BALL IMPACT KINEMATICS AND DYNAMICS IN SOCCER KICKING

Hiroyuki Nunome[1], Hironari Shinkai[2] and Yasuo Ikegami[1]

Research Centre of Health, Physical Fitness & Sports, Nagoya University, Nagoya, Japan[1]
Faculty of Education, Art & Science, Yamagata University, Yamagata, Japan[2]

The purpose of this study was to illustrate dynamic behaviours of shank, foot and ball through ball impact phase. A time-frequency filtering approach succeeded in establishing more representative shank kinematics just before, during and just after ball impact whereas other procedures failed to remove noisy oscillation from the baseline, lost the peaks of rapid changes or produced totally distorted movement patterns frequently seen in many previous studies. Likewise, ultrahigh-speed video cameras (5000 Hz) and a mathematical model of ball deformation clearly demonstrated the dynamic interaction between the foot and ball during ball impact. It can be assumed that effectual duration to accelerate the ball corresponds to approximately three fourths of visually determined ball contact time and a longer contact time did not associated with a higher ball velocity.

KEY WORDS: time-frequency filter, ultra-high speed video, football.

INTRODUCTION: Kicking is the biggest attacking option and most widely studied skill in association football (soccer). Lower leg kinematics at or just before initial ball contact is important for determining both the quality of ball impact and the resultant ball velocity (Asami & Nolte, 1983; Andersen, Dörge & Thomsen, 1999; Dörge, Andersen, Sørensen & Simonsen, 2002). However, the true natures of kinematics and dynamics have been obscured by inadequate data treatment. Studies that have documented kicking biomechanics have typically captured limb movements at relatively low rates between 100 and 400 Hz (Isokawa & Lees, 1988; Rodano & Tavana, 1993; Barfield, 1995; Lees, 1996; Lees & Nolan, 1998; Levanon & Dapena, 1998; Andersen, et al., 1999; Teixeira, 1999; Dörge et al., 2002; Nunome et al., 2002) and then filtered the displacement data with a constant cut-off frequency of 6 - 18 Hz (Andersen et al., 1999; Teixeira, 1999; Dörge et al., 2002; Nunome, Asai, Ikegami & Sakurai, 2002). These methods were likely appropriate for describing the swing phase kinematics. However, as the duration of ball impact during soccer kicking ranges between 9 and 12 ms and rapid deformations of the foot and ankle occur during this time (Asami & Nolte, 1983; Asai, Akatsuka & Kaga, 1995), it is logical to assume that displacement data obtained in studies using lower sampling rates are unable to provide enough data points to adequately describe the curves of these short-duration, high-frequency movement characteristics. Furthermore, the filtering of low-frequency (swing phase) and high-frequency data (ball impact) together with a standard recursive Butterworth filtering approach is likely to distort kinematic information before and after impact (Knudson & Bahamonde, 2001).

Dual pass digital low-pass filtering is commonly used in biomechanics (Winter, 1990). However, this type of filtering is inefficient when processing signals whose frequency content varies dramatically with time. It is also very difficult to achieve sufficient noise elimination while keeping the useful high frequencies intact. Different cut-off frequencies, therefore, must be applied at different signal frequency domains. Most previous studies of the ball kicking motion have failed to acknowledge this limitation (Rodano & Tavana, 1993; Barfield, 1995; Lees, 1996; Lees & Nolan, 1998; Andersen et al., 1999; Teixeira, 1999) and it is likely that the leg swing motion immediately before ball impact has been inadequately documented.

From the standpoint of dynamics, during ball impact, the foot deforms largely as plantar flexion due to the reaction force acting from the ball. Tol, Slim, van Soest and van Dijk (2002) suggested that the impact force (preferably peak force) acting repeatedly on the kicking foot might be related to anterior ankle impingement syndrome. Thus, to comprehend the nature of this reaction force is likely important not only for the enhancement of kicking performance but

also for the prevention of such chronic disorders. Nevertheless, there is only one study by Tsaousidis and Zatsiorsky (1996) that illustrated the foot-ball interaction during ball impact although they used an unusual soccer kicking technique: toe kicking. Furthermore, there are only two studies that have estimated the peak magnitude of the ball reaction force during ball impact using a computer simulation (Asai, et al., 2005) and an approximation from average force during ball contact (Tol, et al., 2002). To date, no study has attempted to calculate the peak reaction force directly from the ball deformation and the displacement of its centre of gravity during ball impact using a fast enough high-speed sampling image of ball kicking.
A series of attempts (Nunome, Lake, Georgakis & Stergioulas, 2006; Shinkai, Nunome, Isokawa & Ikegami, 2009) have been made to clarify the natures of ball impact kinematics and dynamics in soccer kicking. These studies succeeded in demonstrating several unique, unexpected results. Through those, we would like to emphasize the discussion to gain our understanding for the characteristics of the collisions between a ball and the player's body assuming as important for performance enhancement and injury prevention.

FILTERING PROCEDURES: The lower leg motion of the instep kicking through ball impact was captured at 1000 Hz using a six-camera optoelectronic motion analysis system (ProReflex, Qualisys Inc., Sweden). Displacement data were obtained continuously from 30 ms before to 30 ms after ball impact. To those 3D coordinate data, we applied a new time-frequency filtering algorithm (**TFF**) which allowed changing the cut-off frequency along the time (Georgakis, Stergioulas & Giakas, 2002). The filtering algorithm operates on the raw displacement data of the toe, heel and ankle (y and z component only). The highest cut-off frequencies used for ball impact phase, determined by the automatic algorithm were 72 – 247 Hz. The coordinates that did not possess clear peak accelerations during ball impact were filtered by conventional Butterworth filter operating at 83.3 Hz. As the antero-posterior component of the toe marker is expected to have the highest frequency component, the cut-off frequency (83.3 Hz) was determined using the residual analysis (Winter, 1990) between its first derivative and the cut-off frequencies.
To illustrate how the conventional Butterworth filtering approach and lower sampling rate typically used in previous studies influence the transient kinematic features of the distal segment around ball impact, the displacement data were processed using three approaches. First, the coordinates were smoothed by a second-order dual-pass Butterworth digital filter with a cut-off frequency of 200 Hz (**BWF**). Second, the raw coordinates originally sampled at 1000 Hz were re-sampled at 250 Hz (every four frames) but not smoothed (**RSR**) to assess the influence of the lower sampling rate typically reported in the literature. Third, the re-sampled data were then filtered with a second-order dual-pass Butterworth digital filter at 10 Hz to resemble typical sampling and filtering conditions used in previous studies (**RSF**).

BALL IMPACT PHASE KINEMATICS: After the **TFF** and **BWF** processing, the angular and linear velocity curves followed well the changes during ball contact seen in the raw, unsmoothed 1000Hz data (Figure 1 & 2). The **RSF** data demonstrated totally distorted patterns in which the high frequency movement transients were removed completely. This is particularly evident when viewing the shank angular velocity and foot liner velocity curves which were falsely shown to decelerate as the foot approaches the ball, when in fact they were still ascending toward ball impact (**TFF** & **BWF**). Although the movement transients using the **BWF** processing appeared to follow well the raw changes through the ball impact phase (similar to the **TFF** approach), they still possessed appreciable noise in the low frequency movement phase (baseline) prior to ball impact, in particular for the shank angular velocity.
The sudden deceleration caused by ball impact is a difficult phase to capture adequately, which may cause a systematic error in its derivative parameters in the last few frames before ball impact. However, most ball kicking studies have failed to acknowledge this type of potential error (Isokawa & Lees, 1988; Rodano & Tavana, 1993; Barfield, 1995; Lees, 1996; Lees & Nolan, 1998; Andersen et al., 1999; Teixeira, 1999), in which apparent linear and angular deceleration of the distal segment were consistently observed.

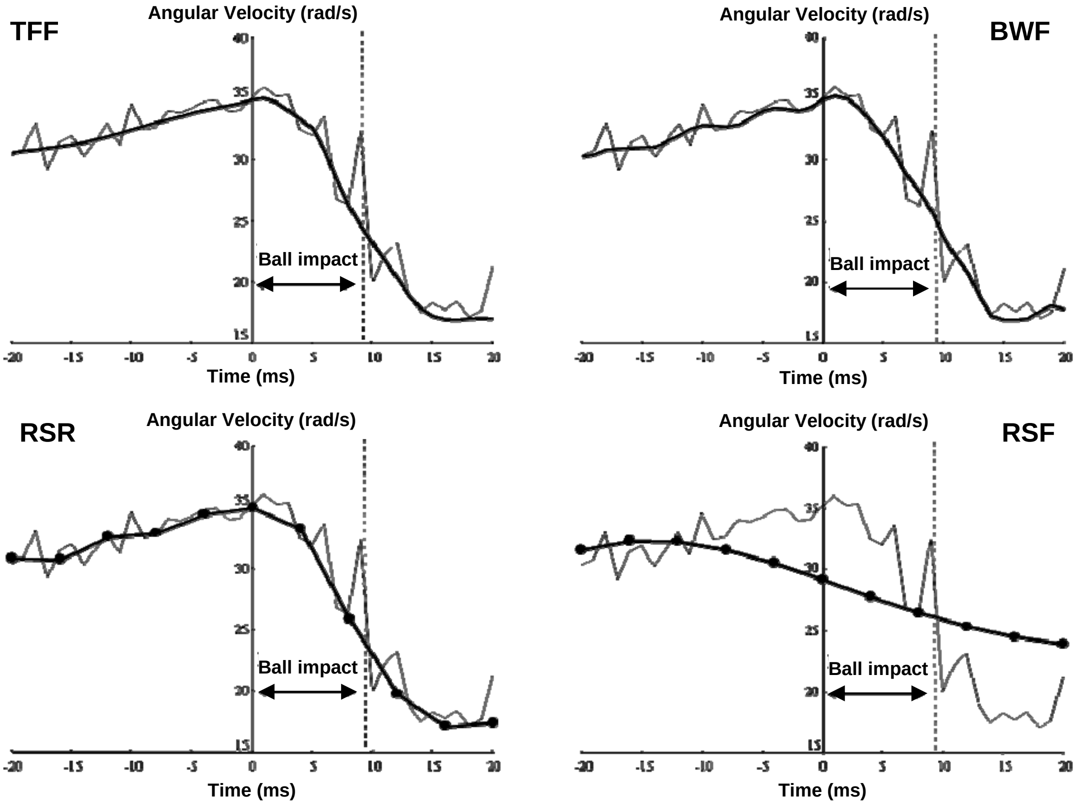


Figure 1. Comparison of changes of angular velocity of the shank around ball impact computed from four different filtering and sampling schemas (TFF, BWF, RSR & RSF). Typical changes (thick solid line) are shown against the original raw change (thin solid line).

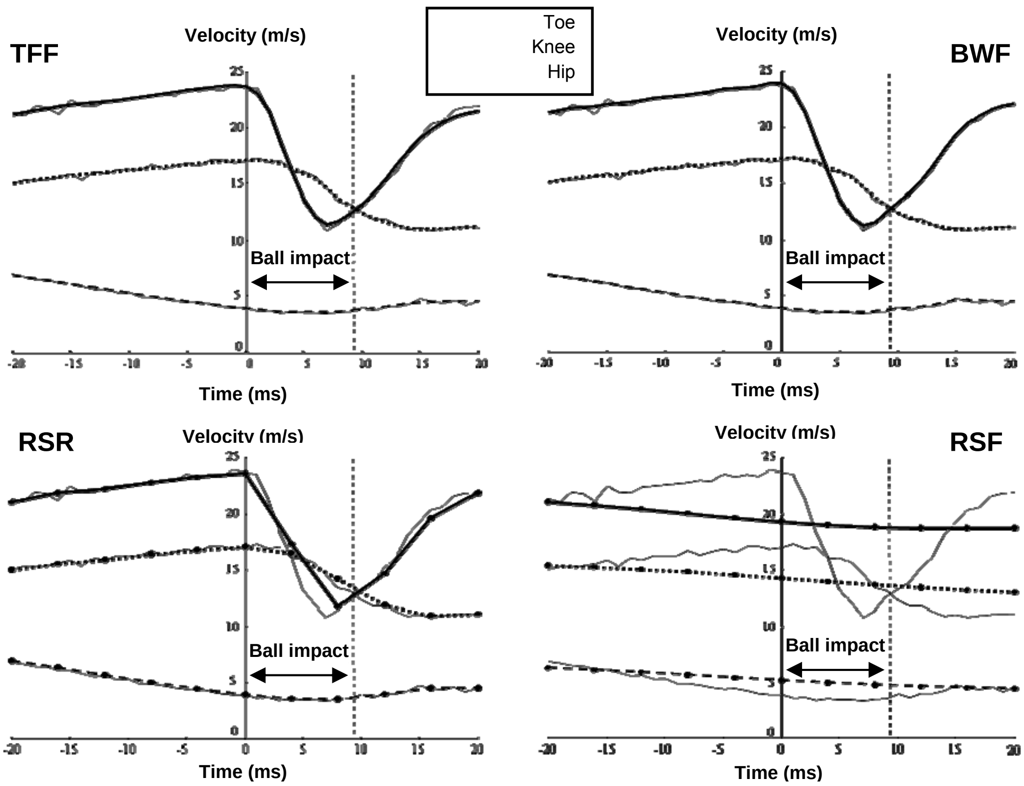
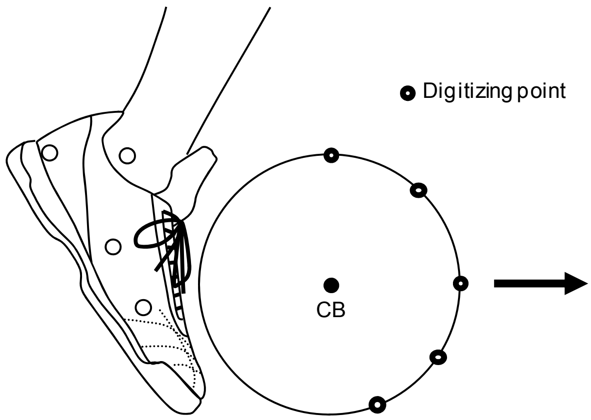


Figure 2. Comparison of changes of linear velocity of the toe, ankle and knee around ball impact computed from four different filtering and sampling schemas (TFF, BWF, RSR & RSF). Typical changes (thick line) are shown against the original raw change (thin solid line).

This nature of leg swing observed in the final phase of kicking has been led to a proposed accuracy enhancing strategy of motor control (Teixeira, 1999). However, angular and linear velocity changes observed in our study (Figure 1 & 2) were very different than those reported previously, and in contrast to the proposed strategy of kicking. In fact, both the shank angular and foot (toe and ankle) linear velocity showed ascending changes until the moment of ball impact. Adequate sampling speeds and filtering techniques succeeded in illustrating the swing motion of the distal segment more accurately. This nature of shank angular motion is in line with the study of Knudson and Bahamonde (2001). Although they used a tennis impact, showed that if the angular and linear data was smoothed through impact using conventional Butterworth filtering, a false peak before ball impact was introduced by over-smoothing (actually caused by a return path of the filtering).
On the field, coaches often advise players to 'kick through the ball', although there is no evidence to support this type of instruction from a biomechanical perspective. Our study is the first to provide evidence that strongly supports the above practical advice of kicking by revealing the 'more representative' distal segment motion before, during and after ball impact.

BALL DEFORMATION MODEL: Two ultra high-speed cameras (MEMRECAM fx-6000; NAC Inc., Tokyo, Japan) were used to capture the foot, the lower leg, and the ball motion of the instep kicking. The sampling rate was set at 5000 Hz to adequately analyze the foot and the ball behaviour during ball impact. The sampling speed was the fastest ever used for soccer kicking.
The ball deformation was obtained by the two-dimensional DLT method (Walton, 1979) using the lateral side image. The ball deformation was computed by the following assumptions: 1) the contact surface between the foot and the ball was flat, and 2) the ball deformation occurred perpendicular to the ball trajectory immediately after ball impact. First, from the coordinates of five points on the circumference of the right half of the ball (opposite side of the foot contacting face), the geometric centre of the ball (CB), which always retains its original sphere was obtained by least square method (Figure. 3). Next, the horizontal distance between the marker on the fifth metatarsal base (assumed to have minimal deformation by ball impact) and the CB was measured in each frame during ball contact. Finally, the change of this distance from the initial ball contact was defined as the ball deformation (BD).



The displacement of the apparent centre of gravity of the ball (CGB) was calculated from the assumed CB data. The ball was modelled a spherical shell, in which the mass (0.43 kg) was uniformly distributed onto the surface. As shown in Figure 4-I, the ball during foot contact was divided into two parts: A) part of hemispherical segment that assumed to retain its original shape and B) dented part by the foot. It was assumed that the part A was constructed the consecutive hollow circular discs (Figure 4-II) and the mass of the part B locates on the centre of the cross section, which was apart from the CB with the distance of $r \cos\alpha$ (Figure 4-I). In this model, the displacement of the centre of the gravity of the part A from the CB at each instant during ball impact was obtained by the following integral computation:

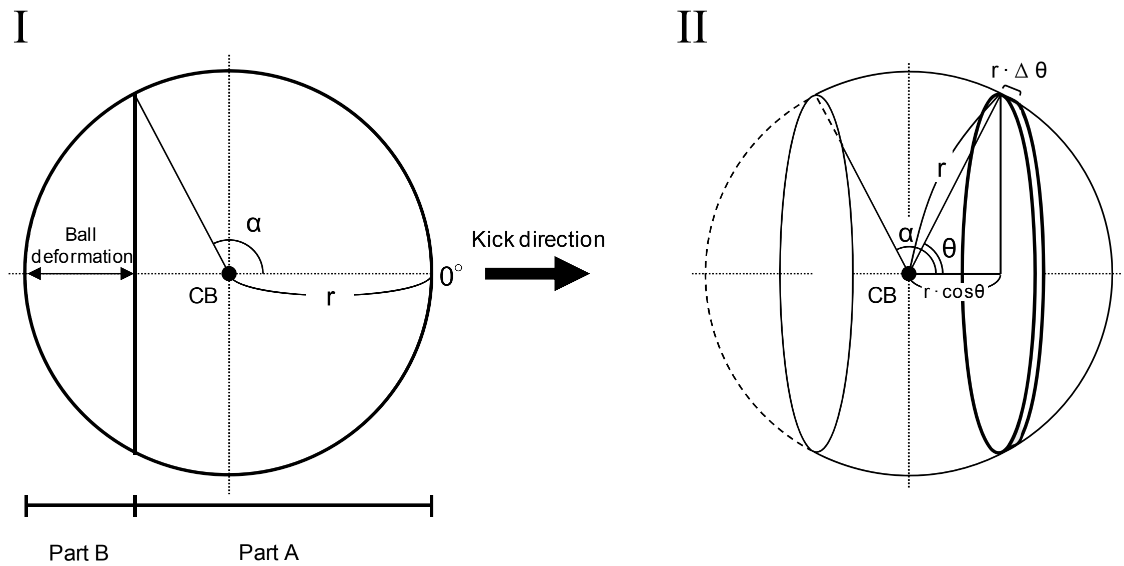


Figure 4. The modeling of the ball during foot contact. I, The deformed ball was divided into two parts using ball deformation data (BD). II, A circular disc constituted part A for calculation of the center of gravity of part A. These discs were sliced flat and perpendicular to the CGB. trajectory.

$$\frac{\int_0^{\alpha}(\rho 2\pi r\ \sin\Theta\ r\ \cos\Theta\ rd\Theta)}{\int_0^{\alpha}\rho 2\pi r\ \sin\Theta\ rd\Theta}$$

whereαis the angle defined by ball deformation (Figure 4-I), and it is calculated by the following expression:

$$\alpha = \cos^{-1}\left(-\frac{r - BD}{r}\right)$$

where BD is the ball deformation. Moreover, the displacement of centre of gravity of part A from the CB can be expanded as follows:

$$= \frac{2\pi r^3 \rho \int_0^{\alpha} \frac{1}{2} \sin 2\Theta\ d\Theta}{2\pi r^2 \rho \int_0^{\alpha} \sin\Theta\ d\Theta} \qquad = \frac{r(1 - \cos 2\alpha)}{4(1 - \cos\alpha)}$$

The CGB location was obtained in each frame from that of the centre of gravity of the above two parts.

BALL IMPACT PHASE DYNAMICS: Transient change of the ball deformation and the velocities of the foot (fifth metatarsal base) and the centre of gravity of the ball (CGB) were clearly illustrated (Figure 5). Tsaousidis and Zatsiorsky (1996) was the only study which is comparable to these results although they used an unusual kicking technique: toe kicking. Basically, the results showed similarities for many points except for the ball deformation model. They measured the ball velocity by its bottom edge thereby causing a distinctive delay (for a few milliseconds) of the onset of forward movement of the ball. One critical advantage of our model is to illustrate the displacement of the apparent CGB being deformed. Using the spherical shell model, we succeeded in illustrating more representative curve of the onset of the CGB velocity immediately after the foot contacted with the ball.
The ball impact phase, although it has quite short duration (typically less than 10 ms) can be divided into four phases (Figure 5). During the phase I, the CGB will move together with its deformation even if the other side of the ball (unchanged part) seems to keep its stationary

position. Until the end of phase II, as the foot velocity always exceeded that of the ball, it can be assumed that the foot mainly and positively propels to accelerate the ball by imparting its linear momentum to the ball. Then, the CGB velocity conversely begins to exceed that of the foot, and the ball decompression begins in phase III. In this phase, it can be supposed that the ball recoil occurs on the foot as a base and mainly contributes to increase the ball velocity to its approximate launching velocity (95% of the launching velocity). At the beginning of phase IV, it seems that the ball velocity was almost levelled, and the foot deceleration was already terminated while the foot still seems contact with the ball. It should be interpreted that effectual duration to increase ball velocity during ball contact is about three fourths of the visually contact time because there observed little change of the ball and the foot velocity during phase IV.

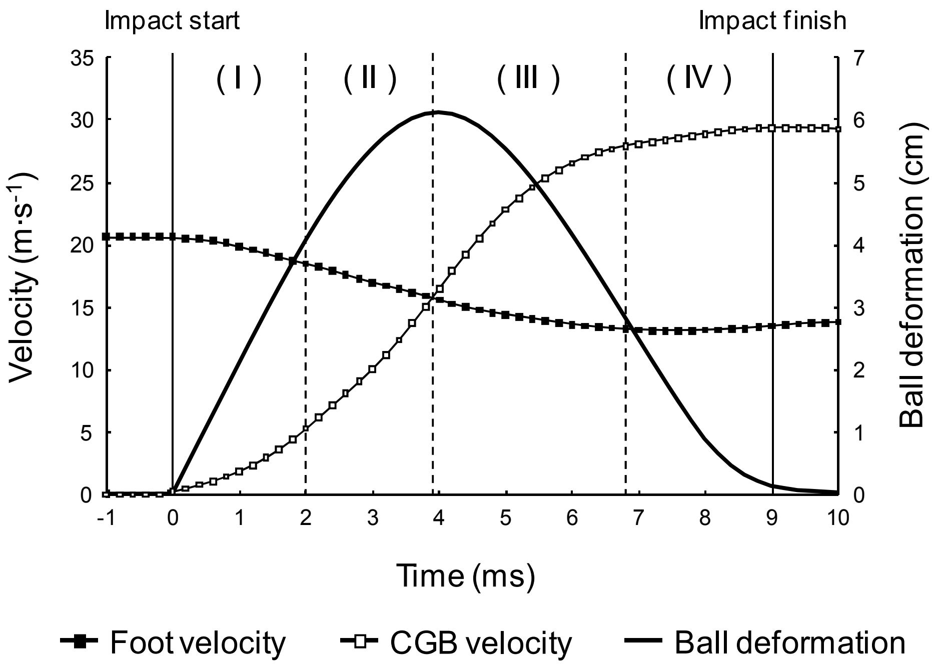


Figure 5. Foot–ball interaction during ball contact with the foot. The ball impact phase is divided into four phases by five key moments related to the foot and the ball behavior.

Only a few studies reported the peak magnitude of ball impact force in the literature. Asai et al. (2005) reported approximately 2500 N by computer simulation, and Tol et al. (2002) reported 1610 N by the change of linear momentum of the ball. In our study, the peak force reached 2926 N, which corresponded to more than four times as much as the player's body weight and its value seems somewhat larger than those of the previous studies. As the estimated peak ball reaction force was even larger than that of Tol et al. (2002), the results of this study reinforce the hypothesis of Tol et al. (2002) that repetitive, large ball reaction force acting on the foot by kicking could contribute to the pathogenesis of anterior ankle impingement syndrome known as ‘‘footballer's ankle.’’

There is a myth among coaches/players that a longer contact time between the ball and the foot during ball impact phase is an essential factor of highly skilled footballers who can produce a faster ball velocity. However, we found only a weak, negative relationship between the ball contact time and resultant ball velocity (Figure 6). The result is clearly in contract to the myth which has been believed in the practical field. According to the foot-ball interaction during ball impact, that result seems very logical because it is impossible for the players to control the ball recoiling on the foot, which was the most dominant factor to increase the ball velocity in the latter half of ball impact phase.

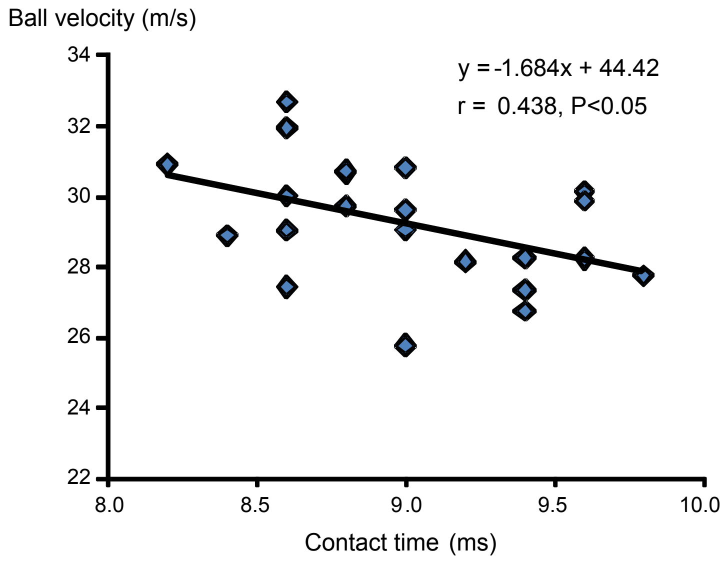


Figure 6. Relationship between resultant ball velocity and ball contact time.

CONCLUSION: Ball impact phase has been considered as a very difficult phase to adequately analyze. Our comprehensive studies of soccer instep kicking revealed several new features during this phase. In contrast to the previous studies, the shank was still angularly accelerated until ball impact as is observed for tennis impact. To reveal that fact, time-frequency filtering procedures demonstrated a distinct advantage in removing noise, yet maintained the peak values of high-frequency movement transients. Likewise, the use of ultrahigh-speed video and mathematical model of ball deformation documented dynamic foot–ball interactions during ball impact. It can be considered that effectual duration to accelerate the ball is roughly three fourth of visually determined ball contact time, and the peak ball reaction force is most likely lager than the values previously estimated.

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