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Relationships between Racket Arm Joint Moments and Racket Head Speed during the Badminton Jump Smash Performed by Elite Male Malaysian Players

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Abstract: Three-dimensional position data of nineteen elite male Malaysian badminton players performing a series of maximal jump smashes were collected using a motion capture system. A 'resultant moments' inverse dynamics analysis was performed on the racket arm joints (shoulder, elbow and wrist). Relationships between racket head speed and peak joint moments were quantified using correlational analyses, inclusive of a Benjamini–Hochberg correction for multiple-hypothesis testing. The racket head centre speed at racket–shuttlecock contact was, on average, 61.2 m/s with a peak of 68.5 m/s which equated to average shuttlecock speeds of 95.2 m/s with a peak of 105.0 m/s. The correlational analysis revealed that a larger shoulder internal rotation moment (r = 0.737), backwards shoulder plane of elevation moment (r = 0.614) and wrist extension moment (r = −0.564) were associated with greater racket head centre speed at racket–shuttlecock contact. Coaches should consider strengthening the musculature associated with shoulder internal rotation, plane of elevation and wrist extension. This work provides a unique analysis of the joint moments of the racket arm during the badminton jump smash performed by an elite population and highlights significant relationships between racket head speed and peak resultant joint moments.

Keywords: shuttlecock; overhead; torque; inverse dynamics

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Citation: Ramasamy, Y.; Sundar, V.; Usman, J.; Razman, R.; Towler, H.; King, M.A. Relationships between Racket Arm Joint Moments and Racket Head Speed during the Badminton Jump Smash Performed by Elite Male Malaysian Players. *Appl. Sci.* **2022**, *12*, 880. https://doi.org/10.3390/app12020880

Academic Editor: Fernando Ribeiro

Received: 19 November 2021
Accepted: 12 January 2022
Published: 15 January 2022

1. Introduction

Badminton is an Olympic sport that many athletes play around the world [1], which requires a large number of overhead strokes (30%) with clear, drop shots and smash shots [2]. The forehand overhead smash is one of the fastest motions among various racket sports [3] and accounts for approximately 15% of all strokes in badminton [2]. The kinematic parameters that determine greater shuttlecock speed as high as 107 m/s [4] are greater shoulder internal rotation at shuttle contact and producing greater pelvis–thorax separation during the retraction phase [5]. In a separate study with elite male Malaysian players, [6] found that maximal ground reaction force during take-off, maximum jump height and greater wrist flexion angular velocity at contact were correlated with greater shuttle speed. Additionally, Ramasamy et al. [7] found that the kinematic parameters related to greater shuttlecock speed were a less extended elbow at contact, and a less elevated and more internally rotated shoulder. The authors explored kinetic parameters related to ground reaction force (normalised peak and rate of force development), however neither were correlated with shuttlecock speed.

Previous studies on throwing and ball striking skills have shown that larger angular velocities of shoulder internal rotation, elbow extension and wrist flexion all happen near to the time of contact/release and make large contributions towards endpoint speed [8–11]. Additionally, peak linear velocity of the wrist joint centre was found to be a strong predictor of shuttlecock speed, suggesting that players should aim to achieve greater linear velocities within distal components of the kinetic chain [5].

Upper body joint moments perform an important role in producing high joint angular velocity for any rapid overhead movement. The contribution of the internal/external rotation torque at the racket arm shoulder joint (primarily eccentric) and the pronation/supination torque at the racket arm elbow joint (primarily concentrically) were found to be the largest contributors to racket head speed during the tennis serve motion [12]. Rasmussen et al. [13] found that the abrupt acceleration of the racket during the smash stroke requires transfer of a high amount of power over the involved joints, and primarily over the wrist joint, where the peak power briefly exceeds 1 kW. The authors concluded that the large rates of energy transfer are beyond what the musculature can perform and are therefore transferred via joint reaction forces in a whip-like motion. The authors also found a transfer of energy from proximal to distal segments and found that the peak power transferred over the joints had a proximal to distal nature with glenohumeral joint peaks first followed by the elbow and finally the wrist. This study only used one elite player; as such the results are not generalisable.

In summary, the jump smash is frequently used in badminton and places high physical demand on the racket-side upper limb. Despite its frequent occurrence, very few analyses have investigated the joint moments during the jump smash within elite participants. The understanding of the moments produced at the upper-limb joints will provide insight into the requirements for producing greater racket head speed/shuttlecock speeds. Therefore, the study aimed to investigate the relationships between racket head speed and upper limb joint moments. It is hypothesised that greater racket head speeds are associated with greater peak shoulder internal rotation moments.

2. Materials and Methods

2.1. Participants

Data were collected from 19 elite male players (age 21 ± 2 years, mass 71.3 ± 5.1 kg, height 1.78 ± 0.05 m) and all the participants were injury free at the time of data collection. All participants were members of Malaysian national team at the time of data collection. The study was approved by the National Sports Institute of Malaysia Research Ethics Committee. The participants were informed of the testing procedure and protocols and informed consent was obtained from all participants. All participants used their racket throughout the testing (manufacturer reported unstrung racket mass; 85 ± 2 g and self-reported string tensions; 30 ± 1 lbs).

2.2. Data Collection

All data were collected on an instrumented full-size badminton court at the Sports Biomechanics Laboratory, National Sports Institute of Malaysia [7]. Twenty-five Oqus 7+ series infrared cameras (Qualisys AB 411 05, Goteborg, Sweden) were placed around the court to collect three-dimensional position data of the player, racket and shuttlecock, with a capture frequency of 700 Hz and a calibrated volume with a reconstruction accuracy of ±0.4 mm for each marker.

Sixty-four 12.5 mm reflective markers were attached to key body landmarks, with markers positioned on both sides of a joint to define the joint centres [7], using double-sided tape (Qualisys) and Hypafix non-woven adhesive to create a 15-segment representation of the body (head, thorax, pelvis, 2 × upper arm, 2 × forearm, 2 × hand, 2 × thigh, 2 × shank and 2 × feet) in Visual 3D v6.00.18 (C-Motion Inc., Maryland, MD, USA). Each segment was defined by a local reference frame using a minimum of three markers on the segment with the z-axis pointing from distal to proximal, the x-axis pointing to the participants' right and the y-axis pointing forward [7]. Global mediolateral data were reversed for left-handed players such that all players could be considered right-handed. An inverse kinematics procedure was performed using all joints within the model with the Quasi-Newton optimisation algorithm. One 12.5 mm marker (on the bottom of the racket handle) and eight pieces of retroreflective tape approximately 10 mm^2 were placed on the racket [7] and new Yonex Aerosense 30 shuttlecocks (Yonex, Tokyo, Japan) with a circle of reflective tape (diameter 19 mm) attached to the tip of the shuttlecock were used for the data collection. Shuttlecocks that were misshapen or broken were discarded. All participants were given approximately 20 min to warm up and 15–30 min to become familiar with the data collection environment. During the data collection, shuttlecocks were fired from a Knight Trainer shuttle launcher that was set up to replicate a high serve/lift and enabled the participant to perform a maximum jump smash. Participants were asked to play 25 maximum jump smashes aiming at a designated area on the opposite side of the court and were able to move freely prior to executing each jump smash.

2.3. Data Analysis

The fastest jump smash (greatest post-impact shuttlecock speed) determined using a curve-fitting methodology [4] for each participant where the shuttlecock landed in the designated area was chosen for further analysis. Position data were labelled using Qualisys Track Manager (QTM2018.1: build 4260, Qualisys, Goteburg, Sweden) and gaps within the data were filled using a combination of linear and polynomial interpolation. All body marker position data were filtered within Visual 3D using a 4th-order, zero-phase, low-pass Butterworth filter with a cut-off frequency of 30 Hz. A 15-segment model in Visual 3D was used to calculate joint moments. Segment inertia parameters were determined using mass distribution ratios [14]. The racket was modelled as two segments (handle and frame) that, when combined, gave typical racket inertia parameters [15]. This allowed some representation of the racket deformation. The racket and hand were linked via a virtual joint that was positioned one-quarter of the way up the grip, allowing transmission of force between the two segments, and this position was assumed constant across all participants. A 'resultants moments' inverse dynamics analysis [16] was performed within Visual 3D. For the full equations, readers are referred to the documentation provided by Visual 3D [17]. An iterative algorithm was used to calculate the proximal joint force and then the inertial moment was calculated, which allows the calculation of the joint moments.

Non-orthogonal joint coordinate systems were created for the elbow and shoulder. The elbow joint coordinate system was calculated based on an XY′Z″ Cardan sequence, corresponding to flexion/extension, adduction/abduction and pronation/supination, where the X and Z″ axes are fixed in the upper arm and forearm coordinate systems, respectively [18]. The shoulder joint coordinate system was calculated based on a ZY′Z″ Cardan sequence, corresponding to the plane of elevation, elevation/depression and internal/external rotation, where the Z and Z″ axes are fixed in the thorax and upper arm coordinate systems [18]. The wrist joint coordinate system was orthogonal and corresponded with the forearm segment, and represented flexion/extension, ulnar/radial deviation and pronation/supination [19].

To allow a comparison between players, kinematic data were normalised to a swing phase that was defined from the instant where the global anterior–posterior velocity of the racket head centre was above a threshold of 5 m/s (Figure 1a), from which it did not decrease, through to racket–shuttlecock contact (Figure 1c). The instant describing the end of the backswing phase/start of the forward swing phase was calculated at the point where the racket head velocity normal to the stringbed became positive [5]; Figure 1b).

Pearson product moment correlation analyses were performed for racket head speed at racket–shuttlecock contact with peak moment data at the shoulder, elbow and wrist using SPSS v.20 (IBM Corp., Armonk, NY, USA). Data were tested for normal distribution using the Shapiro–Wilk test, where the assumption of normality was met where $p > 0.05$. Pearson product moment correlations (r) and their 95% confidence intervals (CI) were interpreted as negligible < 0.3; $0.3 \leq$ low < 0.5; $0.5 \leq$ moderate < 0.7; $0.7 \leq$ high < 0.9; very high ≥ 0.9 [20].

For non-normally distributed variables, the Kendall tau-b (τ_b) correlation was performed, with 95% CI calculated using the 'Fisher's method' [21], and interpreted similarly to Pearson product moment correlations. Combining both effect size and confidence intervals allows interpretation of both the magnitude of the effect and (un)certainty of the parameter estimate [22]. To control for multiple hypothesis testing, the Benjamini–Hochberg correction was used with a false discovery rate of 10%.

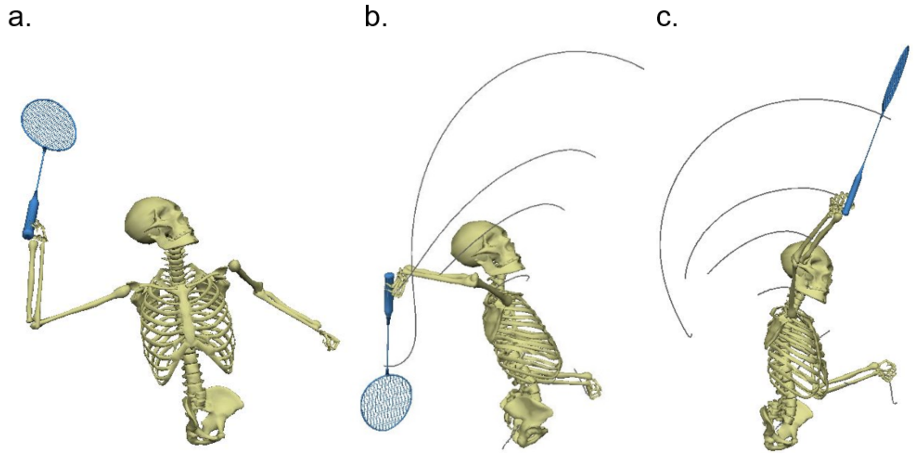

Figure 1. A representation of the normalised swing phase instants for one typical participant; (**a**). start of swing (5 m/s); (**b**) end of backswing, and (**c**). racket–shuttle contact.

3. Results

The fastest racket head speed (at impact) by each participant had an average speed of 61.2 m/s with a peak of 68.5 m/s. Three peak moment data were correlated with racket head speed, namely shoulder internal rotation, backwards plane of elevation and wrist extension (Table 1).

Table 1. Peak moment data during the swing phase at the shoulder, elbow and wrist joints for each participant's fastest smash.

	Variable		Mean	Standard Deviation	$r/(\tau_b)$	95% CI		p
						Lower	Upper	
Moment	Shoulder	Backward plane of elevation	−82.92	36.57	0.614	0.221	0.835	0.005 *
		Forward plane of elevation	85.58	15.42	−0.141	−0.559	0.335	0.565
		Elevation	−50.15	33.26	−0.228	−0.261	0.066	0.172
		Depression	43.72	23.22	0.476	0.028	0.765	0.039
		Internal rotation	74.13	11.70	0.737	0.424	0.892	<0.001 *
		External rotation	−24.49	11.63	−0.156	−0.570	0.321	0.524
	Elbow	Flexion	28.31	14.44	−0.428	−0.739	0.0312	0.067
		Extension	−23.92	7.45	−0.005	−0.458	0.450	0.985
		Pronation	6.56	0.308	0.308	−0.170	0.669	0.199
		Supination	−7.75	2.64	−0.379	−0.711	0.090	0.109
	Wrist	Flexion	20.90	7.04	0.125	−0.349	0.548	0.610
		Extension	−20.44	3.00	−0.564	−0.810	−0.147	0.012 *
		Radial deviation	−18.47	4.25	−0.495	−0.775	−0.053	0.031
		Ulnar deviation	1.51	0.98	0.291	−0.188	0.658	0.226

p * significant following Benjamini–Hochberg correction. Abbreviations: r—Pearson product-moment correlation coefficient, τ_b—tau-b statistic, CI—confidence interval.

A large peak in the shoulder internal rotation was evident just prior to the onset of the forward swing (Figure 2c), whilst a large negative shoulder plane of elevation moment occurred during the forward swing and peaked at racket–shuttlecock contact (Figure 2a). At the elbow joint, a large flexion and supination moment was present just prior to racket–

shuttlecock contact (Figure 3a,b, respectively). Throughout the majority of the swing phase, a wrist-extension moment was present (Figure 4a).

Individual scatter plots for the three correlated variables, indicating the variation in peak moments across the participants and the relationships with racket head speed (Figure 5).

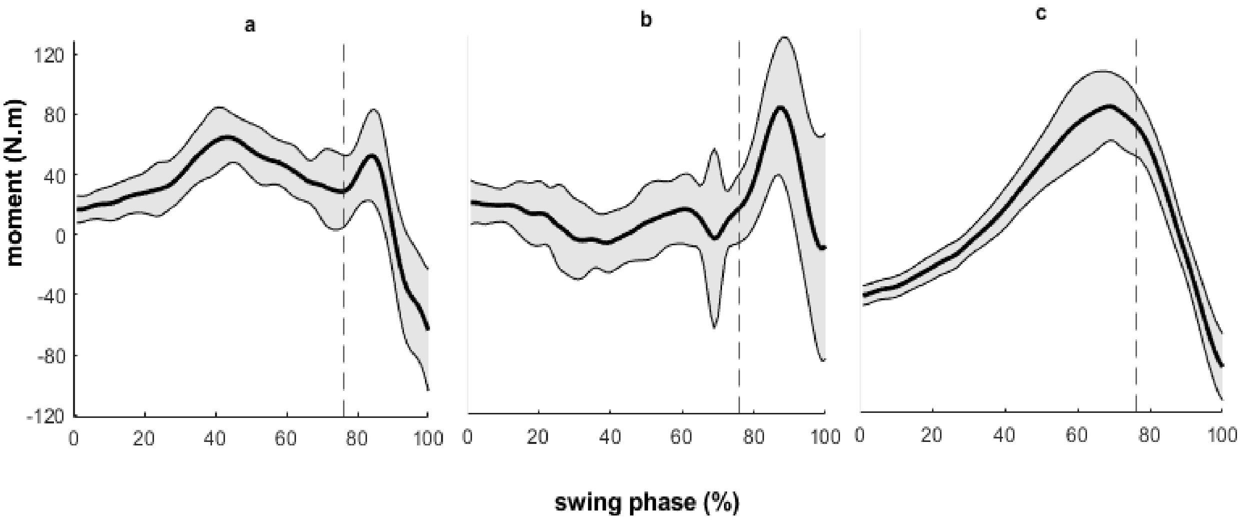

Figure 2. Normalised time histories for shoulder resultant moments: (**a**) shoulder forward plane of elevation [+]/backward plane of elevation [−]; (**b**) shoulder depression [+]/elevation [−] and (**c**). shoulder internal rotation [+]/external rotation [−]. Vertical dashed line indicates the mean end of back swing instant (Figure 1).

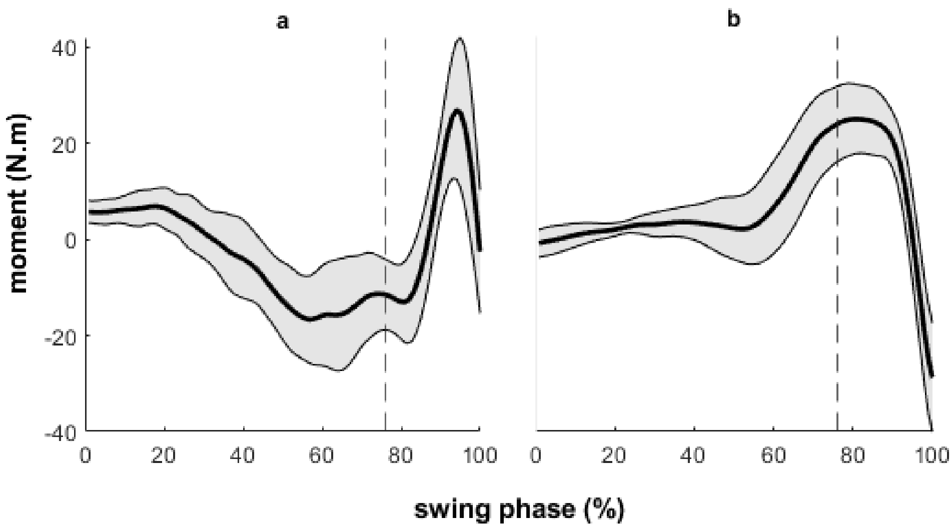

Figure 3. Normalised time histories for elbow resultant moments: (**a**) elbow flexion [+]/extension [−] and (**b**) elbow pronation [+]/supination [−]. Vertical dashed line indicates the mean end of back swing instant (Figure 1).

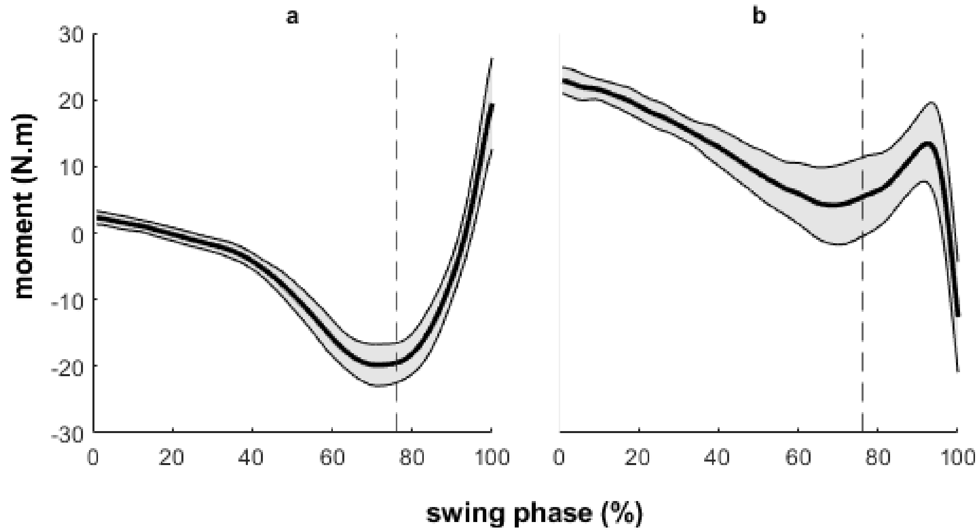

Figure 4. Normalised time histories for wrist resultant moments; (**a**). Wrist flexion [+]/extension [−], and (**b**). Wrist ulnar deviation [+]/radial deviation [−]. Vertical dashed line indicates the mean end of back swing instant (Figure 1).

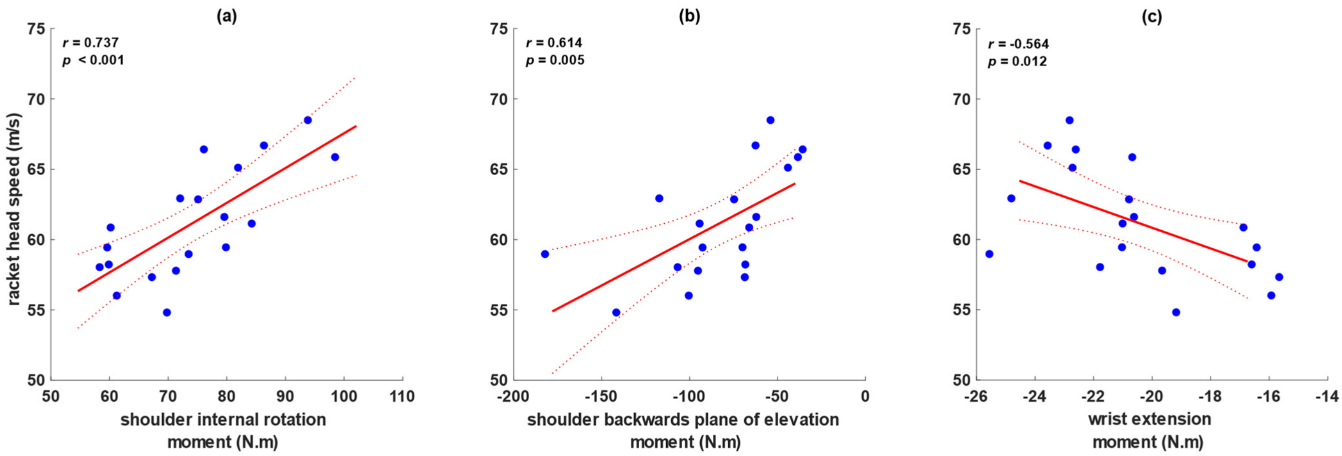

Figure 5. Correlations between racket head speed and (**a**) shoulder internal rotation; (**b**) shoulder backwards plane of elevation and (**c**) wrist extension. Regression line and 95% confidence intervals represented by solid and dashed lines, respectively.

4. Discussion

The purpose of this study was to investigate the relationships between peak upper limb moments of the racket arm joints and racket head centre speed at contact during the performance of the jump smash. The racket head speed (61.2 ± 3.9 m/s) and shuttlecock speed (95.2 ± 5.8 m/s) were similar to previous research within elite populations, as well as shuttlecock speeds [5,13].

Three joint moments were correlated with racket head speed. Most significantly, greater racket head speed was associated with greater peak shoulder internal moments (high, $r = 0.737$, CI: 0.424, 0.892, $p < 0.001$). This has also recently been found to be a differentiating factor between skilled and unskilled badminton players, where skilled players produce greater shoulder internal rotation moments [23]. This result is unsurprising given that much of the racket head speed is derived from the shoulder internal rotation angular velocity contribution in overhead motions [22–24].

In addition to shoulder internal rotation, a smaller backwards plane of elevation moment (noting backwards plane of elevation is negative and resists the forwards movement of the arm relative to the trunk) had a moderate correlation with racket head speed (r = 0.614, CI: 0.221, 0.835, p = 0.005). This peak moment typically occurred at racket–shuttlecock contact and suggests that those who produce greater racket head speed slow down the forwards movement of the arm less prior to racket–shuttlecock contact, and therefore must perform the large proportion of this resistive action after impact, which has been observed in baseball pitching, i.e., after ball release [25]. Finally, participants who produced greater wrist extension moments produced greater racket head speeds (moderate, $r = -0.564$, CI: -0.810, -0.147, p = 0.012). This may be a similar mechanism where the motion of the whole arm would drive the wrist into flexion too early within the movement, and therefore resisting this motion via an extension moment is necessary for a rapid wrist flexion to occur just before contact. This large wrist extension moment during racket motions has been previously observed in tennis [26], in which the wrist extensor muscles counteract the movements of wrist flexion.

It could be recommended that players/coaches should incorporate training that strengthens the musculature that opposes both the forwards shoulder plane of elevation (e.g., posterior deltoid, lower and middle trapezius and infraspinatus, etc.) and wrist flexion (e.g., extension carpi radialis longus and brevis), i.e., acting eccentrically, such that a player can slow the shoulder forwards motion after impact and additionally keep the wrist 'held back' so that it does not come through too early during the swing.

The primary limitation of the present study is the small sample size, where post hoc power analysis (G*Power version 3.1.9.6, Dusseldorf, Germany) revealed that a sample size of 29 subjects would provide an 80% chance of achieving α = 0.05 in a two-tailed bi-variate correlation, assuming a moderate effect size of r = 0.5; therefore, the study was underpowered. Due to the strict inclusion criteria set for the elite population, further recruitment of similar athletes was not possible. Although this limits the power of any statistical test, there is a sufficient sample to identify those variables that best explain the observed variation in each dependent variable, particularly when considering the primary elite athletes studied here. Secondly, although the athletes used their own racket that they were familiar with to perform jump smashes, differences in inertial properties, stiffness properties and geometry may affect racket head speed, and could account for some of the unexplained variation within the data. Kwan et al. [27] have shown that the elastic velocity could provide additional speed (approximately 4%) to the racket speed at impact.

The methods used in this study were appropriate to address the aims of the study. In future studies, the racket hand joint could be improved by directly measuring the force applied at the handle as well as locating the centre of pressure on the hand. The racket model (two rigid segments connected by a virtual joint) is a simplification of the dynamic behaviour of a racket, which adopts an infinite number of mode shapes under loading; however, the current approach has been used previously to measure racket kinematics [15]. Future work should also aim to understand the direct vs. indirect effects of the torques within the smash with respect to the generation of speed [28], i.e., whether the high speeds generated are a result of instantaneous torques produced by the musculature at the joint or developed by cumulative torques from prior torques at other joints. The 'resultant moments' approach used in this study does not allow a distinction between muscular, gravitational and velocity-dependent torques and therefore specific recommendations for strengthening specific muscle groups should be made with caution.

5. Conclusions

In conclusion, this study presents resultant joint moments of the racket arm joints within a group of elite male Malaysian badminton players. The strongest predictor of racket head speed was the ability to produce greater shoulder internal rotation moments. Additionally, moments that resist and delay the forwards plane of elevation motion and wrist flexion were associated with greater racket head speed. It is therefore generally recommended that players/coaches strengthen the musculature associated with these motions to help improve racket head speed and, consequently, shuttlecock speed during the smash stroke.

Author Contributions: Conceptualization, all authors; writing—original draft preparation, Y.R.; writing—review and editing, all authors; supervision, all authors. All authors have read and agreed to the published version of the manuscript.

Funding: This research received internal funding from National Sports Institute of Malaysia.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Ethics Committee of National Sports Institute of Malaysia.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

Acknowledgments: The authors would like to express special thanks to the Badminton Association of Malaysia for the support throughout this project.

Conflicts of Interest: The authors declare no conflict of interest.

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