

Article

Biomechanical Insights for Developing Evidence-Based Training Programs: Unveiling the Kinematic Secrets of the Overhead Forehand Smash in Badminton through Novice-Skilled Player Comparison

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Abstract: Badminton, a dynamic racquet sport demanding agility and power, features the overhead forehand smash as a pivotal offensive shot. Utilizing 3D motion analysis, this research delves into the intricate biomechanical facets underpinning this pivotal shot, with a dual focus on both novice and proficient players. Through a comparative analysis of these two player cohorts, the investigation aims to elucidate the fundamental factors influencing the quality of the forehand smash. Our findings reveal that skilled players exhibit significant improvements in smash quality, including a 60.2% increase in shuttlecock speed, reduced clearance height, and flight angle at release. These enhancements are associated with specific determinants, such as consistent positioning, racket angle at impact, and range of motion (ROM) in various joints. More crucially, full-body tension-arc formation and a four-segment whip-like smash contribute to these improvements. Unique to the whip-like smash is the rapid trunk and shoulder rotations in early whip-like control inducing passive elbow flexion and wrist over-extension, enhancing the stretch-shortening cycle (SSC) effect of muscles for a more powerful smash. Emphasizing this uniqueness and the determinants simplify smash learning, potentially boosting training effectiveness. This research contributes to a deeper understanding of badminton's biomechanics and offers practical implications for coaches and players to enhance their forehand smashes, especially among beginners.

Keywords: full-body tension-arc; x-factor; ROM; whip-like; passive control; SSC



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1. Introduction

Badminton, an exhilarating racquet sport has captivated players and spectators worldwide [1–5]. Among the various shots that define badminton's dynamic gameplay, the overhead forehand smash stands out as a dominant offensive weapon capable of delivering decisive points [2]. This iconic shot is a favorite among fans due to its spectacle and game-changing potential. When a player executes the perfect forehand smash, the shuttlecock accelerates towards the opponent's court with tremendous speed, often making it nearly impossible to return [5].

To achieve such an awe-inspiring smash performance, players need to explore the intricacies of the biomechanics pertaining to its execution [5,6]. In recent years, advancements in 3D motion analysis technology have permitted researchers to delve deeper into the complexities of athletic movements, providing new insights into skill optimization for enhanced training outcomes [7–10]. Notably, research using 3D motion analysis has

provided in-depth biomechanical insights into various sports, such as golf [11–14], tennis [15–17], gymnastics [18–20], soccer [21–23], martial arts [24–27], and beyond [28]. This has helped us better understand the crucial factors that affect success in these sports.

In the context of badminton, previous studies have used smash quality parameters and skill control parameters for the 3D motion quantification of the smash [5,29]. The smash quality parameters involve shuttlecock maximum flight velocity, past-net height of the shuttlecock, and shuttlecock flight angle. A good smash results in high velocity (minimizing the available reaction time for a successful return), has a shorter past-net height, and a steep downward angle of shuttlecock flight (minimizing flight distance and flight time) [5,29]. Skill control parameters are kinematic parameters of body and racket movement, such as racket control, posture control, segments/joints control, as well as their timely coordination [5,29]. Collectively, skill control parameters describe how effective one's body control is during a smash. By using smash quality parameters as evaluating criteria, 3D motion analysis technology could identify the possible key determinants among skill control parameters that notably influence the smash quality [5,29]. Such investigations provide valuable insights that can inform training protocols, enhance coaching strategies, and contribute to a more comprehensive understanding of this essential badminton skill.

Because the forehand smash is so important, it has been a main focus during the training of players who are newcomers to the sport [5,30–32]. Recently, the study of the forehand smash has featured prominently in biomechanical studies of badminton [5,6,33,34]. An exemplary study conducted by Li et al. [29] explored the significance of body positioning during the forehand smash. Their investigation emphasized the role of body alignment and the kinetic chain in facilitating an efficient transfer of energy, leading to enhanced smash velocity and accuracy. Additionally, the study shed light on the potential impact of targeted training interventions to optimize body positioning and, consequently, improve smash proficiency.

Other representative studies [5,6,33,34] have focused on shuttlecock speed and its kinematic determinants during the smash. These studies investigated advanced or elite/professional players' smashes and have found the significance of specific kinematic factors, such as racket movement, the X-factor (emphasizing trunk rotation), shoulder rotation, elbow flexion/extension, and wrist flexion/extension, in influencing shuttlecock velocity during the smash.

The above recent studies have shown that precise coordination and timing are paramount, as players need to anticipate the shuttlecock's trajectory and position themselves optimally to execute the shot. The sequence of movements in the forehand smash is a blend of elegance and power, requiring players to control the full body smoothly while focusing on the torso and arm to generate the necessary force. However, these studies mainly focus on the skill improvement of high-level players. Many biomechanically described technique details may not be relevant for training beginners and/or advanced players.

Clearly, mastering the forehand smash is a journey of continuous improvement, especially for beginners. Learners must engage in deliberate practice, honing their skills through countless repetitions and analyzing their technique from time to time for feedback training to improve skill effectiveness continuously [35]. Using evidence-based information gathered through biomechanical analysis can offer valuable insights and guidance for coaches [36]. This helps players enhance their techniques and improve their overall body control, leading to better quality smashes. However, a practical summary of the biomechanical fundamentals for smash optimization as a coaching guide is scarcely found.

Previous studies have demonstrated that the forehand smash is a complex full-body skill [5,6,33,34]. In the case of intricate full-body sports skills, there is often a language-driven disconnect between the results of scientific research and general coaching practices. In other words, the findings from research must be translated into language that is application-oriented to overcome this gap [37]. This challenge is especially relevant for beginners who are learning an effective method to enhance the quality of their smash [5]. Therefore, there is a need for research that can bridge the divide between scientific investiga-

tions into the biomechanics of the smash during the early stages of full-body biomechanical development and the practical implementation of such research in coaching practices.

Building upon insights garnered from previous research, the present study seeks to conduct a comprehensive 3D motion analysis of the entire sequence of the skill using both novice and advanced players. The hypothesis posits that skilled players will demonstrate a higher level of proficiency in distinct and pivotal biomechanical determinants, exerting a substantial impact on the overall quality of the forehand smash. Utilizing a comparative approach between the two player cohorts, the quantitative analysis is centered on the discernment of the specific biomechanical determinants' influence. These determinants encompass elements such as precise body positioning, the X-factor denoting trunk rotation, and kinetic determinants that encompass control mechanisms related to the racket angle and major joints. These parameters draw upon prior research findings [5,6,29,33,34]. The overarching objective is to unveil the fundamental biomechanical underpinnings that govern the execution of this pivotal shot, thereby facilitating skill acquisition, particularly among novice practitioners in the sport. To bridge the gap between scientific research and coaching practice, the findings target the supply of practical implications for coaches and players by providing biomechanically grounded and coaching-friendly explanations—explanations that directly communicate with the experiences of coaches, practitioners, and learners—regarding skill characteristics and motor control sequencing. As such, relevant biomechanical factors are identified in a way that should help coaches better develop training programs and, at the same time, foster a better understanding of the skill among learners. The ultimate objective is to improve coaches' training effectiveness and better develop plans for novice badminton players. For beginners, we speculate that faster and more effective skill acquisition will potentially increase enthusiasm for and participation rates in the sport.

2. Materials and Methods

2.1. Participants

A concise overview of the demographic attributes of the study participants is presented in Table 1.

Table 1. The overall information of the participants.

General Information of Subjects	Novice Group	Skilled Group
Number of participants	10	14
Years of training	0	6.6 ± 3.1
Age (years)	24.3 ± 4.7	23.2 ± 2.8
Body height (m)	1.71 ± 0.07	1.77 ± 0.05
Body mass (kg)	62.05 ± 9.24	71.56 ± 7.73

The subjects encompassed a total cohort of 24 individuals, of whom 22 exhibited right-handedness while 2 exhibited left-handedness, with ages ranging between 20 and 35 years. The gender distribution consisted of 17 males and 7 females. The participant group designated as the skilled group (SG), consisting of 14 individuals, possessed a minimum of four years of experience within a competitive badminton training milieu, with an average duration of 6.6 ± 3.1 years. Conversely, the novice group (NG), comprises 10 individuals without formal training, i.e., 0 years of experience. The SG and NG were comparable in terms of age (23.2 ± 2.8 years vs. 24.3 ± 4.7 years), stature (1.77 ± 0.05 m vs. 1.71 ± 0.07 m), and mass (71.56 ± 7.73 kg vs. 62.05 ± 9.24 kg). The protocol of this study underwent rigorous scrutiny and approval by the Human Subjects Research Committee at the University of Lethbridge, aligning with the stipulations delineated in the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans, as set forth by the Natural Sciences & Engineering Research Council. All participants in the study were informed of the testing procedures. They signed an approved consent form and voluntarily participated in the data collection.

2.2. 3D Motion Data Collection

A comprehensive 3D motion analysis was conducted by employing a VICON MX40 motion capture system (Oxford Metrics Ltd., Oxford, UK) featuring a configuration of 10 cameras. The system was set at a sampling frequency of 200 frames per second to capture the smash movement patterns through accurately tracing 59 reflective markers (39 on the subject's body, 16 on the racket, 1 on the shuttlecock, and 3 on the net, respectively) [5,29]. Calibration residuals were meticulously determined in strict adherence to the established guidelines provided by VICON, resulting in a precision level of within 1 mm. It is noteworthy to underscore that the intrinsic capabilities of motion capture technology afford substantial latitude of movement to the participants, thereby enabling the unimpeded execution of their inherent motor behaviors. Consequently, this measurement methodology exerts minimal perturbation on the participants' innate playing styles, thereby preserving the authenticity of their actions. This pivotal attribute of the motion capture methodology ensures that the participants' distinctive playing styles remain essentially unaltered throughout the experimental proceedings.

The study's objective was to assess smash quality independently of return quality. Therefore, the utilization of half of a standard badminton court sufficed for the research purpose. Additionally, deploying ten cameras to focus on this reduced court area significantly enhanced the precision of 3D motion capture data. Consequently, a half-standard badminton court (6.7 m in length, 7.0 m in width, and 1.55 m in net height) was set up to mimic a real badminton play environment. The spatial dimensions of the effective 3D motion capture domain were configured to span 6.7 m in length, 6.0 m in width, and 4.0 m in height, aligning with the standard dimensions of a conventional playing field. To accurately emulate the playing environment, a net with a height of 1.55 m, adhering to the established standard net height, was meticulously positioned. The meticulous orchestration of these conditions collectively mirrored the characteristics of an actual playing milieu.

In the course of the experimental trials, uniformity was maintained through the utilization of the YONEX ARCSABER 001 series racket, characterized by specific attributes including a weight range of 85 to 89 g, a length of 684 mm, and a composition primarily comprising graphite material. This choice of racket was consistently accompanied by a standard YONEX shuttlecock, exhibiting a weight span of 4.74 to 5.50 g. Ensuring methodological consistency, sixteen adhesive markers were affixed to the sporting equipment in a strategic configuration. The distribution encompassed twelve markers on the racket, distributed as a singular marker on the handle base, three markers affixed to the shaft, and eight markers allocated to the head of the racket. In a similar vein, a solitary marker was affixed to the shuttlecock, carefully placed upon the cork, while an additional three markers were positioned upon the net structure.

Furthermore, each participant involved in the study was adorned with a constellation of thirty-nine spherical, reflective markers, each manifesting a diameter of 9 mm. The placement of these markers meticulously adhered to standard anatomical landmarks, a necessity in the establishment of a 15-segment (head, upper trunk, lower trunk, upper arms, lower arms, hands, thighs, shanks, and feet) biomechanical model for the smash quantification [5,29]. The markers were placed as follows: four markers on the head (left and right temples as well as two on the posterior portion of the parietal bone); five markers on the upper trunk (sternal notch, xiphoid process, C7 and T10 vertebrae, and the right back); seven markers on each upper limb (acromion processes, lateral epicondyles of the humerus, styloid processes of the ulna and radius, third metacarpophalangeal joints, and upper and lower arms); four markers on the pelvis (left and right anterior as well as posterior superior iliac crests); and six markers on each lower limb (upper thigh, lateral condyle of the tibia, lateral side of the tibia, lateral malleolus of the fibula, calcaneal tuberosity, and head of hallux). This methodological approach, in addition to its previous quantification of the badminton smash, has been successfully applied in demystifying many other complicated sports skills, such as the soccer maximal instep kick [38,39], the axe kick

in taekwondo [40,41] and the hammer throw [42], offering a meticulous and standardized foundation for the current study.

2.3. Experimental Procedure

The experimental protocol was conducted in accordance with the following steps for each participant: (1) The required 39 reflective markers were first affixed to the participant's body, and subsequent system and subject calibrations were performed. (2) Adequate time was allocated to the participant to engage in a preparatory phase, during which he/she was encouraged to acclimate him/herself to the testing environment in a manner that he/she deemed suitable and conducive to optimal performance. (3) To ensure consistent and reliable execution of the dynamic shuttlecock test, a well-trained person was chosen to hit a high serve, or in badminton terms, 'lift' the shuttlecock in the air, for each subject. (4) Subsequent to the acclimatization phase, data acquisition ensued, wherein a series of trial repetitions were executed. Specifically, five instances of forehand smashes were captured for each participant. (5) For the smash, subjects were allowed to jump, stand, or strike the shuttlecock as they liked to produce their hardest smash in the dynamic smash test. No constraints or limitations were imposed on the participants' *modus operandi*, thus allowing for individualized technique. (6) A discerning criterion was applied to the dataset to identify and isolate the three instances of forehand smashes that exhibited the highest shuttle flight velocities. These three exemplary forehand smashes were selected for data analysis.

In summation, the aforementioned methodological procedure outlines the systematic and standardized sequence of actions undertaken within the experimental framework, thereby contributing to the robustness and credibility of the ensuing findings.

2.4. Selection of the Biomechanical Fundamentals

2.4.1. Phase Definition

In order to execute a powerful smash, it is essential to apply biomechanical principles during the various phases of the motion sequence [43,44]. However, previous research has shown inconsistency in defining these phases, with some studies recognizing about two phases, namely the backswing and acceleration phases [33,34,45], while others describe four phases, encompassing preparation, backswing, forward swing, and follow-through [6,46]. Furthermore, these definitions tend to predominantly focus on upper body coordination, overlooking the importance of full-body control. It is worth noting that a smash involves comprehensive control of the entire body. When considering the concept of full-body control, akin to other explosive power-generation sports skills like the javelin throw [47,48] and the maximal instep soccer kick [49,50], the smash can be conceptualized as a process involving the formation of a full-body tension arc followed by a whip-like smash, as illustrated in Figure 1. The whip-like smash (proximal to distal control sequence among the upper body segments) has been confirmed by a previous study [5]. During this whip-like smash, the control of the racket, transitioning from an upward to a downward position, should be a passive movement [51,52], occurring naturally due to inertia without requiring active wrist control. Recognizing the passive nature of this control simplifies the process of motor learning, aligning with the principle that reducing the need for simultaneous joint control makes motor learning easier [53,54].

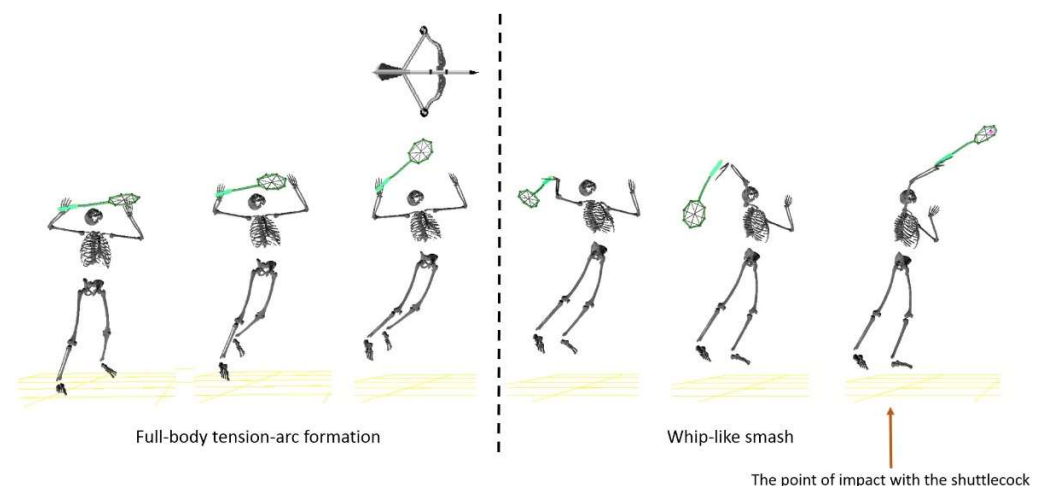


Figure 1. The full-body smash control revealed by a skilled player.

Moreover, the quantitative findings regarding the significance of body positioning in the forehand smash, as presented by Li et al. [29], have not been incorporated into the phase definitions for coaching practices. These results have underscored the potential benefits of specific training interventions aimed at enhancing body positioning to improve the quality of the smash. Adhering to current knowledge standards and with the intention of providing coaches with a comprehensive understanding of the full-body control elements involved in the smash to enhance their coaching effectiveness, this study divides the smash into four control phases: positioning, full-body tension-arc formation, whip-like smash, and follow-through. Such segmentation would effectively divide the process of learning and practicing the smash into four distinct training components, each with its own specific training objectives.

2.4.2. Selection of Determinants

To assess the quality of the smash, we measured parameters including the shuttlecock's maximum flight velocity, its height as it cleared the net, and the angle of its flight [5,29]. The chosen control parameters for skill evaluation, specifically kinematic factors, consisted of components of the badminton smash that prior research studies have already confirmed as linked to smash quality [5,6,29,33,34]. These components encompassed positioning, and the control of the trunk, shoulders, elbows, and wrists, along with consideration of the racket angle at impact. We derived these determinants by analyzing 3D kinematic data and making comparisons between novice and skilled player groups. Building upon findings from earlier studies [5,6,29,33,34], our analysis primarily concentrated on assessing changes in positioning, trunk, shoulder, elbow, and wrist control, as well as variations in the racket angle at the moment of impact. The determinants we identified were those kinematic parameters that exhibited significant alterations due to smash optimization through training.

2.5. Data Processing and Statistical Analysis

We began by smoothing the raw 3D motion capture data using a five-point moving average filter with a weighted distribution (1-3-4-3-1), a function supplied by VICON software NEXUS 1.8.5 (Oxford Metrics Ltd., Oxford, UK). This process provided us with kinematic information, including marker positions, positional changes, velocities, and accelerations. Subsequently, we constructed a biomechanical body model consisting of 15 segments using these refined data [5,29,55]. Additionally, we utilized data from markers on equipment to model the racket, shuttlecock, and net. Employing fundamental principles of physics, we transformed basic positional data from consecutive frames of reconstructed information into the dynamic movements of the forehand smash.

In the realm of 3D body modeling, we determined the inertial characteristics for each segment by applying anthropometric regression equations that took individual body mass, body height, gender and race into account [55]. With our comprehensive biomechanical model, encompassing the racket, shuttlecock, and the entire body, we proceeded to quantify parameters related to the three smash quality parameters and the movement parameters of the forehand smash. The movement parameters included the dynamic data related to body positioning, racket angle, major joints, and the X-factor. The latter is determined by the separation angle between lines connecting the right and left shoulder joint centers and the right and left hip joint centers, respectively, in the transverse plane.

All the parameters derived from the VICON motion capture system and the biomechanical modeling process were subjected to analysis using SPSS Statistics version 22.0 (SPSS Inc., Chicago, IL, USA). We present the results through descriptive statistics (average $\pm$ standard deviation). Furthermore, we conducted independent t-tests to compare differences between novice and skilled players concerning both smash quality and movement parameters. Statistical significance was established at a threshold of $p < 0.05$. To express changes in a parameter as a percentage, we used the following formula: [(large value – small value)/small value]. This same formula was employed to calculate the percentage disparities between the groups.

3. Results

The outcomes of the analysis concerning smash quality exhibit statistically highly significant disparities ($p < 0.01$) across all three parameters associated with smash quality, as shown in Table 2. With progressive years of training, there is a noteworthy increment of 60.2% in the maximum flight velocity ($V_{\max}$), while conversely, the shuttlecock clearance height (H_{p-n}) and the flight angle at release (A_{shuttle}) experience substantial reductions of 485.0% and 212.2%, respectively.

Table 2. Training effects revealed by smash quality parameters.

Smash Quality Parameter	Novice Group	Skilled Group	<i>p</i> -Value	Change (%)
$V_{\max}$ (m/s)	36.7 ± 8.5	58.8 ± 9.9	<0.00	60.2
H_{p-n} (m)	1.17 ± 0.84	0.20 ± 0.16	<0.00	−485.0
A_{shuttle} (°)	18.8 ± 11.8	-21.1 ± 4.6	<0.00	−212.2

$V_{\max}$: Maximum shuttlecock speed, H_{p-n} : shuttlecock clearance height, A_{shuttle} : shuttlecock flight angle at release.

The enhancements in the quality of the smash are evidently linked to alterations in full-body control mechanisms, as illustrated in Figure 2. Notable distinctions encompass (a) the distinction between skilled players who employ jumping techniques during the smash and novice players who do not, (b) the absence of a complete full-body tension-arc formation in novice groups, (c) the heightened degree of trunk rotation observed in the skilled group, and (d) a 2D follow-through (in the sagittal plane) in novices versus a follow-through with the arm-racket crossing in front of the body in the skilled group.

The determinants, denoting kinematic parameters that exhibited significant modifications due to years' training for smash optimization, are quantitatively determined in this study. Figure 3 and Table 3 detail the statistically significant variations identified in the investigation.

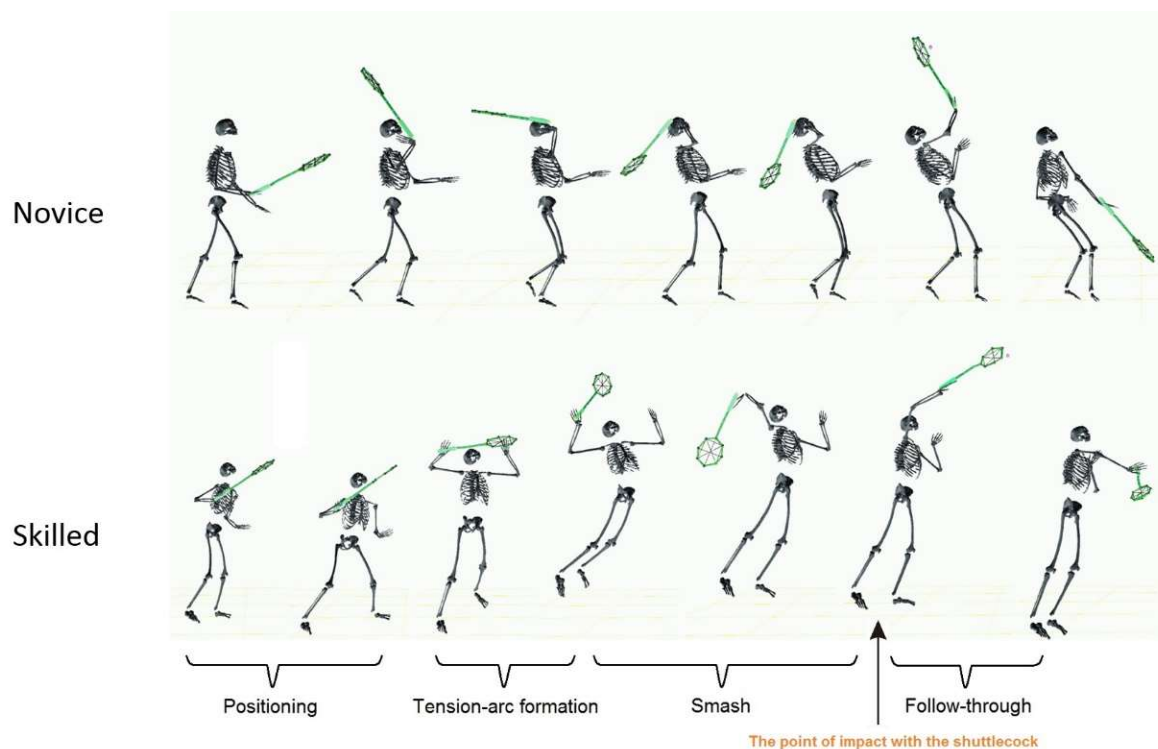


Figure 2. The phase-by-phase comparison of the typical smash performance between novice and skilled players.

Firstly, the novice group displayed inconsistent positioning (Figure 3b–d) in contrast to the consistent positioning observed in the skilled groups (Figure 3a,b). The degree of consistency is determined by the horizontal distance (D_{c-s}) between a player's center of gravity (COG) and the shuttlecock at the moment of impact.

Secondly, the novice group exhibited an upward return ($A_{shuttle}$ in Table 2) resulting from a racket angle of 108° relative to the horizontal direction at the moment of impact (A_{racket} in Table 3), whereas the skilled group executed a downward return due to a 61° A_{racket} .

Thirdly, when compared to the novice players, the skilled group displayed a substantial 75.7% augmentation in trunk rotation (X-factor in Table 3, 24.7° vs. 43.4°).

Fourthly, the range of motion (ROM) in shoulder flexion/extension and abduction/adduction was increased by 175.5% and 231.7%, respectively, when comparing the skilled group to the novices (shoulder flex/ext in Table 3, 25.3° vs. 69.7° and shoulder abd/add in Table 3, 8.2° vs. 27.2°).

Fifthly, the ROM in shoulder rotation was nearly threefold (increased almost two times) in the skilled group when compared to the novice group (shoulder rotation in Table 3, 65.7° vs. 185.4°).

Sixthly, in contrast to the novices, the skilled group exhibited a notable 70.8% increase in the ROM of elbow flexion/extension (elbow flex/ext in Table 3, 48.9° vs. 83.5°).

Lastly, the skilled group demonstrated a substantial 48.7% expansion in the ROM of wrist flexion/extension relative to the novice group (wrist flex/ext in Table 3, 94.4° vs. 140.4°).

Ultimately, in the skilled group, we observed a whip-like smash consisting of four segments: the trunk, shoulder, elbow, and wrist. This smashing technique involved a sequential acceleration, marked by a rapid change in joint rotation. It began with trunk internal rotation, followed by shoulder internal rotation, elbow extension, and concluded with wrist flexion (Figure 4). The whip-like smash benefited from shoulder flexion and adduction for its execution.

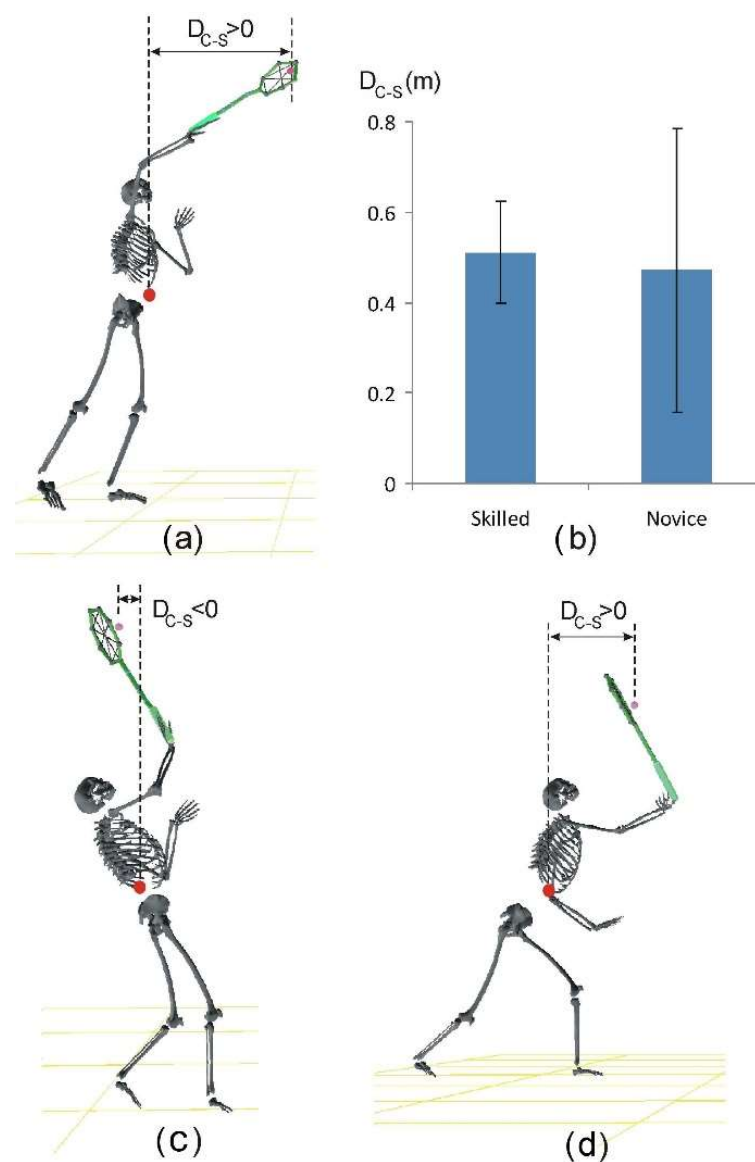


Figure 3. The comparison of positioning effectiveness between novice and skilled players. (a) Positioning of skilled players, (b) Averages and standard deviations of positioning for the two tested groups, (c) Over-positioning observed among novice players, and (d) Improper positioning posture identified among novice players.

Table 3. Key changes in the skill control induced by training.

Skill Control Parameter	Novice Group	Skilled Group	p-Value	Change (%)
A_{racket} at impact ($^{\circ}$)	108.5 ± 9.2	61.0 ± 7.9	<0.00	-77.9
ROM of X-factor ($^{\circ}$)	24.7 ± 8.0	43.4 ± 10.0	<0.00	75.7
ROM of shoulder flex/ext ($^{\circ}$)	25.3 ± 15.7	69.7 ± 9.4	<0.00	175.5
ROM of shoulder abd/add ($^{\circ}$)	8.2 ± 5.5	27.2 ± 7.9	<0.00	231.7
ROM of shoulder rotation ($^{\circ}$)	65.7 ± 23.4	185.4 ± 14.9	<0.00	182.2
ROM of elbow flex/ext ($^{\circ}$)	48.9 ± 14.7	83.5 ± 20.5	<0.00	70.8
ROM of wrist flex/ext ($^{\circ}$)	94.4 ± 37.9	140.4 ± 20.1	<0.00	48.7

The duration for ROM quantification is Phase 2 and Phase 3. flex/ext: flexion/extension, abd/add: abduction/adduction.

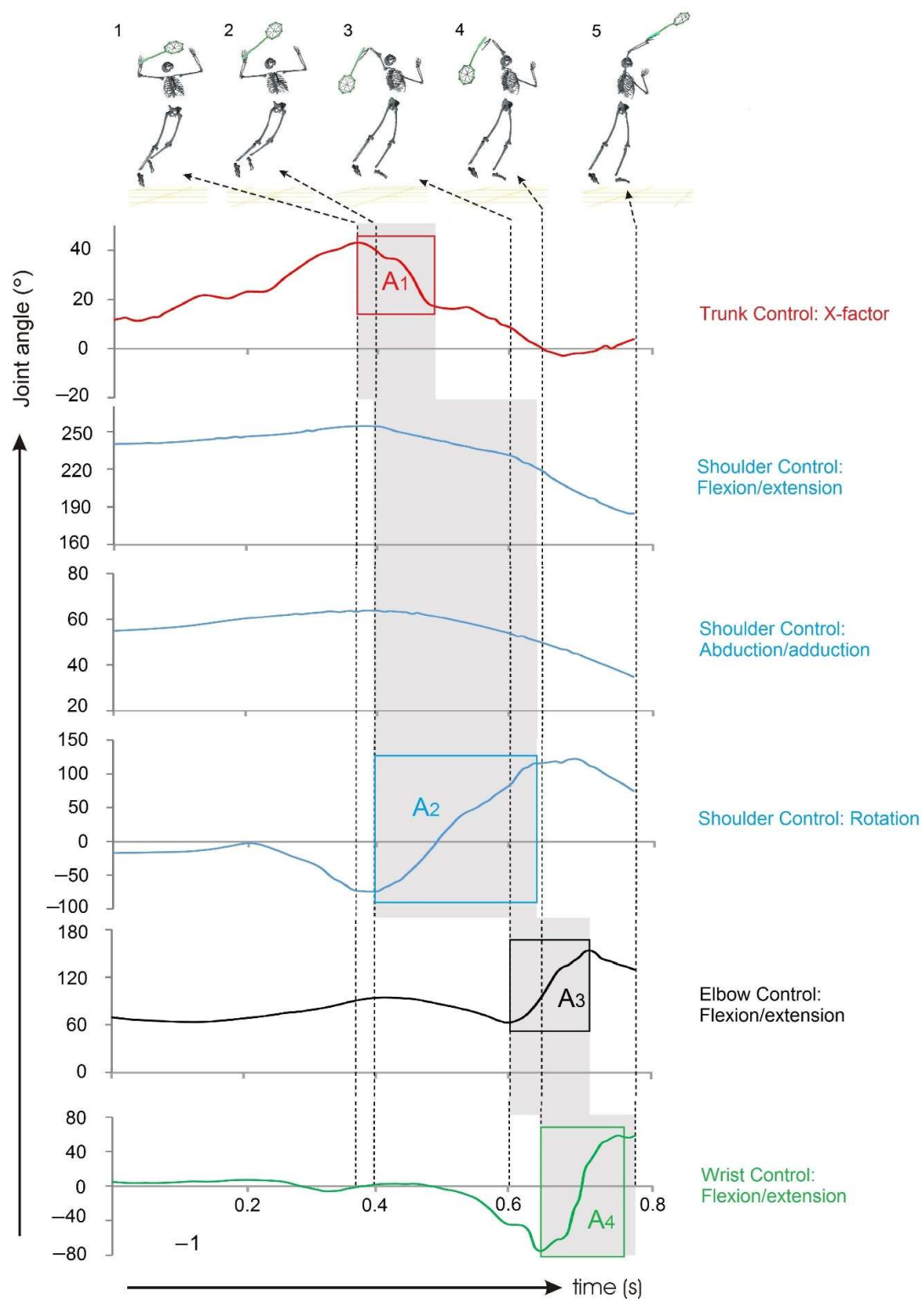


Figure 4. The explosively sequential whip-like smash observed in the skilled group. 1: the initiation of rapid trunk internal rotation (towards the non-smash side), A₁: the duration of the fast trunk internal rotation; 2: the commencement of swift shoulder internal rotation, A₂: the duration of the rapid shoulder internal rotation; 3: the start of rapid elbow extension, A₃: the duration of the quick elbow extension; 4: the beginning of the fast wrist flexion, A₄: the duration of the fast wrist flexion; and 5: impact with the shuttlecock.

4. Discussion

This study represents a pioneering effort to conduct a comprehensive 3D motion analysis encompassing the entire sequence of the badminton forehand smash. It employs both novice and skilled players to uncover the fundamental biomechanical factors that govern this skill and aid in skill acquisition for beginners. The results have unveiled a wealth of information regarding smash quality and the role of full-body control, shedding light on the biomechanical aspects related to optimizing the badminton forehand smash and offering invaluable insights into the skill acquisition process for novice players. As indicated in the introduction, the study aims to bridge the gap between scientific research and coaching practice by providing biomechanically grounded and coaching-friendly explanations on motor control sequencing. Therefore, the discussion and implications are conducted phase-by-phase.

4.1. The Significance of Positioning in Badminton Smash

The primary objective of the positioning phase is to adjust body position and posture in response to the incoming shuttlecock to execute an effective forehand smash. While positioning in badminton smash remains a relatively underexplored aspect, both empirical evidence and biomechanical studies emphasize its crucial role in smash quality, particularly with regard to the release angle of the shuttlecock and the clearance height during an offensive attack [29]. The current study confirms the previous results. The presence of inconsistent positioning among novice players, as opposed to the consistent positioning observed in skilled groups, underscores the importance of mastering positioning as a pivotal factor in enhancing smash quality. Both the findings of the current study and those of previous research [29] suggest that maintaining a horizontal distance (Dc-s) between 0.50 m and 0.65 m results in a high-quality smash.

Positioning necessitates repetitive training to improve pre-judgment of the shuttlecock's trajectory and enhance learners' step control. Drawing from the limited existing literature [29], a two-step training approach can be employed: static (cognitive) and dynamic (associative) training [35]. To facilitate skill acquisition, learners can initially establish their static, comfortable positioning relative to a stationary hanging shuttlecock and then take a step back. This perceptual marker serves as a valuable guide for beginners to learn and train the positioning in badminton [29] as a form of cognitive/perceptual improvement. In the static practice, the training regimen can transition from stationary shuttlecocks to dynamic ones, gradually incorporating dynamic jumping techniques into the skill development process.

4.2. Full-Body Tension-Arc Formation

The formation of a tension arc is an integral aspect of executing a powerful badminton smash and is closely associated with the act of jumping. The absence of a complete full-body tension-arc formation in novice groups underscores the necessity for players to master the coordination of their entire body during the execution of the smash.

The 3D kinematics analysis of skilled players has unveiled the formation of a full-body tension-arc, achieved through a combination of hip over-extension, trunk external rotation, and shoulder over-extension, abduction, and external rotation (Figures 1 and 4). This full-body tension-arc likely accounts for the highly significant 60.2% increase in maximum shuttlecock speed observed in the skilled group compared to the novice group (Table 2). Additionally, the significantly greater ROMs observed in skilled players (Table 3), encompassing trunk rotation, shoulder flexion/extension, abduction/adduction, and rotation, elbow flexion/extension, as well as wrist flexion, signify the fundamental impact of these ROMs on smash quality. Therefore, increasing the amplitude of these determinants should be a focus for novice training.

From a biomechanical perspective, the formation of the tension arc offers several advantages for enhancing smash power. It notably increases the X-factor (trunk rotation), resulting in an ideal body posture conducive to executing a powerful whip-like smash.

Regarding the X-factor, our study aligns with previous research, such as Zhang et al. [5], underscoring the pivotal role of increasing the X-factor in achieving higher maximal shuttlecock release speeds. Consequently, it is imperative to consider and analyze the trunk segment when comprehensively defining the factors governing the forehand smash. This perspective finds support in research across various sports disciplines, including golf, baseball, tennis, and volleyball, where trunk movement has consistently been recognized as a significant contributor to increased ball release speed [56–59]. For example, golf research highlights the importance of a substantial X-factor during a golf backswing for generating higher club head velocity upon impact [14,60]. Similarly, in baseball, variations in ball velocity among pitchers have been linked to different degrees of trunk rotation [61–63]. Tennis strokes involving trunk and shoulder rotation also highlight the X-factor's significance [57,64]. Research conducted by Adrian and Enberg [56] in volleyball has drawn connections between the movement sequence of a spike and that of the badminton forehand smash and tennis serve, emphasizing that trunk rotation plays a pivotal role in initiating these actions. In short, trunk rotation (X-factor) emerges as a pivotal element in power generation across various sports-specific skills.

However, even more crucial than the X-factor, the formation of the tension-arc should be considered the primary contributor enabling a whip-like movement that generates explosive power in the smash. This concept of utilizing the tension-arc formation for explosive power generation is not limited to badminton but also applies to other sports skills, such as the javelin throw [47,48] and the maximal instep soccer kick [49,50]. Researchers studying the javelin throw have found that the tension-arc formation is imperative for enabling a powerful whip-like throw. In the case of the maximal instep soccer kick, two relevant advantages have been identified: firstly, the tension arc provides an ideal initial condition that increases the lengths of trunk flexors, hip flexors, and quadriceps before their contraction. This dynamic muscle pre-lengthening generates greater muscle forces thanks to a muscle control pattern known as the SSC (stretch-shortening cycle) [65,66]. This, in turn, increases the effectiveness of the kicking motion. Studies have revealed that when compared to a pure concentric action, the SSC demonstrates a considerable performance enhancement with increased muscle force [65–67]. Secondly, the tension arc enables an open kinetic chain, allowing the kicking leg to execute a whip-like movement toward the ball [49,50,68].

In summary, the phase of full-body tension-arc formation serves two essential purposes: (1) it increases the amplitude of the ROM in trunk rotation, shoulder flexion/extension, abduction/adduction, rotation, elbow flexion/extension, and wrist flexion (i.e., the determinants) that fundamentally enhance smash quality; and (2) it creates an ideal body posture that empowers players to execute a powerful whip-like smash, thereby increasing shuttlecock speed. Consequently, training focused on increasing the amplitude of the determinants and mastering the full-body tension-arc formation should be two integral parts of the skill development process for training novice players.

4.3. Whip-like Control Smash

The basic element enabling human movement is the angular motion of joints, wherein the angular velocity starts at zero and returns to zero at the end of each joint movement. After the commencement of angular motion, the joint angle undergoes rapid changes over time, with the fastest angular velocity (i.e., the most rapid change in joint angle over time) occurring somewhere in between.

In motion analysis, the human body is mechanically described as a chain system with multiple joints. To maximize the velocity of distal segments, such as throwing, smashing, kicking, or striking in various sports, sequential joint control/coordination (i.e., whip-like control) is required. This whip-like control involves a sequential progression of motion from the core of their body outward to the distal end of their extremities. Ideal timing in whip-like control involves starting the angular motion of a joint when the previous joint reaches its maximum angular velocity. In a diagram depicting angle changes over time, the degree of whip-like control can be assessed by analyzing the timely overlaps of the joint

angle changes involved in a movement [5,14,49]. Perfect whip-like control demonstrates that at the end of the period of the most rapid angle change in a larger joint, the adjoining smaller joint begins its period of the most rapid angle change [69]. When impeccable timing is achieved from proximal to distal control, it results in the highest possible cumulative distal-end velocity. Extensive reports and studies [61,70–74] have consistently documented that, in various throwing and striking endeavors, skilled athletes adhere to the distinctive whip-like control pattern. Illustrative examples of this phenomenon can be observed in activities such as the golf swing [14,60], tennis serve [75], baseball pitch [62,63], javelin throw [47,48], soccer kicking [49,50,76], or taekwondo kicking [24,77]. Research evidence has substantiated that this sequential control motion represents the most effective motor control pattern of generating explosive power and transferring the resultant kinetic energy to a ball, equipment, or opponent [71].

Based on the description above, several points are worth discussing. Firstly, concerning the rapid change periods identified, the whip-like control observed in the skilled group primarily consists of trunk internal rotation (area A1 in Figure 4), shoulder internal rotation (area A2 in Figure 4), elbow extension (area A3 in Figure 4), and wrist flexion (area A4 in Figure 4). This indicates that skilled players have developed a four-segment whip-like control system. Secondly, there are no notable rapid changes in shoulder flexion and adduction during the smash (shoulder control: flexion/extension and abduction/adduction in Figure 4). This phenomenon suggests that the function of shoulder over-extension and abduction is to create a tension arc, establishing the necessary conditions/posture for enabling the whip-like smash. Therefore, their primary role is to support the whip-like smash. It is interesting to note that a previous study has revealed that the rapid shortening of the pectoralis major contributes significantly to the internal rotation of the upper arm during the badminton smash [5]. This confirms that shoulder over-extension and abduction during the tension arc formation (pre-lengthening of the pectoralis major) would enable rapid shoulder internal rotation during the whip-like control. Thirdly, due to the inertia effect, the rapid angular movement of the trunk and shoulders in the first half of the smash results in additional elbow flexion and wrist over-extension (Figure 4), constituting passive movements [51,52]. These passive movements strengthen the SSC effect, leading to a more powerful whip-like smash [65–67]. Since these controls are passive, learners should focus their attention on trunk and shoulder controls in the initial stages of the smash. Such a learning strategy should simplify the learning process [52] and potentially enhance training effectiveness. Further studies are needed to confirm the effects of this learning strategy. Finally, the identified whip-like smash of skilled players has not yet reached its ideal pattern [69]. There is a significant temporal overlap between A1 and A2 (trunk and shoulder), as well as A3 and A4 (elbow and wrist) (Figure 4). This suggests that skilled players could further increase the maximal shuttlecock speed by improving the timing of the whip-like control.

Collectively, through discussion, this section identifies a four-segment whip-like control system, comprising trunk internal rotation, shoulder internal rotation, elbow extension, and wrist flexion. Notably, it underscores the supportive role of shoulder over-extension and abduction in creating a tension arc for the whip-like smash. Furthermore, the inertia effect contributes to passive elbow flexion and wrist over-extension during the smash, enhancing the SSC effect and overall power. While the whip-like smash holds promise, there remains room for improvement, as temporal overlaps between segments indicate. Enhancing the timing of the whip-like control could further increase shuttlecock speed, making it an area of potential development for skilled players aiming for optimal performance.

4.4. Follow-Through

In general, the primary purpose of the follow-through phase is to dissipate residual momentum in athletes' limbs [39,69]. In the badminton smash, this refers to the residual arm-racket momentum after impact with the shuttlecock. The main reason for the discrepancy between the two groups in the follow-through is the different smash control

patterns found in the two groups. Novices primarily execute smashes in the sagittal plane (anterior–posterior direction), while skilled players, due to the three-dimensional movement of shoulder control, naturally follow through with the racket arm crossing in front of the body to dissipate residual arm–racket momentum after a powerful smash. Targeted training in this phase is unnecessary, as the whip-like control develops gradually during training, leading to changes in the follow-through pattern.

The current study has two noticeable limitations. First, due to the geographical constraints of the researchers' institute, no professional players were included in the subjects. Previous biomechanical research has demonstrated that professional/elite players achieve maximal shuttlecock speeds ranging from 80 to 107 m/s [33,34,78]. The fastest shuttlecock speed measured in competitive play reached 118 m/s [79], while in a lab-based test in 2013, Malaysia's Tan Boon Hoeng established a remarkable record of 137 m/s [80]. Notably, the biomechanical findings pertaining to elite players indicate a substantial velocity advantage, ranging from 30% to 80%, over skilled players, with documented record speeds surpassing twofold or more. Consequently, it is logical to infer that further smash optimization, particularly related to whip-like control, might occur during advanced training levels. Future comparative studies involving skilled and professional badminton players to investigate the long-term training effects associated with the four phases of the badminton smash would be valuable for the field of coaching science. Second, due to the limited pool of subjects, it was not feasible to explore the potential influence of gender. This aspect should be considered in future research, as it could reveal gender-based differences. Information regarding disparities in motor skills between genders is increasingly sought after by practitioners in the field.

5. Conclusions

In conclusion, the results of this study provide valuable insights into the biomechanical aspects of badminton forehand smashes and the progression of skills among novice and skilled players. It is evident that with progressive years of training, significant improvements in smash quality are achieved. Skilled players exhibit a remarkable 60.2% increase in maximum shuttlecock speed ($V_{\max}$), which is accompanied by substantial reductions in shuttlecock clearance height (H_{p-n}) and the flight angle at release (A_{shuttle}). These enhancements are closely linked to full-body control mechanisms, including the use of jumping techniques, the formation of a full-body tension arc, increased trunk rotation, and a distinctive whip-like control pattern.

Moreover, the study identifies specific determinants, such as consistent positioning, racket angle at impact, and range of motions (ROMs) in various joints, that significantly contribute to smash quality. Skilled players demonstrate superior performance in these determinants compared to novices, highlighting their importance in the skill development process.

The concept of a full-body tension-arc and the whip-like control pattern emerge as crucial factors for generating explosive power in the smash. Specific to badminton smash, due to the inertia effect, rapid trunk, and shoulder rotations in the early smash phase cause passive elbow flexion and wrist over-extension, reinforcing the SSC effect for a more potent whip-like smash. Focusing on trunk and shoulder control in initial stages simplifies the learning of the four-segment whip-like control, potentially enhancing training effectiveness. This biomechanical understanding extends beyond badminton and can be applied to other sports skills related to throwing or smashing.

Finally, the study emphasizes the importance of mastering positioning, enhancing joint control, and optimizing the whip-like control pattern for novice players. Future research involving professional players and gender-based differences would further enrich our understanding of badminton smash mechanics. Overall, this study bridges the gap between scientific research and coaching practice, providing valuable insights for coaches and players seeking to improve their badminton forehand smashes.

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