

Comparison of traditional badminton waterfowl-feather shuttlecocks vs synthetic-feather shuttlecocks using different test modalities

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Abstract

Although the Badminton World Federation has approved the use of synthetic-feather shuttlecocks in international competitions, they have not been widely adopted. One reason for this may be that the impact of synthetic-feather shuttlecocks on players and their performance is unclear. This study aimed to determine the differences in characteristics between traditional waterfowl-feather and synthetic-feather shuttlecocks. This study involved conducting the following tests: 1) taking physical measurements of the synthetic-feather shuttlecock; 2) carrying out human tests; 3) conducting wind tunnel tests; and 4) performing 2D flight simulations. The synthetic-feather shuttlecock was significantly heavier and shorter. Its velocity immediately after impact was significantly lower, with greater altitude changes. It tended to experience less air resistance at 0° and 15°, but more at 45°. The results of the 2D flight simulations based on the wind tunnel tests showed that the synthetic-feather shuttlecock recorded a longer simulated travel distance. These results suggest that the synthetic-feather shuttlecock has a longer flight distance due to experiencing less air resistance during flight despite a lower initial velocity immediately after impact. Based on these findings, net players may find that the synthetic-feather shuttlecock comes at them at a lower velocity during gameplay, while hitters and line players may find that it travels further. Understanding these characteristics could facilitate the faster adoption of the synthetic-feather shuttlecock in international competitions, which could improve the sport's sustainability.

1. Introduction

Sustainability in sports equipment.

There has been an increasing shift towards sustainable materials for sports equipment and utensils in various sports. For instance, the use of celluloid material for table tennis balls has been banned due to its harmful effects on human health during the manufacturing process [1, 2, 3]. The use of fluorinated waxes on skis and snowboards has also been prohibited due to the associated health and environmental risks [4]. The Fédération Internationale de l'Automobile has announced that, from 2026, Formula 1 competition regulations will require the use of fully sustainable fuels, banning fossil fuels. Specifically, only fuels derived from sustainable sources, such as non-food bio-based materials, municipal waste, or sustainable carbon capture, will be permitted [5]. These changes to equipment regulations aimed at a sustainable society have been a major topic of discussion in various competitive sports.

1.1 Background in Badminton shuttlecock.

In badminton, traditional badminton shuttlecocks are made from waterfowl-feather feathers. Approximately 20 shuttlecocks are consumed per match in international tournaments [6]. The Badminton World Federation (BWF) has approved the use of synthetic-feather shuttlecocks in international competitions to increase sustainability within the sport [7]. This approval of synthetic-feather shuttlecocks may improve the ecological impact of the consumption of shuttlecocks made from waterfowl feathers. Additionally, the durability of synthetic-feather shuttlecocks is estimated to be 208%

of that of traditional waterfowl-feather shuttlecocks, which is expected to reduce the number of shuttlecocks used [8]. So far, only one synthetic-feather shuttlecock that comply with the previous rules for the BWF is now available on the market [8], making the use of synthetic-feather shuttlecocks in international competitions possible. However, there is still no record of synthetic-feather shuttlecocks being used in international competitions to date, with the exception of trials. One of the reasons for the lack of widespread use of synthetic-feather shuttlecocks in international competitions despite their official approval may be that the impact of the introduction of synthetic-feather shuttlecocks in international competitions has not been clarified.

1.2 Previous studies regarding badminton shuttlecock.

Previous studies of synthetic-feather shuttlecocks have examined the aerodynamic and flight characteristics of plastic shuttlecocks. Cooke et al. investigated the critical parameters for a synthetic-feather shuttlecock to exhibit a similar flight trajectory to a waterfowl-feather shuttlecock [9]. Nakagawa et al. compared the turnover behaviour of synthetic-feather and traditional waterfowl-feather shuttlecocks in detail using wind tunnel experiments. It was reported that the natural shuttlecock deviated less from the original flight path [10]. Chan et al. conducted wind tunnel experiments and flight simulations on shuttlecocks made from various synthetic materials to clarify their aerodynamic properties [11]. However, the synthetic-feather shuttlecocks used in these studies were intended for recreational use only and have not been approved by the BWF for use in international competitions. Rusdiana et al. compared the initial velocity of a synthetic-feather shuttlecock with that of a natural shuttlecock, using what appeared to be BWF-approved synthetic-feather shuttlecocks [12]. However, the authors noted that the sampling frequency of the high-speed camera used in the testing was low relative to the shuttlecock's velocity, meaning the shuttlecock's behavior at impact could not be clearly observed. Tan et al. compared the mechanical properties, flight characteristics and player feedback of synthetic and feather shuttlecocks [13]. They reported that, while synthetic shuttlecocks flew faster, they provided poorer control and accuracy during smashes. While this study revealed the impact on player performance, the aerodynamic characteristics of synthetic shuttlecocks remain unclear. Changes in equipment in other racket sports involving high ball speeds, such as table tennis, have shown that changes in ball materials affect players' kinematics and energy demands during gameplay [2, 14]. In badminton, as in table tennis, it is thought that the change to the synthetic-feather shuttlecock would affect competitive performance. However, to the best of the author's knowledge, there are no studies examining the aerodynamic and flying characteristics of BWF-approved synthetic-feather shuttlecocks. The aim of this study was to clarify the aerodynamic and flying characteristics of the BWF-approved synthetic-feather shuttlecock.

2. Methods

2.1 Experimental design and ethic statement

Approval was obtained from the Ethical Review Committee of the Japan Institute of Sports Sciences (approval no. 2021-041-2). The shuttlecocks used as samples in this study were shuttlecocks made of natural waterfowl-feather commonly used in international competitions (TOURNAMENT F-90, Speed: 4, YONEX Co., Ltd., hereinafter referred to as 'WFS') and the only officially recognized synthetic-feather shuttlecock made of synthetic materials by the BWF at present (TECH FEATHER 03, Speed: 4, Mizuno Corporation., hereinafter referred to as 'SFS'). In accordance with current competition rules, the SFS has 16 blades composed of stems and vanes, strung together and bound to a cork (base). Each blade is independent, the stem is made of synthetic resin and the vanes are made of synthetic fibres. The sane part of the SFS is structurally resistant to shagging (Fig. 1).

2.2 Physical measurements

30 shuttlecocks were randomly selected from 30 different tubes in each type of shuttlecock. The mass, skirt diameter, shuttlecock height and centre of mass distance from base (cork) were measured. The mass was established by weighing those shuttlecocks with a precision scale (PR2003 DeltaRange, METTLER TOLEDO, minimum display: 0.001g). Skirt diameter and shuttlecock height were measured by using a digital caliper (BLD-200, Niigata Seiki, minimum display: 0.01mm). To measure the centre of mass distance from the base, a string balance test [11] was conducted. The shuttlecocks were suspended by a string. The centre of mass (COM) distance from the base was defined as the distance between base tip and the knot in the string when the shuttlecock was horizontal.

2.3 Human tests

2.3.1 Participants

10 male and 10 female badminton players (average age $\pm$ range: 19.0 ± 1.0) were recruited. They were among the best in the national university badminton tournaments in Japan and some of the participants were part of the Japanese national badminton team. Prior to the experiment, all the participants were informed of the purpose of the study, its procedure, and associated risks. Written informed consent was obtained from all the participants.

2.3.2 Experimental procedure

The experiment was conducted on a badminton court set up in an indoor sports facility. After sufficient warm-up, the participants were required to smash the two types of shuttlecock (WFS and SFS) launched by the badminton feeder machine (S4025, SIBOASI, China) into a designated target area with maximum effort. The hitting and target areas are depicted in Fig. 2. Participants continued to smash the same type of the shuttlecock until they had successfully landed five trials within the target area. Subsequently, they repeated the process with the other type of shuttlecock. The order of shuttlecock types was randomized for each participant. The participants used their own rackets during the experiment. A new shuttlecock was used for each hit, preventing the impacts of shuttlecock damage.

2.3.3 Data collection

The movement of the shuttlecock before and after the racket-shuttlecock impact were recorded using a high-speed video camera (Phantom V311, Vision Research, USA) at a frame rate of 2,000 fps and an exposure time of 1/5,000 s. The camera was placed on the side of the hitting area (Fig. 2), at the height approximately level with the racket-shuttlecock impact point. The optical axis of the camera lens was perpendicular to the side line of the badminton court. To record the movement of the racket, retro-reflective markers were attached to the top, bottom, right, and left of the racket face. The trajectories of these markers were captured using a motion capture system with 16 cameras (Vantage, Vicon Motion Systems, UK) at 1,000 Hz. These cameras were positioned around the hitting area. The trial with the highest racket velocity in each condition was used as the measured data.

2.3.4 Data acquisition

Motion analysis software (Frame DIAS V, Q'sfix, Japan) was used to obtain the positional coordinates of the shuttlecocks on the video images recorded by the high-speed video camera. The tip of the base and both sides of the feather edge of shuttlecock were manually digitized (Fig. 3A). The pixel size of each video image was calibrated based on the length of the shuttlecocks immediately before impact. To calculate the shuttlecock initial velocity, the launch angle after the impact, and the momentum immediately after the impact, the centre of mass (COM) of the shuttlecock was identified from the digitized points, in accordance with the value presented in Table 1. The time series of the shuttlecock initial velocity for the first ten frames after impact was calculated based on the displacements of the COM coordinates (Fig. 3A). As shown in Fig. 3B, a regression equation was obtained from ten frames of the shuttlecock velocities. The intercept was considered to be the shuttlecock initial velocity. The launch angle was defined as the angle between shuttlecock initial velocity vector and the horizontal plane after racket-shuttlecock impact (Fig. 3A). A negative launch angle indicates a downward direction of the velocity vector. Momentum was calculated as the product of the shuttlecock mass and its initial velocity. The attitude angle was defined as the angle between the launch angle and the long axis of the shuttlecock. A positive attitude angle indicated that the tip of the base was directed upward. The racket velocity immediately before the racket-shuttlecock impact was calculated based on the displacements of the center of the four retro-reflective markers attached around the racket face, as captured by the motion capture system. Additionally, the relative shuttlecock initial velocity to the racket velocity (relative shuttlecock velocity) was calculated.

Table 1
The average of the shuttlecock dimensions.

Variables	WFS	SFS	Cohen's d	Significance (p-value)
Mass [g]	5.23 ± 0.08	5.33 ± 0.06	1.28	< .001**
Skirt diameter [mm]	65.2 ± 0.26	65.8 ± 0.28	2.30	< .001**
Height [mm]	85.1 ± 0.30	82.7 ± 0.33	7.69	< .001**
COM distance from base [mm]	30.4 ± 0.72	29.9 ± 0.46	0.67	< .05*
Relative COM position (COM distance from base/total shuttlecock height) [%]	35.63 ± 0.94	36.21 ± 0.51	0.76	< .05*
Note: ** and * shows significant difference of $p < 0.01$ and $p < 0.05$, respectively.				

2.4 Statistical Analysis

To compare the calculated values (the mass, skirt diameter, shuttlecock height and COM distance from the base, shuttlecock initial velocity, launch angle, momentum, maximum attitude angle, racket velocity, and relative shuttlecock velocity) between the WFS and SFS, a paired t-test was used. The significance level was set at $p < 0.05$. Effect sizes were determined via Cohen's d, with effect size thresholds for d being small = 0.2, medium = 0.5 and large = 0.8 [15].

2.5 Wind tunnel tests

To obtain the basic aerodynamic characteristics of these shuttlecocks, a wind tunnel test was conducted in a closed-circuit wind tunnel (San Technologies Co., Ltd., Japan). The maximum flow velocity of the tunnel was 55 m/s, and the size of the fan outlet was 1.5 m×1.5 m and the turbulence was 0.1% or less. Aerodynamic forces were measured at flow velocities ranging from 5 to 55 m/s in 5 m/s increments, with the shuttlecocks oriented at 0°, 15°, 30° and 45° relative to the direction of the airflow (see Fig. 4). Those angles were chosen based on the attitude angles in the human tests. The measured aerodynamic drag force (D) was converted to the drag force coefficient (Cd):

$$Cd = \frac{2D}{\rho U^2 A} \quad (1)$$

where ρ is the air density ($\rho = 1.2 \text{ kg/m}^3$), U is the flow velocity, and A is the projected area of the shuttlecocks. After the wind speed had stabilized, the average of the values measured for 5 s at a sampling frequency of 100 Hz was taken as the representative value for each trial. The same trial was

repeated five times with a new shuttlecock and the average of the five measurements was taken as the result for each condition.

2.6 Shuttlecock flight simulation

The flight distance of the shuttlecocks when smashing each shuttlecock is a key factor for both hitters and receivers. Hitters need to adjust their racket velocity, launch angle and impact position according to the flight distance of a shuttlecock, while receivers decide if the shuttlecock lands in or out of the court. The maximum wind speed was 55 m/s in the wind tunnel tests. However, in actual competitions, the initial velocity of the shuttlecock at impact is reported to be even faster, reaching a maximum velocity of 113 m/s immediately after impact [10, 16]. The results of wind tunnel tests alone cannot replicate actual competition conditions due to the limitation in the wind tunnel set-up. Therefore, a two-dimensional simulation of the shuttlecock's flight trajectory was carried out based on the drag force and coefficient obtained from the wind tunnel tests. In all cases, the initial attitude was set at an angle of 0° and a launch height was set at 2.5 m from the ground based on the hitting test results. The shuttlecock was assumed to launch horizontally to the ground and its attitude was also assumed to remain unchanged relative to the direction of travel until it landed. The following equations were used in the simulations:

$$ma_h = -D\cos\gamma \quad (2)$$

$$ma_v = -D\sin\gamma - mg \quad (3)$$

where m is the mass of the shuttlecocks, a_h is its horizontal acceleration, a_v is its vertical acceleration, g is its gravitational acceleration, and γ is its velocity vector. 2D shuttlecock velocity and displacement were obtained by the explicit Euler method by interpolating the drag coefficient at each time step (0.001 s) using a second-degree polynomial approximation. Lift and side forces acting on the shuttlecocks were omitted in this shuttlecock trajectory simulation. Flight trajectories were calculated at an initial shuttlecock velocities of 55 m/s (the maximum speed in the wind tunnel tests) and at 90 m/s (close to the actual competition speeds).

3. Results

3.1 Physical measurements

The average of those dimensions and mass of the WFS and SFS are shown in Table 1. The SFS was heavier (by 0.1 g) and shorter (by 2.5 mm) than the WFS. The COM distance from base was higher in the WFS but the relative COM heights was higher in the SFS. The skirt diameter was greater in the SFS. Effect size for mass, skirt diameter, and height differences were large ($d > 0.8$). The absolute and relative COM positions had a medium effect size ($0.5 < d < 0.8$).

3.2 Human tests

Table 2 shows the averages and standard deviations of the shuttlecock initial velocity, launch angle, momentum, maximum attitude angle, racket velocity, and relative shuttlecock velocity in the WFS and SFS. No significant differences were found between the WFS and SFS in launch angle, momentum and racket velocity. On the other hand, shuttlecock initial velocity ($p = .04$, effect size: low) and relative shuttlecock initial velocity to the racket velocity ($p = .01$, effect size: medium) were significantly higher in the WFS. Figure 5 showed the time series of attitude angle of shuttlecocks after impact. Because the number of frames in which the shuttlecock passes through the view of the high-speed camera varies from trial to trial, the data point after 0.02 s were not the same numbers. Both shuttlecocks had a negative attitude angle at the time of impact with the racket and the attitude angle rapidly changed to positive afterwards. The maximum values of the SFS and WFS attitude angles were observed between 0.005 s and 0.008 s, and between 0.0065 s and 0.0095 s, respectively. The average maximum attitude angles of the SFS and WFS were $44.7 \pm 4.6^\circ$ and $40.3 \pm 5.2^\circ$ respectively. The SFS had a significantly greater change in attitude angle ($p < .02$, effect size: large) and the timing of the attitude angle maximum in the SFS was relatively greater than that of the WFS.

Table 2
Results of shuttlecock and racket movement analysis.

	WFS	SFS	Cohen's d	Significance (p-value)
Shuttlecock initial velocity [m/s]	73.7 ± 8.7	71.6 ± 7.2	0.26	= .04*
Launch angle [deg.]	-7.4 ± 2.7	-7.7 ± 2.7	0.01	= .44
Momentum [kg·m/s]	0.39 ± 0.05	0.38 ± 0.04	0.09	= .45
Maximum attitude angle [deg.]	40.3 ± 5.2	44.7 ± 4.6	0.86	= .02*
Racket velocity [m/s]	63.3 ± 9.7	63.8 ± 9.1	0.10	= .48
Relative shuttlecock velocity [m/s]	1.17 ± 0.06	1.13 ± 0.07	0.62	= .01*
Note: * shows significant difference ($p < 0.05$).				

3.3 Wind tunnel tests

Figure 6 shows the average changes in drag force for the SFS and WFS in wind tunnel tests under different conditions. In all cases, an increase in wind speed resulted in a greater drag force. At 0° , the drag force of the WFS was greater than that of the SFS as the speed increased. At 15° , a similar trend was observed, but the difference was smaller. At 30° , no major differences between the shuttlecocks

were observed. At 45°, at high speeds, the relationship between the two shuttlecocks was reversed, with the SFS having a greater drag force.

3.4 Shuttlecock flight simulation

Figure 7 shows the simulation results for the flight distance of each shuttlecock in wind speeds of 55 m/s and 90 m/s. Assuming both shuttlecocks were launched horizontally from the same height, their trajectories were similar up to around 4 m. After this point, the trajectory of WFS was lower than that of the SFS. In the 55m/s condition, the WFS and SFS landed at 9.7 m and 10.4 m from the launch point, respectively. A similar trend was observed in 90 m/s. The WFS and SFS landed at 11.5 m and 12.4 m, respectively.

4. Discussion

This is the first study to evaluate the aerodynamic characteristics of the officially approved synthetic shuttlecock using a combination of physical measurements, human tests, wind tunnel tests and flight simulations. Not only does it combine different methods, it also uses a method to investigate mechanical differences, differences in flight due to simulation, and differences in performance demonstrated by elite badminton players. The main finding in this study was that the initial velocity of the SFS was significantly lower than that of the WFS. Additionally, the change in attitude angle immediately after impact of the SFS was greater than that of the WFS. The aerodynamic drag of the SFS tends to be greater immediately after the impact but lower than that of the WFS after the shuttlecock attitude has stabilized. This may increase the flight distance when smashing. This was also suggested by the results of 2D simulations, despite the SFS having a significantly lower initial velocity than the SFS.

4.1 Physical measurements

The SFS was heavier in mass, lower in height and larger in skirt diameter than the WFS. The COM distance from base was smaller in the SFS and, conversely, the relative COM position was larger in the SFS. Significant differences were found for all items. Tan et al. reported the same synthetic shuttlecock dimensions as in the present study [13]. The results of this study were similar to those of Tan et al. The larger skirt diameter indicated that the shape was subject to greater aerodynamic drag in the longitudinal direction of the shuttlecock during flight. The SFS was shorter than that of the WFS. It means that the moment of rotation around the axis perpendicular to the long axis of the shuttlecock was smaller than that of the WFS, indicating a more rotatable geometry.

4.2 Human tests

The initial velocity of the shuttlecock in this study was lower than that reported in studies by Nakagawa et al. and Ramasamy et al [11, 17]. However, the data in these previous studies were obtained only from male athletes. A study by Tan et al. that included female international-level athletes reported a peak velocity of 43 m/s using the same synthetic shuttlecock as in this study [14]. Therefore, it could be concluded that the subjects in this study were performing an equivalent level to international level

athletes. The results of the human tests showed that the initial velocity immediately after impact of the SFS was significantly lower than that of the WFS. As there was no significant difference between the shuttlecocks in the racket velocity and the momentum, the difference of the initial velocity could be attributed to the difference in the mass of the shuttlecock. The SFS changed its attitude significantly more than the WFS, with a maximum value of 44.7° . The significantly shorter length of the SFS would be a factor in the large change in attitude angle of the SFS.

4.3 Wind tunnel tests and flight simulations

Wind tunnel test results showed that the SFS had greater aerodynamic drag than the WFS at an attitude angle of 45° . This suggests that the SFS may experience greater aerodynamic drag due to greater changes in the attitude angle before the shuttlecock's attitude stabilizes, resulting in a decrease in speed. These indicates that the SFS may be perceived by both the hitter and the net player as having a lower shuttlecock velocity than the WFS at impact. On the other hand, at small attitude angles (0 or 15 degrees), the SFS had less drag. In other words, once the attitude has stabilized, the trajectory of the SFS is likely to be perceived as 'extended' by the opponent in a smash scenario. For reference, the simulation trajectories show that the flying distance is still longer. Hitters may need to adjust the launch angle and launch position to compensate for the increased flight distance and landing out caused by reduced aerodynamic drag when aiming for the back of the opponent's court with a smash.

4.4 Limitations

In the flight simulation in this study, the attitude of the shuttlecock was assumed to be horizontal from impact to landing. Therefore, the actual landing point of the shuttlecock may differ from the calculated results. Future flight simulations should be conducted under conditions where the attitude of the shuttlecock changes from time to time. It is necessary to investigate whether the aerodynamic drag had a similar effect on the decrease in shuttlecock speed.

5 Conclusions

This study compared the WFS and the SFS. The SFS was heavier, with a larger skirt diameter and shorter length. Human tests showed that, although the SFS's initial velocity was lower, it experienced greater attitude changes immediately after impact. Wind tunnel tests indicated greater aerodynamic drag for the SFS at 45° , but less at 0° and 15° . Flight simulations showed that the SFS travelled further. These findings suggest that net players may perceive the shuttlecock to be moving more slowly, while hitters may need to swing faster to increase its initial speed. Additionally, hitters and net players may perceive the smash trajectory as longer than usual. As there are several differences between the SFS and the WFS, players should undergo training to adapt fully to the new shuttlecock and prevent unnecessary injuries when using the SFS. Understanding these differences could help to promote the SFS in international competitions and transform badminton into a more sustainable sport.

Declarations

Author Contribution

Hiroki Ozaki conducted the human testing and wrote the main manuscript text. Hirotaka Nakashima also conducted the human testing and wrote the Methods-Human Tests section as well as prepared figures 2-3. Marcus Lee, Goh WanXiu, and Kenny Tan provided their own shuttlecock trajectory data. Soungchan Hong conducted the wind tunnel testing and flight simulation. Masashi Suita recruited all the participants and offered advice for the human testing setup as a professional badminton coach. Erina Kurosaki primarily conducted the wind tunnel testing. Taeshi Asai provided advice for the wind tunnel setup and also conducted the testing. All authors reviewed the manuscript.

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None

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Figures

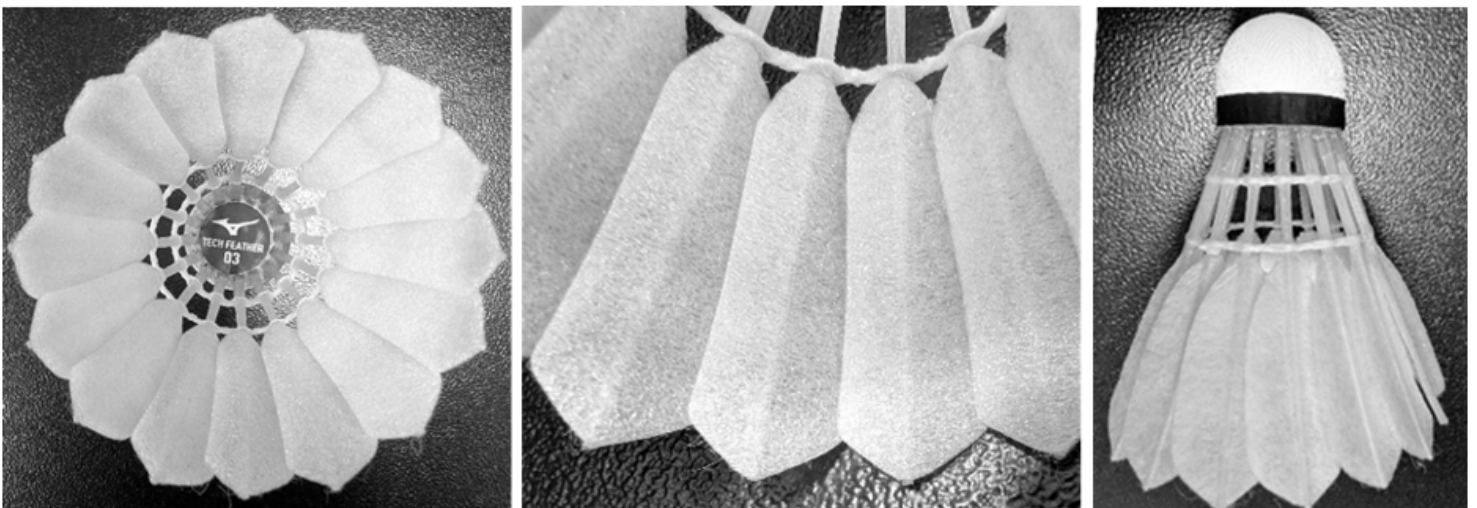


Figure 1

Pictures of the SFS

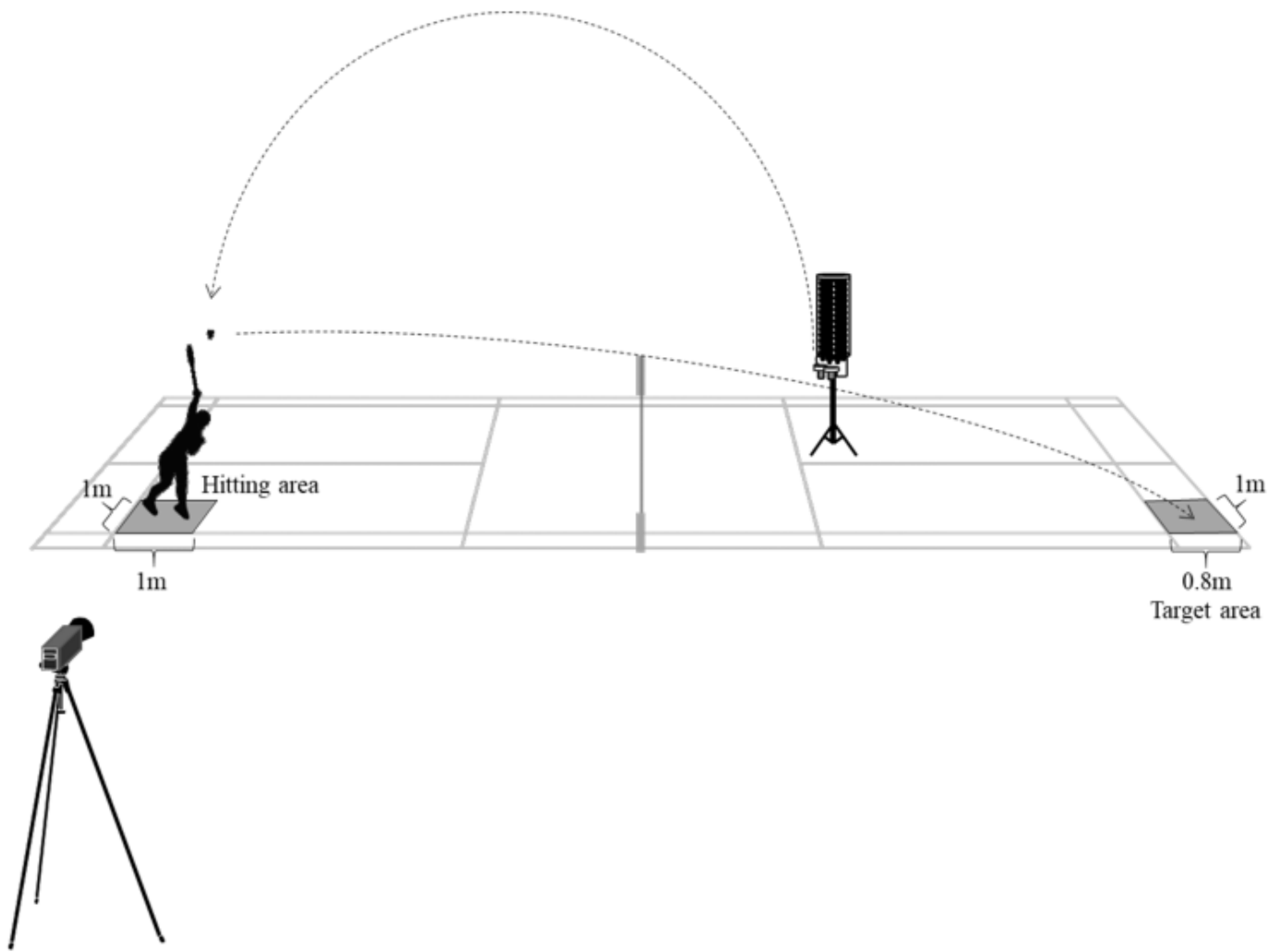
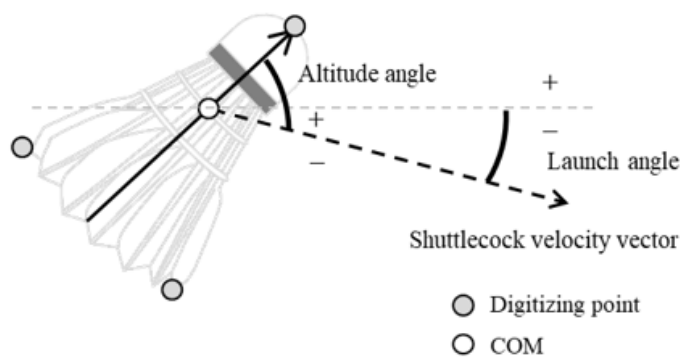


Figure 2

Schematic diagram of the experimental set-up.

(A)



(B)

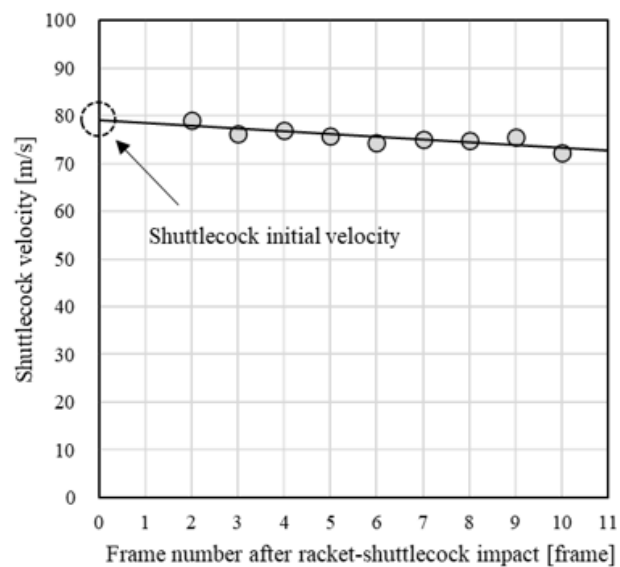


Figure 3

Shuttlecock digitization point and definition of Altitude angle and Launch angle (A) and calculation of the shuttlecock initial velocity (B).

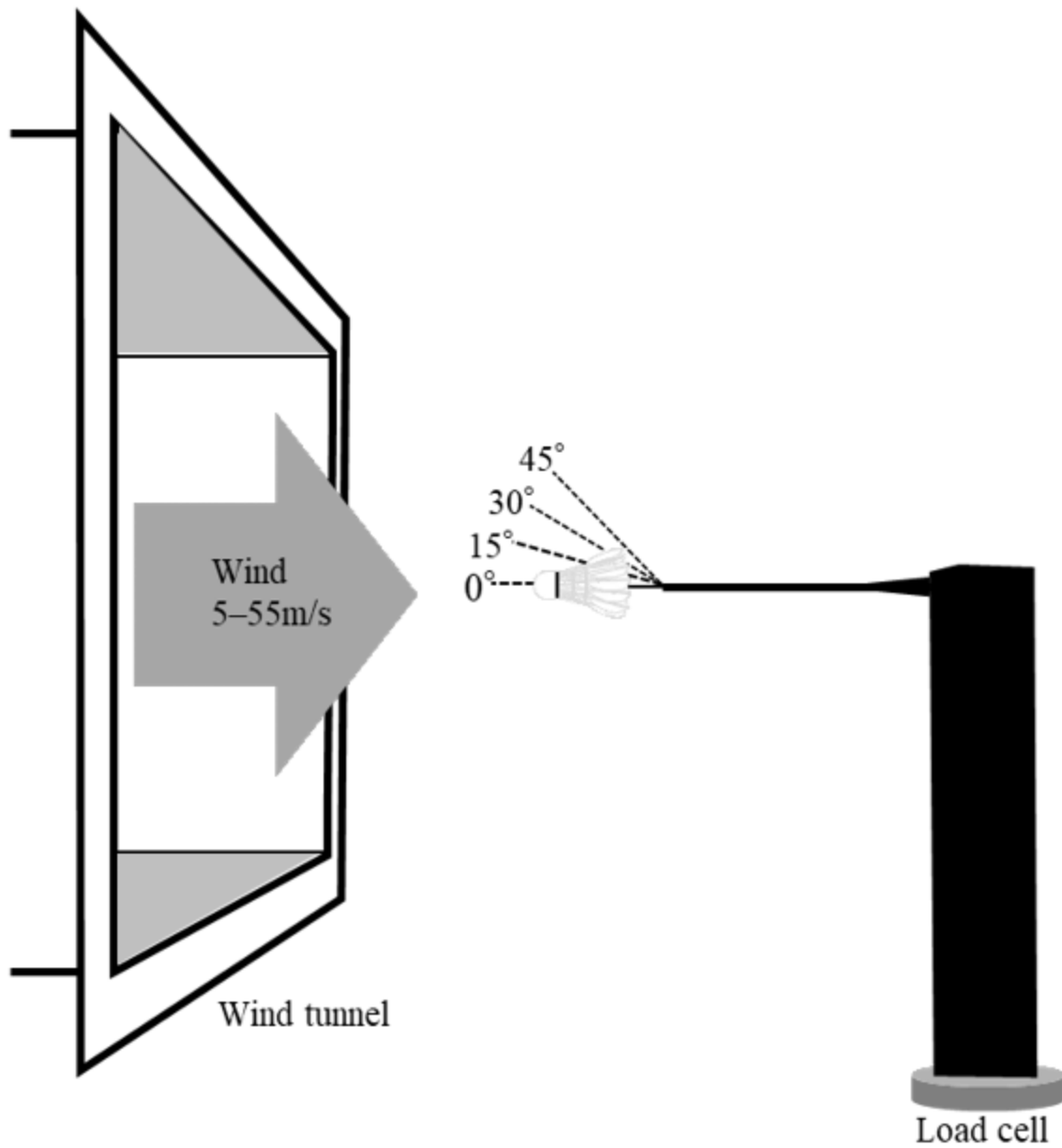


Figure 4

The shuttlecocks set-up in the wind tunnel chamber.

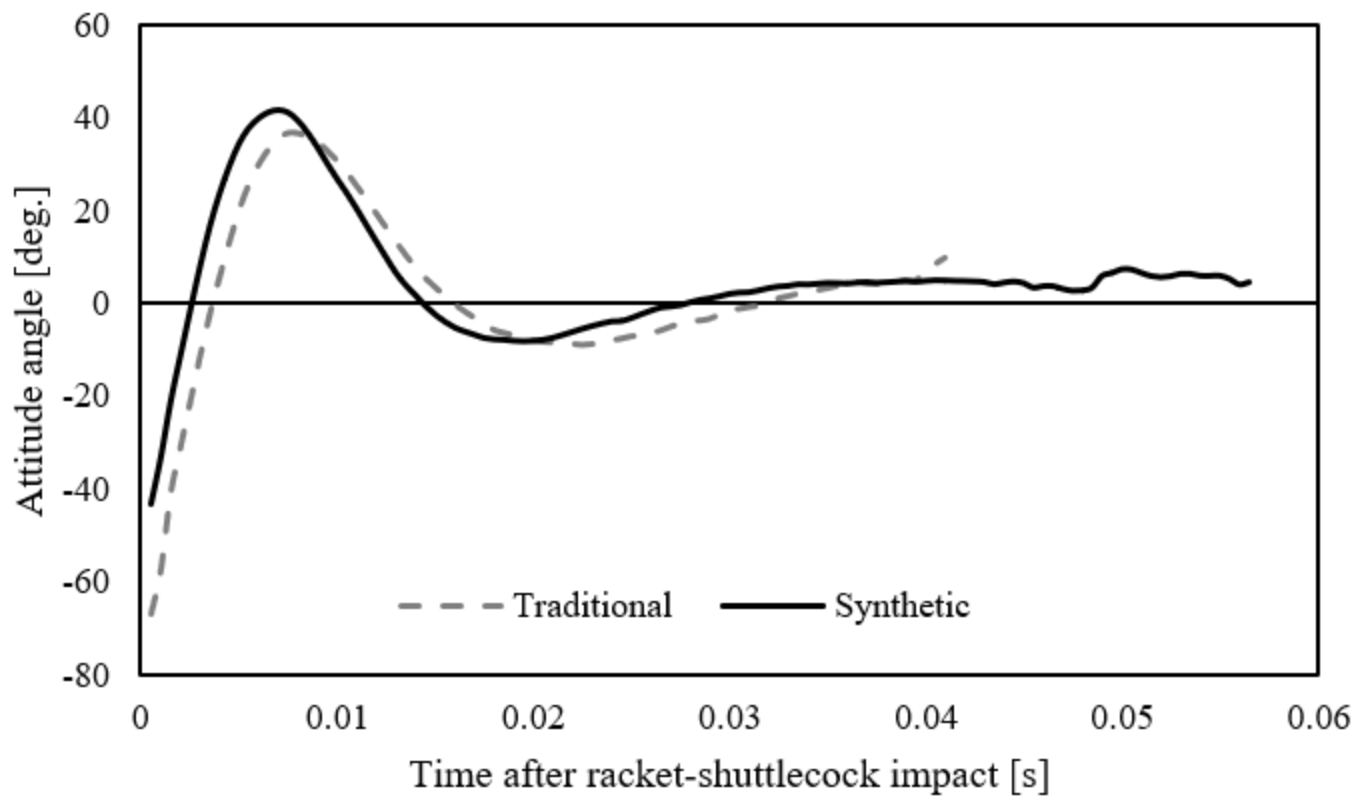


Figure 5

The time series of attitude angle of shuttlecock after impact.

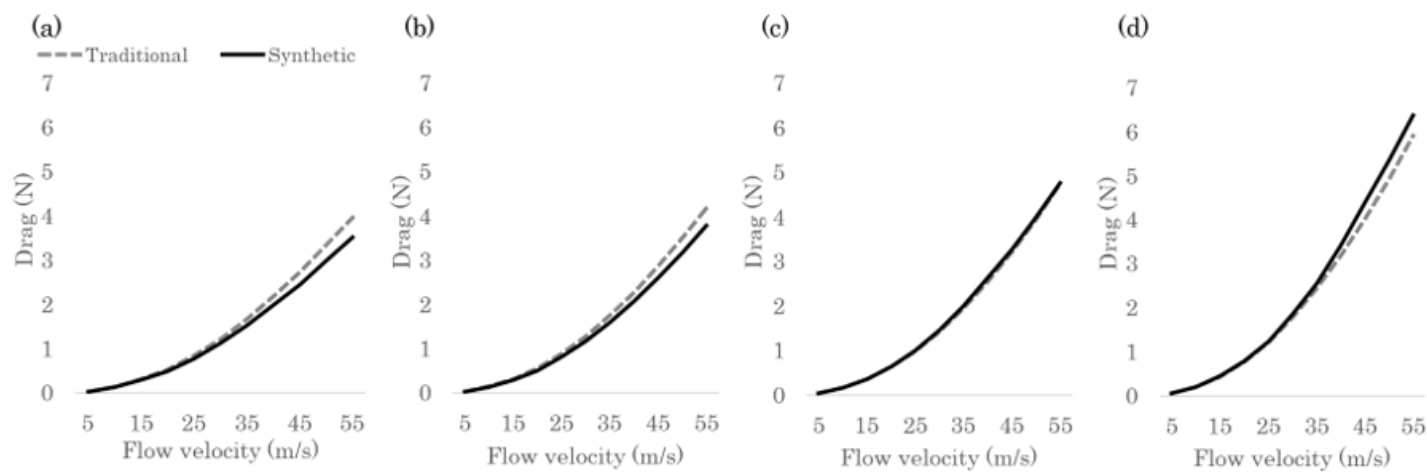


Figure 6

Averages of drag force at the shuttlecock angle conditions of 0° (a), 15° (b), 30° (c), and 45° (d) in the wind tunnel tests.

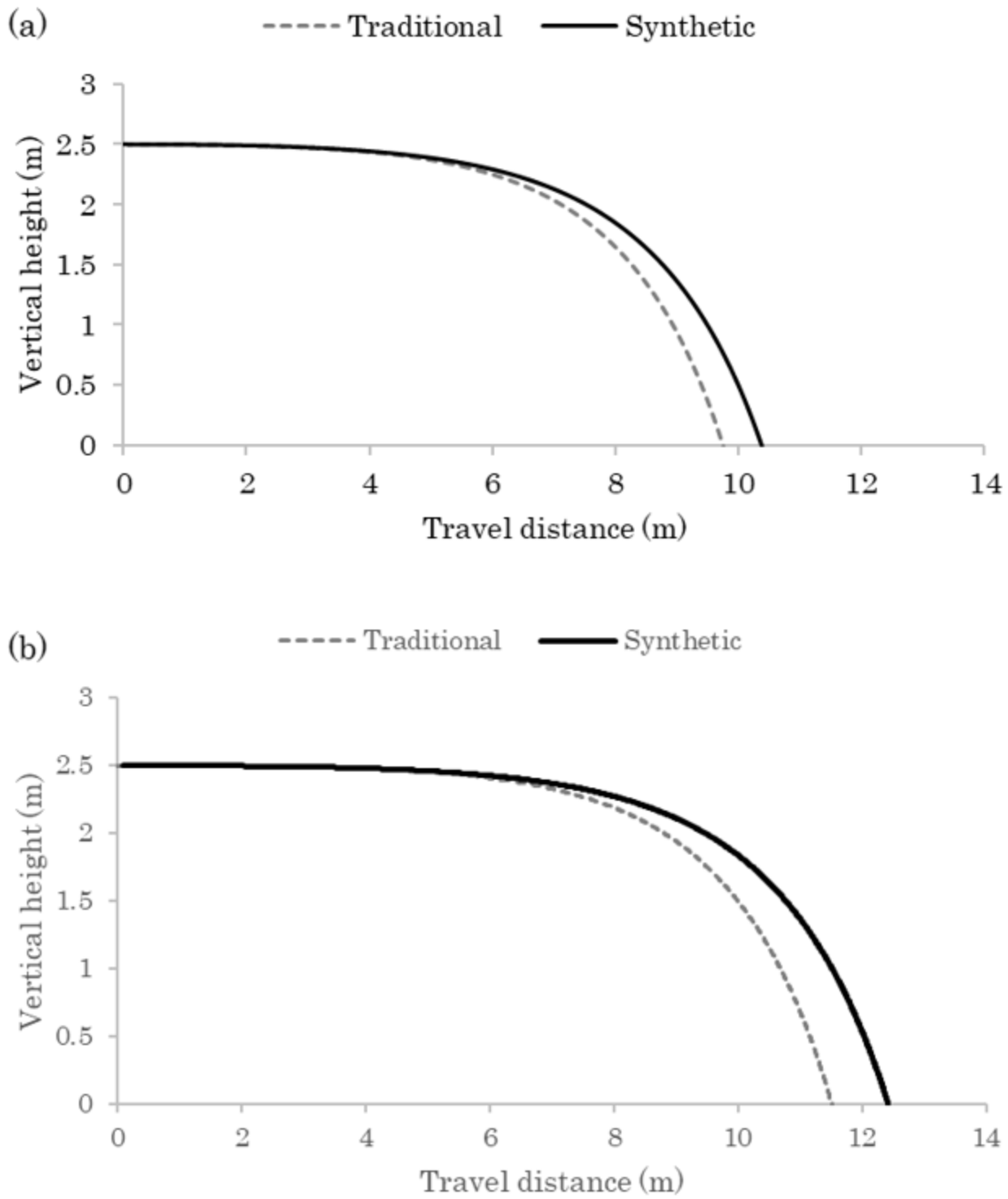


Figure 7

Results of shuttlecock flight distances in 2D flight simulations at wind speeds of 55 m/s (a) and 90 m/s (b).