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COMPARATIVE STUDY OF VELOCITY REDUCTION ON FEATHER AND SYNTHETIC SHUTTLECOCKS USING CORRECTED INITIAL VELOCITY DURING OVERHEAD SMASH

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Abstract

Overhead smash in badminton is a complex condition where high velocity is taking place. Most of the investigations at this overhead smash may find difficulty in finding the initial velocity (after impact) of a shuttlecock. In this study, the flight performance of three shuttlecock models namely Feather Yonex, Nylon Mizuho, and Nylon Gozen was investigated during overhead smash. Additional comparison between standing and jumping smashes was also investigated. Corrected initial velocity by using regression equation method was performed and the reduction of velocity at certain distances was investigated. The record of racquet swing and shuttlecock flight after impact from high speed camera were observed. The shuttlecock release point was drawn in the X-Y coordinate in a linear form. The equation for the racquet swing was Y = a1 X + b1 and the path for shuttlecock was ($Y = a^2.X + b^2$). It was found that Nylon Mizuno had the lowest initial velocity, while Feather Yoned and Nylon Gozen had similar value. After traveling for 5 meters, the velocity of both standing and jumping smashes reduced into 30-40% of the initial velocity. Furthermore, the investigation between standing and jumping smashes showed that the initial velocity of jumping is higher than that of standing smash. Thus, jumping smash can be considered as the main weapon when playing badminton.

Keywords: Initial velocity, Shuttlecock, Overhead smash, Badminton, Regression.

1. Introduction

Badminton is one of the most popular and oldest sports on earth. It is reported that over 200 million people played badminton around the world [1]. Badminton game is a racquet sport played with a feather shuttlecock. The shuttlecock is aerodynamically shaped and has low mass, thus it decelerates very quickly as it flies in the air due to the drag force of the air [2]. Some shuttlecocks are made of natural feather and some others are made of synthetic rubber. Generally, both types of shuttlecocks have a mass around 4.75 – 5.50 grams, diameter of the cork is 25 – 28 mm and the diameter of the circle is around 54 mm [1]. Most amateur players use a synthetic shuttlecock because it is more durable and cheaper compared to feather shuttlecock which is predominantly used by professional players. The flight trajectory of the feather and synthetic shuttlecocks are significantly different from the balls utilized in most racquet sports due to very high initial speed [3,4].

For years researchers have studied the nature of a shuttlecock regarding its trajectory, material, rotation, etc. Several studies had been conducted to investigate the parabolic trajectory of shuttlecock [1,5]. A study at different Reynolds number (Re) shows low drag coefficient for shuttlecock without a gap in comparison to the one with gap [6]. Comparison between natural feather and synthetic shuttlecocks shows lower drag force for natural feather when tested in wind tunnel [1,3,5,7-9]; however, one should keep in mind that calculation of drag force, theoretically, is highly affected by initial velocity (after impact). Thus, initial velocity should be observed carefully to obtain the correct number of drag force.

Among the badminton skills, the overhead smash stroke is the most powerful shot and complex because of its speed and steep trajectory [10]. The speed of shuttlecock decreases significantly due to drag force that is highly influenced influenced by initial velocity [2]. Several methods have been used to measure traveling speed such as radar gun and the high-speed camera. However, both methods cannot measure initial velocity. Radar gun required highly capable operator so it can be used effectively. The radar gun also cannot differ between targets (racquet and shuttlecock), thus operator plays an important role [11]. And most importantly, the radar gun is measuring instantaneous speed rather than initial speed. On the other hand, the high speed camera is commonly-used for higher specs. And speed calculation using high-speed camera is most likely to produce average or instantaneous because of the difficulty of obtaining figure exactly when impact between racquet and shuttlecock occur [8]. The position of shuttlecock when it just releases from the net of a racquet is really hard to decide. In addition, low picture quality and insufficient sampling frequency are among the list of the problems[10]. Fortunately, for real case (not in the wind tunnel), most of the studies investigated in the area of low velocity of shuttlecock like a drop shot, so inaccuracy of initial speed can be negligible.

Since understanding in the area of a high-speed situation during overhead smash is limited, the main objective of this work is a comparative analysis of velocity reduction of natural feather and synthetic using a regression equation to obtain initial velocity. In addition, comparison of the initial velocity of standing and jumping smashes on feather shuttlecock was given.

This study is important since there have not been scientific references of shuttlecock speed release using physics analysis. There are actually several studies on speed release using machines merely; however, in the real life, there is actually difference especially due to the impact of racquets used. Besides, the selection of three different racquets is due to their materials.

2. Method

2.1. Procedure

The participant was a right-handed university badminton player, 20 years old, 1.72m height and had a mass of 60 kg. After a general and a specific badminton warm-up, the subject was asked to hit eight shuttlecocks with the maximal speed smash shot. The shuttlecock trajectory was recorded using a high-speed video camera (Phantom Miro-eX2, USA) set at 200 frames/sec and 1/2000 exposure time. A camera was positioned at right-center side of badminton court so that the optical axis of the camera lens was almost perpendicular to center of the net position with approximately horizontal distance 22m. Fig. 1 shows top view schematic of badminton experiment set-up. The cork of shuttlecock was digitized using Frame DIAZ IV software analysis.

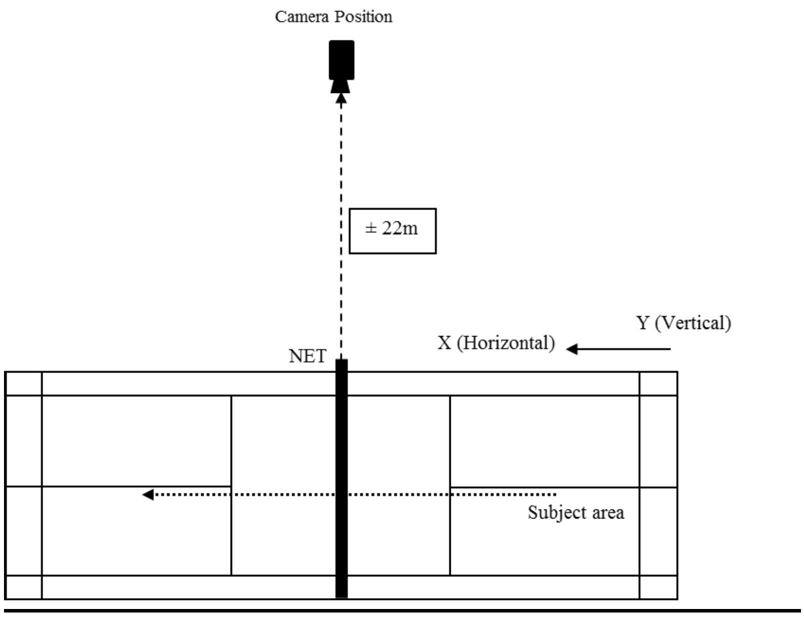

Fig. 1. Top view schematic of badminton experiment set-up.

2.2. Shuttlecocks description

The shuttlecocks were selected for this study, namely the natural feather (Feather Yonex) and synthetics shuttlecocks (Nylon-Mizuno and Nylon-Gozen), see Fig. 2. Generally, all types of shuttlecocks have a mass around 4.7-5.5 grams. Table 1 Show the dimension of the feather and synthetic shuttlecocks in detail.

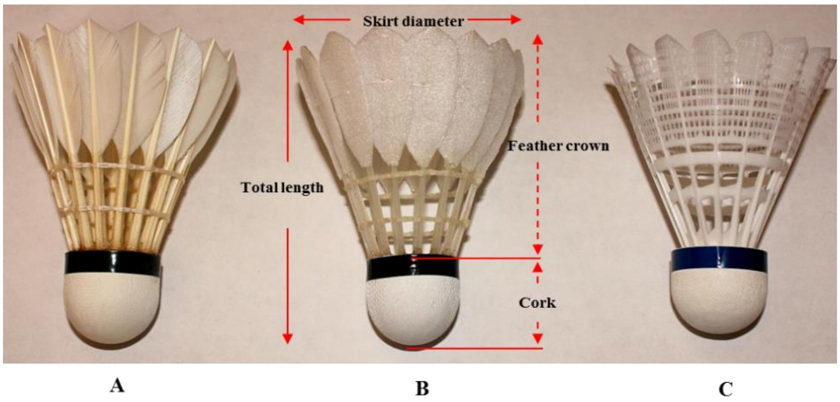

Fig. 2. (A) The natural feather, (B) nylon- mizuno, and (C) nylon-gozen shuttlecock images.

Table 1. Dimensional of the natural feather and synthetic shuttlecocks.

Shuttlecock Characteristics	Shuttlecock Models		
	Feather-Yonex	Nylon-Gozen	Nylon-Mizuno
Skirt diameter, *d* (mm)	66	66	66
Length of shuttlecock, *H* (mm)	89	82	87
Cork diameter, *dn* (mm)	26.5	26.5	26.5
Length of cork, *I* (mm)	5.0	5.0	5.0
Mass, *m* (gram)	26	22	24

2.3. Developments of calculation method

There were several stages to determine shuttlecock initial speed by using a regression equation approach. First, identify the impact position between racquets and shuttlecocks. Second, draw several velocities at several positions after the impact by simply using frame based calculation, then generate regression equation. Finally, inserting the information of position into regression equation.

Figure 2 shows an athlete conducting overhead swing in four frames (50 ms per frame). The impact between racquet and shuttlecock occurred somewhere between frame 3 and 4. This also confirmed the difficulty in capturing exact position of the impact. Figure 3 shows the racquet swing and a shuttlecock flight 5 frames after shuttle release. The black box mark was shuttlecock release point. The continues-straight line and discontinuous arrow line were the racquet swing and a shuttlecock flight analysis, respectively (the first to second phases or two frames after impact). The shuttlecock release point coordinate (X, Y) determined by a cross line interaction between the racquet swing ($X = a_1 \dot{} X + b_1$) and a shuttlecock path ($Y = a_2.X + b_2$) after impact were analyzed by regression equation approach (Fig. 5).

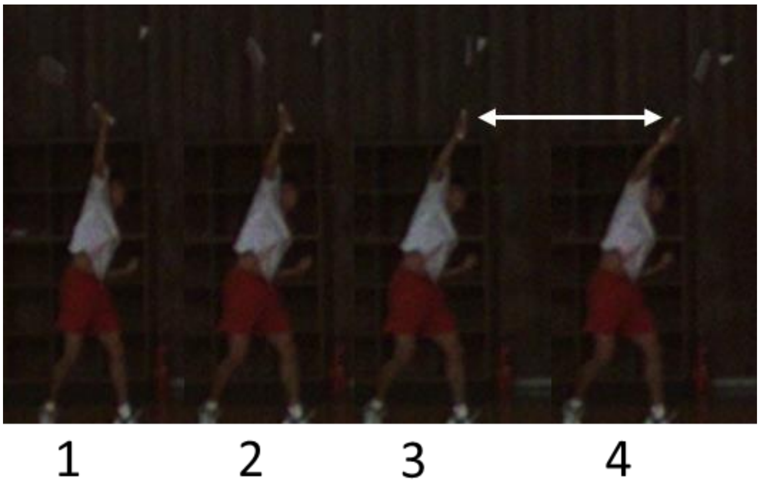

Fig. 3. Racquet head swing and a shuttlecock before and after at impact set-up speed of camera 200 fps and 1/2000 shutter speed (1-4), between the number 3 and 4 occurred the shuttlecock impact in the smash shot.

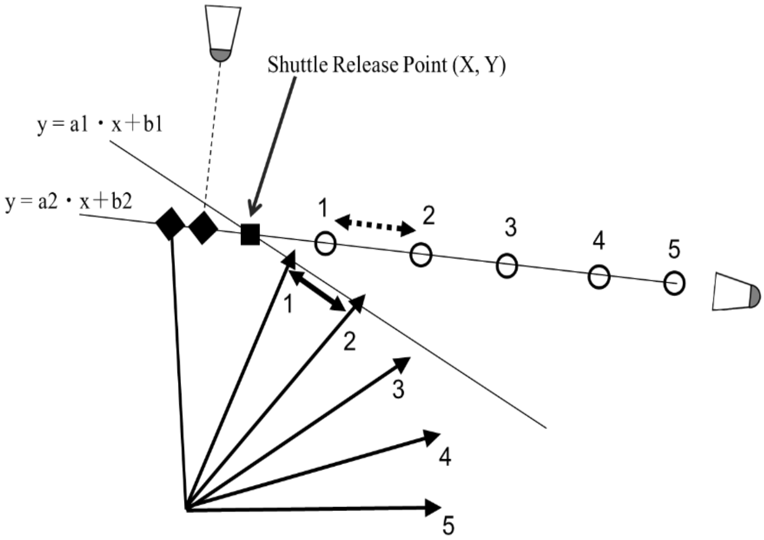

Fig. 4. Racquet swing and a shuttlecock flight before and after impact by the stick picture image.

From the first to fifth phases were the racquet and a shuttlecock around 2m distance from the impact. The black box mark was shuttlecock release point. The straight and discontinuous lines were the racquet swing and a shuttlecock flight analysis, respectively.

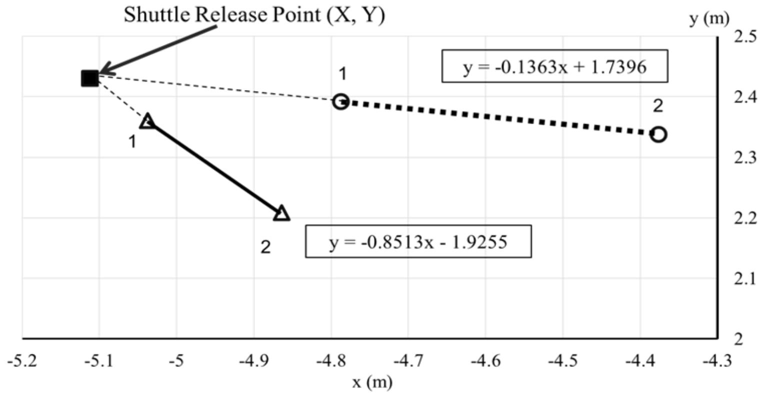

Fig. 5. The straight and discontinuous lines showed the racquet swing and a shuttlecock flight after shuttlecock release (the first and second phases, respectively).

From the description of the Fig. 5, assisted by the statistical method least-squares method approach, it will get the equation of a straight solid line for shuttlecock and dashed line racquet as follows:

$$y_1 = (a_1)x_1 + (b_1) \tag{1}$$

$$y_2 = (a_2)x_2 + (b_2) \tag{2}$$

Number 1 is a representation of the position of the shuttlecock and the number 2 is a position of the racquet. The position of the object - 1 (shuttlecock) can be expressed mathematically as follows:

$$x_1(t) = -\frac{1}{2} a_{1x} t^2 + v_{1x} t + x_1(0) \tag{3}$$

$$y_1(t) = -\frac{1}{2} a_{1y} t^2 + v_{1y} t + y_1(0) \tag{4}$$

The position of the object - 2 (racquet) can be expressed mathematically as follows:

$$x_2(t) = -\frac{1}{2} a_{2x} t^2 + v_{2x} t + x_2(0) \tag{5}$$

$$y_2(t) = -\frac{1}{2} a_{2y} t^2 + v_{2y} t + y_2(0) \tag{6}$$

The impact of the racquet and shuttlecock is assumed to be at t = 0 s, assuming the acceleration of each object is zero, then the above equation will change to:

$$x_1(t) = v_{1x} t + x_1(0) \tag{7}$$

$$y_1(t) = v_{1y} t + y_1(0) \tag{8}$$

$$x_2(t) = v_{2x}\, t + x_2(0) \tag{9}$$

$$y_2(t) = v_{2y}\, t + y_2(0) \tag{10}$$

Substituting t between equations 7 and 8 as well as for the equations 9 and 10, then the equations transform into:

$$y_1(t) = \left(\frac{v_{1y}}{v_{1x}}\right) x_1(t) + \left(y_1(0) - x_1(0)\left(\frac{v_{1y}}{v_{1x}}\right)\right) \tag{11}$$

$$y_2(t) = \left(\frac{v_{2y}}{v_{2x}}\right) x_2(t) + \left(y_2(0) - x_2(0)\left(\frac{v_{2y}}{v_{2x}}\right)\right) \tag{12}$$

By using position data of racquet and shuttlecock at some time, t, then the value will be m_1, b_1, m_2, and b_2, where m is gradient while b is a cross line at the y-axis. Equation of straight line will be obtained, as in Fig. 4. By finding the point of intersection of two lines, we can obtain the point of intersection of the two lines, which the point of impact between the racquet and shuttlecock. Point $P(x_1(0), y_1(0))$ are the same point with $P(x_2(0), y_2(0))$. This situation causes both objects, racquet and shuttlecock, to be at the same point at $t = 0$ s is the point P. Because

$$x_1(0) = x_2(0) = x(0) \;\; ; \;\; y_1(0) = y_2(0) = y(0) \tag{13}$$

$$a_1 = \left(\frac{v_{1y}}{v_{1x}}\right) \; ; \; a_2 = \left(\frac{v_{2y}}{v_{2x}}\right)$$

$$b_1 = \left(y(0) - x(0)\left(\frac{v_{1y}}{v_{1x}}\right)\right) \; ; \; b_2 = \left(y(0) - x(0)\left(\frac{v_{2y}}{v_{2x}}\right)\right) \tag{14}$$

We will get 4 equations with 4 unknown parameters, namely:

$$\boldsymbol{V_{1x}, V_{1y}, V_{2x}, and\ V_{2y}} \tag{15}$$

The four parameters will be obtained. Then, the velocity of the racquet and shuttlecock at $t = 0$ s at the point P can be known.

The next analysis was a regression equation using second-order polynomial functions from the first to fifth phases or 5 frames after impact between X horizontal axis (m) and shuttle velocity (m/s) after shuttlecock release as shown in Fig. 6.

Finally, the initial velocity of shuttlecock determined by X-axis value of release point coordinate and the coefficient of the second order of the regression equation between shuttlecock velocity (m/s) and X axis (m).

All the calculation were applied to three models of shuttlecock, then the results will be compared. Evaluation was conducted after 5 and 9 m traveling distance. Racquet initial velocity also will be evaluated.

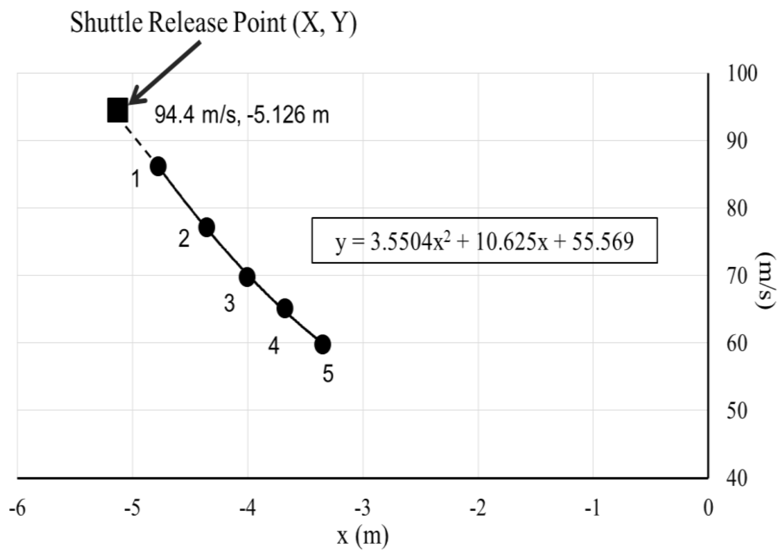

Fig. 6. The regression equation using second order polynomial functions to determine the initial shuttle speed (0 m was the net line).

3. Results

3.1. Standing Smash after 5 m traveling distance

Table 2 until Table 4 show initial and final velocities of feather, Nylon Mizuno, and Nylon Gozen, respectively, at 5 m traveling distance from the overhead smash position. All data obtained from 8 times trial using different types of shuttlecocks. Table 2 shows that average initial velocity, i.e. using regression equation method, of feather shuttlecock was about 86.1 m/s. one the other hand, the average final velocity was 29.8 m/s, it is about 34.7 % of initial velocity. Table 3 shows a value of 79.9 m/s for average initial velocity and 25.5 m/s for final velocity. Meaning that the final velocity was 31.8% of initial velocity. The initial velocity of nylon gozen was about 85.9 m/s, see Table 4.

Figure 7 shows the comparison of shuttlecocks' initial velocities of feather, nylon Mizuno, and nylon Gozen. It can be seen that Nylon-Mizuno has the lowest initial velocity, while feather and Nylon-Gozen have similar value. Figure 8 shows the final velocity of all shuttlecocks. The Nylon-Mizuno has the lowest value, while the nylon gozen has the highest value. These results show that drag force affected the nylon Mizuno the most. And the nylon gozen was less affected by drag force of air.

Table 1. Means of initial speed (m/s), final speed (m/s) and speed reduction (%) of feather shuttlecock (5 m distance).

No	Distance (m)	Initial velocity (m/s)	Final velocity (m/s)	%
1	5	93.6	30.1	32.2
2	5	92.9	33.3	35.8
3	5	83	26.5	31.9
4	5	88.9	33.2	37.3
5	5	78	27.8	35.6
6	5	87.2	31.2	35.8
7	5	75.2	27.6	36.7
8	5	89.6	28.9	32.3
Average	**5**	**86.1**	**29.8**	**34.7**

Table 2. Means of initial speed (m/s), final speed (m/s) and speed reduction (%) of Nylon Mizuno (5 m distance).

No	Distance (m)	Initial velocity (m/s)	Final velocity (m/s)	%
1	5	79.7	25.8	28.8
2	5	62.4	22.2	35.6
3	5	95.8	28.8	30.1
4	5	79.6	22.1	27.8
5	5	76.2	26.1	34.3
6	5	72.4	27.1	37.4
7	5	81.8	27.2	33.3
8	5	91.3	24.7	27.1
Average	**5**	**79.9**	**25.5**	**31.8**

Table 3. Means of initial speed (m/s), final speed (m/s) and speed reduction (%) of Nylon gozen (5 m distance).

No	Distance (m)	Initial velocity (m/s)	Final velocity (m/s)	%
1	5	84.9	34.9	41.1
2	5	91.9	36.6	39.8
3	5	75.3	34.2	45.4
4	5	88.5	36	40.7
5	5	82.7	33.2	40.1
6	5	87.1	36.8	42.3
7	5	92.4	34.1	36.9
8	5	84.6	35.7	42.2
Average	**5**	**85.9**	**35.2**	**41**

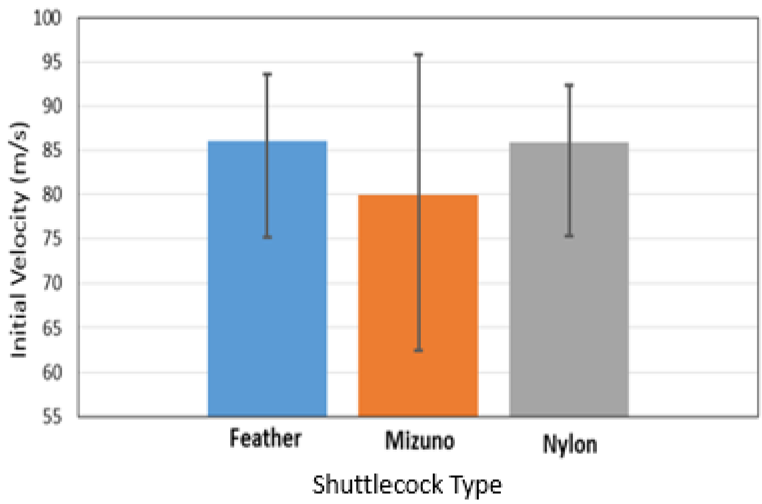

Fig. 7. Initial velocity comparison of feather, Mizuno and Nylon-Gozen.

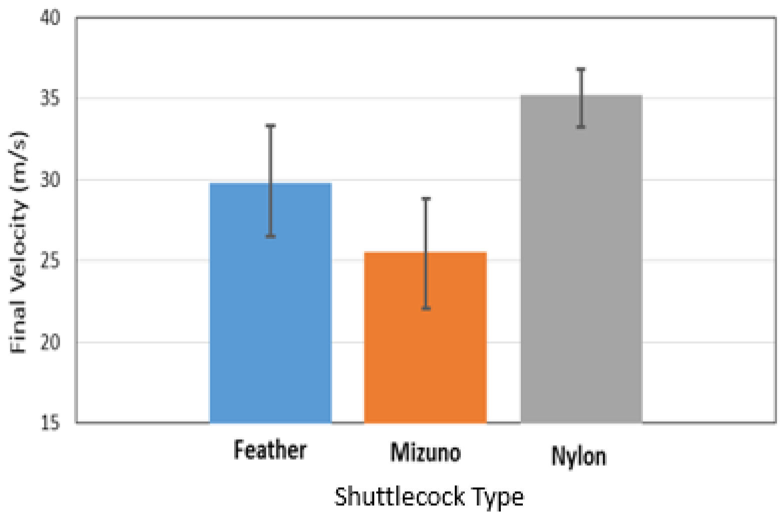

Fig. 8. Final velocity comparison of feather, Mizuno and Nylon-Gozen.

3.2. Jumping smash after 9 m traveling distance

Tables 5-7 show initial and final velocities of feather, Nylon Mizuno, and Nylon Gozen, respectively, for 9 m distance. All data obtained from 8 times trial using different types of shuttlecocks. Table 5 shows that average initial velocity, i.e. using regression equation method, of feather shuttlecock was about 86.1 m/s. One the other hand, the average final velocity was 29.8 m/s, it is about 34.7 % of initial velocity. Table 6 shows value of 79.9 m/s for average initial velocity, while value of 25.5 m/s for final velocity. And this means that the final velocity was

31.8% of initial velocity. The initial velocity of nylon gozen was about 85.9 m/s, see Table 7.

Table 4. Means of initial speed (m/s), final speed (m/s) and speed reduction (%) of feather shuttlecock (9 m distance).

No	Distance (m)	Initial velocity (m/s)	Final velocity (m/s)	%
1	9	93.6	11.8	12.6
2	9	92.9	12.4	13.3
3	9	83	10.7	12.9
4	9	88.9	13.6	15.3
5	9	78	11.8	15.1
6	9	87.2	11.8	15.1
7	9	75.2	11.1	12.7
8	9	89.6	11.4	15.2
Average	**9**	**86.1**	**11.8**	**14**

Table 5. Means of initial speed (m/s), final speed (m/s) and speed reduction (%) of Nylon Mizuno (9 m distance).

No	Distance (m)	Initial velocity (m/s)	Final velocity (m/s)	%
2	9	62.4	8.2	13.1
3	9	95.8	10	10.4
4	9	79.6	8.8	11.1
5	9	76.2	10.2	13.4
6	9	72.4	11.1	15.3
7	9	81.8	9.3	11.4
8	9	91.3	10.2	11.2
Average	**9**	**79.9**	**9.7**	**12.1**

Table 6 Means of initial speed (m/s), final speed (m/s) and speed reduction (%) of Nylon gozen (9 m distance).

No	Distance (m)	Initial velocity (m/s)	Final velocity (m/s)	%
1	9	84.9	15.2	17.9
2	9	91.9	15.4	16.8
3	9	75.3	14.1	18.7
4	9	88.5	15.4	17.4
5	9	82.7	13.3	16.1
6	9	87.1	14.5	16.6
7	9	92.4	14.4	15.6
8	9	84.6	14.3	16.9
Average	**9**	**85.9**	**14.6**	**17**

Figure 9 shows final velocity of all shuttlecocks after 9 m traveling. Overall, it has similar trend with result for 5 m (Fig. 8). However, after 9 m traveling the value reduce about 40% of velocity after 5 m.

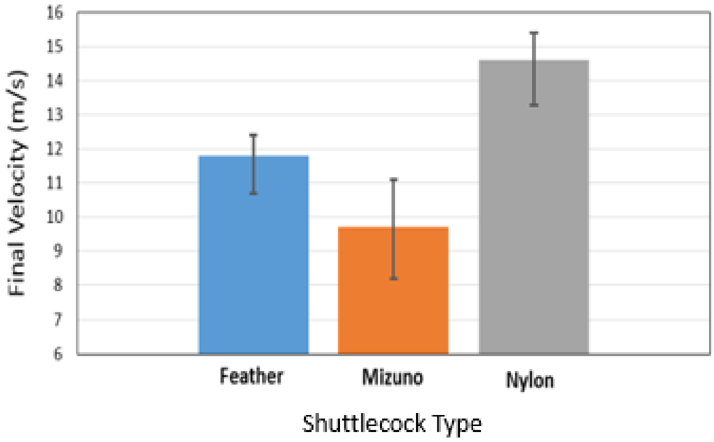

Fig. 8. Final velocity comparison of feather, nylon Mizuno, and Nylon-Goze.

3.3. Standing vs. Jumping smash velocity (feather)

Figure 10 shows comparison of velocity profile between standing and jumping smashes using feather shuttlecock. It can be seen that initial velocity of jumping smash is slightly higher than standing smash. After traveling for 5 m and 9 m, standing smash shows slightly higher than jumping smash. From the graph, it can be seen that velocity reduction was not linear. This is predictable since formulation of drag force utilizes quadratic velocity.

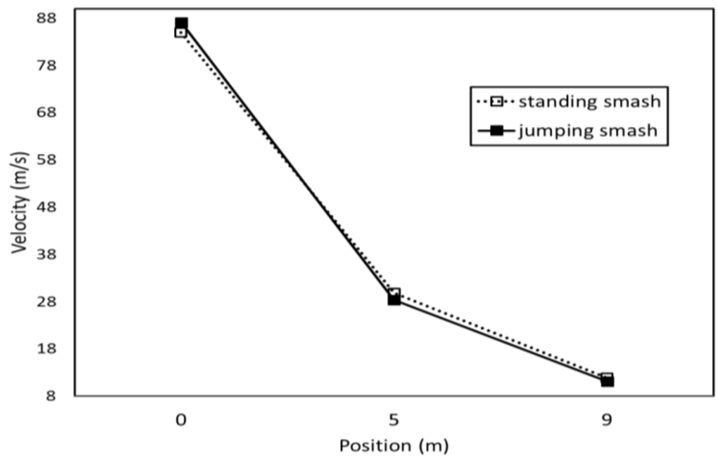

Fig. 9. Comparison of velocity profile between standing and jumping smashes.

3.4. Racquet velocity comparison

Table 12 shows comparison of racquet velocity after impact with shuttlecocks by standing smash. Roughly, the comparison shows slight different among all velocities. However, velocity after impact with feather has the lowest average velocity, while nylon mizuno has the highest velocity. Jumping smash on feather shows increase of racquet velocity in comparison with standing smash.

Table 7. Comparison of racquet velocity right after the impact with particular shuttlecocks.

Shuttle	Feather	Nylon mizuno	Nylon gozen	Jumping smash
Average (m/s)	54.7	56.1	55.4	55.9

4. Discussion

The present investigation has developed a regression approach – based calculation for obtaining initial velocity during overhead smash. This approach enabled the determination of racquet-shuttlecock impact position and initial velocity for overhead smash whilst overcoming the difficulties present by other technology. Most previous studies investigate the trajectory of shuttlecock during drop shot where velocity is not so high [12,13]. McErlain-Naylor et al developed method using curve fitting method which is close to our method [14]. However, in this method, it was assumed that several positions at the beginning, just after impact, was still flight in straight path [15].

The result of initial velocity (Fig. 7) revealed that after impact feather shuttlecock had high initial velocity together with nylon gozen (small difference). This result may strongly related to material of shuttlecock's head. Theoretically, parameters that may affect initial velocity are mass, shooting power, restitution constant of the material. Since all of the tested shuttlecocks had the same mass then this reason should be omitted. Thus, the material of the head had a high possibility of affecting its initial velocity. To elaborate more regarding this reason, further investigation should be conducted. Typical viscoelastic impact characterisation may appropriate for testing [16]. Since the test conducted using the same racquet for every trial, thus effect of restitution of net of the racquet can be eliminated.

The final velocity of shuttlecock after 5 and 9 m seems to be following negative exponential pattern. It was theoretically accepted since reduction of velocity is most likely due to drag force, which is affected by quadrat velocity. On the other hand, difference of percentage among shuttlecock may be due stiffness of the material. After the impact, shuttlecock will be in opposite direction with vector velocity, after then it will rotate and have the same direction with velocity. During this process, due to air resistance, shuttlecock will be deformed a little bit, i.e. get wider, as consequence drag force will increase sharply. Material with high deformation (bigger dimension) will experience higher drag force. According to the result, it seems that nylon mizuno has the highest deformation. And the least deformation exhibit by nylon gozen or in other word this material had high stiffness level. However, further investigation is needed to confirm this hypothesis. Investigation on velocity before shuttlecock rotate and pointing to the same direction as velocity vector.

Comparison between standing and jumping smashes using the feather as shown in Fig. 10 shows quite similar pattern and value. In another word, an only small difference occurs for both mechanisms. However, in detailed observation, jumping smash exhibits higher initial velocity than standing position.

After the impact racquet velocity comparison shows small discrepancy among all values. This shows that racquet velocity was less affected by the type of shuttlecock. This might be due to the reality that the racquet that connected to human body had much higher moment inertia.

The method being used to calculate initial velocity was very useful to overcome difficulty of complex (skill demanding) method and high cost method. More importantly, the method provides better observation of initial velocity, which will affect calculation of drag (air) force. This method can be used using with a low capturing speed camera. Thus, this will contribute to improvement of training method of badminton around the world.

5. Conclusion

Calculation of initial velocity (after impact) in overhead standing and jumping smashes was successfully conducted. Comparison on velocity reduction of natural feather and synthetic was conducted using initial velocity data using regression approach. The comparison shows that Nylon-Mizuno had highest velocity reduction after certain distances (5 and 9 m). In the meantime, Feather Yonex and Nylon-Gozen have similar initial velocity. However, Nylon-Gozen was less affected by air restriction (drag force) in comparison to feather. Furthermore, the investigation between standing and jumping smashes showed that the initial velocity of jumping is higher than that of standing smash. Thus, jumping smash can be considered as the main weapon when playing badminton.

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