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Novel methodology for measuring the coefficient of restitution from various types of balls and surfaces

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Abstract

The determination of the coefficient of restitution is of major interest in the design of balls and surfaces. Tennis courts are required to be resurfaced every five years. Players that slide on the court trust the surface to be uniform. Tennis court surfaces change as the ball fluff builds up, the heavily used playing areas are compacted more, the surface on clay is scuffed, and the sun and rain degrades the surface. Injuries can be caused by a player losing footing because of surface variability. With bouncing balls, the ball type and pressure are variable and depend on temperature and age. An investigation on the bounce of various balls (diameter less than 150mm) from surfaces using an accelerometer on a novel, low cost, portable apparatus is presented. The mechanical structure holds both the moving ball and an inertial sensor. The quality and age of balls and the wear on playing surfaces is particularly important for reflex actions of elite athletes. Courts, pitches and other sports surfaces can be routinely quantified using sport specific balls and this simple, low cost method. Good agreement was observed between the coefficient of restitution using the portable device and a vertical drop test using a high speed camera. The error obtained using the portable device on various types of sports balls with the variation in CoR ≤ 0.01 which falls within the standards of the International Tennis Federation. There is a significant difference ($p = 0.0003$) between a hardcourt tennis CoR and a synthetic grass tennis court.

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Keywords: Coefficient of restitution; accelerometers; inertial sensors; tennis; sports surfaces; sports balls; plexicushion prestige AUS

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1. Introduction

A tennis court surface is defined by four key properties: friction, energy restitution, topography and dimension and consistency [1]. The surface affects the energy loss of the ball and therefore the speed of the play. The Court Pace Rating (CPR) is used for classifying a tennis court. CPR is influenced by the Coefficient of Restitution (CoR) and the Coefficient of Friction (CoF) [1]. These parameters are measured using different methodologies [2-5]. The International Tennis Federation (ITF) [1] mentions that one of the key properties of a court surface is the energy restitution, which is the energy returned by the surface (and ball) following an impact. A decrease in energy return is manifested as a reduction in the vertical velocity of the ball after the impact. The CoR is recognized as a referred parameter of energy loss due to the motion in the normal direction, and it classifies the speed of a court. Several studies have examined the influence of playing surfaces on sports injuries [6, 7]. It was demonstrated that the differences in injury frequency are directly related to the differences in the frictional properties of the surfaces. Both the CoR and CoF are parameters that allow the assessment of the surface variability. However, only the CoR is analysed in this paper, while the CoF will be assessed in a further study.

Different techniques for the analysis of ball–surface interactions have been presented in the literature. The methods used to measure the CoR include the normal drop test [2], which consists of an apparatus based on a drop tower and a steel table. The drop tower includes an adjustable height mechanism and a ball releasing system. The steel table can be inclined for oblique

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impact experiments. A high speed camera was used to record the drop. Another method includes the bounce test [3]. The experiment consists of dropping a ball from a height of 254 cm allowing it to bounce at least twice. A microphone was used to record the time between the impacts. Furthermore, a high speed camera was used to record the peak height of the ball rebound determined by the timing of the impact sound. The use of high speed cameras offer direct measurements of the speed and angles of impact and rebound, the rotation after impact, and the normal and tangential CoRs. In [8], an impact hammer system capable of measuring the impact between a ball and a sport surface was reported.

The previous methods, although accurate, are restricted to large equipment, laboratory environments and/or removable samples of sport surfaces. Such infrastructure can be costly and its access can be limited to specialist research teams or big corporations. Factors such as temperature, humidity and air pressure may affect the measurements undertaken. In the laboratory only small surface segments can be measured. For that reason, a low-cost portable device has been developed to measure the CoR of different sports balls and sports surfaces. Since the CoR may be different at every playing zone on a single court/field, portability allows for the rapid measurement across any playing surface. The device contains a small portable accelerometer [9-11] which provides accurate information of the ball impact and the time between bounces. The accelerometer responds to movement (linear acceleration, angular velocity and angular acceleration), and the data extracted from the sensor is used to determine the CoR. This paper reports the bounce of a various types of sports balls (tennis, table tennis, super bounce) on different surfaces (thin fabric layer over concrete, tennis hardcourt and tennis synthetic grass court), using an accelerometer on a portable mechanical apparatus. To validate the accuracy of the device, the data was compared with a vertical drop test using high speed camera measurements and with the ITF approval test requirements [1].

2. Methods

2.1. Design of the apparatus

A portable device for in-field CoR consists of a wooden base with dimensions 22 cm × 14 cm × 2.2 cm (L×W×H), and a wooden arm (30 cm × 3 cm ×1 cm) attached to one of the ends of the base using a low friction hinge (Fig. 1). On the other end of the arm, the test ball is fixed using Velcro^{tm} so that balls can be easily replaced. A 3-axis accelerometer sensor was fixed on the top at the end of the arm and was used to trace the bounce of the ball based on α, the tilt angle between the horizontal base and the arm. Here h is the diameter of the ball which has an effect on the variation of the tilt angle. Only the x-axis from the sensor data was used, as the dominant axis for the identification of the maximum height from the ball bounce. The device is manually controlled with the initial release height calculated as function of the tilt angle.

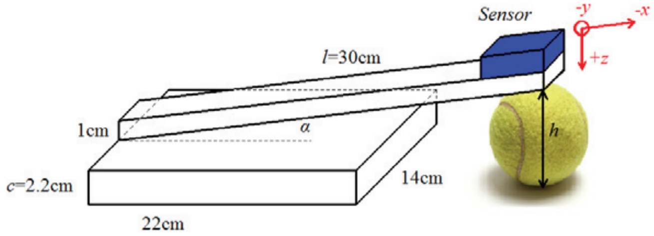


Fig. 1. Portable device used to determine the CoR for in-field measurements. The sensor is an accelerometer. The ball is attached to the arm by Velcro^{tm}.

2.2. Inertial sensor technology

An in-house sensor platform was used for this experiment [9-11]. SABEL Sense is a wearable sensor that collects data from digital MEMS (Microelectromechanical systems) inertial sensors and has dimensions 55 mm × 30 mm × 13 mm (L×W×H), a weight of approximately 23 g and is powered with a 138 mAh high density LiPo battery. The accelerometer is capable of measuring acceleration forces of ±10g in three perpendicular directions (g being the gravitational force). The platform contains wireless connectivity (2.4 GHz) for real-time data streaming.

2.3. Formulation of the CoR

Brody et al. [12] defines the CoR in tennis as the negative of the ratio of the relative tennis racquet and ball speeds after collision divided by the relative speeds before collision. If a ball is dropped on to the tennis court, no racquet velocity exists. In this case, it is possible to determine the CoR through the vertical drop height as

$$\mathrm{CoR} = \frac{v_{b2}}{v_{b1}} = \sqrt{\frac{h_b}{h_d}} \qquad (1)$$

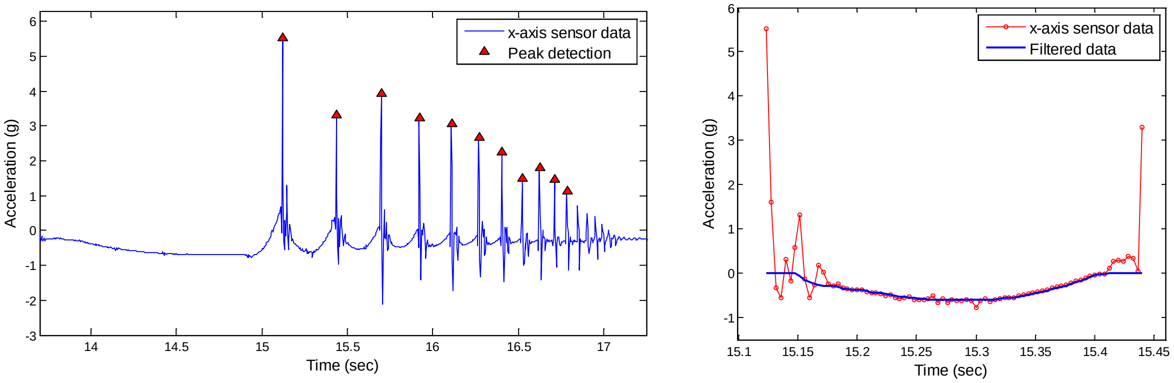
where v_{b1} is the ball velocity before collision, v_{b2} is the ball velocity after collision, h_b is the bounce height and h_d is the drop height of the ball. The device does not take into consideration the vertical drop relevant to the sensor orientation from Figure 1. The maximum tilt angle of the bounce can be determined from the minimum x-axis acceleration value between two consecutive bounces (peaks shown in Figure 2). The tilt angle α [13], can be determined by $\alpha = \mathrm{asin}(a_x/g)$, where a_x is the x component of the acceleration data and g is the gravitational acceleration. Using the tilt angle and an approximation based on the geometry of the device, the CoR can be calculated by

$$\mathrm{CoR} = \sqrt{\frac{h_{i+1} - h_0}{h_i - h_0}} \tag{2}$$

where $h_0 = l\sin(\alpha_0) + c$ is the initial ball height offset due to the acceleration offset measured before the start of the test, l is the arm length and c is the base height (Fig. 1), α_0 is the tilt angle offset at rest, $h_i = l\sin(\alpha_i) + c$ is the maximum height of the ball after the i_{th} bounce and α_i is the tilt angle of the i_{th} bounce.

3. Results

The portable device was tested in the laboratory and on tennis courts. In both cases, the tests consisted of manually lifting the arm and releasing. The ball bounces freely on the surface under test. The sensor data was extracted using SABEL Sense Data Analysis [9] and processed using Matlab®. Figure 2a shows the data extracted from the bounce of a super bounce ball tested on a thin fabric layer over concrete. A peak finder (triangle markers) allows the automatic detection of each bounce impact. The positive bounces in the data are consistent with the orientation of the sensor shown in Figure 1.



(a) (b)

Fig. 2. (a) Data extracted from the accelerometer (x-axis) on a super bounce ball tested on a thin fabric layer over concrete, and a peak finder (triangle markers) for bounce detection; (b) The filtered data between two bounces was used to determine the maximum ball height.

As the acceleration value of the maximum height between bounces is required to determine the ball height as function of both the tilt angle and the geometry of the device, a five point median filter was used to remove the noise and accurately determine the minimum value between two consecutive bounces (peaks). Figure 2b shows the filtered data between the first and second bounce. Once the minimum angle between consecutive bounces is determined, equation (2) was used to calculate the CoR. The results were compared with those from a vertical drop test using a high speed camera.

3.1. Laboratory test

The device was tested in the laboratory for three different balls: a super bounce ball, an aged/worn tennis ball and a table tennis (ping-pong) ball. The first two balls were tested on a thin fabric layer over concrete surface, while the latter was tested on a wooden surface. Three bounce repetitions were performed for each ball. The initial release of the device was set to an approximate height in order to obtain an almost vertical drop. This assumes that both (1) and (2) have no effects due to air resistance during the drop and rebound, as well as a frictionless pivot. The tilt angle offset at rest (α_0) and for the first two bounces (α_i, i = 1, 2) used in equation (2) for each ball tested with the device are shown in Table 1. Here α_i is the tilt angle average of the three tests performed on each ball.

Table 1. Tilt angle offset at rest (α_0) and for the first two bounces (α_i, $i = 1, 2$) for each ball tested in the laboratory using the portable device.

Tilt angle	Super bounce ball	Aged tennis ball	Table tennis ball
α_0 (offset at rest)	14.1°	8.4°	3.3°
α_1 (first bounce)	41.8°	39.1°	24.3°
α_2 (second bounce)	37.2°	24.4°	16.1°

In addition, vertical drop tests were performed for comparison with the super bounce and the tennis ball. The balls were released at approximately 1 m with 0° inclination from the thin fabric layer over concrete, a grid frame (with 9 mm grid marks) was placed behind the drop zone and a high speed camera was used to determine the exact height of each bounce by manually counting the number of grid lines crossed. Equation (1) was used to determine the CoR. The results obtained for the table tennis ball were compared with those presented in [2]. The mean and standard deviation of the CoR results for each ball are shown in Figure 3. There is good agreement between the results obtained with the portable device and those obtained in the vertical drop. According to the ITF standards [1], the variation in the CoR expressed as a standard error, i.e. standard deviation of all tests divided by the square root of the number of tests, must be ≤ 0.05. The highest deviation obtained in the tests using the portable device is 0.01 which is within the standard. There is a significant difference ($p = 0.002$) between the super bounce ball (mean 0.89 ± 0.0125) and the aged tennis ball (mean 0.74 ± 0.0067) for the tests performed using this device.

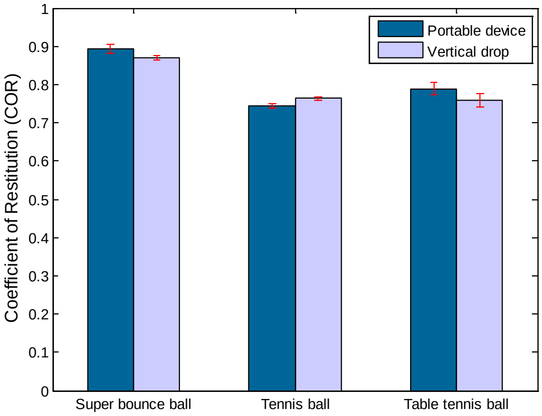


Fig. 3. Mean and standard deviation (error bars) of the CoR of three different types of balls tested on a thin fabric layer over concrete. The results are compared with a vertical drop test.

The data shown in Fig. 3 relates to different impact velocities for various types of balls. The CoR is dependent on the impact velocity for non-linear systems, and it decreases with an increasing impact velocity [14]. The initial release height, calculated as function of the tilt angle (see Section 2.3), was different for each tested ball, and it resulted in impact velocities of approximately 2 m/s. This velocity was determined by the motion equation with an angle dependency. The acceleration was determined by $g\cos\alpha$. The 1 m vertical drop test represents an impact velocity of 4.4 m/s which is almost twice that measured with the device. The differences between both tests may be due to the non-vertical drop, the weight of the sensor located at the end of the arm and above the ball, and the drag force through the air which was not considered significant.

Haake, et al. [14] calculated the CoR by dropping a ball onto a force platform clamped to a rigid surface for a range of 3 to 40 m/s impact velocities. The results presented in Fig. 3 are lower than those from [14], however, the CoR for the tennis ball (mean 0.74 ± 0.0067) is within the ITF approval test requirements for a rigid surface (0.72 to 0.76). Haake, et al. reported that the calculated CoR values were higher due to the non-rigid nature of the force platform employed in their tests.

3.2. Field test

A test was conducted using the portable device on two different tennis surfaces and using two different pressurised balls (aged/worn and new). The tested surfaces were sand filled artificial grass characterized by a medium to low ball bounce, and a Plexicushion Prestige AUS (hardcourt), a cushioned-acrylic system for asphalt and concrete base courts used in the Australian Open [1]. Between 15 to 20 bounces were recorded on each surface and for each ball. The tilt angle at rest (α_0) and the average angle of the first two bounces (α_i, $i = 1,2$) for all tests on each ball are defined in Table 2. The mean and standard deviation of the CoR results are shown in Fig. 4.

Table 2. Average tilt angle offset at rest (α_0) and for the first two bounces (α_i, $i = 1, 2$) for each ball tested in the tennis courts using the portable device.

Tilt angle	Hardcourt/aged tennis ball	Hardcourt/new tennis ball	Synth grass court/aged tennis ball
α_0 (offset at rest)	8.4°	8.5°	8.4°
α_1 (first bounce)	42.9°	46.8°	42.4°
α_2 (second bounce)	29.4°	29.5°	27.8°

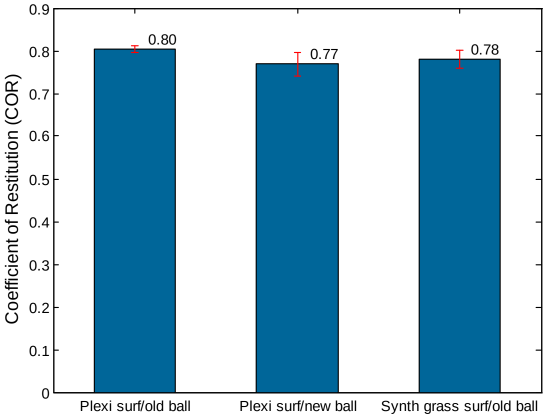


Fig. 4. Mean and standard deviation (error bars) of the CoR on aged and new tennis balls tested on Plexicushion and synthetic grass tennis courts.

There is a significant difference ($p = 0.0003$) between the Plexicushion tennis court CoR (mean 0.80 ± 0.0075) and the synthetic grass court (mean 0.77 ± 0.0204). The error in the Plexicushion using a new ball was ±0.0274, so in the three test cases, the results prove the measurements are consistent. There is also a significant difference ($p = 9\times10^{-11}$) between the aged tennis ball (mean 0.80 ± 0.0075), tested on a thin fabric layer over the concrete surface (see Section 3.1), and the same ball tested on the Plexicushion tennis surface (mean 0.74 ± 0.0067). The CoR for synthetic grass lies within the ITF approval test requirements [1] which range from 0.76 to 0.86. The ITF official document does not provide CoR measurements on a Plexicushion surface, but taking into consideration the reported values for acrylic (outdoor) as a close reference, the values presented in Figure 4 lie within the ITF standard (0.74 to 0.82).

4. Conclusions

A portable, low cost apparatus to measure the coefficient of restitution of various types of surfaces and sports balls was developed. A tri-axial accelerometer was used to obtain accurate information of the ball impact and the time between bounces. The *x*-component data was extracted from the inertial sensor and, together with the geometry of the device, the coefficient of restitution was determined. This prototype allows for low cost, rapid field tests, where factors such as tempreature, humidity and air pressure may affect the measurements undertaken. In-field tests allow for a rapid surface evaluation that could potentially reduce the frequency of injury by assessing the surface variability on the same court and between different courts.

Laboratory measurements were performed on three different types of balls on a thin fabric layer over concrete surface. The results obtained using the portable device were compared with those obtained from a vertical drop test using a high speed camera. A good agremeent between measurements was observed and the error obtained using the portable device was ≤ 0.01 which falls within the standards of the International Tennis Federation. Field measurements for two types of balls (aged and new) performed on two types of tennis surfaces was conducted. The results obtained proved consistency in the CoR with errors ≤ 0.02.

The portable device could replace expensive infrastructure that are limited to specialist research teams and are designed only for laboratory tests. However, the prototype requires some redesign of the sensor placement as the sensor weight may effect the ball bounce, as well as the ball attachment to the moving arm of the device, as the adhesive Velcro^{tm} attachment system employed may affect the ball vibration and the sensor data. The possibility of using the timing markers in the accelerometer profiles has yet to be investigated.

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