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Article

Study on the impact of shoulder flexibility training on smash speed mechanics in badminton using machine learning

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Abstract: The smash stroke in badminton is a key attack style that makes the opponent player miss the strike; the smash requires speed, agility, strength, and precision. The smash demands a high level of shoulder flexibility from the players, which increases the Range of Motion (ROM) during the backswing and forward swing phases. The shoulder flexibility provides excellent energy storage and transfer, improving smash speed. The biomechanical efficiency of Shoulder Flexibility Training (FLT) on smash speed efficiency is still under study. This lack of study leads to modelling training program limitations, which may increase the risk of injury. Examining the process by which smash speed mechanics are impacted by Shoulder Flexibility Training (SFT) programs is the primary goal of the present investigation. It is approximately a 6-week training program for Amateur Players (AP) and National Players (NP), which uses core shoulder motions like flexion, abduction, and rotation as its basis. Motion capture systems and radar sensors investigated joint motion and smash speeds. To address the shortage of study evidence on the subject, a hybrid CNN + LSTM model was applied to predict smash speed concerning improved shoulder flexibility. As reported by the research results, students' smash speed and shoulder flexibility improved significantly during training. There was a 4.35% boost to smash speed at contact and a 4.69% gain in shoulder internal rotation compared to non-contact athletes. Additionally, there was a 9.83% boost in smash speed at contact and a 9.76% boost in shoulder internal rotation for the best athletes. Considering post-training illnesses, the CNN + LSTM model successfully predicted smash speed, with R^3 scores of 0.99 for NP and 0.97 for AP.

Keywords: biomechanical efficiency; shoulder flexibility training; kinematic analysis; motion capture system; speed mechanics; machine learning; CNN; LSTM

1. Introduction

In badminton, the smash is considered a keystroke of an aggressive nature that needs a combination of speed, power, and precision [1,2]. Through this high-speed stroke, the players can gain a significant advantage in rallies, making the smash a vital style in offensive and defensive strategies [3]. A successful smash demands complex biomechanical movements with synchronized and coordinated actions of the shoulder, elbow, wrist, and torso to generate maximum racket speed at the point of contact [4]. Out of the above, the shoulder part of the body determines the effectiveness of the backswing and forward swing phases. To achieve better smash, optimal shoulder flexibility is essential for efficient energy storage and transfer [5]. The shoulder flexibility is vital in making the shoulder freely rotate internally and externally, generating the necessary force to execute a powerful smash [6]. The importance of shoulder flexibility was not given enough in designing badminton training, irrespective of the fact that shoulder flexibility helps optimize the smash mechanics and reduces the risk of injury occurrence [7,8]. Limited focus on shoulder flexibility in badminton will decrease player efficiency due to improper mechanics that could result in overuse injuries in the shoulder and elbow joints [9,10].

Studies have shown that increased shoulder flexibility, in turn, increases the range of motion (ROM) in movements such as shoulder flexion, abduction, and rotation, which help the players execute more efficient and powerful smashes [11,12]. However, compared to studies focused on badminton biomechanics, such as muscle activation patterns and racket speed, there remains a gap in the literature regarding the direct impact of targeted Shoulder Flexibility Training (SFT) on smash mechanics, particularly for the shoulder [13–16]. Recently, Machine Learning (ML) models have been utilized in sports biomechanics, which analyze and predict performance metrics with higher accuracy [17–21]. Convolutional neural networks (CNNs) and long short-term memory (LSTM) networks have been employed more to process the biomechanical data that provide precise assessments of motion and performance. This paper exploits motion-captured data to boost accuracy using a hybrid CNN + LSTM model to predict the correlation between shoulder flexibility and smash speed biomechanics [22–24].

Better badminton smash speed mechanics are the primary goal of the present study, which investigates the results of a shoulder stretch therapy (SFT) program. To predict joint mechanics using motion-captured data, it implements a hybrid CNN + LSTM model. This study focuses on the biomechanics of smash, primarily the shoulder, and how more mobility improves speed and accuracy. In a 6-week SFT program, 25 individuals—10 non-native and 15 senior players—improved their shoulder flexion, abduction, and rotation. Employing speed radar and motion capture cameras, the behaviour was monitored. The hybrid CNN + LSTM model is employed to process the motion capture data that extracts the spatial and temporal features of the players' movements to predict improvements in smash speed. The work uses this hybrid model to precisely analyze kinematic changes in joint angles and movement patterns. This study tries to provide insights into how shoulder flexibility impacts the kinetic chain during the smash.

The key objectives of the work are:

a. To analyze how SFT moves smash speed across different phases of the stroke.
b. To measure improvements in shoulder flexibility (flexion, abduction, internal/external rotation) after the training program.
c. To compare the effectiveness of SFT on smash speed and joint mechanics for NP and AP.
d. A CNN + LSTM model will be applied to predict smash speed improvements based on motion capture data and flexibility changes.

The paper is organized as follows: Section 2 presents the theory about the badminton smash, Section 3 presents the methodology, Section 4 presents the analysis, and Section 5 presents the conclusion

2. Theory

2.1. Biomechanics of the badminton smash

The badminton smash is one of the most potent and decisive strokes in the sport that requires a combination of speed, strength, and precision. Biomechanically, the smash is a complex movement that involves coordinated actions of multiple joints and muscles, particularly the shoulder, elbow, wrist, and torso. Understanding the mechanics behind this stroke is critical for optimizing performance, reducing injury risks, and improving training effectiveness.

2.1.1. Phases of the smash

The smash is divided into four key phases: preparation (backswing), forward swing, contact, and follow-through.

1) Preparation (Backswing): During the backswing, the player rotates the shoulder externally, with the elbow flexed and the racket head positioned behind the player. The shoulder abduction and external rotation in this phase store potential energy, which is later transferred to the shuttle during the forward swing. The upper body, particularly the torso, begins to rotate as the player shifts weight from the back to the front leg, creating torque that aids energy transfer during the next phase.
2) Forward Swing: The forward swing is where the most acceleration occurs. The shoulder internally rotates at high speed, driven by the activation of the shoulder and torso muscles. Elbow extension coincides, contributing to the acceleration of the racket head. The kinetic energy generated by the body's rotation and shoulder motion is transferred down the arm, through the elbow and wrist, toward the racket. Just before contact, the wrist supination and flexion add an extra "snap" to the swing, increasing the racket's speed.
3) Contact: At the point of contact with the shuttlecock, the racket should be at maximum velocity. The body has fully rotated, and the shoulder is in a near-maximal internal rotation position. The elbow is almost fully extended, and the wrist flicks at the last moment to boost speed and control. Proper timing of these joint movements is essential to ensure that the kinetic chain, from the lower body to the racket, functions optimally. This phase is critical because even minor timing errors or misalignments in shoulder or wrist movements can reduce power or imprecise shot placement.
4) Follow-through: After contact, the player's shoulder continues to rotate internally, and the elbow flexes to decelerate the racket in a controlled manner. The torso completes its rotation and the weight shifts to the front leg. The follow-through phase is essential for dissipating the forces generated during the smash and preventing injury, particularly to the shoulder and elbow joints.

2.1.2. Kinematic and kinetic factors

The shoulder joint plays a key role in the smash, with external and internal rotations being key contributors to racket speed. High degrees of shoulder rotation are correlated with increased smash velocity, as they allow for more excellent energy storage and release during the stroke. The elbow acts as a lever during the smash, with an extension providing additional acceleration to the racket. Meanwhile, the wrist contributes to fine control and adds the final burst of speed through rapid flexion and pronation, especially in the last stages of the forward swing. The lower body and torso generate rotational power through the kinetic chain. Proper leg drive and hip rotation allow efficient energy transfer from the ground through the core, amplifying the power reaching the shoulder, arm, and, finally, the racket (see **Figure 1**).

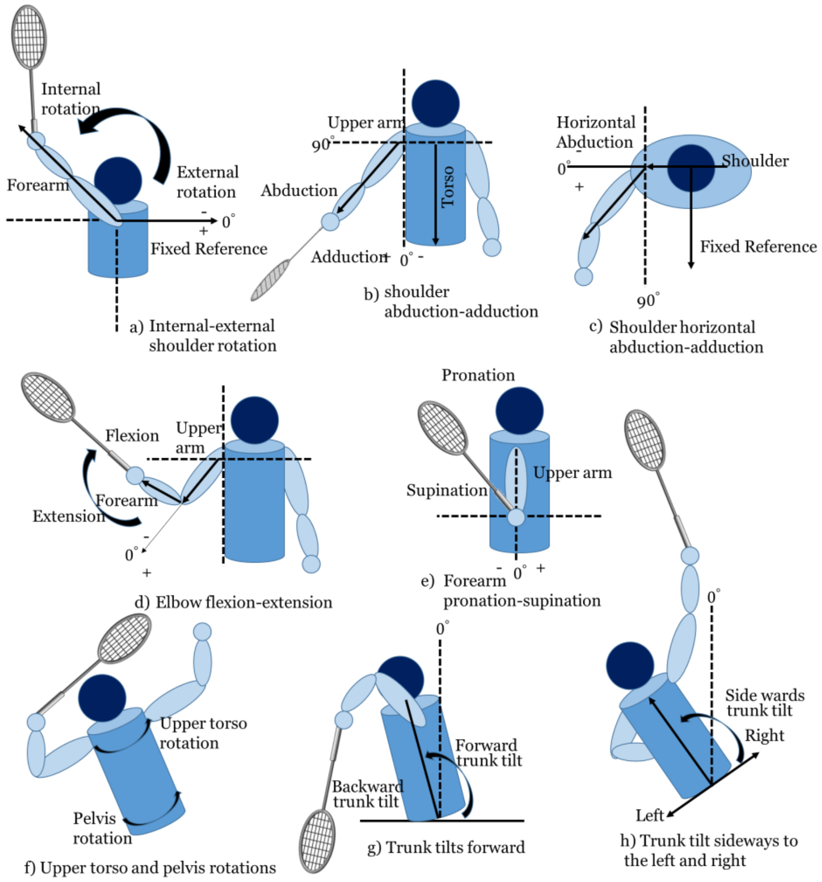

Figure 1. Joint movements in badminton smash.

The badminton smash is a prime example of the kinetic chain in action, where energy is transferred from the ground, through the legs, up through the torso, and finally to the racket via the shoulder, elbow, and wrist. Any disruption in this energy transfer, such as poor shoulder flexibility or improper elbow mechanics, can reduce smash power and increase the risk of injury. Efficient energy transfer depends on precise coordination between joint movements (**Figure 1**), particularly the shoulder's ability to rotate quickly through internal-external rotation, abduction-adduction, and horizontal abduction-adduction, along with synchronized elbow flexion-extension, forearm pronation-supination, and torso and trunk rotations to generate maximum power in the smash.

Smashed biomechanics demand shoulder flexibility, particularly in the backswing and forward swing. It boosts outer rotation, saves kinetic energy accurately, and sustains implementation control and accuracy. However, decreased shoulder flexibility can impair kinetic chain smoothness, increasing performance and the chance of injury. Optimal smash performance involves appropriate mechanics and flexibility.

The thigh muscles, pectoral muscle major, supraspinatus, and infraspinatus are all examples of shoulder muscles demonstrated to be functional in

Electromyographic (EMG) tests during the forward swing and contact phases. Smashes comprise the support of the shoulder joint by the rotator cuff muscles, flexion of the elbow by the quadriceps muscles, and the final flick at impact by the radius of motion flexible muscles.

3. Methodology

3.1. Participant players

The 10 badminton players classified as NP and 15 as AP participated in the experiment; the players ranged in age from 18 to 25. Athletes participating nationally and designated as NP have smash speeds between 270 to 300 km/h for women and 320 to 350 km/h for men. The AP group includes experienced competitors participating in regional and local tournaments; their smash speeds range between 230 and 260 km/h for women and 280 to 310 km/h for men. Injured or chronically ill athletes whose shoulders restricted their range of motion or function did not participate in this study. For proof that every individual achieved health and performance guidelines, an expert in sports medicine analyzed each player's health records comprehensively and performed a physical test (**Table 1**).

Table 1. Players demographics.

Characteristic	NP	AP
Number of Players	10	15
Age Range	20–25 years	18–22 years
Height Range	Males: 182 ± 2.3 cm Females: 170 ± 2.1 cm	Males: 175 ± 2.5 cm Females: 165 ± 2.4 cm
Weight Range	Males: 78 ± 3.4 kg Females: 62 ± 2.5 kg	Males: 72 ± 4.2 kg Females: 57 ± 3.5 kg
Sex Distribution	Males: 7 Females: 3	Males: 10 Females: 5
Competition Level	NP	AP
Background	7 competed in national tournaments; 3 ranked in the top 10	Competed in at least 3 local/regional tournaments
Smash Speed	Males: 335 ± 15 km/h Females: 285 ± 10 km/h	Males: 295 ± 12 km/h Females: 245 ± 15 km/h
Personal Best Smash Speed	Males: 350 ± 10 km/h Females: 300 ± 12 km/h	Males: 310 ± 10 km/h Females: 260 ± 12 km/h
Season Best Smash Speed	Males: 340 ± 8 km/h Females: 290 ± 10 km/h	Males: 305 ± 11 km/h Females: 255 ± 10 km/h

3.2. Training protocol

The shoulder SFT program is focused on improving the range of motion in the shoulder joints to enhance smash speed mechanics. It included three types of exercises: dynamic stretching, static stretching, and mobility drills. Dynamic stretches, such as arm circles, shoulder pendulum swings, and scapular retractions, were performed at the start of each session to loosen the shoulder joints. Static stretches, like cross-body shoulder, doorway, and sleeper, are followed to target long-term flexibility. Mobility drills, such as shoulder dislocations with resistance bands and internal/external rotations, improved shoulder range of motion and control. The program ran for six weeks, with sessions three times a week, each lasting 45 to 60 minutes. The routine began with dynamic stretches, moved to mobility drills, and ended with static stretches. **Table 2** presents the description of the training program.

Table 2. Training program description.

Category	Exercise	Purpose	Reps/Duration	Frequency
Dynamic Stretching	Arm Circles	Warm up and loosen shoulder joints	20 circles in each direction	3 times per week
	Shoulder Pendulum Swings	Increase blood flow and shoulder mobility	20 swings in each direction	3 times per week
	Scapular Retractions	Improve shoulder stability and mobility	15 reps	3 times per week
Static Stretching	Cross-Body Shoulder Stretch	Stretch rear shoulder and upper back	Hold for 30 seconds on each side	3 times per week
	Doorway Stretch	Stretch pectoral muscles and deltoids	Hold for 30 seconds	3 times per week
	Sleeper Stretch	Stretch posterior shoulder	Hold for 30 seconds on each side	3 times per week
Mobility Drills	Shoulder Dislocations with Resistance Band	Improve shoulder mobility and stability	10–15 reps	3 times per week
	Internal and External Rotations (Resistance)	Strengthen rotator cuff and improve flexibility	12–15 reps each side	3 times per week

3.3. Experimental design

Twenty-five badminton players, divided into two groups based on their competitive level (10 AP and 15 AP), participated in this study. All players had a competitive badminton experience and were provided with a familiarization session before the main testing. On the testing day, motion capture data and shoulder flexibility measurements were recorded before and after the 6-week SFT program. The two key conditions assessed were Pre-training (baseline) and Post-training (after 6 weeks of SFT) to evaluate the training's effect on smash speed mechanics. Testing began with a 10-minute warm-up that included dynamic shoulder stretches to prepare the muscles and joints for performance (**Figure 2**). Each player then completed a series of smashes under both conditions, ensuring that the same movements were performed for consistency in the performance assessment.

Each test condition consisted of three sets of smashes, with 3-minute rest intervals between sets. Motion analysis systems captured detailed kinematic data on shoulder and arm movements, joint angles, and the range of motion during each smash. Smash speed was measured using radar technology, and shoulder flexibility was evaluated using a goniometer to assess improvements in range of motion, mainly focusing on flexion, abduction, and rotation. Players first completed the Pre-training baseline smashes, and after six weeks of SFT, the same smash routine was repeated for the Post-training condition. Changes in shoulder flexibility and smash speed mechanics between the pre- and post-training performances were analyzed using a hybrid CNN + LSTM model to evaluate patterns in movement and predict improvements based on flexibility data.

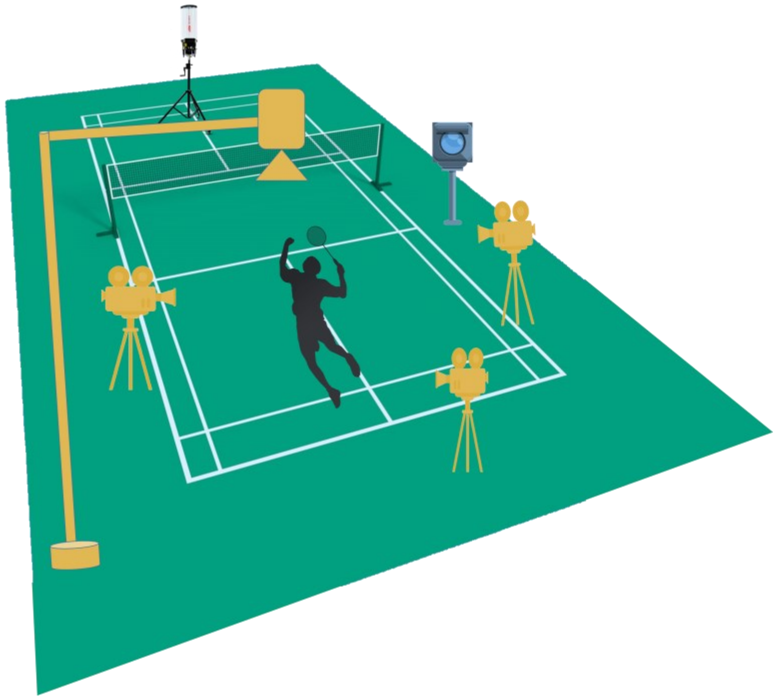

Figure 2. Experiment environment.

3.4. Apparatus and measurements

The study was conducted in a controlled badminton court with equipment to capture precise data on smash mechanics, shoulder flexibility, and smash speed (Fig. 2). Three high-speed motion cameras (Vicon Vantage V5) were positioned around the players to record their movements. Two cameras were placed at 45-degree angles in front of and behind the player, capturing detailed shoulder and arm mechanics, while a third camera was positioned laterally to capture the entire motion trajectory. An additional overhead camera provided a top-down view for comprehensive data collection. Reflective markers were placed on specific anatomical landmarks (shoulders, elbows, wrists, and racket) to enable the motion capture system to track joint angles and movements during each smash accurately.

A radar-based speed gun (Stalker Pro II Radar Gun) was used to measure smash speed, while a Yonex Pro Shuttlecock Launcher delivered shuttlecocks at consistent speeds and angles to maintain uniform smash conditions. Shoulder flexibility was assessed using a goniometer to measure the range of motion in shoulder flexion, abduction, and internal/external rotation. The motion capture system tracked joint angles and shoulder movements, and the speed gun recorded smash velocity. Together, this equipment provided a detailed analysis of how SFT impacted smash mechanics.

Weekly Progression:

- Weeks 1–2 focus on developing baseline shoulder flexibility through dynamic and static stretching.

- Weeks 3–4: Functional flexibility drills are introduced to integrate static and dynamic stretching gains into the smash technique.
- Weeks 5–6: All exercises are combined, and intensity is gradually increased by adjusting resistance (using heavier resistance bands or balls) and repetitions, focusing on maintaining flexibility under badminton-specific movements.

Tracking Progress

- Flexibility Assessments: Shoulder flexibility is measured at the program's start, mid-way (end of Week 3), and conclusion (end of Week 6) using a goniometer to assess range of motion.
- Smash Speed and Mechanics: Smash speed and kinematic data will be recorded simultaneously to track improvements in shoulder flexibility, smash mechanics, and speed. (see **Table 3**)

Table 3. Measurements and units.

Measurement	Description	Unit
Smash Speed	Velocity of the shuttle during the smash	Kilometers per hour (km/h)
Shoulder Flexion	Range of motion in forward shoulder movement	Degrees ()
Shoulder Abduction	Range of motion in lateral shoulder movement	Degrees ()
Shoulder Internal Rotation	Range of inward rotation at the shoulder joint	Degrees ()
Shoulder External Rotation	Range of outward rotation at the shoulder joint	Degrees ()
Joint Angles	Angles of shoulder, elbow, and wrist during smash	Degrees ()
Shuttlecock Launch Speed	Speed of the shuttlecock launched for smash trials	Kilometers per hour (km/h)
Smash Timing	Time duration from backswing to impact	Seconds (s)
Reflective Marker Data	Positional data from markers to track joint movements	Millimetres (mm)

3.5. CNN + LSTM model architecture for smash speed prediction

The work employs a hybrid CNN + LSTM model (**Figure 3**), with the CNN (VGG-16) used for spatial feature extraction and the LSTM network employed to capture the temporal dependencies in joint movements during the smash. The model receives input in motion capture frames of size 224 × 224 × 3, each representing a specific phase of the badminton smash (backswing, forward swing, contact, and follow-through). Let the input frame be denoted as Equation (1).

$$X \in \mathbb{R}^{224\times224\times3} \tag{1}$$

representing the height, width, and RGB channels. Each sequence of these frames captures the temporal progression of joint movements during the smash. The VGG-16 CNN processes each input frame to extract spatial features. Convolutional layers apply 3 × 3 filters to detect low-level features, such as edges and textures, essential for understanding joint movements. The convolution operation is defined as Equation (2).

$$X^{l+1} = f\left(W^l * X^l + b^l\right) \quad (2)$$

where W^l and b^l are the weights and biases of the convolutional filters, and f is the ReLU activation function. After each set of convolutional layers, max-pooling is applied to reduce the spatial dimensions while preserving essential features Equation (3).

$$X^{l+1} = \text{MaxPool}\left(X^l\right) \quad (3)$$

Once feature extraction is completed, the output is flattened into a feature vector F, which represents the spatial features learned from the smash movements Equation (4).

$$F \in \mathbb{R}^n \quad (4)$$

where n is the dimensionality of the feature space. The feature vector F is passed through a fully connected layer, where the features are combined into a high-dimensional representation of the smash mechanics, summarizing the joint positions, velocities, and racket movement. This vector serves as input for the LSTM to analyze the temporal sequence of frames. The LSTM network models the temporal dependencies between frames by processing the sequence of feature vectors $\{F_t\}$, where t represents the time step. At each time step, the LSTM updates its hidden state h_t and cell state c_t using the following set of Equations (5)–(10).

(1) Forget Gate (decides what information to discard from the cell state):

$$f_t = \sigma\left(W_f[F_t, h_{t-1}] + b_f\right) \quad (5)$$

(2) Input Gate (determines which new information to store in the cell state):

$$i_t = \sigma(W_i[F_t, h_{t-1}] + b_i) \quad (6)$$

(3) Candidate Cell State (generates a candidate for updating the cell state):

$$\tilde{c}_t = \tanh\left(W_c[F_t, h_{t-1}] + b_c\right) \quad (7)$$

(4) Cell State Update (combines the forget and input gate results to update the cell state):

$$c_t = f_t \odot c_{t-1} + i_t \odot \tilde{c}_t \quad (8)$$

(5) Output Gate (controls the output of the current hidden state):

$$o_t = \sigma(W_o[F_t, h_{t-1}] + b_o) \quad (9)$$

(6) Hidden State Update (produces the hidden state based on the output gate and cell state):

$$h_t = o_t \odot \tanh\left(c_t\right) \quad (10)$$

The final hidden state h_T at time step T captures the entire sequence of movements from the backswing to follow-through, providing a comprehensive temporal understanding of the smash. The hidden state h_T from the LSTM layer is passed to a fully connected output layer to predict the smash speed. The final prediction $\hat{y}$ is computed as Equation (11).

$$\hat{y} = W_{\text{out}} h_T + b_{\text{out}} \tag{11}$$

where W_{out} and b_{out} are the weights and bias of the output layer. This output provides the predicted smash speed based on the joint movements and flexibility data over time. The model is trained using the Mean Squared Error (MSE) loss function, which minimizes the difference between the predicted smash speed $\hat{y}$ and the actual speed y.

The MSE is calculated as Equation (12).

$$L = \frac{1}{N} \sum_{i=1}^{N} (\hat{y}_i - y_i)^2 \tag{12}$$

where N is the number of training samples. The Adam optimizer is used to train the model. This optimizer adjusts the learning rate dynamically based on the gradients to minimize the loss function efficiently.

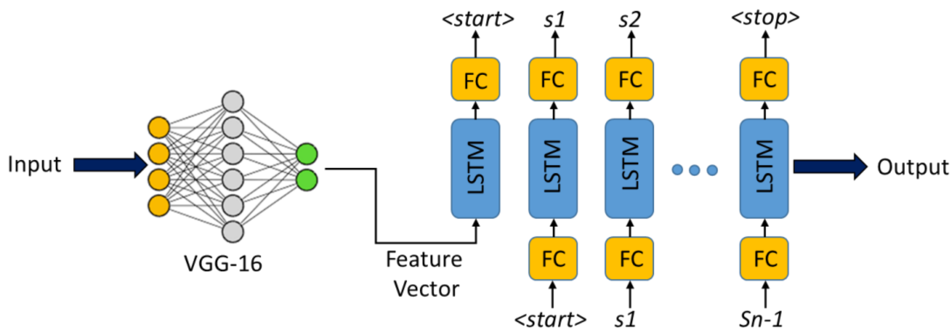

Figure 3. CNN + LSTM model.

The study utilized a hybrid CNN + LSTM due to the specific nature of the data and study objectives, enabling the model to effectively capture spatial and temporal dependencies in biomechanical data, which is crucial for analyzing complex badminton smash motion.

4. Analysis

4.1. Smash speed analysis

The findings from the Smash Speed Analysis are provided in **Table 4** and visually depicted in **Figure 4**. The findings show that the follow-through phase showed the most significant improvement for NP, with a 6.86% increase from 231.73 km/h to 247.65 km/h. The forward swing phase saw a 5.77% increase, from 253.64 km/h to 268.31 km/h. The backswing phase improved by 5.19%, increasing from 182.47 km/h to 191.93 km/h. The most minor improvement was in the contact phase, with a 4.35% increase from 336.25 km/h to 350.84 km/h. The forward swing phase showed the most enormous improvement for AP, with a 15.41% increase from 211.37 km/h to 243.94 km/h. The backswing phase saw a 14.10% improvement, from 151.58 km/h to 172.92 km/h. In the contact phase, smash speed increased by 9.83%, from 297.49 km/h to 326.72 km/h. The follow-through phase improved by 13.11%, from 192.14 km/h to 217.34 km/h. AP showed more percentage improvements across all phases than NP, with the most significant gains in the forward and backswing phases.

Table 4. Results for the smash speed.

Group	Phase	Pre-Training Smash Speed (km/h)	Post-Training Smash Speed (km/h)	Speed Improvement (%)
NP	Backswing	182.47 ± 8.12	191.93 ± 7.46	5.19%
	Forward Swing	253.64 ± 12.28	268.31 ± 10.89	5.77%
	Contact	336.25 ± 14.77	350.84 ± 12.36	4.35%
	Follow-through	231.73 ± 9.44	247.65 ± 10.32	6.86%
AP	Backswing	151.58 ± 9.74	172.92 ± 8.83	14.10%
	Forward Swing	211.37 ± 14.63	243.94 ± 13.27	15.41%
	Contact	297.49 ± 12.14	326.72 ± 10.83	9.83%
	Follow-through	192.14 ± 7.86	217.34 ± 7.19	13.11%

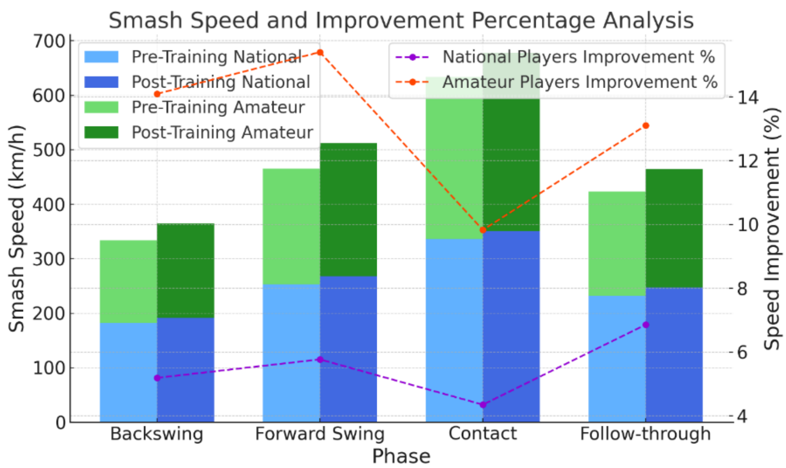

Figure 4. Smash speed analysis between pre and post-trained NP and AP.

4.2. Shoulder flexibility range of motion (ROM) analysis

The Shoulder Flexibility Range of Motion (ROM) Analysis, as illustrated in **Table 5** and **Figure 5**, shows clear improvements in shoulder movements for NP and AP following the SFT program. The internal rotation saw the greatest improvement for NP, with a 4.65% increase from 86° to 90°. External rotation improved by 4.04%, from 99° to 103°. Abduction increased by 3.77%, from 159° to 165°, and flexion improved by 3.49%, from 172° to 178°. For AP, the improvements were more pronounced. External rotation saw the largest increase, with a 10.87% improvement, from 92° to 102°. Internal rotation increased by 9.88%, from 81° to 89°. Abduction improved by 8.05%, from 149° to 161°, and flexion increased by 6.67%, from 165° to 176°. The data indicates that AP experienced greater percentage improvements across all shoulder movements than NP, particularly in internal and external rotation, showing the most substantial gains in range of motion following the training program.

Table 5. Results for the ROM analysis.

Group	Shoulder Movement	Pre-Training ROM (degrees)	Post-Training ROM (degrees)	ROM Improvement (%)
NP	Flexion	172 ± 5	178 ± 4	3.49%
	Abduction	159 ± 4	165 ± 3	3.77%
	Internal Rotation	86 ± 3	90 ± 2	4.65%
	External Rotation	99 ± 3	103 ± 3	4.04%
AP	Flexion	165 ± 6	176 ± 5	6.67%
	Abduction	149 ± 4	161 ± 4	8.05%
	Internal Rotation	81 ± 3	89 ± 3	9.88%
	External Rotation	92 ± 4	102 ± 3	10.87%

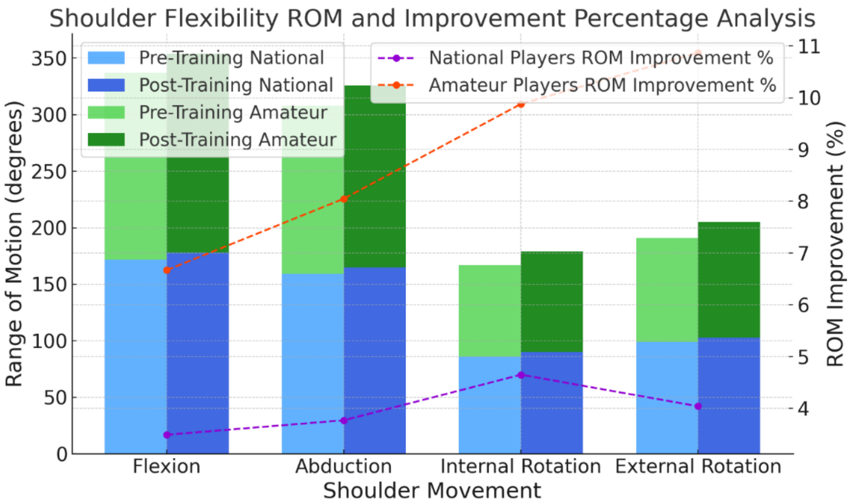

Figure 5. Shoulder flexibility ROM analysis between pre and post-trained NP and AP.

4.3. Kinematic analysis

The Kinematic Analysis for NP and AP across different phases of the badminton smash following the SFT program is shown in **Table 6**. For NP, during the backswing, shoulder external rotation improved by 7.22%, from 97° to 104°, while elbow flexion increased by 4.35%, from 115° to 120°, and trunk rotation improved by 7.14%, from 42° to 45°. In the forward swing, shoulder internal rotation increased by 5.45%, from 110° to 116°, with a minor improvement in elbow extension of 1.71%, from 175° to 178°, and trunk rotation increased by 6.25%, from 80° to 85°. During the contact phase, shoulder internal rotation improved by 4.69%, from 128° to 134°, and trunk forward tilt increased by 8.33%, from 24° to 26°. In the follow-through phase, shoulder internal rotation improved by 5.45%, from 110° to 116°, and elbow flexion increased by 8.57%, from 35° to 38°, while trunk lateral flexion improved by 10.71%, from 28° to 31°.

For AP, the improvements were more substantial across all phases. In the backswing, shoulder external rotation increased by 14.13%, from 92° to 105°, while elbow flexion improved by 10.00%, from 110° to 121°, and trunk rotation saw a considerable improvement of 21.05%, from 38° to 46°. In the forward swing, shoulder internal rotation increased by 14.29%, from 105° to 120°, with a 4.07% increase in elbow extension, from 172° to 179°, and trunk rotation improved by 18.06%, from 72° to 85°. During the contact phase, shoulder internal rotation improved by 9.76%, from 123° to 135°, and trunk forward tilt saw the most significant increase of 35.00%, from 20° to 27°. In the follow-through phase, shoulder internal rotation increased by 12.38%, from 105° to 118°, with a significant improvement of 26.67% in elbow flexion, from 30° to 38°, and trunk lateral flexion improved by 23.08%, from 26° to 32°.

Table 6. Results for the kinematic analysis.

Group	Phase	Kinematic Parameter	Pre-Training Value (degrees)	Post-Training Value (degrees)	Improvement (%)
NP	Backswing	Shoulder External Rotation	97 ± 4	104 ± 3	7.22%
		Elbow Flexion	115 ± 5	120 ± 4	4.35%
		Trunk Rotation	42 ± 3	45 ± 2	7.14%
	Forward Swing	Shoulder Internal Rotation	110 ± 4	116 ± 3	5.45%
		Elbow Extension	175 ± 3	178 ± 3	1.71%
		Trunk Rotation	80 ± 5	85 ± 4	6.25%
	Contact	Shoulder Internal Rotation	128 ± 4	134 ± 3	4.69%
		Elbow Extension	180 ± 2	182 ± 2	1.11%
		Trunk Forward Tilt	24 ± 3	26 ± 3	8.33%
	Follow-through	Shoulder Internal Rotation	110 ± 5	116 ± 4	5.45%
		Elbow Flexion	35 ± 3	38 ± 3	8.57%
		Trunk Lateral Flexion	28 ± 3	31 ± 2	10.71%
AP	Backswing	Shoulder External Rotation	92 ± 5	105 ± 4	14.13%
		Elbow Flexion	110 ± 6	121 ± 5	10.00%
		Trunk Rotation	38 ± 4	46 ± 3	21.05%
	Forward Swing	Shoulder Internal Rotation	105 ± 5	120 ± 4	14.29%
		Elbow Extension	172 ± 4	179 ± 3	4.07%
		Trunk Rotation	72 ± 6	85 ± 5	18.06%
	Contact	Shoulder Internal Rotation	123 ± 4	135 ± 4	9.76%
		Elbow Extension	178 ± 3	183 ± 2	2.81%
		Trunk Forward Tilt	20 ± 3	27 ± 3	35.00%
	Follow-through	Shoulder Internal Rotation	105 ± 5	118 ± 4	12.38%
		Elbow Flexion	30 ± 4	38 ± 3	26.67%
		Trunk Lateral Flexion	26 ± 3	32 ± 2	23.08%

The Comparison Between AP and NP's performance in smash speed and joint kinematics after the SFT program is shown in **Table 7** and **Figure 6**. Smash speed at contact was higher for AP, with an average of 350.84 km/h, compared to 326.72 km/h, reflecting a 6.88% difference. This indicates that NP retained an edge in power generation despite the improvements seen in both groups. Shoulder flexion was nearly identical between the two groups, with NP at 178° and AP at 176°, showing a small 1.14% difference. Shoulder external rotation was also similar, with NP at 103°

and AP at 102°, showing a 0.98% difference. These minimal differences suggest that SFT levelled the range of motion for both groups.

Table 7. Comparison between NP and AP.

Parameter	NP (Post-Training)	AP (Post-Training)	Difference (%)
Smash Speed (Contact, km/h)	350.84 ± 12.36	326.72 ± 10.83	6.88%
Shoulder Flexion (degrees)	178 ± 4	176 ± 5	1.14%
Shoulder External Rotation (degrees)	103 ± 3	102 ± 3	0.98%
Shoulder Internal Rotation (degrees)	116 ± 3	120 ± 4	−3.45%
Elbow Extension (Contact, degrees)	182 ± 2	183 ± 2	−0.55%
Trunk Rotation (Forward Swing, degrees)	85 ± 4	85 ± 5	0.00%
Trunk Forward Tilt (Contact, degrees)	26 ± 3	27 ± 3	-3.85%
Elbow Flexion (Follow-through, degrees)	38 ± 3	38 ± 3	0.00%
Trunk Lateral Flexion (Follow-through, degrees)	31 ± 2	32 ± 2	−3.23%

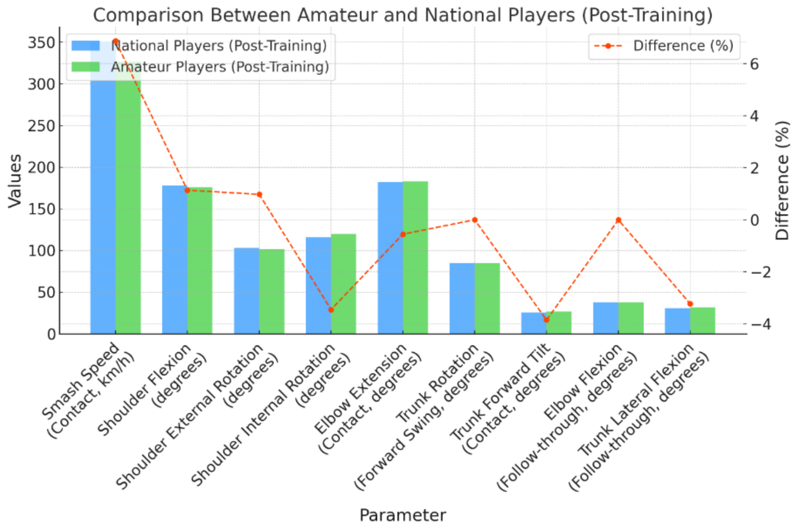

Figure 6. Smash speed and joint kinematics between pre and post-trained NP and AP.

Interestingly, shoulder internal rotation was slightly higher in AP at 120°, compared to 116° for NP, resulting in a −3.45% difference, indicating a more remarkable improvement in internal rotation flexibility for AP. Similarly, elbow extension at contact was slightly higher in AP, with 183° compared to 182° in NP, reflecting a −0.55% difference. Trunk rotation during the forward swing was the same for both groups at 85°, while trunk forward tilts at contact were slightly higher in AP (27° vs. 26°), with a −3.85% difference. Both groups showed identical elbow flexion during follow-through at 38°, indicating similar post-contact control. Trunk lateral flexion during follow-through was slightly higher in AP (32° vs. 31°), with a −3.23% difference.

4.4. ML model performance analysis

The Model Performance Metrics of the CNN + LSTM model are shown in **Figure 7** and **Table 8**. For NP, the model performed with high accuracy. The pre-training actual smash speed was 336.25 km/h, with a predicted value of 335.32 km/h, resulting in a Mean Absolute Error (MAE) of 1.89 km/h and a Mean Squared Error (MSE) of 4.11 km/h. The R^2 score of 0.98 indicates that the model explains 98% of the variance in smash speed pre-training. Post-training, the model's predictions improved, with an actual smash speed of 350.84 km/h and a predicted value of 349.57 km/h, resulting in an even lower MAE of 1.65 km/h and MSE of 3.29 km/h. The R^2 score increased to 0.99, demonstrating excellent model performance in post-training conditions. The model also showed predictive solid performance for AP with slightly larger errors than for NP. Pre-training, the actual smash speed was 297.49 km/h, and the predicted value was 294.78 km/h, yielding an MAE of 2.71 km/h and an MSE of 7.35 km/h. The R^2 score was 0.96, indicating that the model captured 96% of the variance in smash speed. Post-training, the model's accuracy improved slightly, with an actual smash speed of 326.72 km/h and a predicted value of 324.16 km/h, resulting in an MAE of 2.56 km/h and an MSE of 6.78 km/h, while the R^2 score increased to 0.97.

Table 8. CNN + LSTM performance results.

Group	Training Condition	Actual Smash Speed (km/h)	Predicted Smash Speed (km/h)	Mean Absolute Error (MAE)	Mean Squared Error (MSE)	R^2 Score
NP	Pre-training	336.25 ± 14.77	335.32 ± 13.89	1.89	4.11	0.98
	Post-training	350.84 ± 12.36	349.57 ± 11.92	1.65	3.29	0.99
AP	Pre-training	297.49 ± 12.14	294.78 ± 11.85	2.71	7.35	0.96
	Post-training	326.72 ± 10.83	324.16 ± 10.65	2.56	6.78	0.97

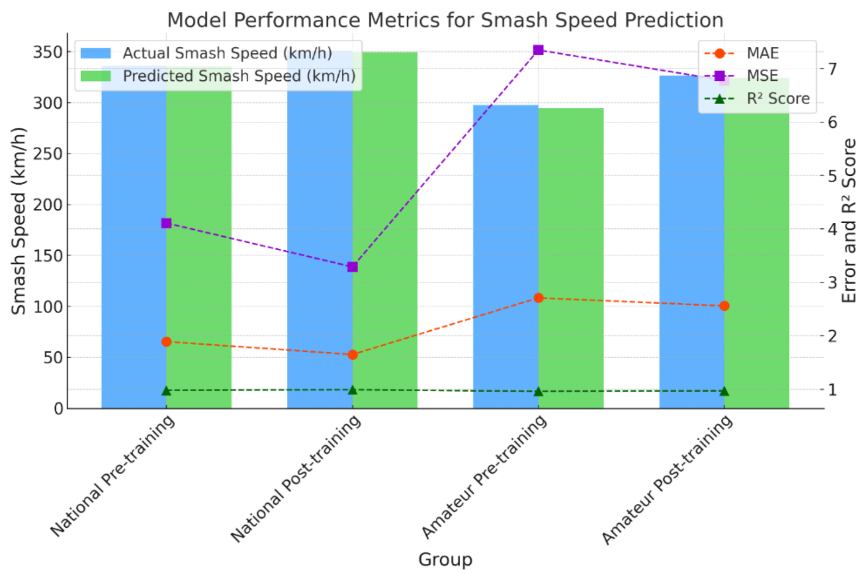

Figure 7. Proposed CNN + LSTM performance analysis.

4.5. Statistical analysis

The results of the paired t-tests for pre- and post-training comparisons are shown in **Table 9** and **Figure 8**. For smash speed at contact, the improvements were significant for both NP (p = 0.012) and AP (p = 0.001). Similarly, shoulder flexion showed significant changes for NP (p = 0.033) and AP (p = 0.004). Shoulder external rotation also improved significantly for both groups, with p-values of 0.041 for NP and 0.002 for AP. Shoulder internal rotation demonstrated significant improvements, with p-values of 0.027 for NP and 0.001 for AP. In contrast, elbow extension at contact was only significant for AP (p = 0.043), while NP did not show a statistically significant change (p = 0.065). Trunk rotation during the forward swing was significant for AP (p = 0.003) but not for NP (p = 0.051). For trunk forward tilts at contact, both groups saw significant improvements, with p-values of 0.018 for NP and 0.002 for AP. Lastly, elbow flexion and trunk lateral flexion during follow-through were significant for NP and AP, with p-values of 0.042 and 0.029 for NP and 0.005 and 0.001 for AP, respectively.

Table 9. Paired *t*-tests for Pre- and Post-Training comparisons results.

Parameter	NP (p-value)	AP (p-value)	Statistical Significance
Smash Speed (Contact)	0.012	0.001	Significant ($p < 0.05$)
Shoulder Flexion	0.033	0.004	Significant ($p < 0.05$)
Shoulder External Rotation	0.041	0.002	Significant ($p < 0.05$)
Shoulder Internal Rotation	0.027	0.001	Significant ($p < 0.05$)
Elbow Extension (Contact)	0.065	0.043	Significant for AP
Trunk Rotation (Forward Swing)	0.051	0.003	Significant for AP
Trunk Forward Tilt (Contact)	0.018	0.002	Significant ($p < 0.05$)
Elbow Flexion (Follow-through)	0.042	0.005	Significant ($p < 0.05$)
Trunk Lateral Flexion (Follow-through)	0.029	0.001	Significant ($p < 0.05$)

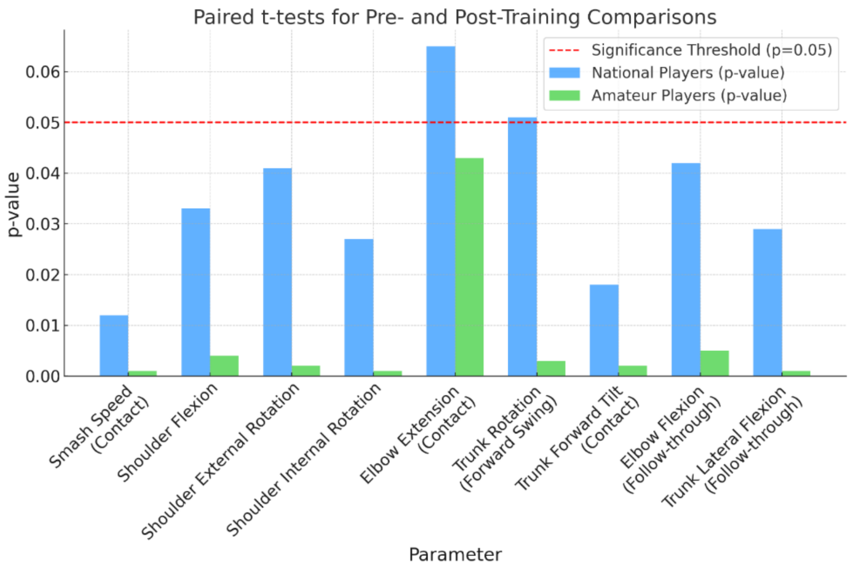

Figure 8. Paired t-tests for Pre- and Post-Training between NP and AP.

The Repeated Measures ANOVA results are shown in **Table 10** and **Figure 9**. The player level had an *F*-value of 12.67 and a *p*-value of 0.003, indicating a significant difference between NP and AP. The training condition had an *F*-value of 19.43 and a *p*-value of 0.001, showing significant effects of pre- vs. post-training. The phase of the smash was significant, with an *F*-value of 10.22 and a *p*-value of 0.004. Interaction effects were also significant. Player level x condition had an *F*-value of 8.78 and a *p*-value of 0.012, while condition x phase had an *F*-value of 14.56 and a *p*-value of 0.002. Player level x phase showed significance with an *F*-value of 6.92 and a *p*-value of 0.019.

Table 10. Repeated measures ANOVA results.

Factor	*F*-value	*p*-value	Statistical Significance
Player Level	12.67	0.003	Significant ($p < 0.05$)
Training Condition	19.43	0.001	Significant ($p < 0.01$)
Phase of Smash	10.22	0.004	Significant ($p < 0.01$)
Player Level x Condition	8.78	0.012	Significant ($p < 0.05$)
Condition x Phase	14.56	0.002	Significant ($p < 0.01$)
Player Level x Phase	6.92	0.019	Significant ($p < 0.05$)

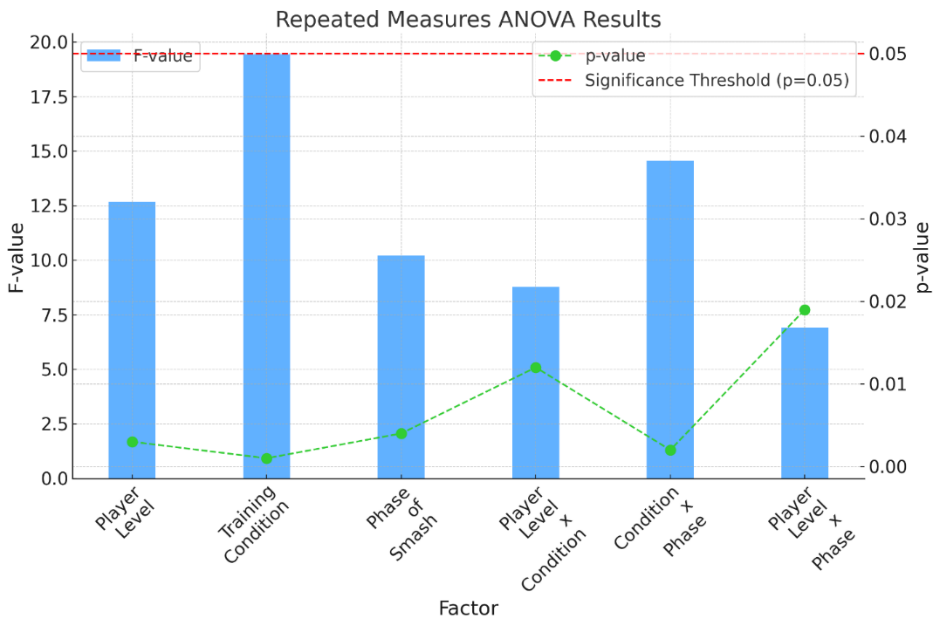

Figure 9. Repeated measures ANOVA results.

The Effect Size (Cohen's d) for NP and AP is shown in **Figure 10** and **Table 11**. The effect size for smash speed at contact was 0.68 for NP and 1.21 for AP, showing a more prominent effect for AP. Shoulder flexion had a Cohen's d of 0.52 for NP and 1.10 for AP, while shoulder external rotation showed 0.55 for NP and 1.30 for AP. Shoulder internal rotation had an effect size of 0.62 for NP and 1.24 for AP. The effect size for elbow extension at contact was 0.35 for NP and 0.80 for AP. Trunk forward tilts at contact had an effect size of 0.65 for NP and 1.35 for AP. Lastly, elbow flexion during follow-through had a Cohen's d of 0.58 for NP and 1.12 for AP.

These values indicate larger effect sizes for AP across all parameters, reflecting more significant improvements post-training than NP.

Table 11. Effect Size (Cohen's *d*) results.

Parameter	**NP (Cohen's *d*)**	**AP (Cohen's *d*)**
Smash Speed (Contact)	0.68	1.21
Shoulder Flexion	0.52	1.10
Shoulder External Rotation	0.55	1.30
Shoulder Internal Rotation	0.62	1.24
Elbow Extension (Contact)	0.35	0.80
Trunk Forward Tilt (Contact)	0.65	1.35
Elbow Flexion (Follow-through)	0.58	1.12

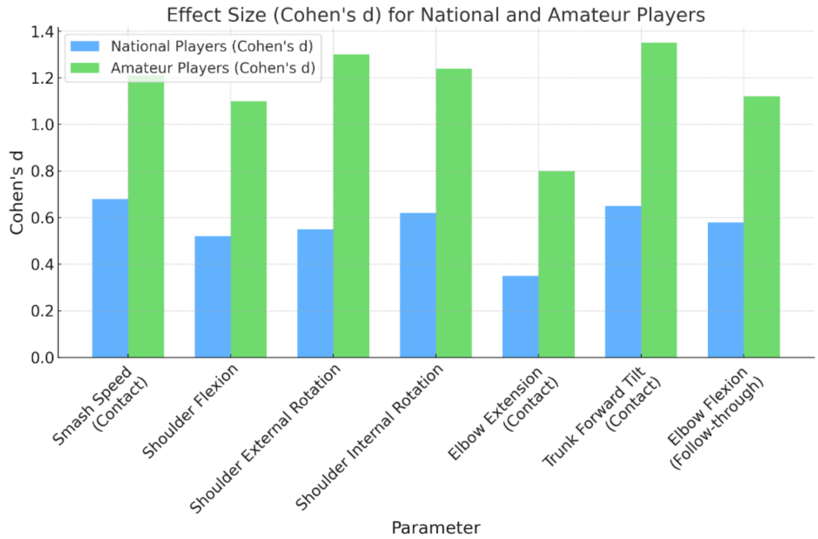

Figure 10. Effect Size (Cohen's d) results.

5. Conclusion and future work

The current study examines how badminton smash performance is impacted by Shoulder Flexibility Training (SFT). To predict joint biomechanics from motion-captured data, it adopts a CNN + LSTM hybrid model. In order to improve shoulder flexion, abduction, and rotation, 25 people completed a 6-week SFT consisting of an array of tests comprising dynamic, static, and flexibility training. Biomechanical adjustments to joint angles and motion patterns have been investigated using the model. The results demonstrated that a more flexible kinetic chain, which in turn permitted higher energy transfer during the smash and overall performance, was made possible through improved shoulder flexibility. In terms of ROM and smash speed, the AP group outperformed their national-level competitors. After impact, smash speed was 9.83% greater and shoulder rotation internally was 9.76% superior in AP. NP has also shown improvements, with a 4.35% increase in smash speed and a 4.69% improvement in internal rotation. The hybrid CNN + LSTM model used in this work has achieved better predicting smash speed improvements with high accuracy (R^2 = 0.99 for NP, 0.97 for AP). The study thus justified that SFT enhances smash speed mechanics and reduces injury risks, particularly in athletes with lower initial flexibility.

Future research will explore the long-term effects of SFT and its impact on injury prevention, along with further refinement of ML models for predictive analysis in other sports biomechanics.

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