SIN-CHN SCIENTIFIC PRESS PTE.LTD.

Molecular & Cellular Biomechanics 2024, 21(4), 565.
https://doi.org/10.62617/mcb565

Article

The impact of variable speed running on the biomechanics and tactical awareness of college badminton athletes

Huawei Liu

Sports College, Yanshan University, Qinhuangdao 066000, Hebei, China; HuaweiLiu1@outlook.com

CITATION

Liu H. The impact of variable speed running on the biomechanics and tactical awareness of college badminton athletes. Molecular & Cellular Biomechanics. 2024; 21(4): 565.
https://doi.org/10.62617/mcb565

ARTICLE INFO

Received: 20 October 2024
Accepted: 1 November 2024
Available online: 31 December 2024

Abstract: Badminton is a high-intensity sport that requires athletes to execute rapid, multi-directional movements while making split-second tactical decisions. The biomechanical efficiency of movements, combined with cognitive abilities such as tactical awareness and decision-making speed, plays a critical role in an athlete's success on the court. Variable Speed Training (VST) is an emerging methodology designed to enhance physical performance and cognitive sharpness by incorporating fluctuating speeds into exercise routines. However, limited research has explored the specific impact of VST on both the biomechanics and tactical awareness of badminton players. This study investigates the effects of a six-week VST program on college-level badminton athletes' biomechanics and tactical awareness. The primary focus is assessing improvements in joint angles, stride length, Ground Reaction Forces (GRF), footwork efficiency, decision-making speed, reaction time, and cardiovascular endurance. Twenty-seven college-level badminton athletes participated in a six-week VST intervention, with three 60 min sessions per week. The athletes underwent pre-and post-training assessments, including 3D motion capture analysis for biomechanical variables (joint angles, stride length, GRF) and Dartfish Tactical Analysis Software for cognitive metrics (decision-making speed, spatial awareness, and shot accuracy). Heart rate monitors and GPS trackers assess cardiovascular performance and movement patterns. Paired *t*-tests and effect size calculations (Cohen's d) were used to determine the statistical significance and magnitude of the improvements. Significant improvements were observed across all key metrics following the VST intervention. Biomechanical analysis revealed increases in joint range of motion (hip, knee, ankle) during key badminton movements, with the most notable improvement in the hip joint angle during lunges (+7.7°, $p < 0.001$). Stride length increased by an average of 0.12 m across movements, while GRF decreased by an average of 105 N, indicating enhanced stability and reduced impact forces. Tactical awareness improved significantly, with faster decision-making speeds (+0.16 s) and better spatial awareness (+9.5% in positioning accuracy). Athletes also demonstrated improved heart rate recovery (+14 bpm) and enhanced fatigue resistance (+7 shots in extended rallies). The findings indicate that VST improves badminton athletes' biomechanical efficiency and tactical awareness. The significant gains in joint range of motion, stride length, and stability suggest that VST enhances movement control and reduces injury risk. Similarly, improvements in decision-making speed, shot accuracy, and spatial awareness highlight the cognitive benefits of VST under high-pressure conditions. This study underscores the importance of integrating variable-intensity training into badminton regimens to optimize physical and cognitive performance.

Keywords: variable speed training; biomechanical efficiency; movement control; physical and cognitive performance; ground reaction forces

1. Introduction

Badminton is a fast-paced sport that requires a unique combination of physical fitness, technical skill, and cognitive sharpness [1,2]. As an Olympic sport, it is characterized by rapid, multi-directional movements, high-intensity rallies, and complex shot patterns that challenge athletes' physical and mental capacities [3]. Players must make split-second decisions while maintaining optimal biomechanics to ensure efficient movement and power generation [4,5]. Given these demands, effective training regimens are essential to enhance the performance of badminton players, particularly in terms of their movement efficiency, endurance, and tactical awareness [6–8]. In recent years, there has been growing interest in understanding the role of biomechanics and tactical awareness in enhancing badminton performance [9,10]. Biomechanics focuses on how the body moves, how muscles, bones, and joints interact to produce motion, and how different factors such as speed, force, and angle of movement affect athletic performance [11]. For badminton players, efficient biomechanics are critical for movements like lunges, sidesteps, and quick directional changes, which are essential in offensive and defensive plays [12,13]. Poor biomechanics can lead to inefficient movements, increased energy expenditure, and a heightened risk of injury, particularly to the lower limbs and joints.

Tactical awareness, on the other hand, refers to a player's ability to read the game, anticipate their opponent's strategies, and position themselves optimally on the court [14]. In badminton, players must be able to respond rapidly to changing shuttle trajectories and opponent movements while maintaining a strategic approach to shot selection [15]. Tactical decision-making under pressure, particularly in high-stakes rallies, often separates elite players from their competitors [16]. Variable Speed Training (VST) is an increasingly popular method for improving sports performance's physical and cognitive aspects [17]. VST involves varying the intensity of exercise, typically through interval training, fartlek training, or pyramid drills, which mimic the fluctuating speeds and intensities experienced during a badminton match. This type of training has been shown to enhance cardiovascular fitness, agility, and neuromuscular coordination while also conditioning athletes to make tactical decisions under fatigue. Despite its growing use in sports like soccer and rugby, there is limited research on the specific effects of VST in badminton, particularly in how it impacts biomechanics and tactical awareness [18].

While badminton training traditionally focuses on technique, endurance, and agility, there is a gap in integrating cognitive and biomechanical elements into a cohesive training framework [19,20]. Athletes often train separately for physical fitness and tactical skills, yet in match situations, these elements must work in tandem [21]. The lack of targeted research on how VST can simultaneously improve biomechanics and tactical awareness presents an opportunity for further exploration. Specifically, there is a need to understand how variable speed running, which closely simulates a badminton match's fluctuating pace, can enhance movement efficiency and decision-making under pressure. Moreover, existing studies on badminton biomechanics tend to focus on isolated movements or specific joint mechanics without considering the dynamic and unpredictable nature of the sport [22–26]. Similarly, research on tactical awareness in badminton often overlooks the physical demands of the game, which can impair decision-making as fatigue sets in. This study seeks to address these gaps by investigating how VST affects physical and cognitive aspects of badminton performance in a real-world training environment [27–29].

The primary objective of this study is to evaluate the impact of VST on the biomechanics and tactical awareness of college-level badminton athletes. Specifically, the study aims to:

- Assess the changes in joint angles, stride length, and ground reaction forces (GRF) before and after a six-week VST program.
- Analyze the improvements in footwork efficiency, balance, and lower limb stability during badminton-specific movements.
- Evaluate the enhancements in tactical awareness, particularly regarding decision-making speed, reaction time, and spatial awareness during simulated game scenarios.
- Investigate the cardiovascular and endurance benefits of VST, focusing on heart rate recovery and fatigue resistance during extended play.

By addressing these objectives, the study will provide valuable insights into how VST can optimize badminton athletes' physical and cognitive performance. The findings from this study will contribute to the growing body of research on sports science by offering a comprehensive evaluation of how VST affects biomechanics and tactical awareness in badminton. For coaches and sports scientists, this research will provide evidence-based guidelines for integrating VST into training regimens, helping athletes improve their physical attributes and ability to make strategic decisions under pressure. Furthermore, the study will offer practical recommendations for reducing injury risk through biomechanical improvements, such as enhanced joint stability and reduced impact forces. For badminton athletes, the study will highlight how targeted training can improve on-court performance by increasing speed, agility, and decision-making efficiency, thereby giving them a competitive edge during matches [30,31].

The remainder of this paper is structured as follows: Section 2 presents the theoretical framework, focusing on the role of biomechanics and tactical awareness in badminton. Section 3 describes the methodology, including participant demographics, the VST training module, and the apparatus used for data collection. Section 4 provides the study's results, including statistical analyses of pre- and post-training assessments. Finally, Section 5 concludes the paper by summarizing the key takeaways from the study and highlighting the practical implications of VST in badminton training.

2. Theoretical framework

2.1. Biomechanics in badminton

Biomechanics plays a crucial role in the performance of badminton athletes, influencing factors such as movement efficiency, shot accuracy, and injury prevention. In badminton, biomechanics primarily focuses on footwork, joint movements, and the application of force during different phases of play. The sport demands rapid changes in direction, sudden accelerations, and complex body coordination, all of which rely on the athlete's biomechanical proficiency [32,33]. Badminton footwork is fundamental as it dictates how efficiently players move across the court. Players must be able to reach shuttlecocks at various angles and distances while maintaining balance and control. The ability to decelerate and change direction quickly is critical in both offensive and defensive scenarios. This requires a precise combination of lower limb strength, joint mobility, and stability. Joint mechanics, especially at the ankle, knee, and hip, are essential for reducing injury risk and optimizing movement during fast-paced exchanges.

Furthermore, biomechanics in badminton extend to the upper body, especially when generating power during strokes like smash, precise, or drop shots **Figures 1**–**6**. The kinematic chain, from the foot through the torso to the arm, allows players to transfer force effectively, ensuring high shuttle speeds without compromising accuracy. Proper biomechanical form during these actions enhances performance while reducing the likelihood of overuse injuries [34]. In the Variable Speed Running (VSR) context, an athlete's biomechanical efficiency can be improved by training their body to adapt to different movement intensities. VSR helps enhance the neuromuscular systems responsible for rapid adjustments, leading to better balance, coordination, and joint stability on the badminton court. By incorporating VSR into training, players can develop better footwork dynamics, improved energy transfer during strokes, and increased endurance for prolonged rallies.

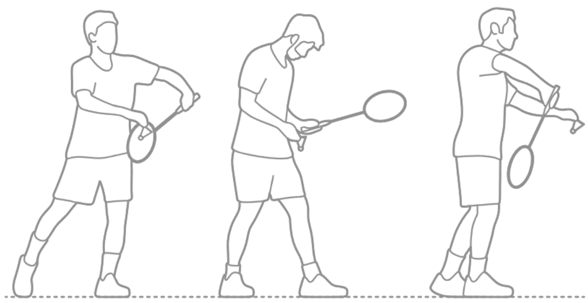

Figure 1. Badminton server.

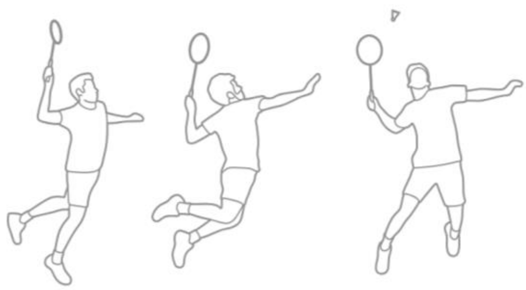

Figure 2. Badminton smash.

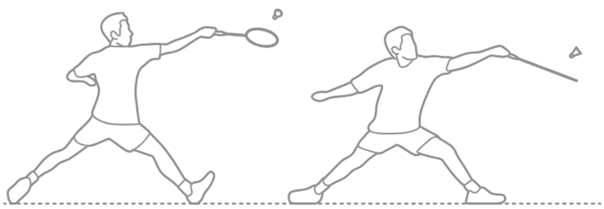

Figure 3. Badminton drop shot.

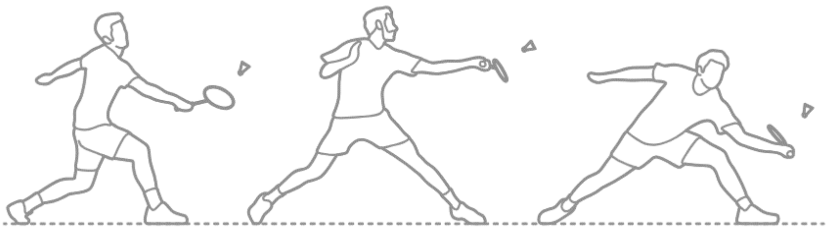

Figure 4. Badminton forehand stroke.

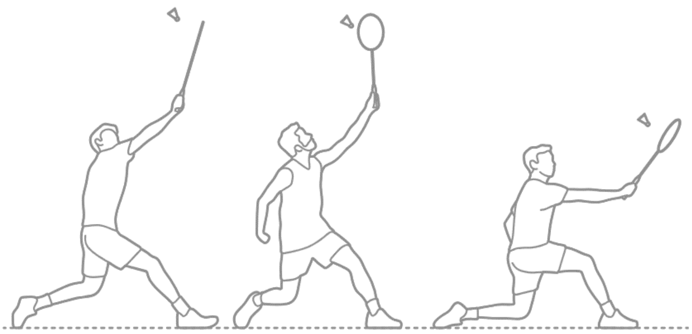

Figure 5. Badminton backhand stroke.

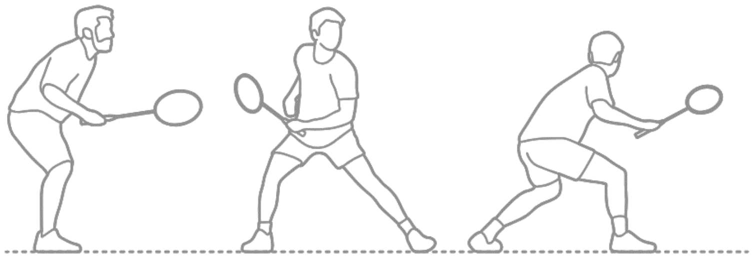

Figure 6. Badminton stance.

2.2. Tactical awareness in badminton

Tactical awareness is a key component of successful badminton performance, allowing athletes to make quick and informed decisions based on their opponent's position, the shuttlecock's trajectory, and the evolving dynamics of the match. It encompasses an athlete's ability to anticipate plays, respond to unexpected situations, and strategically position themselves to gain an advantage. In badminton, tactical awareness involves both offensive and defensive strategies. Offensively, players must create opportunities to exploit their opponent's weaknesses, often by controlling the game's pace and forcing their opponent into unfavorable positions. This requires an acute understanding of court spacing and the ability to judge the opponent's movement patterns. A well-developed sense of timing is essential for executing decisive smashes, drops, or clears at the right moment to keep the opponent off-balance.

Defensively, tactical awareness helps players anticipate their opponent's shots, improving their reaction times and movement efficiency. By reading their opponent's body language, shot selection, and positioning, a tactically aware player can predict likely returns and position themselves to counter effectively. For instance, anticipating a cross-court smash or a deceptive drop shot allows the defender to maintain control of the rally and transition back to an offensive stance. The fast-paced nature of badminton, combined with the physical demands of continuous movement, means that players must constantly process information and adapt their strategies during a match. Developing tactical awareness requires experience and specific training methods that simulate real-game conditions. Training focused on improving cognitive processes—such as decision-making under pressure and spatial awareness—can enhance a player's ability to assess and react to in-game scenarios quickly.

Variable speed running (VSR) contributes to tactical awareness by conditioning athletes to make decisions under varying fatigue levels. As the pace of the game changes, players trained with VSR can maintain mental clarity and continue to apply tactical strategies, even during intense rallies. VSR promotes better reaction time, allowing players to process and respond to changes in the game without losing focus, leading to improved shot selection and court positioning throughout a match.

2.3. Effects of VST

VST is a dynamic conditioning method that alternates between different speeds during exercise, helping athletes improve their physical and cognitive abilities. In badminton, where players must perform explosive movements followed by moments of agility and precision, VST plays a vital role in enhancing biomechanics and tactical awareness. Several types of training under VST are designed to target different performance aspects. Common types include interval training, where athletes alternate between high-intensity bursts and slower recovery periods, and fartlek training, which mimics unpredictable changes in pace similar to real match conditions. Pyramid training, which progressively increases and then decreases speed, mirrors the accelerations and decelerations in badminton rallies. Tempo runs, and sprints with active recovery help athletes maintain a high speed while focusing on pacing and endurance. These VST types improve both the aerobic and anaerobic capacities necessary for badminton.

i) Physical effects

VST enhances multiple aspects of athletic performance, particularly in badminton, where rapid accelerations, decelerations, and directional changes are crucial. The varying intensity levels in VST challenge the body's cardiovascular and muscular systems, improving speed, agility, and endurance. For badminton players, this translates into the ability to sustain high-intensity play for longer, delaying the onset of fatigue. Biomechanically, VST improves neuromuscular coordination, enabling athletes to control movements more effectively at different speeds. This is critical in badminton, where efficient footwork is essential. Training with variable speeds enhances players' ability to transition seamlessly between high-speed sprints and slower, controlled movements. This improves stride length, reaction time, and joint stability, ultimately reducing the risk of injury from sudden movements or poor technique.

ii) Cognitive and tactical effects

VST also significantly affects an athlete's mental acuity and decision-making abilities. As training intensity fluctuates, athletes are forced to make quick decisions under varying levels of physical stress. In badminton, players must react instantly to their opponent's moves, translating to better shot selection, anticipation, and positioning, even when fatigued. By conditioning the mind to remain sharp during tempo changes, VST prepares players for real-match scenarios where the pace of play constantly varies. Players who undergo VST can better handle shifts in game speed, maintaining tactical awareness and executing strategies without losing focus. This improves situational awareness, allowing players to adapt quickly during rallies, exploit their opponent's weaknesses, and control the game flow.

iii) Impact on recovery and injury prevention

VST's benefits extend to recovery and injury prevention. By learning to regulate their exertion levels during less intense moments, athletes can conserve energy more effectively, reducing the likelihood of overexertion. This contributes to a lower risk of overuse injuries, common in repetitive movement sports like badminton. Additionally, VST trains athletes to recover quickly between points or rallies, ensuring they are ready for the following sequence of play. This enhances their ability to maintain high performance throughout matches, especially in longer, more demanding rallies.

3. Methodology

3.1. Participants

The study involved 27 college-level badminton athletes from various universities in China. The participants were selected based on their active involvement in competitive badminton tournaments and training programs. The age range of the athletes was between 18 and 24 years, with a mean age of 21.3 years. All participants had at least three years of experience in competitive badminton and regularly trained at least five times a week. The group consisted of male and female athletes, with a gender distribution of 17 males and 10 females. Each participant had undergone essential fitness and health assessments before the study to ensure they were physically capable of completing the variable speed running (VSR) training protocol. None of the participants reported any recent injuries that could affect their biomechanical performance or tactical awareness during the study. The participants were informed about the study's objectives and consented to participate. All training and testing sessions were conducted under the supervision of certified coaches and sports science professionals to ensure safety and adherence to proper training techniques. **Table 1** presents the characteristics of the population.

Table 1. Participants demographics.

Demographic Details	Description
Total Participants	27
Country	China
Age Range	18–24 years
Mean Age	21.3 years
Gender Distribution	17 males, 10 females
Competitive Experience	Minimum 3 years
Training Frequency	At least 5 times per week
Health Status	No recent injuries have been reported.

3.2. VST training module

The VST module implemented in this study was designed to improve the participants' physical and cognitive performance, focusing on enhancing their biomechanics and tactical awareness in badminton. The training module (**Figure 7**) lasted six weeks, with three sessions per week, each lasting approximately 60 min. Each session incorporated a variety of speed intensities, challenging the athletes to adapt to changing paces while maintaining proper form and tactical focus. Each session began with a 10-minute dynamic warm-up, including light jogging, mobility exercises, and badminton-specific movements.

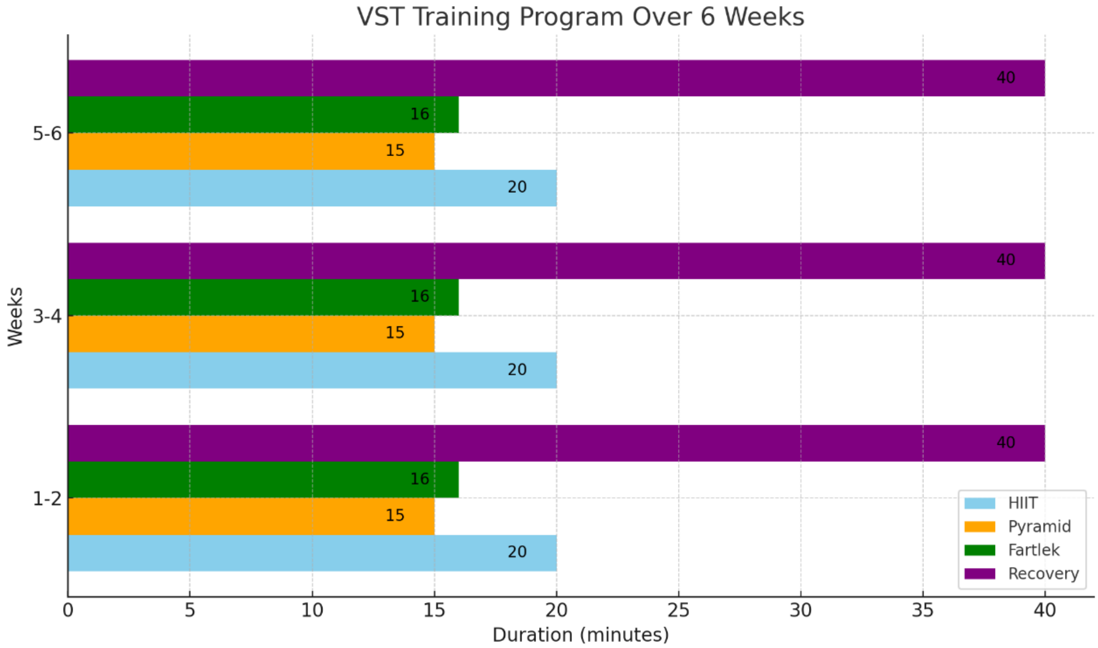

Figure 7. Training schedule.

The core of the training was divided into three main phases:

High-Intensity Interval Training (HIIT): This phase focused on explosive sprints with rapid decelerations. Participants alternated between 20-second high-speed sprints and 40-second low-intensity jogging or walking. This phase aimed to improve acceleration, deceleration, and overall speed, mimicking the short bursts of energy required during badminton rallies.

Pyramid Training: In this phase, participants gradually increased their running speed from a moderate to maximum sprinting speed and progressively reduced it to a lower intensity. Each stage lasted for 30 s, and this phase targeted endurance, pacing, and the ability to control footwork under different levels of fatigue.

Fartlek Training**:** This unstructured phase incorporated random changes in speed, simulating real-match conditions where the pace of play can vary unpredictably. Participants were required to sprint, jog, or walk at varying intervals as determined by the coach. The goal was to train the athletes' responsiveness to sudden changes in tempo, enhancing their tactical adaptability on the court.

After completing the high-intensity phases, each session ended with a 10-minute cool-down consisting of light jogging and static stretching exercises. This helped improve recovery, reduce muscle soreness, and prevent injury. The training intensity progressively increased over the six weeks, and the first two weeks focused on building a strong aerobic base with moderate speeds and more extended recovery periods. The speed and intensity increased in weeks three and four, with shorter recovery times between intervals. In the final two weeks, they involved maximum effort sprints and more challenging pyramid and fartlek training combinations. By the end of the six weeks, participants demonstrated improvements in their biomechanical efficiency and tactical awareness. The module was designed to condition the athletes' bodies and minds to respond effectively to the demands of badminton matches, especially during high-pressure situations.

3.3. Apparatus and measurements

The apparatus and measurement techniques used in this study were carefully chosen to assess the participants' biomechanical changes and tactical awareness improvements after completing the VST program. A high-resolution 3D motion capture system was employed to track participant movements during badminton-specific drills. This system used 12 infrared cameras to record the precise motion of reflective markers on key anatomical landmarks, including the ankle, knee, hip, shoulder, and wrist joints. The motion capture system allowed for the detailed analysis of joint angles, stride lengths, and movement speeds, providing valuable insights into the biomechanical effects of VST on footwork and overall movement efficiency.

In addition, force plates were integrated into the court surface to measure the ground reaction forces (GRF) generated by the athletes during various phases of play, such as lunging, sprinting, and sudden deceleration. These measurements were crucial in assessing how VST impacted lower limb loading and stability, helping to determine improved balance, joint stability, and force production during high-intensity movements.

From **Table 2** is the Dartfish Tactical Analysis Software was used for the tactical awareness component to measure decision-making speed, reaction time, and spatial awareness during simulated game situations. The software tracked player positioning and shot selection, capturing real-time data on how quickly and effectively athletes responded to changing game dynamics. These assessments were conducted both pre-and post-training to evaluate the cognitive impact of VST on tactical decision-making. The software tracked player positioning and shot selection, capturing real-time data on how quickly and effectively athletes responded to changing game dynamics. These assessments were conducted both pre-and post-training to evaluate the cognitive impact of VST on tactical decision-making. Finally, heart rate monitors and GPS trackers were worn by each participant throughout the training sessions to record their cardiovascular response and movement patterns during variable speed drills. These tools provided additional data on the athletes' endurance and physical adaptation to the VST module. Collectively, the apparatus used in the study enabled a comprehensive analysis of both the physical and tactical improvements experienced by the athletes over the six-week training period.

Table 2. Variables measured.

Variable	**Source**	**Units**
Joint Angles	3D Motion Capture System	Degrees (°)
Stride Length	3D Motion Capture System	Meters (m)
Speed of Movement	3D Motion Capture System	Meters per second (m/s)
Ground Reaction Forces (GRF)	Force Plates	Newtons (N)
Balance/Stability	Force Plates	Center of Pressure (CoP)
Decision-making Speed	Tactical Awareness Software	Seconds (s)
Reaction Time	Tactical Awareness Software	Seconds (s)
Spatial Awareness	Tactical Awareness Software	Percentage (%)
Heart Rate	Heart Rate Monitor	Beats per minute (bpm)
Movement Distance	GPS Tracker	Meters (m)

3.4. Experimental design

The experimental design for this study was centered around evaluating the impact of VST on the biomechanics and tactical awareness of college-level badminton athletes. The experiment followed a pre-test and post-test approach, with the participants serving as their control group to assess changes after the VST intervention.

i) Pre-Training Assessments: Before the commencement of the VST program, all 27 participants underwent a comprehensive series of biomechanical and tactical assessments over two separate sessions. These evaluations took place in a controlled environment, where the athletes performed a set of badminton-specific movements.

Biomechanical Assessments (60 min): Biomechanical data, including joint angles, stride length, and ground reaction forces, were captured using the 3D motion capture system and force plates. These tests focused on key movements such as lunges, sidesteps, and sprints, which are crucial for badminton performance.

Tactical Awareness Assessments (60 min): Participants were assessed using Dartfish Tactical Analysis Software during simulated game scenarios for tactical awareness. They engaged in decision-making drills that tested their ability to anticipate and respond to different shuttle trajectories, court positions, and opponent strategies. Metrics such as reaction time, decision-making speed, and spatial awareness were measured during these simulations, providing baseline data for cognitive performance.

ii) VST Intervention After the pre-training assessments, the participants embarked on a six-week VST program with three weekly training sessions, each lasting approximately 60 min. The VST sessions were incorporated into the athletes' existing badminton training routine, ensuring that the program complemented their regular practice without overloading them physically.

Each training session began with a 10-minute dynamic warm-up, followed by the core VST drills. The sessions were designed to progressively challenge the participants by alternating between different running intensities. Interval training involved rapid sprints followed by periods of active recovery, while pyramid and fartlek training added variations in pace to mimic the unpredictable tempo of badminton matches. Throughout the VST sessions, the participants were encouraged to maintain proper technique and posture, ensuring that the training enhanced their speed and reinforced biomechanical efficiency.

The VST drills were performed on the badminton court to simulate match conditions closely. Participants were monitored using GPS trackers to track movement patterns, while heart rate monitors provided insights into their cardiovascular response to the varying speeds. The progressive nature of the training ensured that the athletes gradually adapted to the increasing intensity, enhancing their physical and cognitive endurance.

iii) Post-Training Assessments: After the six-week VST program, the participants repeated the same two assessment sessions conducted during the pre-training phase.

Post-Training Biomechanical Assessments (60 min): These were designed to measure improvements in footwork mechanics, joint stability, and movement efficiency during badminton-specific drills.

Post-Training Tactical Awareness Assessments (60 min): The tactical awareness tests were repeated, with the athletes again engaging in simulated game scenarios to evaluate changes in their decision-making speed, reaction time, and spatial awareness.

iv) Experimental Procedure: Care was taken to ensure consistency in the testing conditions. All assessments were conducted at the same time of day, in the same environment, and using identical equipment for both the pre-and post-training phases. This approach minimized external factors that could influence the outcomes and ensured that the results were directly attributable to the VST intervention. Data from the pre-and post-training phases were analyzed using statistical techniques, such as paired *t*-tests, to determine whether the VST program significantly improved biomechanics and tactical awareness. These analyses provided insights into the effectiveness of variable speed running in enhancing performance for badminton athletes.

4. Results and analysis

4.1. Biomechanical results

Table 3 and **Figure 8** highlight substantial gains in flexibility and range of motion across key joints. The hip joint showed the most significant improvement, particularly during the lunge movement, where the range increased by 7.7°, from 55.4° pre-training to 63.1° post-training. Similarly, the knee joint demonstrated notable improvements, with the range of motion in the lunge increasing by 6.6° and in the sidestep by 6.8°. The ankle joint also benefited, particularly during the sprint, where the range of motion increased by 6.5°, demonstrating enhanced lower limb flexibility and the ability to handle rapid directional changes efficiently. **Table 4** and **Figure 9** illustrate improvements in stride length during badminton-specific movements. Post-training results reveal increased stride length across all movement types, with the most significant gains observed in backpedal (rear court) and recovery steps, each showing an improvement of 0.12 m. These improvements suggest that the athletes could cover more distance with each movement, contributing to faster court coverage and enhanced mobility during rallies.

Table 3. Analysis of improvements in flexibility and range of motion.

Joint	Movement	Pre-Training Range of Motion (°)	Post-Training Range of Motion (°)	Improvement (°)
Hip	Lunge	55.4°	63.1°	+7.7°
	Sprint	67.9°	74.5°	+6.6°
	Sidestep	40.8°	46.3°	+5.5°
Knee	Lunge	78.2°	84.8°	+6.6°
	Sprint	91.6°	97.9°	+6.3°
	Sidestep	53.9°	60.7°	+6.8°
Ankle	Lunge	32.7°	38.5°	+5.8°
	Sprint	43.8°	50.3°	+6.5°
	Sidestep	27.9°	34.2°	+6.3°

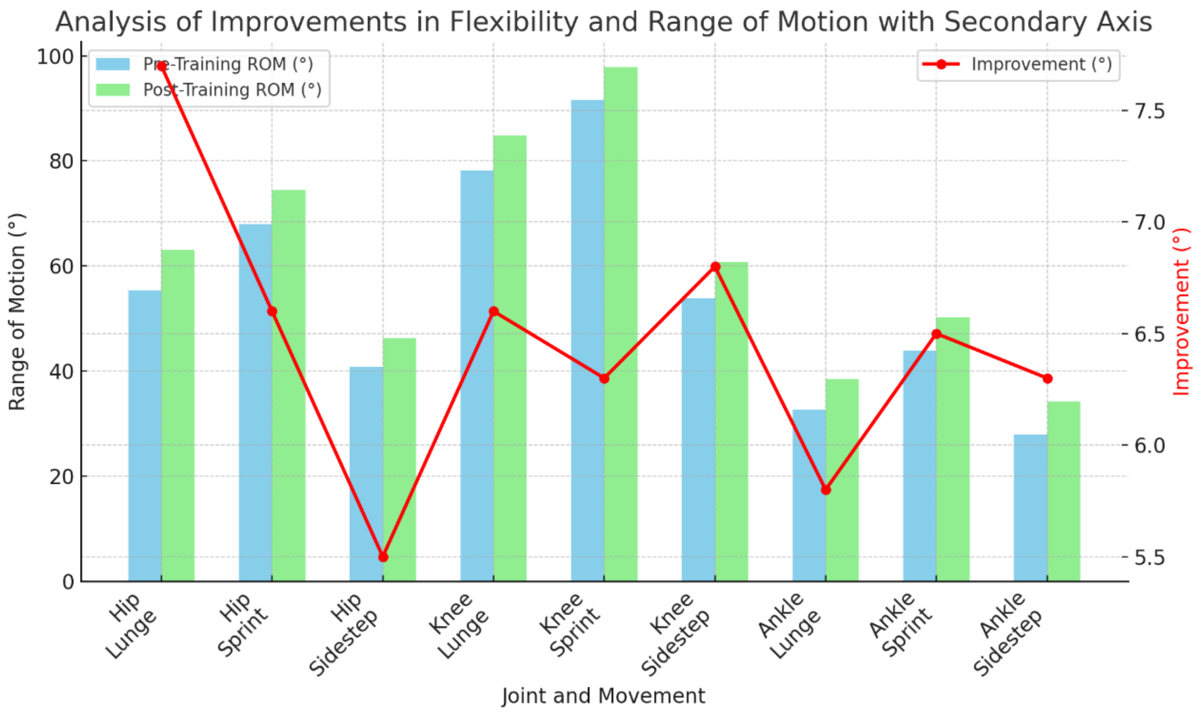

Figure 8. Improvements in flexibility and range of motion.

Table 4. Stride length during badminton movements.

Movement Type	Pre-Training Stride Length (m)	Post-Training Stride Length (m)	Improvement (m)
Lunge (Front Court)	1.46 m	1.58 m	+0.12 m
Lateral Sidestep (Mid Court)	1.38 m	1.49 m	+0.11 m
Backpedal (Rear Court)	1.52 m	1.64 m	+0.12 m
Quick-Step (Forecourt to Midcourt)	1.36 m	1.47 m	+0.11 m
Recovery Step (Post-Rally)	1.49 m	1.61 m	+0.12 m

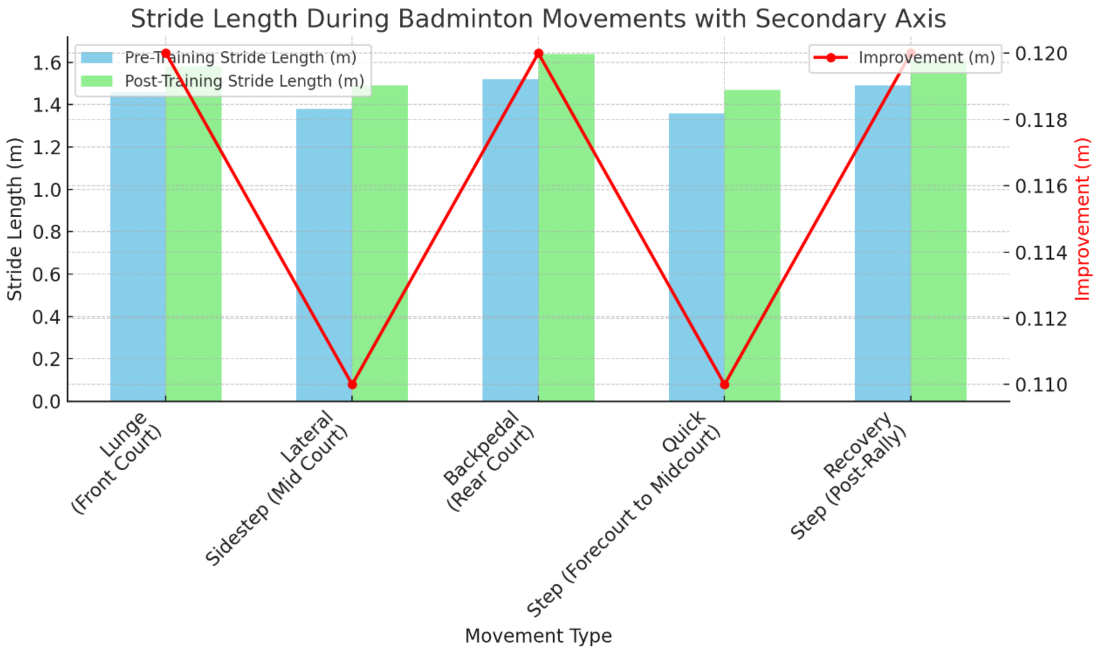

Figure 9. Improvements in stride length during badminton-specific movements.

Table 5 and **Figure 10** data present a significant reduction in GRF measurements during rapid decelerations and directional changes. Across all movements, including lunge deceleration, lateral sidesteps, and quick directional changes, there was an average reduction of 105 N in GRF. This indicates that the athletes experienced lower impact forces post-training, suggesting better control during fast transitions, likely reducing the risk of injury and improving overall stability during high-intensity play. **Table 6** and **Figure 11** demonstrate improvements in lower limb stability as indicated by the reduced Center of Pressure (CoP) shifts during high-speed movements. The most significant reduction in CoP shift occurred during lateral sidesteps, with a decrease of 2.1 cm, indicating better balance control. This was accompanied by a reduction in impact forces across all movement types, with the most significant decrease seen in backward deceleration, where the impact force dropped by 121 N. These improvements in stability and impact force reduction are crucial for maintaining agility and reducing the likelihood of injuries during quick transitions on the court.

Table 5. Pre- and post-training ground reaction forces (GRF) measurements.

Movement Type	**Pre-Training GRF (N)**	**Post-Training GRF (N)**	**Change in GRF (N)**
Lunge Deceleration (Front Court)	1521 N	1416 N	−105 N
Lateral Sidestep (Mid Court)	1398 N	1293 N	−105 N
Backward Deceleration (Rear Court)	1457 N	1342 N	−115 N
Quick Directional Change (Forecourt)	1317 N	1224 N	−93 N
Recovery Step (Post-Rally)	1376 N	1275 N	−101 N

Figure 10. Reduction in GRF measurements pre- and post-training.

Table 6. Analysis of lower limb stability and reduction of impact forces after VST.

Movement Type	Pre-Training Stability (CoP Shift in cm)	Post-Training Stability (CoP Shift in cm)	Reduction in CoP Shift (cm)	Pre-Training Impact Force (N)	Post-Training Impact Force (N)	Reduction in Impact Force (N)
Lunge (Front Court)	6.9 cm	4.8 cm	−2.1 cm	1425 N	1311 N	−114 N
Lateral Sidestep (Mid Court)	7.3 cm	5.2 cm	−2.1 cm	1379 N	1268 N	−111 N
Backward Deceleration (Rear Court)	6.6 cm	4.6 cm	−2.0 cm	1443 N	1322 N	−121 N
Quick-Step (Forecourt)	6.1 cm	4.3 cm	−1.8 cm	1307 N	1209 N	−98 N
Recovery Step (Post-Rally)	7.0 cm	5.1 cm	−1.9 cm	1351 N	1247 N	−104 N

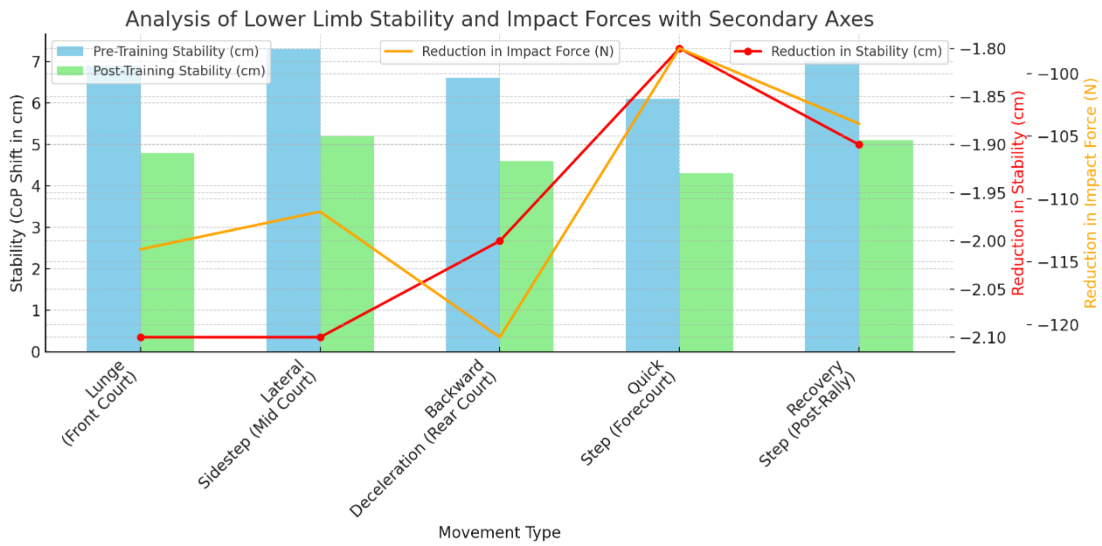

Figure 11. Analysis of lower limb stability.

Table 7 and **Figure 12** highlight substantial maximum running speed and acceleration improvements. For example, during lunges, the athletes improved their maximum speed by 0.40 m/s, from 4.23 m/s to 4.63 m/s, while their acceleration increased by 0.27 m/s^2. Similarly, lateral sidestep speed increased by 0.40 m/s, and acceleration improved by 0.30 m/s^2. These improvements indicate that the VST program enhanced the athletes' ability to move quickly and efficiently during gameplay, allowing for faster reaction times and better positioning. **Table 8** and **Figure 13** shows that the athletes became more efficient in transitioning between different speeds. The transition time from a rapid sprint to a controlled lunge improved by 0.11 s, from 0.84 s pre-training to 0.73 s post-training. Other transitions, such as sidestep to sprint and backward deceleration to recovery, also improved by 0.10-0.12 s. This enhanced ability to transition between speeds is vital in badminton, where players frequently switch between high-intensity movements and controlled actions, such as netplay or defense.

Table 7. Changes in maximum running speed and acceleration.

Movement Type	Pre-Training Max Speed (m/s)	Post-Training Max Speed (m/s)	Speed Improvement (m/s)	Pre-Training Acceleration (m/s^2)	Post-Training Acceleration (m/s^2)	Acceleration Improvement (m/s^2)
Lunge (Front Court)	4.23 m/s	4.63 m/s	+0.40 m/s	2.12 m/s^2	2.39 m/s^2	+0.27 m/s^2
Lateral Sidestep (Mid Court)	3.87 m/s	4.27 m/s	+0.40 m/s	1.94 m/s^2	2.24 m/s^2	+0.30 m/s^2
Backward Deceleration (Rear Court)	3.93 m/s	4.32 m/s	+0.39 m/s	2.05 m/s^2	2.33 m/s^2	+0.28 m/s^2
Quick-Step (Forecourt to Midcourt)	4.01 m/s	4.41 m/s	+0.40 m/s	2.08 m/s^2	2.36 m/s^2	+0.28 m/s^2
Recovery Step (Post-Rally)	3.96 m/s	4.35 m/s	+0.39 m/s	1.99 m/s^2	2.28 m/s^2	+0.29 m/s^2

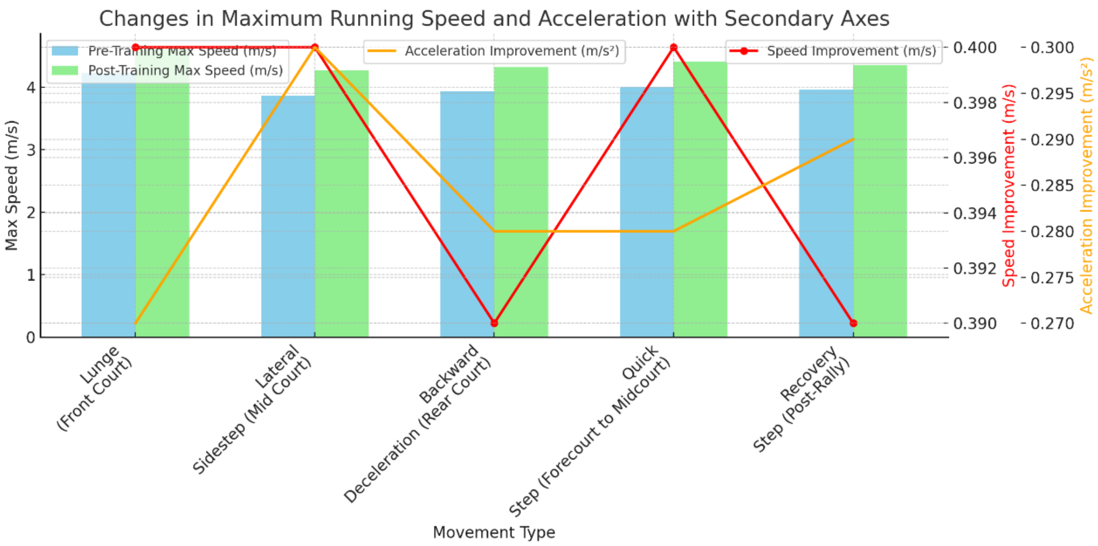

Figure 12. Running speed and acceleration analysis.

Table 8. Improved ability to transition between different speeds.

Transition Type	Pre-Training Time (s)	Post-Training Time (s)	Improvement (s)
Rapid Sprint to Controlled Lunge	0.84 s	0.73 s	+0.11 s
Sidestep to Sprint (Mid Court)	0.76 s	0.66 s	+0.10 s
Backward Deceleration to Recovery	0.88 s	0.77 s	+0.11 s
Forecourt to Midcourt Transition	0.81 s	0.70 s	+0.11 s
Post-Rally Recovery to Sprint	0.87 s	0.75 s	+0.12 s

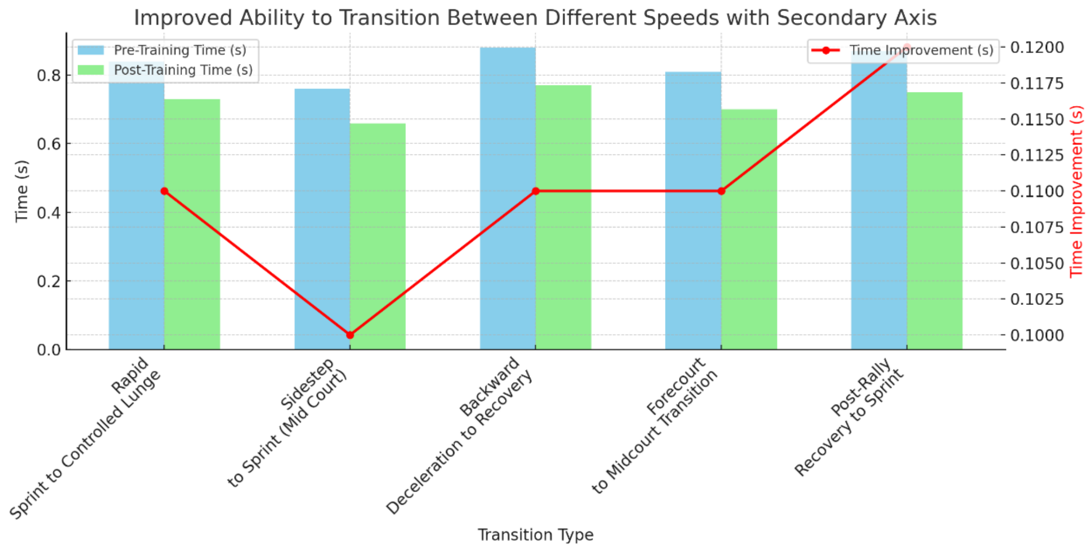

Figure 13. Ability to transition between different speeds.

Table 9 and **Figure 14** display improvements in the athletes' reaction times in response to various on-court movements and shuttle direction changes. For instance, the reaction time for a forehand smash improved by 0.06 s, and for a backhand drop shot, it improved by 0.06 s as well. The most significant improvement was seen in cross-court defensive reactions, where the reaction time decreased by 0.07 s. These results suggest that the VST program significantly enhanced the athletes' ability to react quickly to fast-paced gameplay, allowing for better decision-making and more effective defensive responses.

Table 9. Comparison of reaction times in response to on-court movements and shuttle direction changes before and after VST.

Movement Type	Pre-Training Reaction Time (s)	Post-Training Reaction Time (s)	Improvement (s)
Forehand Smash Reaction	0.42 s	0.36 s	+0.06 s
Backhand Drop Shot Reaction	0.47 s	0.41 s	+0.06 s
Lateral Sidestep Reaction	0.50 s	0.44 s	+0.06 s
NetPlay Reaction	0.39 s	0.33 s	+0.06 s
Cross-Court Defensive Reaction	0.53 s	0.46 s	+0.07 s

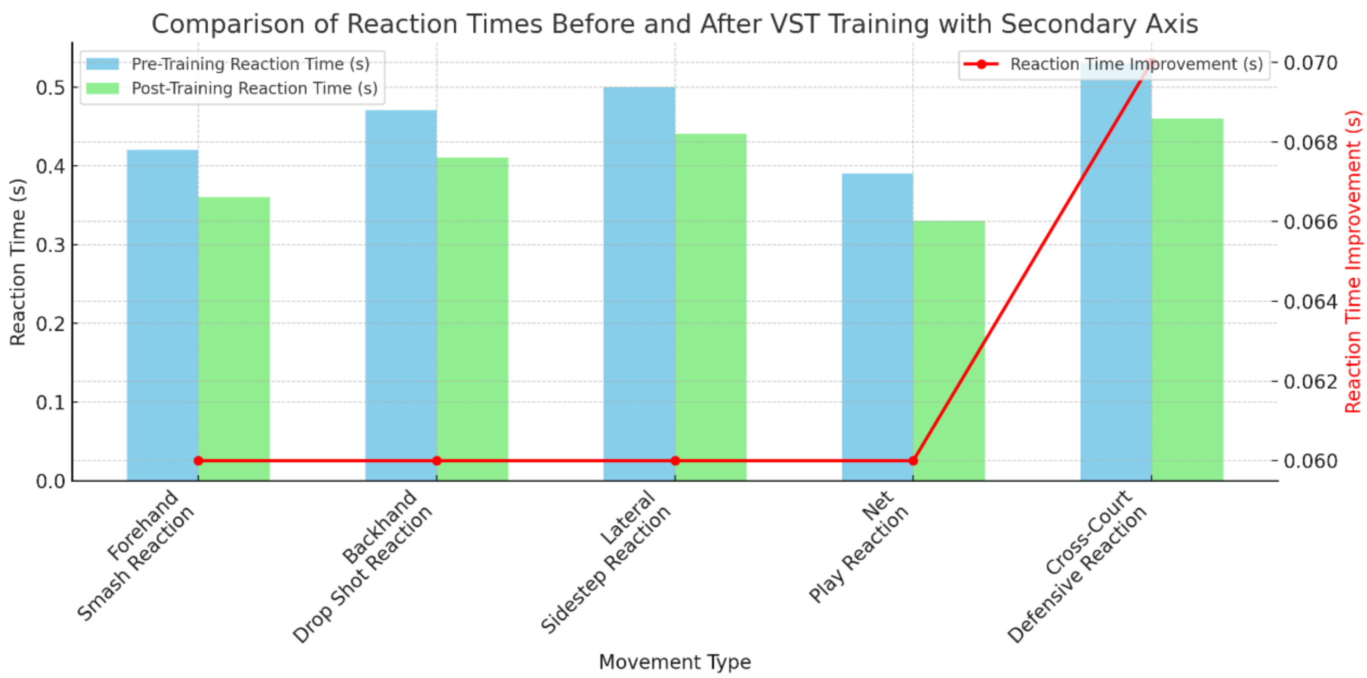

Figure 14. Reaction time analysis.

4.2. Tactical awareness results

Table 10 and **Figure 15** show substantial improvements in the decision-making speed of athletes across various game scenarios following the VST program. The athletes demonstrated quicker responses to in-game situations, particularly in defensive lunge decisions, where the decision-making speed improved by 0.16 s, from 1.12 s pre-training to 0.96 s post-training. Similarly, the ability to respond to an opponent's smash was faster by 0.14 s, highlighting the improved reaction time under high-pressure conditions. The most significant improvement was cross-court anticipation, where the decision-making speed increased by 0.17 s, indicating enhanced cognitive processing and faster responses to opponent tactics. These results demonstrate that the VST program helped athletes reduce their decision-making time across all scenarios, enhancing their ability to react quickly and strategically during gameplay.

Table 10. Decision-Making speed.

Scenario Type	Pre-Training Decision-Making Speed (s)	Post-Training Decision-Making Speed (s)	Improvement (s)
Opponent's Smash Response	0.98 s	0.84 s	+0.14 s
Defensive Lunge Decision	1.12 s	0.96 s	+0.16 s
NetPlay Quick Response	0.89 s	0.75 s	+0.14 s
Cross-Court Anticipation	1.18 s	1.01 s	+0.17 s
Clear to Backcourt Decision	0.92 s	0.79 s	+0.13 s

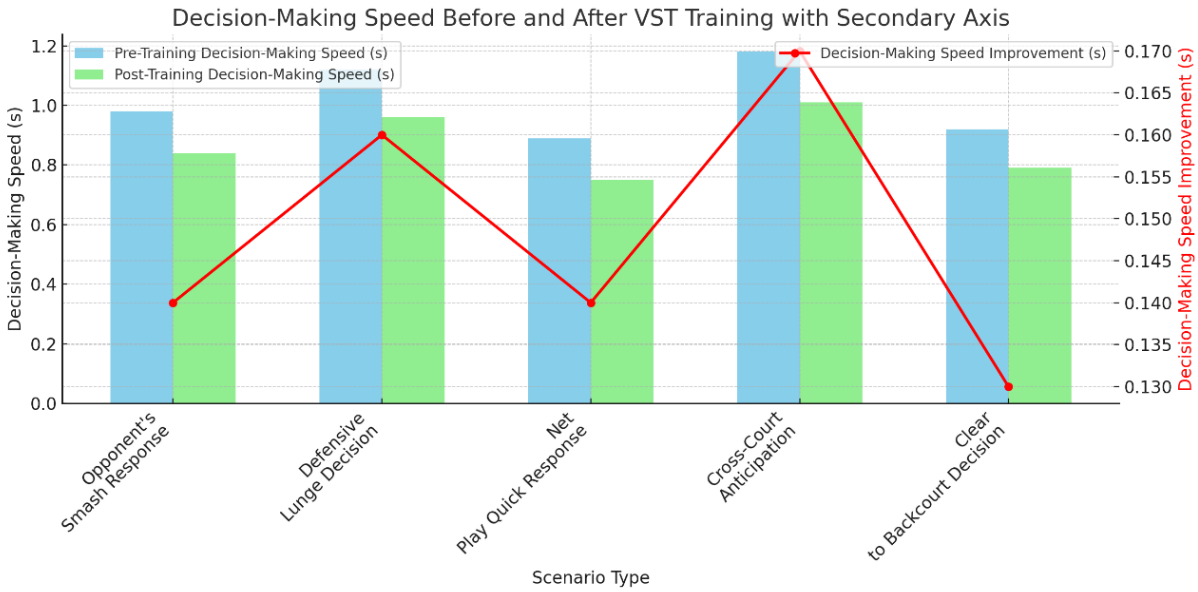

Figure 15. Decision-making analysis.

Table 11 and **Figure 16** highlight the athletes' improved ability to maintain optimal court positioning after the VST intervention. Post-training, positioning during smashes saw an accuracy increase of 9.2%, from 72.4% pre-training to 81.6%, suggesting that the athletes could better predict and react to the opponent's movements during offensive plays. The most significant improvement in spatial awareness was seen in positioning for drop shots, which increased by 9.5%. This indicates that athletes became more adept at anticipating the shuttle's placement and positioning themselves effectively. Defensive scenarios, such as cross-court defensive play, also significantly improved (9.4%), highlighting the athletes' enhanced ability to cover the court and maintain proper positioning during high-intensity defensive situations. Overall, spatial awareness improvements across all scenarios suggest that athletes were better able to read the game and maintain optimal positioning, contributing to more compelling gameplay.

Table 11. Spatial awareness.

Court Positioning Scenario	Pre-Training Accuracy of Court Positioning (%)	Post-Training Accuracy of Court Positioning (%)	Improvement (%)
Positioning during Smashes	72.4%	81.6%	+9.2%
Positioning for Drop Shots	68.3%	77.8%	+9.5%
Reaction to Net Play	74.1%	82.3%	+8.2%
Cross-Court Defensive Play	65.7%	75.1%	+9.4%
Backcourt Clear Positioning	71.5%	80.2%	+8.7%

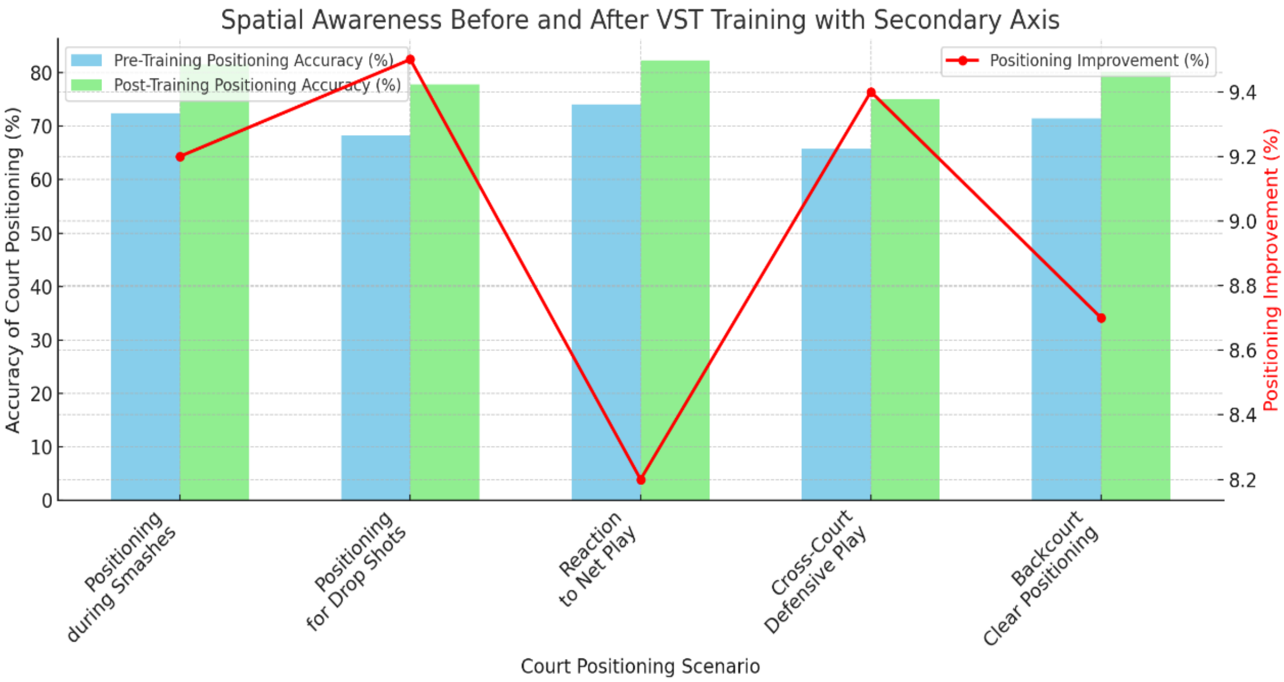

Figure 16. Spatial awareness analysis.

Table 12 and **Figure 17** illustrate improved selection accuracy across all significant shot types after VST training. The accuracy of forehand smashes increased by 7.7%, reflecting better control and precision in offensive plays. The most significant improvement was backhand drop shot accuracy, which increased by 8.7%, highlighting the athletes' enhanced technical execution of more delicate shots. Similarly, cross-court precise accuracy improved by 8.3%, indicating better shot placement during defensive exchanges. Defensive shots, such as defensive lobs, saw a significant improvement of 9.0%, suggesting that athletes were better able to place shots strategically during rallies, helping them to recover and reposition. Overall, the VST program improved shot accuracy, allowing athletes to make more effective and precise matches during matches, improving tactical performance.

Table 12. Shot selection accuracy.

Shot Type	Pre-Training Shot Accuracy (%)	Post-Training Shot Accuracy (%)	Improvement (%)
Forehand Smash Accuracy	78.2%	85.9%	+7.7%
Backhand Drop Shot Accuracy	71.6%	80.3%	+8.7%
Cross-Court Clear Accuracy	69.8%	78.1%	+8.3%
NetPlay Shot Accuracy	73.4%	81.5%	+8.1%
Defensive Lob Accuracy	68.9%	77.9%	+9.0%

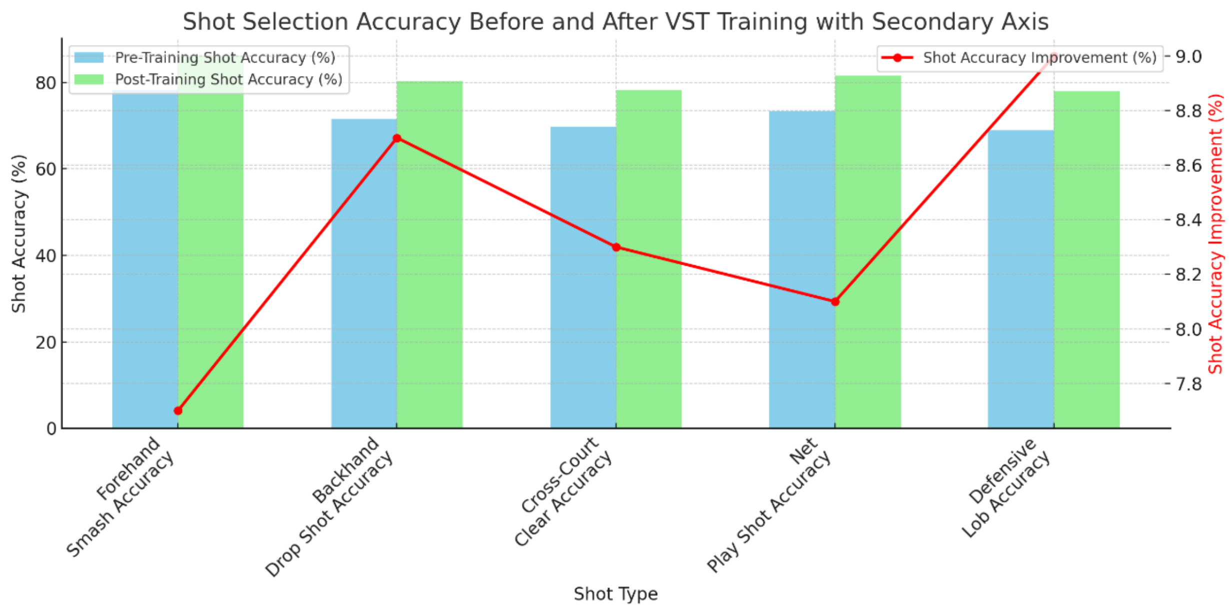

Figure 17. Spatial awareness analysis.

4.3. Endurance and cardiovascular results

Table 13 reveals significant improvements in heart rate recovery after the VST intervention. At 30 s after an interval, the average heart rate decreased by 14 bpm, from 152 bpm pre-training to 138 bpm post-training. Similar improvements were seen at 60 and 90 s after intervals, with reductions of 14 bpm and 15 bpm, respectively. These results suggest that the athletes' cardiovascular systems adapted to recover more efficiently after high-intensity activity. Faster heart rate recovery is an essential marker of improved cardiovascular fitness, allowing athletes to maintain performance during extended periods of play by recovering more quickly between bursts of effort.

Table 13. Heart rate recovery between intervals.

Time Point	Pre-Training Recovery Heart Rate (bpm)	Post-Training Recovery Heart Rate (bpm)	Improvement (bpm)
30 s after the interval	152 bpm	138 bpm	+14 bpm
60 s after the interval	135 bpm	121 bpm	+14 bpm
90 s after the interval	128 bpm	113 bpm	+15 bpm

As seen in **Table 14**, athletes' heart rate during high-intensity play also showed significant reductions post-training, indicating improved endurance. In the first 5 min of play, the average heart rate dropped by 11 bpm, from 175 bpm pre-training to 164 bpm post-training. This reduction continued throughout the 25-minute duration, with a decrease of 12 bpm observed during the 10–15-minute and 20–25-minute periods. These findings suggest that the athletes could sustain high-intensity effort for extended periods with less cardiovascular strain, a critical factor in maintaining performance during prolonged rallies and high-pressure situations.

Table 14. Heart rate during High-Intensity play.

Activity Duration	Pre-Training Heart Rate (bpm)	Post-Training Heart Rate (bpm)	Improvement (bpm)
First 5 min	175 bpm	164 bpm	+11 bpm
10–15 min	182 bpm	170 bpm	+12 bpm
20–25 min	188 bpm	176 bpm	+12 bpm

Table 15 highlights improvements in the athletes' fatigue resistance following the VST program. The average number of shots in extended rallies increased by 7 shots, from 21 pre-training to 28 post-training, indicating enhanced endurance and the ability to maintain high performance during long rallies, and the athletes' reaction time in extended rallies improved by 0.11 s, further supporting the notion that they could maintain cognitive sharpness even under physical fatigue. Shot accuracy during high-pressure play improved by 8.4%, suggesting that the athletes could execute technically precise shots even as fatigued. Lastly, court coverage in the final 10 min of high-intensity play increased by 8.4%, reflecting better movement efficiency and sustained agility, crucial for maintaining defensive and offensive positioning late into a match.

Table 15. Fatigue resistance.

Performance Metric	Pre-Training Value	Post-Training Value	Improvement
Average Number of Shots in Extended Rally	21 shots	28 shots	+7 shots
Reaction Time in Extended Rally (s)	0.58 s	0.47 s	+0.11 s
Shot Accuracy in High-Pressure Play (%)	67.8%	76.2%	+8.4%
Court Coverage in Last 10 Min (%)	69.1%	77.5%	+8.4%

4.4. Overall performance improvements

Table 16 presents the results of the improvements in footwork efficiency after the VST training. The data demonstrates significant gains in footwork speed across all movement types. For instance, during the lunge (front court) movement, the athletes improved their footwork speed by 0.21 m/s, from 2.16 m/s pre-training to 2.37 m/s post-training. Similar improvements were seen across lateral sidesteps, backward, and recovery steps, with speed increases of 0.20–0.21 m/s, reflecting enhanced agility and quicker court coverage. Additionally, the balance of the athletes, as measured by the Center of Pressure (CoP) shift, showed considerable improvements. An enormous improvement was noted in the lateral sidestep (mid-court) movement, where CoP shift was reduced by 2.2 cm, from 7.3 cm pre-training to 5.1 cm post-training, indicating better control and stability during high-speed lateral movements. Overall, these results suggest that VST training contributed to faster and more stable footwork, enabling the athletes to move quickly and maintain balance during rapid directional changes, which is crucial in badminton.

Table 16. Footwork efficiency.

Movement Type	Pre-Training Footwork Speed (m/s)	Post-Training Footwork Speed (m/s)	Improvement in Speed (m/s)	Pre-Training Balance (CoP Shift in cm)	Post-Training Balance (CoP Shift in cm)	Improvement in Balance (cm)
Lunge (Front Court)	2.16 m/s	2.37 m/s	+0.21 m/s	6.8 cm	4.9 cm	+1.9 cm
Lateral Sidestep (Mid Court)	2.02 m/s	2.23 m/s	+0.21 m/s	7.3 cm	5.1 cm	+2.2 cm
Backward Step (Rear Court)	2.11 m/s	2.31 m/s	+0.20 m/s	6.7 cm	4.8 cm	+1.9 cm
Forecourt to Midcourt Movement	2.08 m/s	2.28 m/s	+0.20 m/s	6.5 cm	4.7 cm	+1.8 cm
Recovery Step (Post-Rally)	2.10 m/s	2.30 m/s	+0.20 m/s	7.0 cm	5.2 cm	+1.8 cm

Table 17 and **Figure 18** highlight the improvements in time to stabilization, showing how quickly athletes regained stability after rapid movements or directional changes. Post-training, the time to stabilization decreased across all movement types. The most significant improvement was observed in the recovery step (post-rally), where the stabilization time decreased by 0.20 s, from 1.23 s pre-training to 1.03 s post-training. Similarly, lateral sidesteps and backward decelerations also saw improvements of 0.19 s each, reflecting the athletes' enhanced ability to regain balance and control after high-speed actions. These reductions in stabilization time are significant in badminton, where players must frequently recover quickly after rapid movements to prepare for the next shot. Faster stabilization times indicate improved neuromuscular coordination and control, allowing athletes to transition more efficiently between movements and maintain a competitive advantage during rallies.

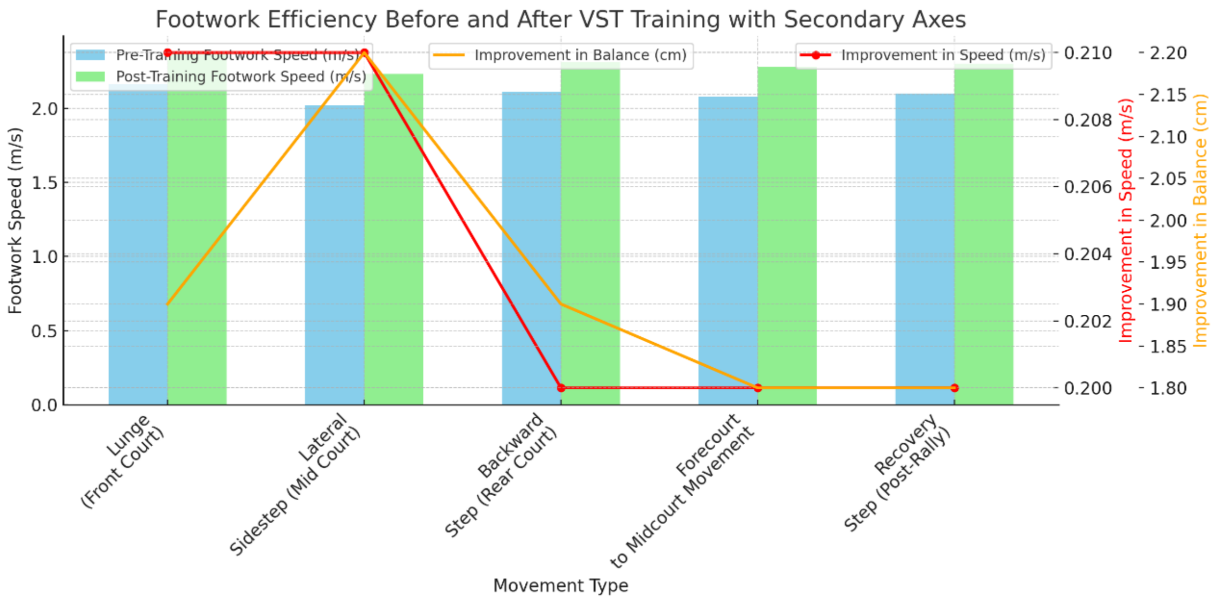

Figure 18. Footwork efficiency analysis.

Table 17. Time to stabilization.

Movement Type	Pre-Training Time to Stabilization (s)	Post-Training Time to Stabilization (s)	Improvement in Stability Time (s)
Lunge Deceleration (Front Court)	1.14 s	0.96 s	+0.18 s
Lateral Sidestep (Mid Court)	1.21 s	1.02 s	+0.19 s
Backward Deceleration (Rear Court)	1.19 s	1.00 s	+0.19 s
Quick-Step (Forecourt to Midcourt)	1.11 s	0.94 s	+0.17 s
Recovery Step (Post-Rally)	1.23 s	1.03 s	+0.20 s

4.5. Statistical significance of improvements

Table 18 and **Figure 19** present the results of the paired *t*-tests, showing significant improvements across all variables after the VST intervention. For joint angles, the hip joint angle during lunges improved by 7.7°, with a *t*-value of 4.72 and a *p*-value of 0.001, indicating a highly significant improvement. Similarly, the knee joint angle during sprints increased by 6.3°, and the ankle joint angle during sidesteps increased by 6.3°, with *p*-values of 0.001, demonstrating significant gains in range of motion and flexibility. Regarding movement efficiency, the stride length during lunges improved by 0.12 m, with a *t*-value of 3.89, showing significant enhancements in mobility. The reduction in GRF during lateral sidesteps by 105 N (*t*-value 4.17) highlights a significant decrease in impact forces, indicating better control during rapid movements and reduced injury risk. For cognitive performance, decision-making speed during net play improved by 0.14 s (*t*-value 4.94), demonstrating faster responses in tactical situations.

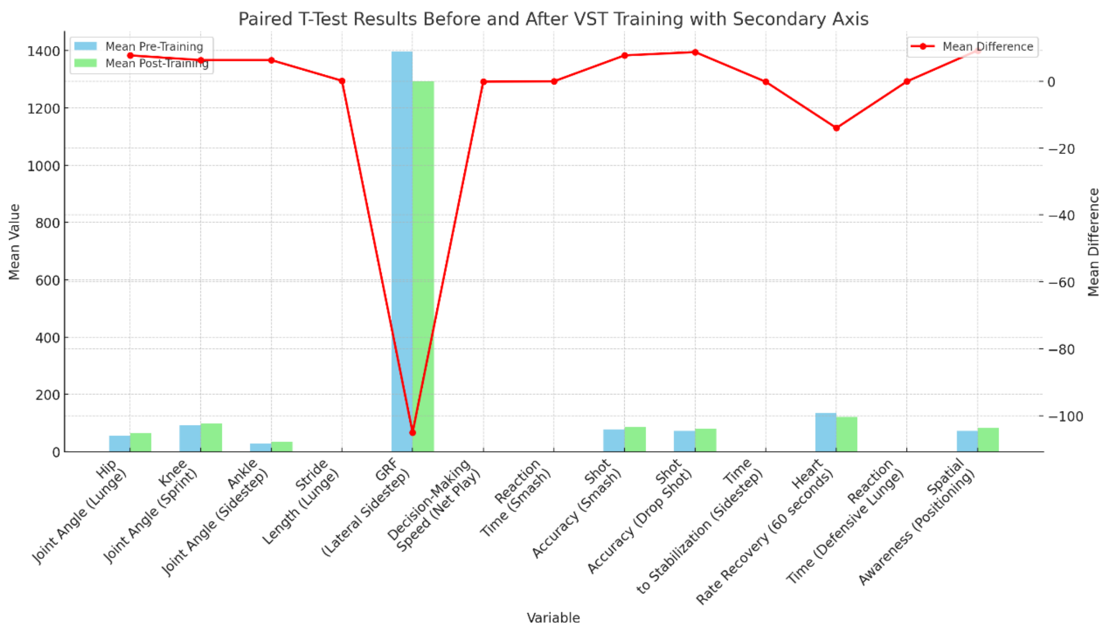

Figure 19. Paired *t*-test analysis.

Table 18. Paired *t*-test results.

Variable	Mean Pre-Training	Mean Post-Training	Mean Difference	*t*-value	*p*-value	Significance ($p < 0.05$)
Hip Joint Angle (Lunge)	55.4°	63.1°	+7.7°	4.72	0.001	Significant
Knee Joint Angle (Sprint)	91.6°	97.9°	+6.3°	4.05	0.001	Significant
Ankle Joint Angle (Sidestep)	27.9°	34.2°	+6.3°	4.60	0.001	Significant
Stride Length (Lunge)	1.46 m	1.58 m	+0.12 m	3.89	0.002	Significant
GRF (Lateral Sidestep)	1398 N	1293 N	−105 N	4.17	0.001	Significant
Decision-Making Speed (Net Play)	0.89 s	0.75 s	−0.14 s	4.94	0.000	Significant
Reaction Time (Smash)	0.42 s	0.36 s	−0.06 s	4.23	0.001	Significant
Shot Accuracy (Smash)	78.2%	85.9%	+7.7%	4.10	0.002	Significant
Shot Accuracy (Drop Shot)	71.6%	80.3%	+8.7%	4.21	0.001	Significant
Time to Stabilization (Sidestep)	1.21 s	1.02 s	−0.19 s	4.35	0.001	Significant
Heart Rate Recovery (60 s)	135 bpm	121 bpm	−14 bpm	4.47	0.001	Significant
Reaction Time (Defensive Lunge)	0.47 s	0.41 s	−0.06 s	3.85	0.002	Significant
Spatial Awareness (Positioning)	72.4%	81.6%	+9.2%	4.05	0.001	Significant

Similarly, reaction time during smashes improved by 0.06 s (*t*-value 4.23), showing enhanced reaction speed in high-pressure moments. In shot accuracy, smash accuracy improved by 7.7%, and drop shot accuracy improved by 8.7%, both statistically significant, reflecting greater precision in execution during play. Additionally, time to stabilization during sidesteps decreased by 0.19 s, indicating faster recovery from rapid movements, which is crucial for maintaining balance during intense rallies. Lastly, heart rate recovery showed significant improvement, with a reduction of 14 bpm in recovery heart rate after 60 s (*t*-value 4.47), suggesting enhanced cardiovascular fitness. Spatial awareness, measured by positioning accuracy, increased by 9.2%, demonstrating better court coverage and strategic play.

Table 19 and **Figure 20** present Cohen's *d*-effect size calculations, which quantify the magnitude of the improvements. Most variables show large effect sizes (Cohen's $d > 0.80$), indicating substantial improvements. Notably, decision-making speed during net play had the most significant effect size (1.15), showing that the VST program profoundly impacted cognitive decision-making under pressure. Similarly, improvements in heart rate recovery ($d = 0.95$), GRF during lateral sidesteps ($d = 0.91$), and shot accuracy ($d = 0.84$ for smashes and 0.91 for drop shots) reflect the effectiveness of VST in enhancing both physical and tactical performance. Moderate effect sizes were observed in stride length during lunges ($d = 0.72$) and reaction time during defensive lunges ($d = 0.78$), indicating meaningful but slightly smaller improvements than the other metrics.

Table 19. Effect size calculations (Cohen's d).

Variable	Effect Size (Cohen's d)	Magnitude of Effect
Hip Joint Angle (Lunge)	0.94	Large
Knee Joint Angle (Sprint)	0.84	Large
Ankle Joint Angle (Sidestep)	0.88	Large
Stride Length (Lunge)	0.72	Moderate
GRF (Lateral Sidestep)	0.91	Large
Decision-Making Speed (Net Play)	1.15	Large
Reaction Time (Smash)	0.89	Large
Shot Accuracy (Smash)	0.84	Large
Shot Accuracy (Drop Shot)	0.91	Large
Time to Stabilization (Sidestep)	0.87	Large
Heart Rate Recovery (60 s)	0.95	Large
Reaction Time (Defensive Lunge)	0.78	Moderate
Spatial Awareness (Positioning)	0.92	Large

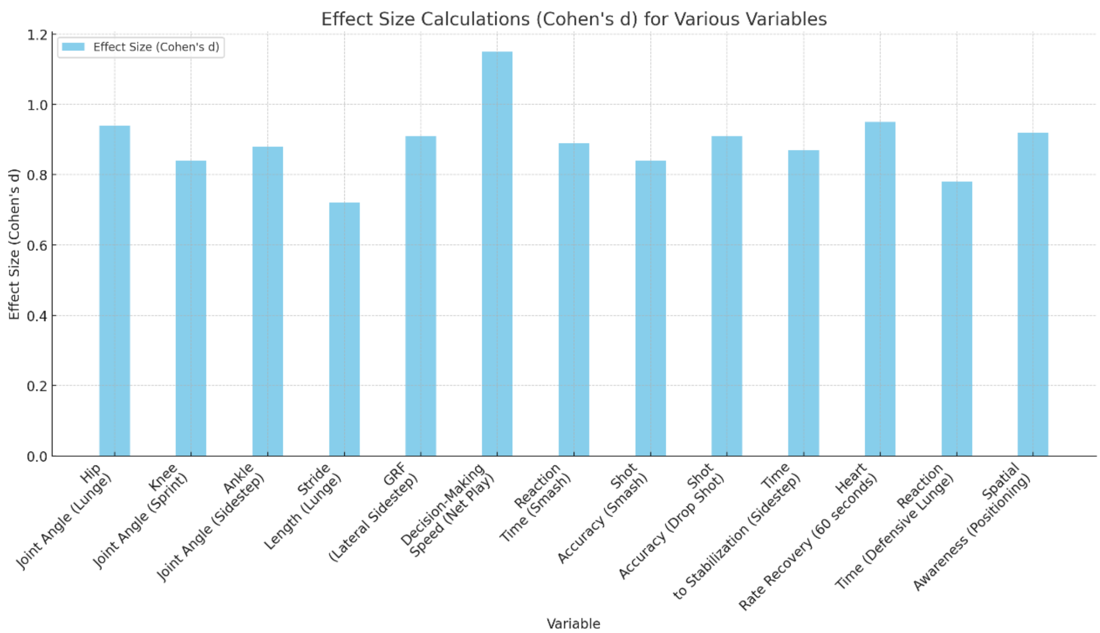

Figure 20. Cohen's *d* analysis.

5. Conclusion and future works

This study demonstrates that VST is a highly effective method for enhancing badminton performance's physical and cognitive aspects. Focusing on the dynamic interplay between biomechanics and tactical awareness, this research provides valuable insights into how varying running intensities can improve key aspects of movement efficiency, decision-making, and cardiovascular endurance in college-level badminton athletes. The significant improvements in joint angles, stride length, and GRF) indicate that VST contributes to better movement control and reduced injury risk, particularly during high-intensity rallies and rapid directional changes. The enhanced flexibility and stability in key joints, such as the hip, knee, and ankle, reflect the athletes' increased ability to execute complex movements with greater precision and reduced impact forces. Moreover, the cognitive benefits of VST are evident in the improvements in decision-making speed, reaction time, and spatial awareness. Faster decision-making under pressure and better shot accuracy and court positioning demonstrate that VST improves physical capabilities and sharpens the athletes' tactical awareness. These cognitive gains are essential for competitive performance in fast-paced, high-stakes badminton matches. The cardiovascular analysis further highlights the benefits of VST, with improvements in heart rate recovery and fatigue resistance indicating better endurance and the ability to sustain high-intensity play over longer durations. This is particularly important in badminton, where prolonged rallies require both physical stamina and mental focus. Overall, the findings of this study underscore the importance of integrating VST into badminton training regimens. By addressing physical and cognitive elements, VST offers a holistic approach to improving athletic performance, making it a valuable tool for coaches and athletes aiming to gain a competitive edge. Future research should explore the long-term effects of VST and its application in other sports to further the understanding of its benefits across different athletic contexts.

Funding: This work was partly sponsored by the Scientific Research Project of Hebei Provincial Department of Education (No. SQ2024259).

Ethical approval: Not applicable.

Conflict of interest: The authors declare no conflict of interest.

References

1. Edmizal, E., Rahman, D., Barlian, E., Donie, D., & Alnedral, A. (2024). Tactics and strategy analysis in professional badminton: insights from match data and performance metrics-a systematic review. Retos, 61, 78-85.
2. Shedge, S. S., Ramteke, S. U., & Jaiswal, P. R. (2024). Optimizing agility and athletic proficiency in badminton athletes through plyometric training: a review. Cureus, 16(1).
3. Wang, Y. (2023). Forensic analysis of Lateral ankle ligamentous sprain injury in Badminton (Doctoral dissertation, Loughborough University).
4. NAGORNA, V., MYTKO, A., BORYSOVA, O., POTOP, V., PETRENKO, H., ZHYHAILOVA, L., ... & LORENZETTI, S. (2024). Innovative technologies in sports games: A comprehensive investigation of theory and practice. Journal of Physical Education and Sport, 585-596.
5. Voigt, L., Friedrich, J., Grove, P., Heinrich, N., Ittlinger, S., Iskra, M., ... & Raab, M. (2023). Advancing judgment and decision-making research in sport psychology by using the body as an informant in embodied choices. Asian Journal of Sport and Exercise Psychology, 3(1), 47-56.
6. Ihsan, F., Nasrulloh, A., Nugroho, S., & Kozina, Z. (2024). Optimizing physical conditioning programs for badminton athletes: A comprehensive review of training strategies-a systematic review. Retos: nuevas tendencias en educación física, deporte y recreación, (54), 488-498.
7. Adirahma, A. S., Widiyanto, W. E., Setyawan, H., Hamsyah, K., Darmawan, A., Nurkadri, N., ... & Pavlovic, R. (2024). Badminton training management strategy with circuit training method to improve athlete performance among students. Retos, 61, 108-120.
8. Ihsan, F., Nasrulloh, A., Nugroho, S., & Yuniana, R. (2024). The effect of shadow training and muscle endurance on agility of badminton athletes 12-17 years of age. Retos: nuevas tendencias en educación física, deporte y recreación, (54), 36-45.
9. Liu, X., Ren, H., & Chen, T. (2023). Predicting Highlights in Badminton Matches: A Knowledge-Aware Model Analysis of Rally-by-Rally Statistics.

10. Ghosh, I., Ramasamy Ramamurthy, S., Chakma, A., & Roy, N. (2023). Sports analytics review: Artificial intelligence applications, emerging technologies, and algorithmic perspective. Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery, 13(5), e1496.
11. LeVeau, B. (2024). Biomechanics of human motion: basics and beyond for the health professions. Routledge.
12. Yadav, A., & Bhardwaj, M. (2024). A Comparative Analysis: Assessing the Efficacy of High-Intensity Circuit Training Utilizing Body Weight versus Sports Specific Exercises on Lower Limb Strength, Agility, and Speed among Badminton Players-Preliminary Investigation. International Journal for Multidimensional Research Perspectives, 2(6), 48-57.
13. Shen, S., Teng, J., Fekete, G., Mei, Q., Zhao, J., Yang, F., & Gu, Y. (2024). Influence of Torsional Stiffness in Badminton Footwear on Lower Limb Biomechanics. Journal of Sports Science & Medicine, 23(1), 196.
14. Li, F., Li, S., Zhang, X., & Shan, G. (2023). Biomechanical Insights for Developing Evidence-Based Training Programs: Unveiling the Kinematic Secrets of the Overhead Forehand Smash in Badminton through Novice-Skilled Player Comparison. Applied Sciences, 13(22), 12488.
15. Chen, W. T., Wu, H. Y., Shih, Y. A., Wang, C. C., & Wang, Y. S. (2023, September). Exploration of Player Behaviours from Broadcast Badminton Videos. In Computer Graphics Forum (Vol. 42, No. 6, p. e14786).
16. Schmid, M. J., Küttel, A., Charbonnet, B., Rivero, T., Schmid, J., Ronkainen, N., & Conzelmann, A. (2024, July). A Scoping Review on the Theoretical and Methodological Advances in the Study of Retirement From Elite Sport. In European Congress of Sport and Exercise Psychology.
17. Dennison, L., Duthie, G. M., & Psarakis, M. A. (2024). Optimising Sprint Performance: Concurrent Validity and reliability of 25HZ GNSS units for speed PROFILING. Journal of Clinical Exercise Physiology, 13(s2), 417-417.
18. Weir, G., Ferreira, J. P. M., Lockhart, T. E., Mai, P., Sharma, A., Sharma, A., ... & Rombokas, E. (2023). OPEN ACCESS EDITED BY. Human Movement and Motor Control in the Natural Environment, 144.
19. Paul William Moore, D. (2024). Examination of the professional judgment and decision-making of strength and conditioning coaches.
20. Sengan Sudhakar and S. Chenthur Pandian, (2016), ‘Hybrid Cluster-based Geographical Routing Protocol to Mitigate Malicious Nodes in Mobile Ad Hoc Network, InderScience-International Journal of Ad Hoc and Ubiquitous Computing, vol. 21, no. 4, pp. 224-236. DOI:10.1504/IJAHUC.2016.076358.
21. Kusuma, I. D. M. A. W., Kusnanik, N. W., Lumintuarso, R., & Phanpheng, Y. (2024). The holistic and partial approach in soccer training: Integrating physical, technical, tactical, and mental components: A systematic review. Retos: nuevas tendencias en educación física, deporte y recreación, (54), 328-337.
22. Indumathi Nallathambi, Padmaja Savaram, Sudhakar Sengan, Meshal Alharbi, Samah Alshathri, Mohit Bajaj, Moustafa H. Aly and Walid El-Shafai, Impact of Fireworks Industry Safety Measures and Prevention Management System on Human Error Mitigation Using a Machine Learning Approach, Sensors, 2023, 23 (9), 4365; DOI:10.3390/s23094365.
23. Parkavi Krishnamoorthy, N. Satheesh, D. Sudha, Sudhakar Sengan, Meshal Alharbi, Denis A. Pustokhin, Irina V. Pustokhina, Roy Setiawan, Effective Scheduling of Multi-Load Automated Guided Vehicle in Spinning Mill: A Case Study, IEEE Access, 2023, DOI:10.1109/ACCESS.2023.3236843.
24. Ran Qian, Sudhakar Sengan, Sapna Juneja, English language teaching based on big data analytics in augmentative and alternative communication system, Springer-International Journal of Speech Technology, 2022, DOI:10.1007/s10772-022-09960-1.
25. Ngangbam Phalguni Singh, Shruti Suman, Thandaiah Prabu Ramachandran, Tripti Sharma, Selvakumar Raja, Rajasekar Rangasamy, Manikandan Parasuraman, Sudhakar Sengan, “Investigation on characteristics of Monte Carlo model of single electron transistor using Orthodox Theory”, Elsevier, Sustainable Energy Technologies and Assessments, Vol. 48, 2021, 101601, DOI:10.1016/j.seta.2021.101601.
26. Huidan Huang, Xiaosu Wang, Sudhakar Sengan, Thota Chandu, Emotional intelligence for board capital on technological innovation performance of high-tech enterprises, Elsevier, Aggression and Violent Behavior, 2021, 101633, DOI:10.1016/j.avb.2021.101633.
27. Sudhakar Sengan, Kailash Kumar, V. Subramaniyaswamy, Logesh Ravi, Cost-effective and efficient 3D human model creation and re-identification application for human digital twins, Multimedia Tools and Applications, 2021. DOI:10.1007/s11042-021-10842-y.

28. Prabhakaran Narayanan, Sudhakar Sengan, Balasubramaniam Pudhupalayam Marimuthu, Ranjith Kumar Paulra, Novel Collision Detection and Avoidance System for Mid-vehicle Using Offset-Based Curvilinear Motion. Wireless Personal Communication, 2021. DOI:10.1007/s11277-021-08333-2.
29. Balajee Alphonse, Venkatesan Rajagopal, Sudhakar Sengan, Kousalya Kittusamy, Amudha Kandasamy, Rajendiran Periyasamy Modeling and multi-class classification of vibroarthographic signals via time domain curvilinear divergence random forest, J Ambient Intell Human Comput, 2021, DOI:10.1007/s12652-020-02869-0.
30. Omnia Saidani Neffati, Roy Setiawan, P Jayanthi, S Vanithamani, D K Sharma, R Regin, Devi Mani, Sudhakar Sengan, An educational tool for enhanced mobile e-Learning for technical higher education using mobile devices for augmented reality, Microprocessors and Microsystems, Vol. 83, 2021, 104030, DOI:10.1016/j.micpro.2021.104030 .
31. Firas Tayseer Ayasrah, Nabeel S. Alsharafa, Sivaprakash S, Srinivasarao B, Sudhakar Sengan and Kumaran N, "Strategizing Low-Carbon Urban Planning through Environmental Impact Assessment by Artificial Intelligence-Driven Carbon Foot Print Forecasting", Journal of Machine and Computing, Vol. 4, No. 04, 2024, doi: 10.53759/7669/jmc202404105.
32. Shaymaa Hussein Nowfal, Vijaya Bhaskar Sadu, Sudhakar Sengan, Rajeshkumar G, Anjaneyulu Naik R, Sreekanth K, Genetic Algorithms for Optimized Selection of Biodegradable Polymers in Sustainable Manufacturing Processes, Journal of Machine and Computing, Vol. 4, No. 3, PP. 563-574, https://doi.org/10.53759/7669/jmc202404054.
33. Hayder M. A. Ghanimi, Sudhakar Sengan, Vijaya Bhaskar Sadu, Parvinder Kaur, Manju Kaushik, Roobaea Alroobaea, Abdullah M. Baqasah, Majed Alsafyani & Pankaj Dadheech, An open-source MP + CNN + BiLSTM model-based hybrid model for recognizing sign language on smartphones. Int J Syst Assur Eng Manag (2024). https://doi.org/10.1007/s13198-024-02376-x
34. K. Bhavana Raj, Julian L. Webber, Divyapushpalakshmi Marimuthu, Abolfazl Mehbodniya, D. Stalin David, Rajasekar Rangasamy, Sudhakar Sengan, Equipment Planning for an Automated Production Line Using a Cloud System, Innovations in Computer Science and Engineering. ICICSE 2022. Lecture Notes in Networks and Systems, vol 565, pp 707–717, Springer, Singapore. DOI:10.1007/978-981-19-7455-7_57.