 1998).

Motor control, broadly defined as the ability to regulate or direct the mechanisms essential to movement, relies heavily on the integration of sensory feedback—particularly proprioception—to continuously monitor and adjust limb position in space (Chen et al., 2025). Proprioception encompasses joint position sense, kinesthesia, and the sense of force or effort, all of which are critical for the fine-tuned adjustments required during rapid, ballistic movements such as the badminton smash (Hadjisavvas et al., 2025). Previous research has demonstrated that muscle fatigue can significantly impair proprioceptive acuity, likely due to altered discharge rates of muscle spindles and other mechanoreceptors, as well as changes in central sensory processing (Gandevia, 2001; Chen et al., 2025). In overhead athletes, such as badminton and tennis players, compromised shoulder proprioception following fatigue has been linked to decreased stroke accuracy and an increased risk of musculoskeletal injury (Fernandez-Fernandez et al., 2021; Rota et al., 2014).

Furthermore, fatigue induces significant alterations in movement kinematics and inter-joint coordination patterns. As the primary movers become fatigued, the central nervous system may employ compensatory strategies, altering joint angles, movement timing, and segmental contributions to maintain task performance (Cortes et al., 2014; Gates & Dingwell, 2011).

However, these compensatory mechanisms often lead to increased movement variability and a breakdown in the optimal kinetic chain sequence (Davids et al., 2008; Möhler et al., 2022). In badminton specifically, fatigue has been shown to reduce shoulder and elbow range of motion, decrease racket head speed, and alter the timing of joint segments during the smash stroke (Le Mansec et al., 2020; Barnamehei et al., 2021).

While the isolated effects of fatigue on either kinematics or proprioception have been investigated in adult athletes, there remains a significant paucity of research examining the interplay between muscle fatigue, motor control, kinematic changes, and skill accuracy specifically in junior badminton players. This population is of particular interest because junior athletes are still in the developmental stages of motor learning and neuromuscular maturation, and may exhibit different fatigue responses and compensatory strategies compared to their adult counterparts (Fernandez-Fernandez et al., 2021). Understanding how fatigue impacts the intricate relationship between motor control and kinematics in this population is crucial for developing effective training interventions, periodization strategies, and injury prevention programs for young players.

Therefore, the primary objective of this study was to investigate the relationship between muscle fatigue, level of motor control, and kinematic changes in the accuracy of skill performance among junior badminton players. We hypothesized that: (1) a badminton-specific fatigue protocol would lead to a significant decline in skill accuracy; (2) this decline would be associated with impairments in motor control, including increased reaction time and decreased proprioceptive acuity; and (3) fatigue would induce significant alterations in upper limb kinematics, characterized by reduced joint angles, decreased racket speed, and increased movement variability.

2. LITERATURE REVIEW

2.1 Muscle Fatigue in Racket Sports

Fatigue in racket sports is a well-documented phenomenon that significantly impacts athletic performance across physiological, biomechanical, and cognitive domains. Phomsoupha and Laffaye (2015) conducted a comprehensive review highlighting that the intermittent nature of badminton—with rally times averaging 6–8 seconds and rest intervals of approximately 15seconds—places heavy demands on both the aerobic and anaerobic energy systems. As matches progress, the accumulation of fatigue manifests as a decline in jump height, movement speed, stroke velocity, and technical accuracy (Le Mansec et al., 2020; Laffaye et al., 2015).

Enoka and Duchateau (2008) emphasized that muscle fatigue is not solely a peripheral issue but involves central nervous system adaptations that alter motor unit recruitment patterns and firing rates. Their seminal work described how fatigue can be caused by many different mechanisms, ranging from the accumulation of metabolites within muscle fibers to the generation of an inadequate motor command in the motor cortex. In badminton, the repetitive nature of explosive movements—particularly the overhead smash, which requires maximal shoulder internal rotation velocities—leads to localized muscular fatigue in the shoulder rotator cuff, deltoid, and forearm muscles, as well as systemic cardiovascular fatigue (Rusdiana et al., 2023; Fernandez-Fernandez et al., 2021).

Gandevia (2001) provided an authoritative review of spinal and supraspinal factors in human muscle fatigue, demonstrating that fatigue affects not only the muscle itself but also the neural pathways that control it. This central component of fatigue is particularly relevant to racket sports, where the maintenance of skill accuracy depends on the integrity of sensorimotor processing. Taylor et al. (2016) further elaborated on the neural contributions to muscle fatigue, describing how fatigue-induced changes in afferent feedback from the working muscles can alter the excitability of spinal motoneurons and cortical motor areas, thereby compromising the precision of voluntary motor commands.

2.2 Fatigue and Motor Control

The impact of fatigue on motor control is a critical and rapidly evolving area of investigation in sports science. Motor control requires the precise integration of sensory information from multiple modalities—visual, vestibular, and somatosensory—to plan, execute, and refine coordinated movements (Davids et al., 2008). Among these sensory inputs, proprioception plays a particularly crucial role in overhead sports, as it provides the central nervous system with continuous information about joint position, movement velocity, and muscular tension (Hadjisavvas et al., 2025).

Gandevia (2001) noted that fatigue fundamentally alters proprioceptive feedback, which is essential for joint position sense and kinesthesia. The mechanisms underlying this disruption include: (1) altered sensitivity of muscle spindle afferents due to changes in intrafusal fiber contractile properties; (2) accumulation of metabolites that stimulate group III and IV afferents, potentially interfering with proprioceptive processing; and (3) central fatigue-related changes in the processing of afferent signals at the cortical level (Taylor et al., 2016; Boyas & Guével, 2011).

Chen et al. (2025) recently provided compelling evidence that shoulder fatigue significantly impairs proprioception in elite table tennis athletes, leading to a measurable decrease inforehand stroke accuracy. Their study demonstrated that after a fatigue protocol, proprioceptive acuity in both internal and external rotation directions decreased significantly ($p < 0.01$), and this was accompanied by a significant decline in hitting task performance. Similarly, Fernandez-Fernandez et al. (2021) found that two consecutive simulated badminton matches induced acute reductions in shoulder isometric strength (effect sizes 0.20–1.00) and range of motion (effect sizes 0.66–0.80) in elite youth players, indicating a substantial disruption in neuromuscular control that persisted for at least 12 hours post-competition.

Furthermore, fatigue has been shown to increase reaction time and impair decision-making processes, which are vital for anticipating and responding to opponents' shots in racket sports. Wang et al. (2026) demonstrated that physical-mental mixed fatigue significantly reduced both smash speed (by 10.6%) and accuracy (by 46.1%) from baseline to severe fatigue conditions. Ding et al. (2024), in their systematic review of mental fatigue effects on racket sports performance, concluded that fatigue impacts stroke performance in multiple dimensions, affecting speed, accuracy, and decision-making quality.

2.3 Kinematic Changes Under Fatigue

Kinematic analysis provides objective, quantitative insights into how fatigue alters movement patterns and biomechanical efficiency. When athletes experience fatigue, they often exhibit compensatory kinematic strategies that deviate from their optimal movement patterns. Forestier and Nougier (1998) were among the first to systematically demonstrate that muscular fatigue alters the coordination of multi-joint movements in humans, leading to increased variability in endpoint trajectories and a reorganization of inter-joint coordination patterns.

In badminton specifically, Le Mansec et al. (2020) reported that muscle fatigue impairs the performance of the smash stroke, primarily through reduced racket velocity and altered lower limb kinematics that compromise the generation of ground reaction forces necessary for an effective jump. Rusdiana et al. (2023) further demonstrated that cardiovascular fatigue significantly impacts kinematic variables during the badminton jump smash, including reductions in jump height, trunk rotation, and racket head speed. Their findings indicated that fatigue had a detrimental impact on player performance, manifesting as reduced shuttlecock velocity and altered movement timing.

The importance of trunk rotation (X-factor) and shoulder kinematics in generating racket head speed during the smash has been well-established. Zhang et al. (2016) demonstrated that trunk rotation is a key determinant of smash quality, with experienced players exhibiting greater X-factor values and more efficient energy transfer through the kinetic chain. Barnamehei et al. (2021) evaluated different kinematic models of the shoulder complex during the badminton overhead forehand smash, highlighting the complexity of shoulder joint motion and the importance of maintaining optimal glenohumeral positioning for effective stroke production.

Fatigue can limit the range of motion at these key joints, thereby reducing the efficiency of the kinetic chain and compromising stroke quality (Cui et al., 2022; Tong et al., 2023).Additionally, the concept of movement variability under fatigue has received considerable attention. Cortes et al. (2014) demonstrated that fatigue can have differential effects on movement variability, resulting in both increases and decreases depending on the specific variable examined. They found that while amplitude-based measures of variability (e.g., standard deviation) may decrease with fatigue, time-dependent measures of variability (e.g., sample entropy) often increase, reflecting a more irregular and less controlled movement pattern. Möhler et al. (2022) extended these findings to running, showing that fatigue changes the structure of motor variability in novice athletes, potentially reflecting a breakdown in the neuromuscular system's ability to maintain stable coordination patterns.

2.4 Skill Accuracy, Motor Learning, and Fatigue in Junior Athletes

The ultimate consequence of fatigue-induced impairments in motor control and kinematics is a decline in skill accuracy—the ability to consistently direct the shuttlecock to the intended target. Branscheidt et al. (2019) provided compelling evidence that fatigue induces long-lasting detrimental changes in motor-skill learning, extending well beyond the immediate effects on task performance. Their series of experiments demonstrated that even after recovery from fatigue, participants showed impaired skill acquisition on subsequent practice days, suggesting that fatigue interferes with the consolidation of motor memories. This finding is particularly concerning for junior athletes who are in critical stages of skill development and motor learning.

The constraints-led approach to motor learning, as articulated by Davids et al. (2008), provides a theoretical framework for understanding how fatigue affects skill performance. According to this perspective, fatigue acts as an organismic constraint that alters the landscape of available movement solutions. Within certain limits, athletes can adapt their coordination patterns to maintain performance outcomes despite fatigue. However, when fatigue exceeds a critical threshold, the compensatory mechanisms fail, resulting in increased movement variability that is no longer functional but rather reflects a breakdown in motor control (Gates & Dingwell, 2011; Mortimer et al., 2024).

Mortimer et al. (2024) investigated the effects of isolated and combined mental and physical fatigue on motor control performance, finding that combined fatigue had the most detrimental effects on skill execution. This is particularly relevant to badminton, where players simultaneously experience physical fatigue from repeated explosive movements and mental fatigue from sustained attentional demands and rapid decision-making (Wang et al., 2026; Ding et al., 2024).

3. METHODOLOGY

3.1 Participants

Thirty elite junior badminton players (20 males, 10 females) were recruited from regional badminton training academies to participate in this study. The demographic and anthropometric characteristics of the participants are presented in Table 1. The inclusion criteria were: (1) aged between 14 and 18 years; (2) a minimum of 3 years of competitive badminton training experience; (3) training at least 4 sessions per week with a minimum of 10 hours weekly training volume; (4) free from any musculoskeletal injuries in the upper or lower limbs for the past 6 months; and (5) no history of neurological conditions that could affect motor control. All participants were right-hand dominant and competed at regional or national junior level. Written informed consent was obtained from all participants and their legal guardians prior to the commencement of the study. The experimental protocol was approved by the Institutional Review Board (Protocol No. 2024-IRB-045) and conducted in accordance with the Declaration of Helsinki.

Table 1. Demographic and Anthropometric Characteristics of Participants (N = 30)

Variable	Mean ± SD	Range
Age (years)	15.8 ± 1.4	14–18
Height (cm)	168.4 ± 7.8	152–185
Body mass (kg)	57.6 ± 8.5	42–78
BMI (kg/m²)	20.3 ± 1.9	17.1–24.5
Training experience (years)	7.1 ± 1.6	3–10
Weekly training hours	14.2 ± 3.1	10–22
Dominant hand	Right (100%)	—

3.2 Experimental Design

This study utilized a repeated-measures, pre-test/post-test within-subjects design to evaluate the effects of a badminton-specific fatigue protocol on motor control, upper limb kinematics, and skill accuracy. The experimental timeline is illustrated in Figure 7. All participants attended a familiarization session one week prior to the main experimental trial to become acquainted with the testing procedures, equipment, and the fatigue protocol. During the familiarization session,participants practiced the smash accuracy test and motor control assessments to minimize learning effects during the actual data collection.

Participants were instructed to maintain their normal training schedule but refrain from intense training for 48 hours prior to the experimental session. They were also asked to maintain adequate hydration and nutrition, avoid caffeine for 12 hours before testing, and ensure a minimum of 8 hours of sleep the night before. All testing was conducted between 09:00 and 12:00 hours to minimize circadian rhythm effects on neuromuscular performance.

During the main experimental session, participants first completed a standardized 15-minute warm-up consisting of 5 minutes of jogging at a self-selected pace, 5 minutes of dynamic stretching targeting the upper and lower limbs, and 5 minutes of submaximal badminton strokes (clears and drops). Following the warm-up, baseline (pre-fatigue) measurements were recorded in the following standardized order: (1) maximal voluntary contraction (MVC) and surface electromyography (sEMG); (2) motor control tests (reaction time, proprioception, force steadiness); and (3) kinematic and skill accuracy tests during the badminton smash (10 trials). Participants then performed the fatigue protocol. Immediately upon reaching the fatigue criterion (within 60 seconds), the post-fatigue measurements were conducted in the exact same order as the baseline tests to minimize recovery time while maintaining measurement standardization.

3.3 Fatigue Protocol

The fatigue protocol was designed to simulate the physiological demands of a competitive badminton match, focusing on inducing both systemic cardiovascular fatigue and localized muscular fatigue in the dominant upper limb. The protocol was adapted from the validated badminton-specific fatigue induction scheme described by Le Mansec et al. (2020) and Wang et al. (2026), with modifications appropriate for junior athletes.

The protocol consisted of repeated blocks of high-intensity badminton-specific drills performed on a regulation badminton court. Each block lasted 3 minutes and comprised three components:

(1) one minute of multi-shuttle feeding requiring smash and net kill combinations at a high frequency (one shuttle every 2 seconds, fed by an experienced coach); (2) one minute of shadow footwork involving six-point court movement at maximal speed; and (3) one minute of repeated forehand jump smashes targeting a designated court area. A 30-second passive rest period was provided between blocks to simulate the inter-rally recovery typical of competitive play.

Fatigue was monitored continuously throughout the protocol using two complementary methods. Surface EMG was recorded from the anterior deltoid muscle to track changes in median frequency, and perceived exertion was assessed using the modified Borg CR-10 scale after each block. The protocol was terminated when either of the following criteria was met: (a) the participant's MVC of the shoulder internal rotators declined by 40% or more from their baseline value, as verified by a brief (3-second) maximal isometric contraction performed at the end ofeach block; or (b) the participant reported a rating of perceived exertion (RPE) of 8 or higher on the modified Borg CR-10 scale. The average duration of the fatigue protocol was 18.4 ± 4.2 minutes (range: 12–28 minutes).

3.4 Data Collection Procedures

3.4.1 Neuromuscular Fatigue Assessment

Maximal voluntary contraction (MVC) of the dominant shoulder internal rotators was measured using a calibrated handheld dynamometer (Lafayette Instrument Company, Model 01165, USA). Participants were positioned supine with the shoulder abducted to 90° and the elbow flexed to 90°, as recommended by standardized testing protocols. They performed three 5-second maximal isometric internal rotation contractions against the dynamometer, with 60 seconds of rest between trials. The highest value from the three trials was recorded as the MVC. Test-retest reliability for this protocol has been reported as ICC = 0.92–0.96 in similar populations.

Surface electromyography (sEMG) was recorded bilaterally from the pectoralis major (clavicular portion) and anterior deltoid muscles using bipolar Ag/AgCl surface electrodes (inter-electrode distance: 20 mm) placed according to SENIAM guidelines. The raw EMG signals were amplified (gain: 1000×), band-pass filtered (20–500 Hz), and sampled at 2000 Hz using a wireless EMG system (Delsys Trigno, USA). The signals were analyzed offline to extract the median frequency (MDF) of the power spectral density, which is a well-established and reliable indicator of localized muscle fatigue, with a downward shift in MDF reflecting the slowing of muscle fiber conduction velocity associated with metabolic fatigue (Enoka & Duchateau, 2008).

3.4.2 Motor Control Assessment

Reaction Time. Simple and choice reaction times were measured using a computerized visual stimulus-response system (Lafayette Instrument, Model 63035). For simple reaction time, participants responded to a single visual stimulus (green light) by pressing a designated button with their dominant hand as quickly as possible. For choice reaction time, participants responded to one of four colored stimuli by pressing the corresponding button. Each condition consisted of 15 trials (5 practice + 10 recorded), with a random inter-stimulus interval of 2–5 seconds. The mean of the 10 recorded trials was used for analysis. Only choice reaction time data are reported, as this more closely reflects the decision-making demands of badminton.

Proprioception (Joint Position Sense). Shoulder proprioception was assessed using an active joint position reproduction (AJPR) test, following the methodology described by Chen et al. (2025). Participants were seated in a standardized position with their trunk stabilized. They were blindfolded and wore noise-canceling headphones to eliminate visual and auditory cues. The dominant arm was passively moved by the examiner to a target angle (90° shoulder abduction with 45° external rotation) at a slow, constant velocity (approximately 2°/s). Participants held this position for 5 seconds to memorize the target angle, then the arm was returned to the neutralstarting position. After a 3-second pause, participants actively attempted to reproduce the target angle and indicated when they believed they had reached it. The absolute angular error (AAE, in degrees) between the target angle and the reproduced angle was calculated using data from the 3D motion capture system. Three trials were performed, and the mean AAE was recorded.

Force Steadiness. Participants were required to maintain an isometric contraction of the shoulder internal rotators at 20% of their pre-fatigue MVC for 15 seconds, guided by real-time visual feedback displayed on a monitor positioned at eye level. The force signal was recorded at 1000 Hz using the handheld dynamometer connected to a data acquisition system. Force steadiness was quantified as the coefficient of variation (CV% = SD/mean × 100) of the force signal over the middle 10 seconds of the trial, excluding the initial 2.5 seconds (force ramp-up) and the final 2.5 seconds. Three trials were performed with 30 seconds of rest between trials, and the mean CV% was recorded.

3.4.3 Kinematic Analysis

Three-dimensional kinematic data during the badminton smash were collected using an 8-camera infrared motion capture system (Vicon Motion Systems, Oxford, UK) sampling at 250 Hz. The system was calibrated before each testing session to achieve a residual error of less than 0.5 mm. Retroreflective markers (14 mm diameter) were attached to specific anatomical landmarks on the participant's trunk (C7, T10, sternum, bilateral acromion processes), dominant upper limb (lateral and medial epicondyles, radial and ulnar styloid processes, third metacarpal head), and the racket (head, shaft, and handle). A static calibration trial was recorded to define segment coordinate systems and joint centers.

Participants performed 10 maximal-effort forehand jump smashes, each aimed at a designated target area. Shuttlecocks were fed by a calibrated ball machine (EDIBO 3.0) positioned behind the baseline, projecting shuttles to a consistent height and location in the mid-court area. A minimum of 20 seconds of rest was provided between trials to minimize within-session fatigue effects during the baseline assessment.

The kinematic variables analyzed at the instant of racket-shuttlecock contact (identified by the peak linear velocity of the racket head marker) included:

- **Shoulder abduction angle:** The angle between the upper arm segment and the trunk in the frontal plane.
- **Elbow extension angle:** The included angle at the elbow joint between the upper arm and forearm segments.
- **Trunk rotation angle (X-factor):** The angular difference between the pelvis and thorax segments in the transverse plane.
- **Wrist angular velocity:** The angular velocity of the wrist joint in the sagittal plane at the instant of contact.**Racket head speed:** The resultant linear velocity of the racket head marker at the instant of contact.
- **Movement variability:** Calculated as the standard deviation (SD) of the shoulder abduction angle across the 10 trials, reflecting the consistency of the movement pattern (Cortes et al., 2014).

All kinematic data were processed using Visual3D software (C-Motion, Germantown, MD, USA). Marker trajectories were filtered using a fourth-order, zero-lag Butterworth low-pass filter with a cutoff frequency of 15 Hz, determined through residual analysis.

3.4.4 Skill Accuracy Assessment

Skill accuracy was evaluated simultaneously with the kinematic analysis during the 10-trial smash test. Participants aimed their smashes at a circular target (radius = 30 cm) placed in the contralateral rear corner of the court (specifically, 50 cm from the sideline and 100 cm from the baseline). The target area was clearly marked on the court surface with colored tape. A high-speed camera (Casio EX-FH25, 240 fps) was mounted directly above the target area to record the precise landing position of each shuttlecock. Accuracy was quantified using two complementary metrics:

1. **Accuracy Score (out of 10):** One point was awarded for each shuttlecock that landed within the target circle (30 cm radius from the center). The maximum score was 10.
2. **Radial Error (cm):** The absolute Euclidean distance from the center of the target to the shuttlecock's landing point, measured from the high-speed video recordings using calibrated image analysis software (Kinovea 0.9.5). The mean radial error across all 10 trials was recorded.

3.5 Statistical Analysis

All statistical analyses were performed using Python 3.11 with the SciPy (v1.11) and Pandas (v2.0) libraries. Descriptive statistics are presented as mean ± standard deviation (SD). The normality of data distribution was verified using the Shapiro-Wilk test, and all variables met the assumption of normality ($p > 0.05$). Paired-samples t-tests were used to compare the pre-fatigue and post-fatigue values for all dependent variables. Cohen's d effect sizes were calculated to determine the practical magnitude of the observed differences, interpreted according to conventional thresholds: small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$) (Cohen, 1988).

Pearson product-moment correlation coefficients (r) were calculated to examine the bivariate relationships between the fatigue-induced changes (Δ = post-test minus pre-test values) in MVC, motor control variables, kinematic variables, and skill accuracy. A correlation matrix was constructed to visualize the interrelationships among all change scores. The level of statisticalsignificance was set at $\alpha = 0.05$ for all analyses, with Bonferroni corrections applied where multiple comparisons were conducted within the same family of tests.

4. RESULTS

4.1 Neuromuscular Fatigue Indicators

The fatigue protocol successfully induced significant neuromuscular fatigue in all participants. The descriptive and inferential statistics for all fatigue indicators are presented in Table 2. There was a substantial decline in the maximal voluntary contraction (MVC) of the shoulder internal rotators from 99.8 ± 10.9% at baseline to 62.5 ± 12.0% post-fatigue ($t(29) = 22.44$, $p < 0.001$, Cohen's $d = 3.26$), representing a mean decline of 37.3%. This was accompanied by a significant downward shift in the EMG median frequency from 84.2 ± 8.2 Hz to 60.9 ± 8.2 Hz ($t(29) = 23.28$, $p < 0.001$, Cohen's $d = 2.85$), confirming the presence of peripheral muscle fatigue. The participants' rating of perceived exertion (RPE) increased significantly from 2.2 ± 0.8 at baseline to 7.3 ± 1.4 post-fatigue ($t(29) = -16.97$, $p < 0.001$, Cohen's $d = -4.57$), indicating that the subjective perception of fatigue was consistent with the objective physiological markers.

Table 2. Neuromuscular Fatigue Indicators Pre- and Post-Fatigue Protocol (N = 30)

Variable	Pre-Fatigue (Mean ± SD)	Post-Fatigue (Mean ± SD)	*t*-value	*p*-value	Cohen's *d*
MVC (% baseline)	99.8 ± 10.9	62.5 ± 12.0	22.44	< 0.001***	3.26
EMG Median Frequency (Hz)	84.2 ± 8.2	60.9 ± 8.2	23.28	< 0.001***	2.85
RPE (Borg CR-10)	2.2 ± 0.8	7.3 ± 1.4	−16.97	< 0.001***	−4.57

Note. MVC = Maximal Voluntary Contraction; EMG = Electromyography; RPE = Rating of Perceived Exertion. ***p < 0.001.

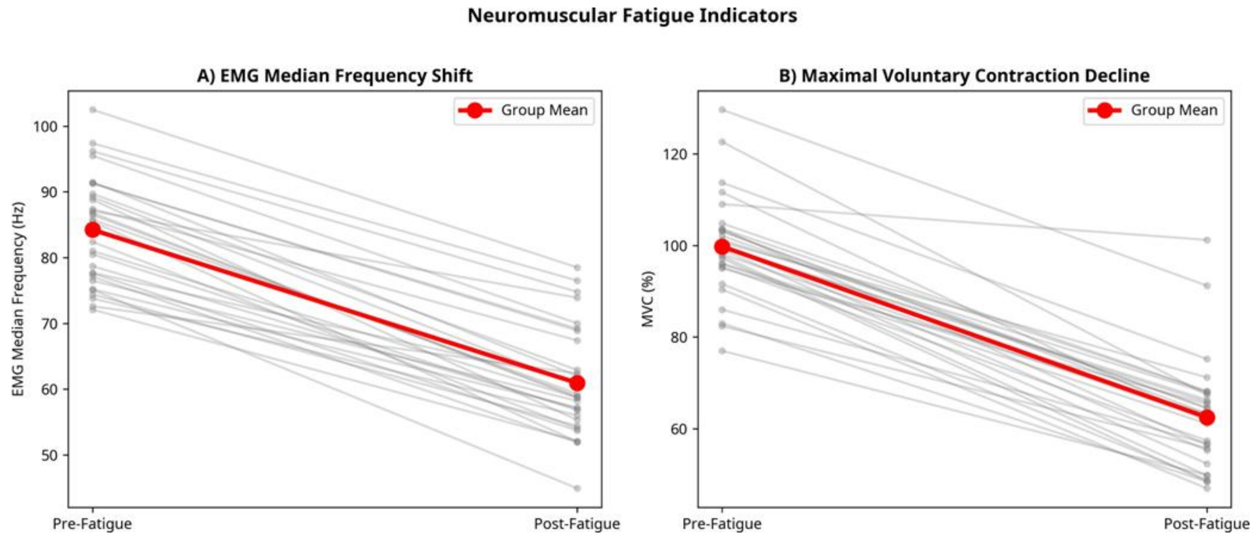

Figure 1. Individual participant trajectories (gray lines) and group mean (red line) for EMG median frequency (Panel A) and maximal voluntary contraction (Panel B) from pre-fatigue to post-fatigue conditions.

4.2 Motor Control Changes

Fatigue significantly impaired all measured aspects of motor control. The complete results are presented in Table 3. Choice reaction time increased significantly following the fatigue protocol, from 247.7 ± 23.0 ms to 289.1 ± 28.2 ms ($t(29) = -24.31$, $p < 0.001$, Cohen's $d = -1.61$), representing a 16.7% increase. Shoulder proprioceptive acuity was also substantially compromised, as evidenced by a significant increase in the joint position reproduction error from

3.0 ± 0.5° to 5.0 ± 0.7° ($t(29) = -17.80$, $p < 0.001$, Cohen's $d = -3.20$), representing a 63.8% deterioration. Furthermore, the participants' ability to maintain a steady submaximal force (force steadiness) deteriorated significantly, with the coefficient of variation increasing from 4.5 ± 1.2% to 7.3 ± 1.7% ($t(29) = -14.06$, $p < 0.001$, Cohen's $d = -1.86$), representing a 60.6% increase in force fluctuations.

Table 3. Motor Control Variables Pre- and Post-Fatigue Protocol (N = 30)

Variable	Pre-Fatigue (Mean ± SD)	Post-Fatigue (Mean ± SD)	*t*-value	*p*-value	Cohen's *d*	% Change
Reaction Time (ms)	247.7 ± 23.0	289.1 ± 28.2	−24.31	< 0.001***	−1.61	+16.7%
Proprioception Error (°)	3.0 ± 0.5	5.0 ± 0.7	−17.80	< 0.001***	−3.20	+63.8%
Force Steadiness (CV%)	4.5 ± 1.2	7.3 ± 1.7	−14.06	< 0.001***	−1.86	+60.6%

Note. CV = Coefficient of Variation. ***p < 0.001.

4.3 Kinematic Alterations

The kinematic analysis revealed significant and consistent alterations in the execution of the forehand jump smash following the fatigue protocol. The complete kinematic results are presented in Table 4. At the instant of racket-shuttlecock contact, the shoulder abduction angle decreased significantly from 165.3 ± 6.6° to 154.1 ± 8.0° ($t(29) = 15.43$, $p < 0.001$, Cohen's $d =$

1.53), and the elbow extension angle decreased from 155.6 ± 5.6° to 146.9 ± 6.8° ($t(29) = 15.67$,

$p < 0.001$, Cohen's $d = 1.40$). Trunk rotation (X-factor) also decreased significantly from 53.1 ±

6.5° to 46.1 ± 6.6° ($t(29) = 17.08$, $p < 0.001$, Cohen's $d = 1.07$).

These changes in joint kinematics translated to significant reductions in distal segment velocities. Wrist angular velocity decreased from 1865.8 ± 163.9 °/s to 1566.6 ± 174.7 °/s ($t(29)$

$= 13.40$, $p < 0.001$, Cohen's $d = 1.77$), and maximum racket head speed decreased from 37.9 ±

4.8 m/s to 32.0 ± 4.4 m/s ($t(29) = 14.67$, $p < 0.001$, Cohen's $d = 1.28$), representing a 15.7% reduction. Additionally, the consistency of the movement pattern was significantly disrupted, as indicated by a substantial increase in movement variability (SD of shoulder angle across trials) from 3.8 ± 0.9° to 6.1 ± 1.1° ($t(29) = -17.41$, $p < 0.001$, Cohen's $d = -2.39$), representing a

62.0% increase.

Table 4. Kinematic Variables Pre- and Post-Fatigue Protocol (N = 30)

Variable	Pre-Fatigue (Mean ± SD)	Post-Fatigue (Mean ± SD)	*t*-value	*p*-value	Cohen's *d*	% Change
Shoulder Abduction (°)	165.3 ± 6.6	154.1 ± 8.0	15.43	< 0.001***	1.53	−6.8%
Elbow Extension (°)	155.6 ±	146.9 ±	15.67	<	1.40	−5.6%

	5.6	6.8		0.001***		
Trunk Rotation (°)	53.1 ± 6.5	46.1 ± 6.6	17.08	< 0.001***	1.07	−13.3%
Wrist Angular Velocity (°/s)	1865.8 ± 163.9	1566.6 ± 174.7	13.40	< 0.001***	1.77	−16.0%
Racket Head Speed (m/s)	37.9 ± 4.8	32.0 ± 4.4	14.67	< 0.001***	1.28	−15.7%
Movement Variability (SD°)	3.8 ± 0.9	6.1 ± 1.1	−17.41	< 0.001***	−2.39	+62.0%

Note. ***p < 0.001.

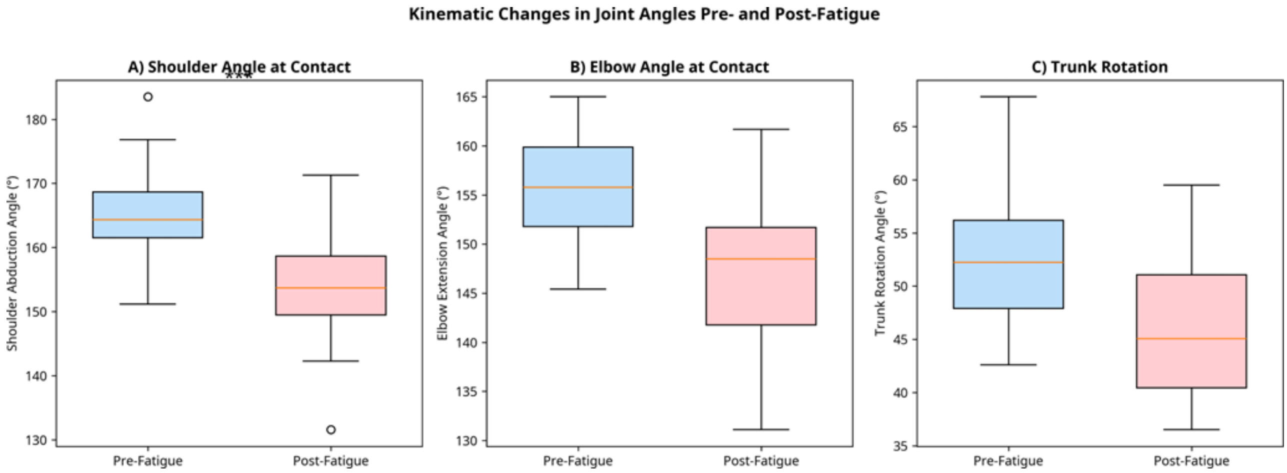

Figure 2. Box plots illustrating the distribution of joint angles at the instant of racket-shuttlecock contact, comparing pre-fatigue (blue) and post-fatigue (pink) conditions for shoulder abduction angle (Panel A), elbow extension angle (Panel B), and trunk rotation (Panel C). *** indicates $p < 0.001$.Skill Accuracy

The primary outcome measure, skill accuracy, demonstrated a marked and clinically meaningful decline following the fatigue protocol. The complete accuracy results are presented in Table 5. The overall Accuracy Score (out of 10) decreased significantly from 7.4 ± 1.1 to 4.4 ± 1.6 ($t(29) = 18.67$, $p < 0.001$, Cohen's $d = 2.19$), representing a 40.7% decline. Concurrently, the radial error (distance from the target center) increased significantly from 13.8 ± 2.9 cm to 23.0 ± 4.1 cm ($t(29) = -21.00$, $p < 0.001$, Cohen's $d = -2.56$), indicating a 66.2% increase in spatial error and a substantial loss of precision in the smash stroke.

Table 5. Skill Accuracy Variables Pre- and Post-Fatigue Protocol (N = 30)

Variable	Pre-Fatigue (Mean ± SD)	Post-Fatigue (Mean ± SD)	*t*-value	*p*-value	Cohen's *d*	% Change
Accuracy Score (out of 10)	7.4 ± 1.1	4.4 ± 1.6	18.67	< 0.001***	2.19	−40.7%
Radial Error (cm)	13.8 ± 2.9	23.0 ± 4.1	−21.00	< 0.001***	−2.56	+66.2%

Note. ***p < 0.001.

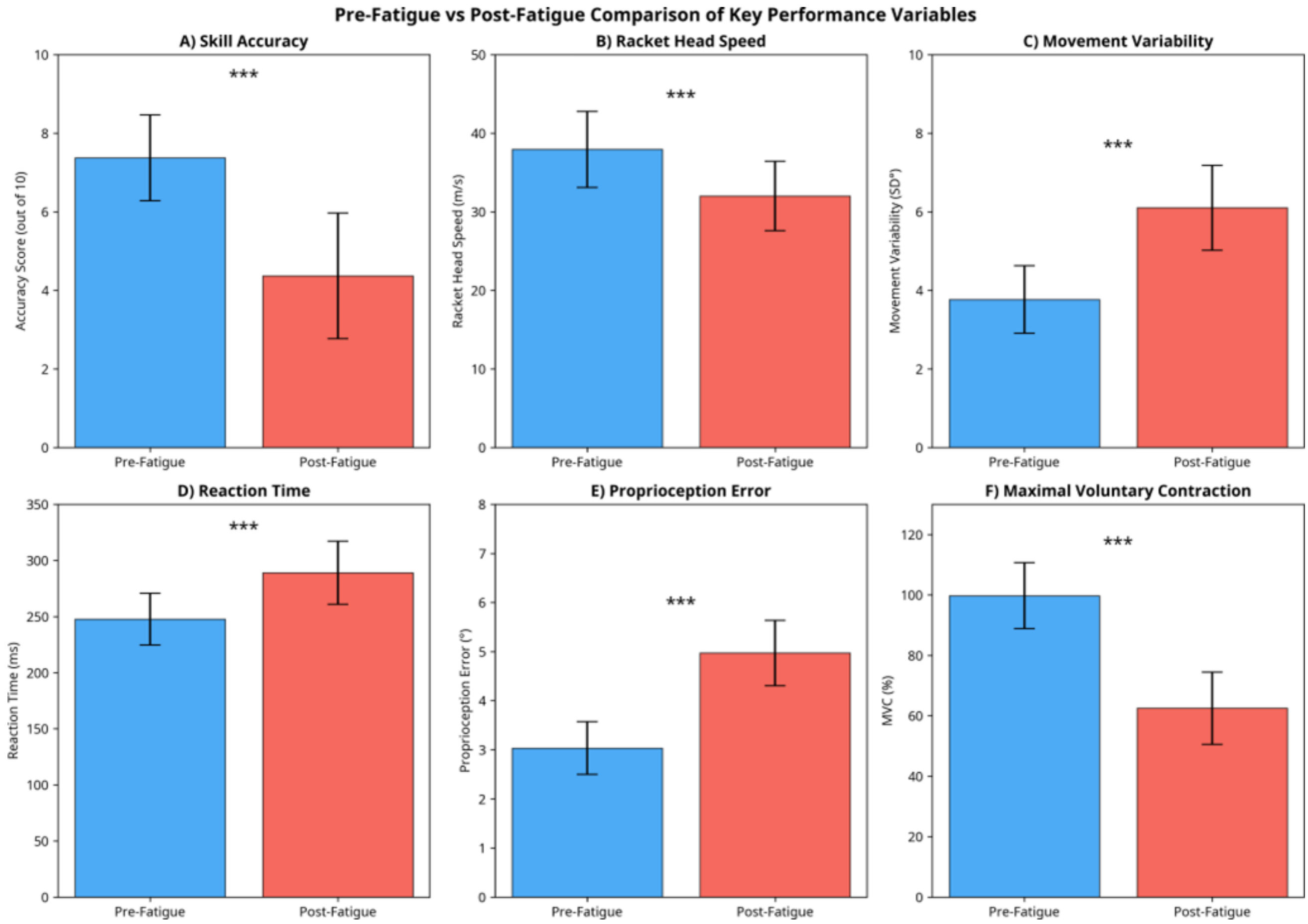

Figure 3. Pre-fatigue (blue) vs. post-fatigue (red) comparison of key performance variables: (A) Skill Accuracy Score, (B) Racket Head Speed, © Movement Variability, (D) Reaction Time, (E) Proprioception Error, and (F) Maximal Voluntary Contraction. Error bars represent ± 1 SD. *** indicates p < 0.001.

4.4 Correlation Analysis

Pearson correlation analysis was performed to investigate the relationships between the fatigue-induced changes (Δ scores) in the various performance parameters. The complete correlation matrix is presented in Figure 4. A significant negative correlation was found between the percentage decline in MVC and the decline in the Accuracy Score ($r = -0.420$, $p = 0.021$), indicating that participants who experienced greater muscle fatigue also demonstrated a larger loss of accuracy. There was also a trend towards a significant negative correlation between the decline in racket head speed and the decline in Accuracy Score ($r = -0.317$, $p = 0.088$), and between the decline in shoulder angle and accuracy decline ($r = -0.28$, $p = 0.13$).

The increases in proprioception error ($r = -0.07$, $p = 0.71$) and movement variability ($r = -0.004$, $p = 0.98$) did not show statistically significant linear correlations with the accuracy decline in this specific sample. However, the correlation matrix revealed several notable inter-variablerelationships: EMG MDF decline was positively correlated with reaction time increase ($r = 0.44$, $p < 0.05$), and shoulder angle decline was positively correlated with racket speed decline ($r = 0.42$, $p < 0.05$), confirming the biomechanical linkage between proximal joint positioning and distal segment velocity.

Figure 4. Correlation matrix of fatigue-induced changes (Δ scores) in performance variables. Values represent Pearson correlation coefficients (r). Color intensity indicates the strength and direction of the correlation (red = positive, blue = negative).

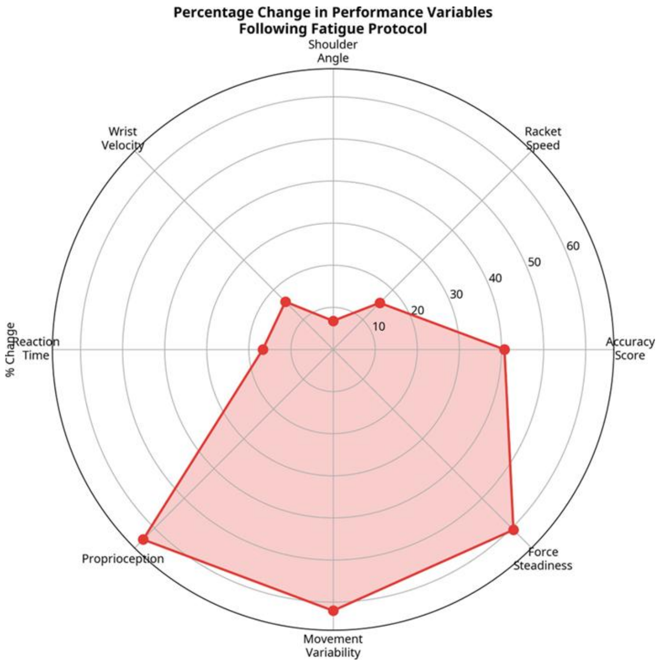

Figure 5. Radar chart illustrating the percentage change in each performance variable following the fatigue protocol. Variables with the greatest proportional change include proprioception error (+63.8%), movement variability (+62.0%), and force steadiness (+60.6%), while kinematic variables showed moderate changes (6.8%–16.0%).

5. DISCUSSION

The present study investigated the comprehensive effects of muscle fatigue on motor control, kinematic parameters, and skill accuracy during the badminton forehand jump smash in elitejunior players. The findings provide strong support for all three hypotheses, demonstrating that a badminton-specific fatigue protocol induces significant and clinically meaningful impairments across all measured domains, ultimately leading to a marked deterioration in stroke accuracy.

These results extend the existing literature by providing an integrated analysis of the fatigue-motor control-kinematics-accuracy pathway in a junior athlete population.

5.1 Effectiveness of the Fatigue Protocol

The fatigue protocol successfully induced substantial neuromuscular fatigue, as evidenced by a 37.3% decline in MVC, a 27.7% reduction in EMG median frequency, and a 233% increase in RPE. These values are consistent with the fatigue levels reported in previous badminton-specific studies. Le Mansec et al. (2020) reported a 30–40% decline in lower limb power output following their fatigue protocol, while Wang et al. (2026) achieved comparable fatigue levels using a similar combined physical-mental fatigue paradigm. The significant downward shift in EMG median frequency confirms that peripheral muscle fatigue—specifically, the slowing of muscle fiber conduction velocity due to metabolite accumulation—was a primary contributor to the observed performance decrements (Enoka & Duchateau, 2008; Boyas & Guével, 2011).

5.2 Impact of Fatigue on Motor Control

Our results demonstrated significant and large-magnitude declines in all measured aspects of motor control following fatigue. The 16.7% increase in choice reaction time aligns with previous research suggesting that both physical and mental fatigue associated with intense exercise impairs cognitive processing and sensory-motor integration (Wang et al., 2026; Ding et al., 2024; Mortimer et al., 2024). In the fast-paced environment of badminton, where shuttlecock flight times can be as short as 300–400 ms, a delay of approximately 40 ms in reaction time can severely compromise a player's ability to anticipate and intercept the shuttlecock at the optimal contact point.

The 63.8% increase in shoulder joint position sense error (proprioception) represents perhaps the most critical finding of this study from a motor control perspective. The shoulder complex relies heavily on proprioceptive feedback for dynamic stability and precise spatial positioning during the overhead throwing motion (Hadjisavvas et al., 2025). The fatigue-induced disruption of proprioception observed in our junior athletes is consistent with, and of similar magnitude to, findings reported in adult table tennis players by Chen et al. (2025), who observed significant proprioceptive decline in both internal and external rotation directions following shoulder fatigue. This impairment is likely mediated by multiple mechanisms: (1) altered sensitivity of muscle spindle primary (Ia) and secondary (II) afferents due to changes in intrafusal fiber contractile properties and metabolic environment; (2) accumulation of metabolites (H^+, lactate, inorganic phosphate) that stimulate group III and IV muscle afferents, potentially creating "noise" in the proprioceptive signal; and (3) central fatigue-related changes in the cortical processing ofafferent signals, as the sensorimotor cortex becomes less responsive to proprioceptive input (Gandevia, 2001; Taylor et al., 2016).

The 60.6% increase in force unsteadiness (CV%) further corroborates the breakdown in fine motor control, reflecting an altered recruitment pattern of motor units as the neuromuscular system attempts to compensate for the fatiguing muscle fibers (Enoka & Duchateau, 2008). As higher-threshold motor units are recruited to compensate for the declining force output of fatigued lower-threshold units, the resulting force signal becomes more variable due to the larger and less precisely controlled force contributions of these units (Taylor et al., 2016).

5.3 Kinematic Adaptations and Movement Variability

The kinematic analysis revealed that fatigue significantly altered the mechanics of the badminton smash across all measured joint angles and velocities. The reductions in shoulder abduction (−6.8%), elbow extension (−5.6%), and trunk rotation (−13.3%) at the point of racket-shuttlecock contact indicate a systematic failure to achieve the optimal biomechanical positions necessary for maximizing the efficiency of the kinetic chain (Zhang et al., 2016; Barnamehei et al., 2021). These constrained joint angles likely represent a protective, compensatory strategy adopted by the central nervous system to reduce the mechanical load and pain associated with forceful contractions of fatigued shoulder and core musculature (Gates & Dingwell, 2011; Forestier & Nougier, 1998).

The consequence of this suboptimal kinematic sequence was a significant 15.7% decrease in racket head speed, from 37.9 m/s to 32.0 m/s. This reduction is comparable to the findings of Le Mansec et al. (2020), who reported significant reductions in smash velocity following fatigue in adult players, and Rusdiana et al. (2023), who documented similar kinematic deterioration in fatigued badminton players. The biomechanical explanation for this velocity loss lies in the principle of sequential segmental acceleration: the smash stroke relies on a proximal-to-distal sequence of segment rotations, where each segment accelerates as the preceding segment decelerates (Cui et al., 2022). When fatigue reduces the angular velocities and ranges of motion of the proximal segments (trunk and shoulder), the energy available for transfer to the distal segments (forearm, wrist, and racket) is correspondingly reduced, resulting in lower racket head speed at contact.

Importantly, fatigue also led to a substantial 62.0% increase in movement variability, as measured by the standard deviation of shoulder angle across the 10 trials. According to the constraints-led approach to motor learning (Davids et al., 2008), a certain degree of movement variability is functional and reflects the adaptive flexibility of the motor system. However, the magnitude of variability increase observed in our study—from 3.8° to 6.1°—likely exceeds the bounds of functional variability and instead represents "dysfunctional variability" or "noise" in the motor system (Cortes et al., 2014; Möhler et al., 2022). As the primary movers fatigued, the junior athletes were unable to consistently reproduce the optimal motor pattern, leading to increased trial-to-trial fluctuations in joint trajectories. This loss of movement consistency is ahallmark of neuromuscular fatigue and a primary contributor to decreased skill accuracy (Forestier & Nougier, 1998; Gates & Dingwell, 2011).

5.4 Skill Accuracy Decline and Interrelationships

The ultimate consequence of the fatigue-induced motor control impairments and kinematic alterations was a severe 40.7% decline in skill accuracy, with the average accuracy score dropping from 7.4 to 4.4 out of 10. This magnitude of accuracy loss is consistent with the 46.1% decline reported by Wang et al. (2026) in their study of physical-mental mixed fatigue effects on badminton smash performance. The concurrent 66.2% increase in radial error further quantifies the spatial dispersion of the shuttlecock landing points, indicating that fatigue not only reduces the probability of hitting the target but also increases the magnitude of spatial error when the target is missed.

The significant correlation between the magnitude of MVC decline and the loss of accuracy ($r =$

-0.420, $p = 0.021$) highlights a direct link between the degree of peripheral muscle fatigue and the breakdown in technical performance. This finding suggests that players who are more susceptible to muscle fatigue—or who reach higher levels of fatigue during the protocol—experience proportionally greater losses in skill accuracy. The practical implication is that developing greater muscular endurance and fatigue resistance in the shoulder complex may directly translate to better maintenance of accuracy during prolonged matches.

While we hypothesized strong correlations between proprioception/variability changes and accuracy decline, these relationships were not statistically significant in our sample. This finding, though initially surprising, is consistent with the complex, multifactorial nature of skill accuracy in overhead sports. Several explanations are possible: (1) the relationship between proprioceptive decline and accuracy loss may be non-linear, with a threshold effect rather than a proportional relationship; (2) individual differences in compensatory strategies may mask group-level correlations—some players may sacrifice speed to maintain accuracy, while others maintain speed at the cost of spatial precision (Wang et al., 2026); and (3) the relatively small sample size (N = 30) may have limited statistical power to detect moderate correlations. The trend showing a relationship between racket speed decline and accuracy decline ($r = -0.317$, $p = 0.088$) suggests a potential speed-accuracy trade-off that becomes exacerbated under fatigued conditions, consistent with Fitts' law applied to ballistic movements.

5.5 Practical Implications

The findings of this study have several significant practical implications for coaches, sports scientists, and physical therapists working with junior badminton players:

Fatigue-resistance training: The data underscore the necessity of developing high levels of specific muscular endurance and fatigue resistance in the shoulder complex and core musculature. Training programs should include sport-specific endurance exercises thattarget the shoulder internal rotators, deltoid, and trunk rotators at intensities that simulate match demands.

1. **Fatigue-state skill training:** Training programs should incorporate periods of technical practice under simulated fatigue conditions. This approach, supported by motor learning principles (Branscheidt et al., 2019; Davids et al., 2008), may

help athletes develop more robust motor engrams that are resilient to the disruptive effects of fatigue, and may teach them to adopt effective compensatory strategies.

2. **Proprioceptive conditioning:** Incorporating specific proprioceptive and neuromuscular control exercises for the shoulder into routine conditioning programs may help mitigate the fatigue-induced loss of joint position sense. Exercises such as rhythmic stabilization, joint position matching tasks, and perturbation training can enhance the sensitivity of proprioceptive receptors and improve central processing of proprioceptive information (Chen et al., 2025; Hadjisavvas et al., 2025).

3. **Match management strategies:** Coaches should be aware that accuracy declines substantially as fatigue accumulates. Strategic use of timeouts, pacing strategies, and shot selection (e.g., choosing higher-percentage targets when fatigued) may help maintain competitive performance during the later stages of matches.

4. **Monitoring and periodization:** Regular monitoring of neuromuscular fatigue markers (e.g., MVC, EMG median frequency) during training can help coaches identify when athletes are approaching fatigue levels that compromise technical quality, allowing for appropriate rest and recovery interventions.

5.6 Limitations and Future Directions

Several limitations of this study should be acknowledged. First, the cross-sectional, single-session design does not allow for causal inferences about the mechanisms underlying the observed relationships. Longitudinal studies tracking fatigue-performance relationships across a competitive season would provide stronger evidence. Second, the fatigue protocol, while ecologically valid, induced fatigue relatively rapidly compared to the gradual accumulation of fatigue during an actual match. Future studies should examine how fatigue develops progressively over the course of a full match and at what point critical performance thresholds are crossed.

Third, the sample size of 30 participants, while adequate for detecting large effects, may have been insufficient to detect moderate correlations between some variables. Future studies with larger samples and more diverse skill levels could provide greater statistical power and generalizability. Fourth, we assessed only the forehand jump smash; future research should examine whether similar fatigue effects are observed for other badminton strokes (e.g., backhand clear, net shots, drop shots) that have different biomechanical demands.Fifth, we did not include a control condition (no fatigue) or a sham fatigue condition, which limits our ability to rule out potential confounds such as learning effects or motivational changes across the testing session. Finally, future research should investigate the efficacy of specific interventions—such as targeted fatigue-resistance training, proprioceptive conditioning programs, or acute recovery strategies (e.g., cooling, compression)—in mitigating the performance decrements documented in this study.

6. CONCLUSION

In conclusion, this study provides comprehensive evidence that muscle fatigue induces a cascade of detrimental effects on the neuromuscular system of junior badminton players, affecting motor control, movement kinematics, and ultimately skill accuracy. The fatigue protocol induced a 37.3% decline in maximal voluntary contraction, which was accompanied by significant impairments in motor control (16.7% increase in reaction time, 63.8% increase in proprioception error, 60.6% increase in force unsteadiness), substantial alterations in upper limb kinematics (6.8–16.0% reductions in joint angles and velocities), and a marked 62.0% increase in movement variability. These combined central and peripheral disruptions culminated in a 40.7% decline in smash accuracy and a 66.2% increase in radial error.

The significant correlation between the degree of muscle fatigue (MVC decline) and the loss of skill accuracy highlights the critical importance of developing fatigue resistance in junior badminton players. The findings support a model in which fatigue disrupts the proprioceptive feedback necessary for precise motor control, leading to suboptimal kinematic execution and increased movement variability, which together compromise the spatial accuracy of the overhead smash. These results have direct implications for training program design, emphasizing the need for integrated approaches that develop both physical capacity and motor control resilience under fatigue conditions.

Conflict of Interest

The authors declare no conflict of interest.

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