Velocity Measurement of a Sports Ball during the Drop Test by a High-speed Camera

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***Abstract*—This paper provides effective techniques that can act as a guideline to calculate the velocity from a high-speed camera. A table tennis ball was vertically dropped with no initial spin from a 0.5 m drop height and collided with a rigid steel plate before rebound. A high-speed camera with a frame rate of 1000 frames/s was used to record the motion of the ball during pre- and post-impact. Manual and automatic tracking measurements were used to generate the distance–time profile of the ball during the impact event. In the manual tracking measurement, the distance–time data were manually identified, whereas in the automatic tracking measurement, the distance–time data were automatically generated by software. As a result, both these methods provide identical results. Four different methods were used to measure the velocity of the ball on the basis of the distance–time data. Three of these methods are (i) averaging the distance or velocity data, (ii) curve fitting with a linear and second-order polynomial trend line and (iii) fitting the trend line with the kinematic equation of free-fall motion. The fourth method, the automatic tracking measurement and the second-order polynomial trend line fitted with the kinematic equation of free-fall motion, was found to be the best method to obtain the velocity of the ball during impact.**

***Index Terms*—high-speed camera, drop test, velocity measurement, impact**

I. INTRODUCTION

Impact is defined as the collision between two bodies at an instant of time [1]. Two phases arise during the impact: (i) the compression phase when the bodies initially start to contact and compress against each other and (ii) the restitution phase when the bodies start to separate but are still in contact [2]. The latter phase ends when the bodies are completely separated. The kinematic coefficient of restitution (COR), *e*, is the ratio between the final and initial velocities during impact. The value of e is in the range $0 \leqslant e \leqslant 1$, where e = 0 indicates a perfectly plastic collision (total energy loss) and e = 1 indicates a perfectly elastic collision (no energy loss). A high-speed camera is widely used to measure the velocity and subsequently COR in either two or three dimensions of direct or oblique impact [3,4]. Aryaei, Hashemnia and Jafarpur [5] used a high-speed camera to study the effect of using different sizes of balls impacting steel and aluminium surfaces in direct impact. Their experimental work was well verified by ANSYS, and they finally concluded that the COR value slightly decreases as the size of the ball becomes larger. Dong and Moys [3] measured the normal and tangential COR of the ball impacting the steel plate with initial spin introduced on the ball. With a 50 frames/s (fps) of camera speed, it was possible to measure the displacement and rotation of the steel ball. As a result, they found that the results of impact without initial spin confirmed the rigid body theory, but not for the impact with initial spin. Mathavan, Jackson and Parkin [6] mounted a high-speed camera on the ceiling to determine the dynamics interaction between snooker balls and cushions. Gibson, Gopalan, Pisupati and Shadle [7] also used a high-speed camera to determine the velocity of some particles for coal gasification applications. They used a higher frame rate (up to 3000 fps) to capture the object at higher speeds (6–8 m/s), but they reduced the frame rate at lower velocities to obtain the best resolution. Furthermore, image analysis was performed using a manual tracking measurement, conducted in ImageJ software. High-speed cameras have

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also been used in geotechnical applications. Watanabe, Koseki and Tateyama [8] used a high-speed camera to evaluate the deformation characteristics of geomaterials in both static and dynamic test models. Moreover, the crack process on any material can be observed using high-speed cameras. For example, Wong and Einstein [9] used a high-speed camera to study crack initiation, propagation and coalescence in rocks under uniaxial compression.

Extensive studies have been reported on the application of high-speed cameras to solve various problems. However, specific studies and standards that describe methods of obtaining results from high-speed cameras are still very less. As a matter of fact, the methods used by researchers to obtain results from high-speed cameras greatly influence the final results. To address this concern, this paper provides detailed guidelines and presents several methods that can be used to obtain velocity results from high-speed cameras.

II. EXPERIMENTAL TECHNIQUES

A. Experimental Set-up

Fig. 1 shows a schematic set-up of all the equipment used in the experiment. Experimental devices can be divided into four main parts: (i) a ball-releasing system, (ii) an impact plate, (iii) a high-speed camera and (iv) image processing. The ball-releasing system is located at the top of the drop tower, where the height can be adjusted up to 3 m. In this paper, a table tennis ball is dropped from a 0.5 m height. A vacuum nozzle is attached at the top of the drop tower and connected to a vacuum pump by a tube. A table tennis ball is held to this nozzle by the vacuum created by the vacuum pump. To release the ball, the vacuum in the tube is removed by switching off the vacuum pump. In this way, the ball is dropped by a free-fall motion without spin. An impact plate is a rectangular steel block 260 × 250 × 25 mm located at the bottom of the drop tower. Furthermore, using an inclinometer, both the high-speed camera and the target surface are confirmed in a horizontal plane position during the tests. This is an important setting to ensure that the impact is collinear.

Fig. 2 shows the process flow to obtain results from a high-speed camera. A Fastec Imaging InLine high-speed camera was used to record the motion of the ball during impact. This monochrome high-speed camera is equipped with an F0.95 lens and can capture images at speeds from 60 to 1000 fps. To obtain precise results of speed before, after and at the point of impact, 1000 fps of camera speed with 320 × 240 pixels of resolution was considered optimum. A black fabric was also attached at the background of the drop tower to improve the observation and quality of the images. A network connection between the computer and the high-speed camera was established to visualise the recorded video in the computer.

B. Motions Analysis: Position of the Object

Two techniques can be used to track the motion of a ball from a high-speed camera: manual and automatic. These techniques are used to determine distance vs. time data before and after impact.

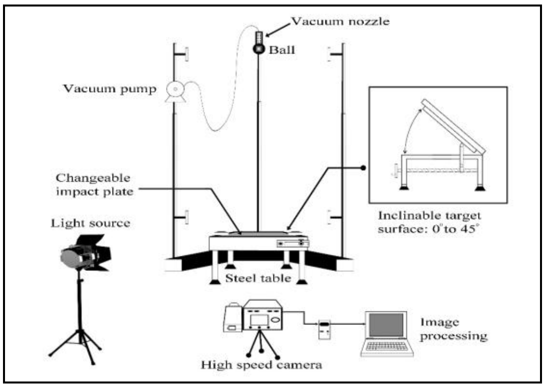


Figure 1. Schematic diagram of the experimental set-up.

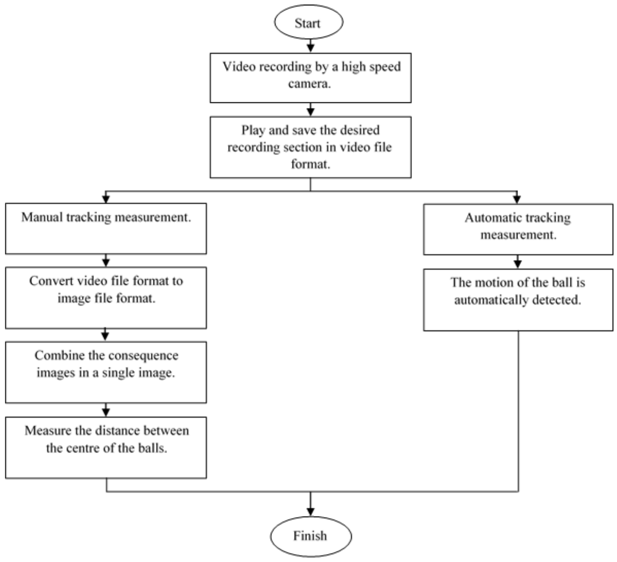


Figure 2. Flowchart of the process to obtain data from a high-speed camera.

1) Manual tracking measurement

According to Fig. 2, the recorded video that was obtained from the camera is converted to the image file (such as a jpeg or jpg file). An image at the point of impact (also called a datum point) is recognised when the centre of the ball approaches nearest to the impact plate. The distance between images to the next image is called frame, and the total number of frames is measured from the datum point. In this paper, the analysis considers within 10 frames of data before and after impact. Adobe Photoshop CS5 Portable software was used to recognise and combine the images into a single image. Then, ImageJ software was used to measure the distance between the centre of the ball and the datum in every frame.

2) Automatic tracking measurement

The motion of the ball can be automatically detected using motion analysis software such as Tracker Video Analysis and Modelling Tool, ProAnalyst, Photron FASTCAM Analysis and Qualisys Video Analysis. In this paper, Tracker Video Analysis and Modelling software (later referred to as Tracker) was used for the automatic tracking measurement [10]. Initially, the centre of the ball in the first image must be accurately recognised to be selected as a reference or template for the next images, as shown in Fig. 3. The evolution rate and automark are set to the default: 20% and 4, respectively. These values are chosen because changes in these values could lead to false matches. The next images of the ball are tracked automatically by software based on the template image. The best match is the one with the highest match score, a number that is inversely proportional to the sum of the squares of the RGB differences between the template and match pixels [10]. Once the best match is found, it is compared with nearby match scores to determine an interpolated sub-pixel best-match position. As a result, the motions of the balls during pre-impact, impact and post-impact can be easily obtained.

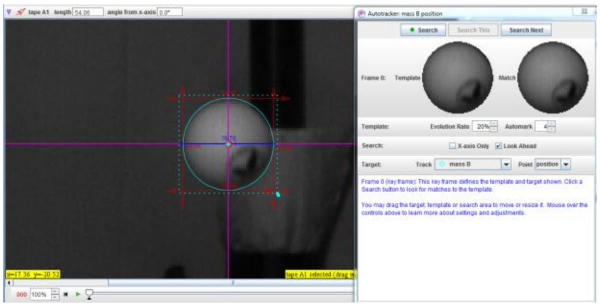


Figure 3. Screenshot of the process of locating the centre of the ball and template for autotracker in Tracker software.

III. Results

A. Comparison between Manual and Automatic Tracking Measurements

The impact event was recorded at 1000 fps; thus, the duration in one frame is equivalent to one millisecond (ms). The measurements are considered from 10 frames in pre-impact until 10 frames in post-impact. Furthermore, the impact is assumed to take place at time $t = 0$ ms, and the rebound phase (after impact) takes place after that moment. Each drop test is repeated three times to reduce measurement errors. Fig. 4 shows the differences between manual and automatic tracking measurements. It can be seen that the distance of the ball from the datum at every frame is almost similar when using either manual or automatic tracking measurements.

B. Methods to Obtain Velocity–time Data

The result of the velocity is obtained from distance vs. time data. Several methods can be used to measure velocity data (e.g. by averaging the distance or velocity from several frames during impact and also from curve fitting). In the next section, manual tracking measurements will be used to obtain the velocity results by means of several methods.

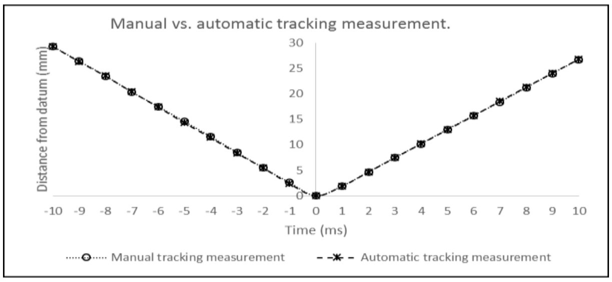


Figure 4. Distance from datum vs. time for manual and automatic tracking measurements.

1) Method I: averaging distance or velocity data

The easiest way to measure velocity from distance–time data is by averaging the distance or velocity data according to the required time or frames. Table 1 shows details of the data obtained using this method. All measurements were calculated from the point of impact (datum point), when $t = 0$ ms. In every image, the centre of the ball is recognised; hence, the distance from the datum point to any other centre of the balls can also be measured. Moreover, velocity is calculated on the basis of the simple formula

$$v_{avg} = \frac{dh}{dt} \quad (1)$$

where v_{avg} is the average velocity, dh is the distance between the centre of the balls, and dt is the time duration.

TABLE I. Dynamics Results Obtained from Manual Tracking Measurement and Method I

	Time (ms)	Image no.	Frame	Frame distance (mm)	Distance from datum point (mm)	Average cumulative velocity (m/s)
Pre-impact	-10	61	-	-	29.287	2.929
	-9	62	61-62	2.884	26.402	2.934
	-8	63	62-63	2.884	23.518	2.940
	-7	64	63-64	3.183	20.335	2.905
	-6	65	64-65	2.809	17.526	2.921
	-5	66	65-66	2.958	14.568	2.914
	-4	67	66-67	2.955	11.613	2.903
	-3	68	67-68	3.112	8.501	2.834
	-2	69	68-69	3.036	5.465	2.733
	-1	70	69-70	2.882	2.584	2.584
Impact	0	71	70-71	2.584	0.000	0.000
Post-impact	1	72	71-72	1.881	1.881	1.881
	2	73	72-73	2.789	4.670	2.335
	3	74	73-74	2.786	7.456	2.485
	4	75	74-75	2.714	10.170	2.542
	5	76	75-76	2.857	13.027	2.605
	6	77	76-77	2.704	15.731	2.622
	7	78	77-78	2.631	18.362	2.623
	8	79	78-79	2.859	21.221	2.653
	9	80	79-80	2.789	24.010	2.668
	10	81	80-81	2.711	26.721	2.672

The average cumulative velocity from the datum point until a certain centre of the ball was measured by the ratio of the total distance from the datum and the total time duration. For example, in 5 ms during pre-impact, the average cumulative velocity is 2.914 m/s, and in 5 ms during post-impact, the average cumulative velocity is 2.605 m/s. Moreover, the number of frames chosen during pre-impact must be similar during post-impact so as to create a relevant comparison. The velocity after impact is always lower than that before impact owing to energy loss during impact.

2) Curve fitting

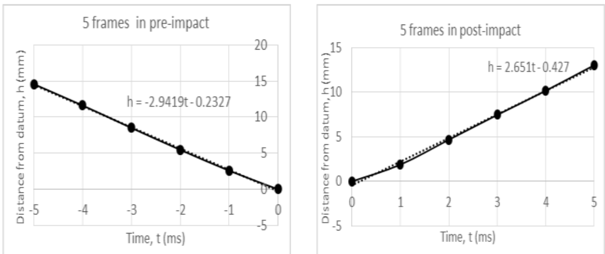
A trend line that can fit the distance–time curve was created in order to obtain an equation that can present velocity. Three types of curve fitting were fitted to obtain the average velocity: a linear trend line, differentiation of a second-order polynomial trend line, and a second-order polynomial trend line fitted with a kinematic equation of free-fall motion.

a) Method II: Linear trend line

This method was used by Roux and Dickerson [11] to measure the velocity during pre- and post-impact. The distance of the ball from the datum at every frame was plotted and fitted by a linear trend line. Previous results proved that the number of chosen frames has a significant effect on the velocity results. As such, in this section, a linear trend line that fits the curves was created individually for every number of chosen frame. Fig. 5(a) and 5(b) shows an example of the linear trend line fitted on the distance vs. time curve when 5 frames were chosen during pre- and post-impact, respectively. The general equation of this straight line is given by

$$h = mt + c \tag{2}$$

where h is the distance of the centre of the ball from the datum, m is the line slope, t is time, and c is a point at which the line crosses at the h-axis. From (1), it is clearly seen that velocity is determined as the ratio of change in distance over time. This value is actually represented by the slope of the linear trend line, m, which is presented in (2). For example, according to Fig. 5, the average velocities are 2.9419 and 2.651 m/s within 5 frames in pre-impact and post-impact, respectively.



(a) (b)

Figure 5. Linear trend lines of distance from datum vs. time for (a) 5 frames in pre-impact and (b) 5 frames in post-impact.

b) Method III: Differentiation of the second-order polynomial trend line

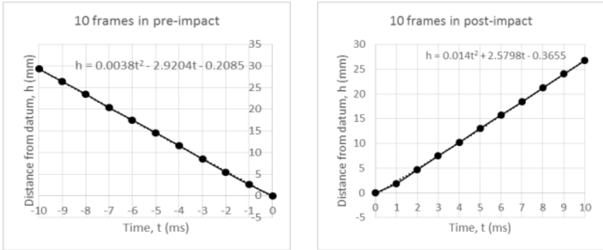
Instead of a linear trend line applied in the previous section, a second-order polynomial trend line was used to fit the distance vs. time curve. The general equation of the second-order polynomial is shown in Fig. 6 and (3):

$$h = at^2 + bt + c \tag{3}$$

where a, b and c are coefficients. By differentiating (3), we obtain

$$\frac{dh}{dt} = 2at + b \tag{4}$$

where the left-hand side of (4) is similar to (1), which is equal to the average velocity.



(a) (b)

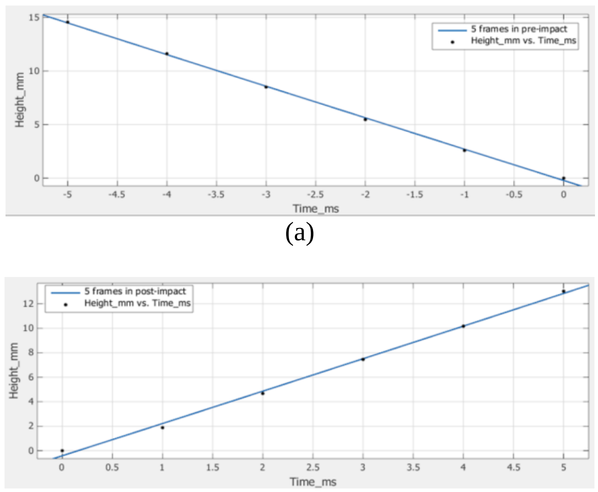
Figure 6. Second-order polynomial trend lines of distance from datum vs. time for (a) 10 frames in pre-impact and (b) 10 frames in post-impact.

c) Method IV: Second-order polynomial trend line fitted with the kinematic equation of free-fall motion

The kinematic equation of free-fall motion is given by

$$h = \frac{1}{2}gt^2 + v_0 t + h_0 \tag{5}$$

where g is acceleration due to gravity (9.81 m/s^2), v_0 is the initial velocity, and h_0 is the initial height of the ball at time zero. Fig. 7 shows an example of the second-order polynomial trend line fitted with the kinematic equation of free-fall motion on the distance–time plot obtained by Matlab software.



(b)

Figure 7. Second-order polynomial trend line fitted with the kinematic equation of free-fall motion on the distance–time plot within (a) 5 frames in pre-impact and (b) 5 frames in post-impact.

IV. DISCUSSION

Fig. 8 compiles the overall results obtained from all the previous methods. The number of frames used actually represents the total number of frames that were chosen in every analysis. In general, when the number of frames used increased, the velocity result also increased.

Moreover, the differences in the results were large when using 1 frame and 10 frames. These percentage errors are 12.67% and 30.85% for pre- and post-impact, respectively, when using method IV. Besides, it is obvious that the increment values are large when using a small number of frames (i.e. from frame 1 until frame 4). Conversely, the increments are smaller from 5 frames onwards because the curves start to converge in this section.

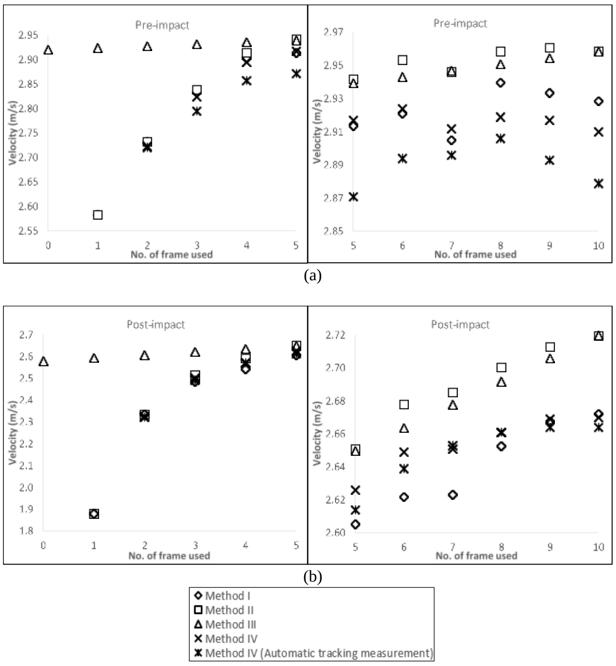


Figure 8. Results of velocity vs. number of frames used by all the measurement methods for (a) pre-impact and (b) post-impact.

The analysis using method I is the easiest method compared with the other methods. However, this method assumes that impact occurs at the datum point (or at the lowest altitude). Therefore, the ball's displacement and velocity are considered as zero at this point. In fact, the displacement and velocity of the ball have nonzero value at this point. This is because the high-speed camera has a limitation in showing the accurate image at a time when maximum deformation of the ball is actually happening. To solve this problem, curve fitting tools were used to create the best trend line on the distance–time data and were utilised in methods II, III and IV.

The slope of the linear trend line in method II is assumed to represent the velocity of the moving ball. In method III, fitting the curve by a second-order polynomial was conducted on the 10 frames of the distance–time data. The generated equation was differentiated to find the velocity equation as a function of time. Consequently, the result of velocity could be obtained at any time phase during pre- or post-impact. Furthermore, this is the only method that can predict the velocity at zero frame by substituting time equal to zero on the differentiated trend line equation. However, methods II and III have a weakness with the developed trend line equation where the equation does not show similarities with any equation of motion.

In contrast with previous methods, method IV uses a second-order polynomial trend line. The developed trend line equation is adjusted to have the same coefficient with the kinematic equation of free-fall motion as discussed in the previous section. Adjusting the coefficient on the trend line equation may reduce the goodness of the trend line. Nevertheless, as the adjustment only involves very small values and just one coefficient, there is only a small deviation in the root mean square error of the adjusted trend line. This method also solved the problem in method I, where the displacement and velocity obtained at the point of impact are nonzero. Moreover, the equation in method IV is based on the physics of the equation of free-fall motion, thus eliminating the rising issue in methods II and III. As a result, it can be concluded that method IV provides the most accurate and useful results compared with the other methods.

V. Conclusions

A 1000 fps high-speed camera was used to record the motion of a table tennis ball in a drop test. Good agreement was achieved between the manual and automatic tracking measurements, with percentage errors of less than 0.5% for both the pre- and post-impact velocities. Furthermore, automatic tracking measurement is preferred in future work because analysis can be easily carried out with minimal measurement errors. Four methods to calculate the velocity have been introduced. Method IV, which is the second-order polynomial trend line fitted with the kinematic equation of free-fall motion, is recognised as the best method. This is because the displacement and velocity measured at the point of impact are nonzero. Moreover, the equation in method IV is based on the physics of the equation of free-fall motion, thus eliminating the emerging issue in methods II and III. For future work, it has been suggested that we conduct the drop test at a faster drop speed and use a higher frame rate of the high-speed camera in order to optimise the boundary of current analysis.

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