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Original Article

Impact of cardiovascular fatigue on kinematic changes in badminton overhead jump smash: A descriptive analysis

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Abstract:
Badminton is an intermittent sport marked by rapid and explosive actions, demands specialized movement patterns involving quick accelerations, decelerations, and direction changes over short distances. The forehand overhead jump smash, a high-speed and powerful motion, plays a pivotal role in various racket sports. This study aimed to examine the influence of cardiovascular fatigue on kinematic variables during the execution of the overhead jump smash in badminton. In this study, we used a descriptive quantitative method. The study included 12 male badminton players, with an average age of 19.4 ± 1.6 years, height of 1.73 ± 0.12 m, and weight of 60.8 ± 3.7 kg. Three high-resolution handycams, the motion software Frame DIAZ IV, and 14 manual markers were utilized to analyze body segments movements during the jump smash. Fatigue levels were assessed using an ergo treadmill for running tests. The study revealed that shuttlecock velocity was higher in the prefatigue condition. A significant difference showed in compared to the under-fatigue condition compared to the under-fatigue condition. Significant differences were observed in the angle of shoulder internal rotation ($p = 0.048$) and wrist palmar flexion at the moment of maximal shoulder external rotation phase. Additionally, considerable variations were noted in shoulder internal angular velocity, elbow extension, forearm supination, and wrist dorsi flexion at the moment of maximal shoulder external rotation phase. This study showed that fatigue had a detrimental impact on player performance during the jump smash in badminton, manifesting as reduced shuttlecock speed and alterations in body segment movements.

Keywords: Sports biomechanics, badminton, jump smash, fatigue, kinematics

Introduction

Badminton is a racket sport usually played by two or four players on a rectangular court. It is characterized by multiple intense actions as well as specialized movement patterns such as fast accelerations, decelerations, and several explosive movements associated with changes of direction over short distances (Huang, Liang, et al., 2019). The duration of international single matches for this sport varies from 25 to 110 minutes with the length of each point ranging from a few seconds to several minutes (Deka et al., 2017). Moreover, several rallies are normally decided in less than 10 seconds and the match play requires rapid intensity repetitive movements within a short duration (Le Mansec et al., 2020). Elite players usually perform at their maximum limits of speed, agility, flexibility, endurance, and strength. This shows that badminton is a combination of high-intensity short rallies (anaerobic system) and longer, moderate, or high-intensity rallies (aerobic system) to sustain efforts and promote recovery between rallies (Phomsoupha et al., 2018). During a match, players are required to maintain a high level of intensity for as long as possible and the energy expended depends on their morphological factors and displacement efficiency. Agus reported that 60–70 % of the energy yielded during games was derived from the aerobic system while 30 % was from the anaerobic system with a great demand on the alactic aspect and, to a lesser degree, the lactic anaerobic metabolism (Laffaye et al., 2015). Furthermore, players adapt their movements using biomechanical factors of efficiency to respond to the full set of visual information. This requires quick changes in direction, jumps, lunges at the net, and rapid arm movements from a variety of postural positions (Matsunaga & Kaneoka, 2018).

The badminton forehand overhead techniques were divided into three strokes including drop, clear, and smash, and the stroke was further categorized into clear, drop, smash, block, lift, push, and net (Awatani et al., 2018). The overhead smash movement was also classified into two groups, including the standing and the jumping smashes (Taylor et al., 2014). Moreover, an effective smash was said to be an important means of gaining points to win a game compared to the other strokes of badminton. The dominant skill in double matches was identified to be the forehand overhead jumping smash which accounted for 1/5 of the attacks during a game (Park et al., 2017). The jumping smash technique can produce a shuttlecock velocity capable of disabling the movement of an opponent and contributes to higher score attainment up to 39.8%. The shuttlecock velocity often exceeds those obtainable from other racket sports such as tennis, squash, and soft tennis. This was confirmed by

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the 493 km/hour recorded by a Chinese athlete, Tan Boon Heong, during the trial of a new racket product (Yonex ArcSaber Z-Slash) in 2013 (Reid et al., n.d.) as well as 332 km/hour linked to Fu Haifeng, a player in China men's doubles in Sudirman Cup 2005. The shuttlecock velocity from a jumping smash movement of an Indonesian men's singles badminton player, Taufik Hidayat, in the World Tournament 2006, was also recorded to reach 305 km/hour (Rusdiana, 2016).

The player doing a jumping smash needs maximum power and a complex movement supported by physical components such as the power of the muscles in the leg, arm, abdomen, and hands (Hirashima et al., 2010). This jumping smash is a series of continuous movements associated with the coordination of the body as a whole. Meanwhile, it is normally affected by the skeletal muscle, which gives stimulation to the somatic motor neurons inducing movements in all body segments to cause a change of position through the motor segment movement (Wagner et al., 2011). A strong and long muscle contraction during the continuous smash movements in a tournament usually leads to a decrease in energy resources in the body and subsequently causes fatigue (Ooi et al., 2009). This energy reduction can affect the contraction strength and speed of the muscle, leading to the delay of the stimulation order (Mansec et al., 2017). Therefore, a slower and less controlled movement often indicates a player is experiencing fatigue condition (Aragonés et al., 2017).

Fatigue is defined as the lack of ability to produce the required power or maintain the duration to perform a targeted activity (M. Á. Gomez et al., 2019). It usually leads to a reduction in power generation ability, neuromuscular coordination, motion control precision, proprioception, joint stability, and muscle contraction, and has the ability to increase reaction time, thereby causing a significant decline in the function of the muscle. This summarily means that fatigue occurs in central muscles and transfers the effect on distal joints to cause dysfunction in a kinetic chain. The trend normally leads to a destructive effect on core muscles and the subsequent coordination with the lower to limit functional movements. Meanwhile, several factors have been identified to be affecting the ability of a person to maintain or restore postural control and these include damage to the nervous system, inefficient optic nerves, stress, vestibular mechanism, and fatigue.

Muscle fatigue can generally be defined as the reduction in the ability of muscles to generate favored power due to the chain of events cutting off their fibers from the central nervous system (M. A. Gomez et al., 2020). Fatigue can be classified into the peripheral and central. Peripheral fatigue usually occurs in a certain group of muscles associated with movement and can lead to the dysfunction of the neuromuscular region, excitation-contraction mechanism, stimulated emission by the transverse tubules, release of calcium, and the stimulation of contraction components generating power (Fong et al., 2019). Meanwhile, central fatigue is related to the upper part of the brain and invokes alpha motor neurons with further effect on the whole body (Deka et al., 2017). This shows that movement command often remains the same or increases in the peripheral but normally reduces in the central with subsequent reduction in the tension or power of the muscle. Muscle fatigue is one of the disruptive factors of neuromuscular control as indicated by those in the lower limb muscles and joints such as the ankle having the capacity to change and reduce the ability of these muscles to produce responses for balance and stability. The condition can lead to instability and loss of balance while landing. However, jumping smash requires the perfect combination of three factors including timing, power, and control (Zhao & Gu, 2019). This means a player needs to exert a greater force on the take-off foot to propel upward using the center of mass vertical velocity (Park et al., 2017). A previous study shows that repeated jumps and deviations in jumping and landing technique during the games are becoming the primary causes of muscle fatigue (Sasaki et al., 2018).

Limited studies were observed to have been conducted on biomechanics, especially overhead smash technique, in badminton despite the high number of publications on other types of sports with similar movements such as service and smash in tennis, throwing in handball, bowling in cricket, and pitching in baseball (Mei et al., 2016). Sakurai *et al.* (2000) studied smash and jump performances of elite and collegiate players and discovered that the elite players generally achieved a greater angular velocity of elbow movement which was radio-ulnar pronation but had lesser movement times from the preparation phase to the point of contact than collegiate players (Sakurai & Ohtsuki, 2010). Moreover, an assessment of the factors contributing to the shuttlecock velocity in the badminton smash showed that 53% of the final output was due to the combination of shoulder rotation and radio-ulnar pronation. The standing and jump smashes were also compared and it was observed that jump smashes generated higher racquet-head angular and shuttlecock velocities. (Huang, Fu, et al., 2019). The studies conducted on serve in tennis (Mosoi Adrian Alexandru, 2015), overarm throw in baseball (Laudner et al., 2018), overhead throw in handball (Waghmare et al., 2012), and forehand squash (Wilkinson et al., 2009) showed that the expansion of movement space in the upper extremity contributed significantly to the velocity and acceleration of body segment movements with subsequent influence on the maximum ball velocity. Moreover, the movement of palmar flexion at wrist joint or wrist snap was observed to have a 20% contribution to shuttlecock velocity while the movement of forearm pronation supination had 10% (Gawin et al., 2017). Shoulder joint movements, especially during the maximal external rotation followed by internal shoulder rotation to the follow-through movement, were also discovered to be the major factors affecting the velocity of the ball during tennis serve movement as indicated by their over 40% contribution (Gordon, 2006). Therefore, this study was conducted to analyze the effect of fatigue on the changes in the kinematic variable movement during overhead jump smash in badminton.

Materials and Methods

Participants

This study was conducted by selecting 15 male badminton athletes with overhead jumping smash technique (19.4 ± 1.6 years of age, height of 1.73 ± 0.12m, and weight of 60.8 ± 3.7kg) as participants through the purposive sampling approach. All the participants were discovered to have had over 8 years of experience playing badminton. Moreover, a descriptive quantitative method with pre-test and post-test design was adopted and the participants were fully informed about the protocol before participating in this study. They were also required to provide informed consent before the tests were applied. Furthermore, the study was conducted in line with the recommendations of the ethics research committee of the Faculty of Sport and Health Education, Universitas Pendidikan Indonesia.

Instruments

The instruments used include two high-resolution handy-cams (Sony HXR-MC2500, Japan), a unit of high-speed camera (FASTEC Imaging TS5-H, USA), 14-point manual markers, a set of 3-dimension calibration, a motion analysis software (Frame DIAZ IV, Japan), COSMED direct gas analyzer Fitmate MED (COSMED srl-Italy), a heart rate sensor (Polar H10, Finland), fly power shuttlecock shooting machine (BGH 800, Indonesia), and a speed radar gun (Bushnell 101922, Germany).

Procedures

Camera 1 was placed perpendicularly on the top subject area with 5m of distance to record the shoulder and hip joint movement during the jump smash. Meanwhile, Camera 2 was placed on the right side of the subject area and Camera 3 was placed perpendicularly behind the subject area with the aim to obtain a comprehensive depiction of the whole upper body joint movements and the result of the jumping smash. A shuttlecock shooting machine launcher was located perpendicularly in the opposite area of the subject area to capture a more stable, accurate, and speed of the shuttlecock as presented in Figure 1.

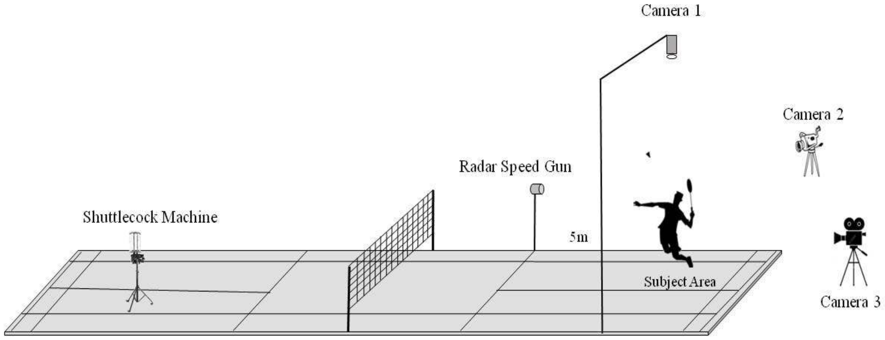


Figure 1. The scheme of the data collection process

The participants were instructed to do a general warm-up for 15 min followed by a 3-minute rest, and then a jump smash to hit the shuttlecock as fast as possible towards the court area of the opponent. The shuttlecock velocities were measured using a radar gun Bushnell 101922, Germany in km/h followed by the calculation of the mean value for 6 hits.

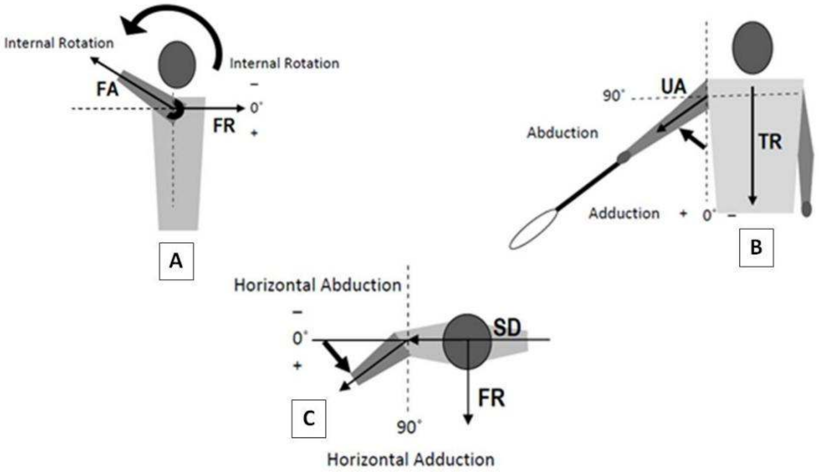
All the participants were also required to perform a fatigue test on a treadmill after being equipped with a heart rate monitoring system (Polar H10 Polar Electro OY, Finland). The treadmill speed was set at 8 $km \cdot h^{-1}$ for the warm-up session and later increased to 10 $km \cdot h^{-1}$ followed by a 2 $km \cdot h^{-1}$ increment every 3 min with a continuous straight line running until the participants were exhausted. They were subsequently asked to be hitting the shuttlecock continuously for 6 times as fast as possible and this was followed by the calculation of the mean velocity value in km/h.

Statistical Analysis

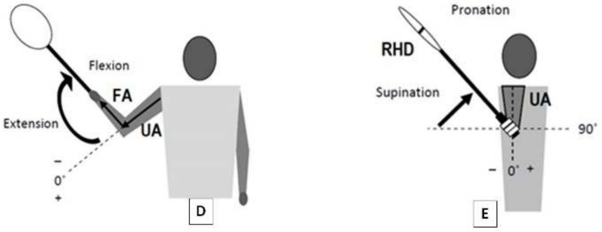
SPSS program version 21.0 for Windows was used for the data analysis with a focus on descriptive statistics (mean ± SD). A paired sample t-test was also applied to identify the differences between pre-fatigue and fatigue conditions in terms of maximal shuttlecock velocity during jump smash at a 95% degree of confidence. Moreover, position-time data were filtered using a fourth-order Butterworth low-pass filter with a cutoff frequency of 13.5 Hz.

Kinematic Parameter Definition

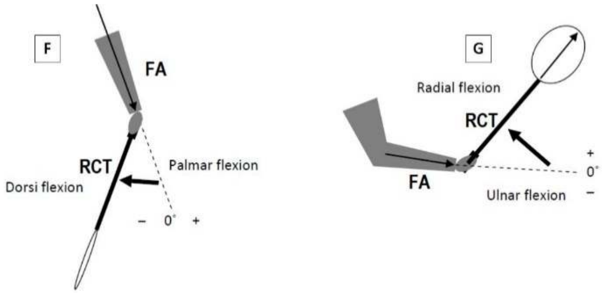
The characteristics of the jumping smash mechanism were determined using models considered relevant to the principles of movement anatomy. For example, the shoulder joints had internal-external rotation (A), abduction-adduction (B), and horizontal abduction-adduction (C) as presented in Figure 2.



The elbow joints had two characteristics of movement including elbow flexion-extension (D) and forearm pronation-supination (E).



The wrist joints were associated with two characteristics of movement including palmar-dorsi flexion (F) and radial-ulnar flexion (G).



The next movement was upper torso rotation and pelvis rotation (H), trunk tilts forward and trunk tilts backward (I), and trunk tilt left and right sideways (J).

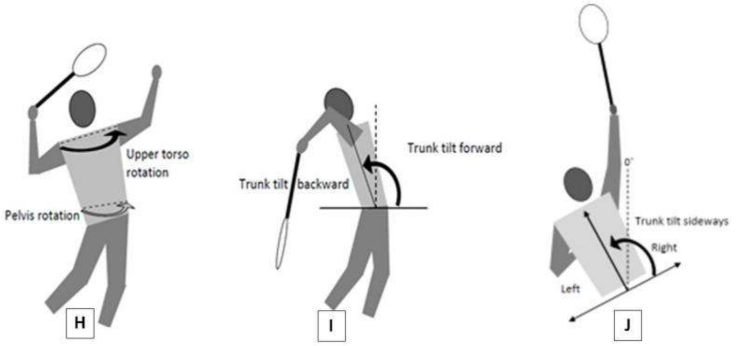


Figure 2. The kinematic of motion parameters for the upper body joints (Rusdiana et al, 2016)

Results

The results related to the difference between the shuttlecock velocity and the changes in kinematic motion under fatigue and non-fatigue conditions during overhead jumping smash in badminton are presented in this section.

Table 1. Kinematic parameters during maximal shoulder external rotation phase

Kinematic Parameter Analysis	Means ± SD	
	Fatigue	Non Fatigue
*Shuttlecock velocity (km/h)**	145 ± 5.7	188 ± 3.5
Jump height (cm)	43 ± 6.8	46 ± 5.1
*Shoulder external rotation (deg)**	-162 ± 3.5	-134 ± 4.2
Shoulder abduction (deg)	101 ± 1.2	106 ± 1.4
Shoulder horizontal adduction (deg)	7 ± 0.83	9 ± 0.96
Elbow flexion (deg)	94 ± 1.1	102 ± 1.3
Forearm pronation (deg)	14 ± 1.1	1 ± 1.3
*Wrist palmar flexion (deg)**	-21 ± 2.1	-47 ± 2.4
Trunk tilt backward (deg)	21 ± 3.5	24 ± 3.1
Trunk tilt sideways left (deg)	19 ± 1.4	21 ± 1.6

** Significance of difference at level 0.05*

Table 1 shows that three out of the ten kinematic parameters during the maximal shoulder external rotation phase were significantly different for the fatigue and non-fatigue conditions. The parameters include the shuttlecock velocity (p= 0.035), angle of shoulder external rotation (p= 0.048), and wrist palmar flexion (p= 0.037).

Table 2. Kinematic parameters in the maximum angular velocity

Kinematic Parameter Analysis	Means ± SD	
	Fatigue	Non Fatigue
*Shoulder internal rotation (deg/s)**	1623 ± 3.5	2111 ± 4.2
Upper torso rotation (deg/s)	761 ± 1.2	782 ± 1.4
Pelvis rotation (deg/s)	421 ± 0.83	429 ± 0.96
*Elbow extension (deg/s)**	776 ± 1.1	985 ± 1.3
*Forearm supination (deg/s)**	442 ± 1.1	694 ± 1.3
*Wrist dorsi flexion (deg/s)**	413 ± 2.1	855 ± 2.4
Trunk tilt forward (deg/s)	185 ± 3.5	199 ± 3.1

** Significance of difference at level 0.05*

Table 2 shows that four out of the ten kinematic parameters during the maximal angular velocity phase were significantly different for the fatigue and non-fatigue conditions. These parameters were the shoulder internal rotation (p= 0.042), elbow extension (p= 0.035), forearm supination (p= 0.024), and wrist dorsi flexion (p= 0.040).

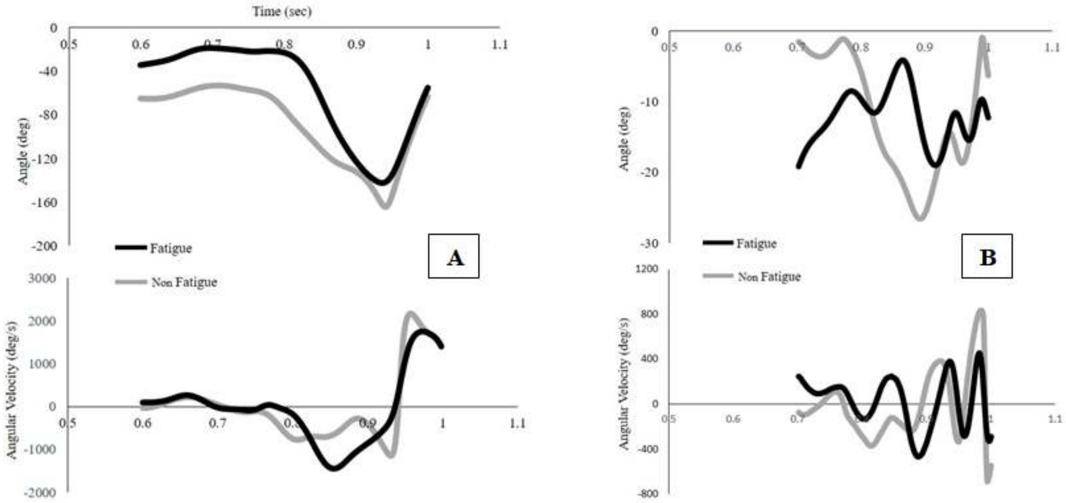


Figure 3. The maximum change of angle and angular velocity of the shoulder internal rotation (A) and the change of angle and angular velocity of the forearm pronation supination angular velocity (B).

Figure 3 shows the existence of a significant difference in the change of the angle of shoulder external rotation (-162° vs -134°) and the internal shoulder angular velocity (1623°/s vs 2111°/s) between fatigue and non-fatigue conditions. A similar trend was also observed for the change in the angular velocity of forearm pronation (14° vs 1°) and forearm supination (442°/s vs 694°/s).

Table 3. Kinematic parameters during the shuttlecock release

Kinematic Parameter Analysis	Means ± SD	
	Fatigue	Non Fatigue
Shoulder abduction (deg)	23 ± 3.5	27 ± 4.2
*Shoulder horizontal abduction (deg)**	14 ± 1.2	37 ± 1.4
Elbow extension (deg)	78 ± 1.1	81 ± 1.3
Wrist palmar flexion (deg)	5 ± 1.1	8 ± 1.2
Trunk tilt forward right (deg)	17 ± 3.5	21 ± 3.1

* *Significance of difference at level 0.05*

Table 3 shows that only one out of five kinematic parameters, shoulder horizontal abduction, had a significant difference between fatigue and non-fatigue conditions during the shuttlecock release phase.

Discussion and Conclusions

Badminton is a sport that requires a lot of overhead shoulder movement including abduction and external rotation and generally proximal-to-distal sequence. An effective smash has been identified to be very important in gaining points to win a game compared to other several strokes. This is due to its ability to score directly or cause the opponent to be in a passive defense. Smash also has better efficacy than any other technique in badminton attack because it (1) scores directly, (2) creates a favorable opportunity to score, (3) inhibits the attack from an opponent, and (4) transforms defense to offense. Meanwhile, the quality of a smash can be influenced by some practical and relevant parameters such as positioning, stance, striking height, grip as well as racquet angle, string tension, and swing speed. This means there is a need for biomechanical principles to improve the performance of the smash and shuttle velocity to increase the range of motion of joint actions to allow greater acceleration and better usage of muscular force, proximal-to-distal sequencing, and stretch-shortening cycle.

The results showed that the shuttlecock velocity was faster during the pre-fatigue at 188 km/h compared to under fatigue conditions at 145 km/h. This was observed to be similar to the findings of Alberto Nuno et al. (2016) that the speed of the ball reduced after the application of circuit training in the throw of handball as the intervention. It was also in line with the observation of Ferraz et al. (2012) that used a specific circuit for five times to provoke fatigue in soccer. Moreover, several factors were identified to be slowing the speed of the shuttlecock down during jump smash made with a reduction at the body segment rotation, and these include shoulder internal angular velocity, elbow extension, forearm supination, and wrist dorsi flexion during maximal shoulder external rotation phase. It was discovered that the series of movement patterns for the overhead jump smash required both linear and angular velocity and acceleration of the body movement, shuttlecock, and racket swing. Some previous studies explained that certain movements were related to the forehand overhead stroke technique, especially the jumping smash. However, Brian J.G. (2006) concluded that a maximum shoulder external rotation was the initial moment to produce a higher velocity in the shoulder internal rotation and later in the ball during the process of analyzing the contribution of the angular velocity of upper body joints in tennis serve (Gawin et al., 2017). A similar observation was made by Agus et al. (2015) that internal shoulder rotation had the largest contribution (up to 66%) to shuttlecock velocity or racket-head speed in the badminton smash or tennis serve. Furthermore, the results of this research showed that a lot of overhead shoulder movement was required, especially the abduction and external rotation as well as the proximal-to-distal sequence. Gowitzke and Waddell (2000) published a biomechanical study of the badminton strokes of players of international standing and reported that the extension movement of the elbow almost ceased before impact in the forehand smash. A similar trend was also reported by Seki et al. (2014) that elbow extension ended before impact. It was originally thought that much of the power of the badminton smash was generated through what was termed the 'wrist snap' or palmar flexion. The majority of the early research emphasized the importance of shoulder internal rotation and radio-ulnar pronation but dismissed the contribution of palmar flexion.

The results were also relevant to the discovery of Gordon (2006) during the analysis of tennis serve that elbow joints contributed to the velocity of the ball. In the elbow extension movement, faster rotation was observed to have led to a stronger push from the upper arm and forward swing of the racket before hitting the shuttlecock. It was stated that the flexion and extension movements on the elbow joints contributed approximately 30% to the velocity of the racket swing. Moreover, the angular velocity of the pronation-supination elbow joints was also reported to be important to the racket swing velocity (Gordon, 2006). The movement of these joints, especially the angular velocity of the lower arm supination, before the impact with the shuttlecock, contributed significantly to the velocity of the shuttlecock and racket (Gawin et al., 2017). This was observed to be clearer among players possessing high skills related to this technique. Therefore, it was expected that a professional player would produce a much higher shuttlecock velocity than the junior ones.

In conclusion, the results showed that the shuttlecock velocity produced from a jumping smash in a non-fatigue condition was higher than the fatigue condition. This was associated with the fatigue experienced after a strong and long muscle contraction which affected the sustenance of the muscles. The fatigue in this case was discovered to be close to the real physiological definition as the decrease of response to the coming stimulation. This was observed from the fact that it was difficult for the players to control the direction of the shuttlecock. Moreover, the internal shoulder rotation, wrist palmar flexion, and forearm supination reduced in the fatigue condition and this led to a decrease in the velocity of the shuttlecock during the overhead jumping smash in badminton compared to the non-fatigue condition.

Acknowledgments

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