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BASIC MECHANICAL ANALYSIS OF SOCCER BALL IMPACT

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The present study aimed to provide a reference of the nature and the magnitude of the ball reaction force during ball impact. A soccer ball directly fired to the force platform and the sagittal motion was captured at 5000Hz. The peak forces and impulses during ball contact were computed from the displacement of the ball geometric centre (CB force / impulse) and the centre of the gravity (CGB force / impulse), and those values were compared with the force directly measured from the force platform (D force / impulse). Overall, the CGB forces were comparable to the D force while the CB forces were substantially overestimated. Those impulses were well matched with the theoretical value computed from the change of ball momentum before and after the contact. Those findings of the present study confirmed the reliability of the CGB model.

KEY WORDS: soccer, ball deformation, peak reaction force, impulse

INTRODUCTION: In soccer, ball impact technique forms an important part of kicking techniques and can be regarded as a collision between foot and ball. To date, several studies have examined the ball impact dynamics during instep or similar full kicking. Of these, only a few studies reported the peak magnitude of ball reaction force acting on the players' foot. Asai et al. (2002) reported that the peak magnitude of the impact force of the instep kick was 2439N and that of the infront curve kick was 2206N using ultra high speed video records (4500Hz) and a computer simulation. Tol et al. (2002) approximated the impact force-time curve by a half sine wave, and reported 1610N. Shinkai at al. (2009) made a novel attempt to directly estimate the peak magnitude (2926N) from the movement of the centre of the gravity of the ball being deformed. It seems that the magnitudes are likely dependent on the computational procedures. Tol et al. (2002) suggested that the ball reaction force acting repeatedly on the foot during ball impact is capable of damaging anatomic structures and maybe linked to "footballer's ankle". On the other hand, most of players strive to achieve a faster ball velocity because the ability to produce a faster ball velocity is a big advantage of players; however, those players will suffer a bigger ball reaction force on the foot in exchange for the faster ball velocity. Thus, to reveal and validate the nature and magnitude of the ball reaction force acting on the foot would be beneficial information regarded to improve the kicking performance and/or to prevent chronic disorders.

In the present study, an attempt was made to provide a reference of ball reaction force through an experiment that the ball directly fired to the force platform and the movement was captured enough high sampling rate. Therefore, the present study aimed 1) to provide a reference of the nature and the magnitude of the ball reaction force and 2) to validate several models used to estimate those parameters of the ball reaction force.

METHODS: A soccer machine (Soccer machine, JUGS Sports, Oregon, USA) was used to fire a soccer ball to a force platform (Type 9281E, Kistler Instruments, Winterthur, Switzerland) 2 m ahead. The force platform was fixed vertically at a specially made steel pedestal. The pedestal was immobilized on a bare, flat concrete surface with additional weights. An approved size five soccer ball (Pelada 405, Molten Corporation, Hiroshima, Japan ; diameter = 22 cm, mass = 426 g) was used, and its inflation was controlled at 0.9 bar throughout the experiment. The ball was fired to the force platform in five different velocities. The trials were repeated five times in each velocity condition. An ultrahigh-speed camera

(MEMRECAM HX-3, NAC Inc., Tokyo, Japan) was used to sample the ball motion within the sagittal plane at 5000Hz, positioned perpendicular to the ball fired direction. Ball reaction force was recorded simultaneously at 10 kHz by force platform. The two dimensional coordinates in the lateral side image were defined as follows: The horizontal X axis was pointed to opposite direction of ball launching, and the vertical Y axis was pointed upward. A digitizing system (Frame DIAS, DKH Inc., Tokyo, Japan) was used to manually digitize seven points on the circumference of the nondeformed part of the ball in the lateral side image from 0.01s before to 0.01s after ball contact.
According to the procedure of Shinkai et al. (2009), the geometric centre of the ball (CB) was obtained by least square method, and was assumed as the imaginary CB, which always retains its original sphere shape while being deformed by the contact. The displacement of apparent centre of gravity of the ball (CGB) was calculated from the method of the previous study by the following procedure: 1) The ball was modelled as a spherical shell in which the mass was uniformly distributed onto the surface. 2) The ball during contact was divided into two parts, nondeformed part (A) and missing part dented by the force platform (B). 3) The part A was modelled that constructed the consecutive hollow circular, and the displacement of centre of the gravity of the part A from the CB during contact was calculated by integral computation. 4) The mass of part B was located on the centre of the cross section. 5) The coordinates of the centre of the gravity of the deformed ball (CGB) was computed by the coordinates of the centre of gravity of the parts A and B in each frame during ball contact. The ball velocity before the contact was represented by CB velocity and it was calculated for horizontal (X) component as the first derivative of linear regression line fitted to nonfiltered displacement during 0.01s just before the contact. The ball velocity after the contact was also calculated in the same procedure. The change of the CB and CGB velocity during ball contact were computed from the raw X coordinates from 0.01s before to 0.01s after the contact and then smoothed by a fourth-order Butterworth low-pass filter at 350Hz of cutoff frequency. Change of the X coordinate of the CB from the initial ball contact was defined as the ball deformation. The contact time was measured visually from the number of the frames that contact of the ball with the force platform was observed. The peak ball reaction force was calculated by multiplying the value of the peak ball acceleration that was computed from the velocity slope from 0.001s before to 0.001s after the time of peak deformation(11 points for 2ms) and mass of the ball (Shinkai et al., 2009). The peak forces were computed from CB velocity change (CB force) and CGB velocity change (CGB force) and those values were compared with the force that was directly measured from the force platform (D force). Moreover, those impulses during ball contact were calculated as CB impulse, CGB impulse and D impulse and those impulses were compared with the theoretical value computed from the change of ball momentum before and after the contact.

RESULTS: Selected kinematic parameters are summarized in Table 1. Figure 1 shows the relationship between the ball contact time and the ball velocity. The ball contact time decreased curvilinear against the increase of the ball velocity and also the contact time seemed to be levelled at approximately 15m/s of the ball velocity. Figure 2 shows the average change of ball deformation during ball contact in each velocity condition. As shown, the ball deformation systematically increased along with the increase of the ball velocity. Figure 3 shows the average change of the linear velocity of the centre of the ball(CB) and of the centre gravity of the ball (CGB) just before, during, and after ball contact in the fastest

Table 1: Selected kinematic parameters

	Mean(SD)									
Trial number	1		2		3		4		5	
Ball contact time (ms)	8.5	(0.1)	8.3	(0.2)	7.9	(0.1)	7.7	(0.1)	7.4	(0.0)
Ball X velocity										
Before Ball X velocity(m/s)	-9.05	(0.09)	-11.36	(0.12)	-13.68	(0.20)	-16.27	(0.10)	-19.46	(0.18)
After Ball X velocity(m/s)	7.21	(0.07)	8.90	(0.14)	10.56	(0.24)	12.25	(0.08)	14.40	(0.18)
Velocity-changing(m/s)	16.27	(0.14)	20.26	(0.25)	24.24	(0.43)	28.52	(0.12)	33.86	(0.33)
Ball deformation										
Peak deformation (cm)	2.45	(0.10)	3.13	(0.15)	3.57	(0.12)	4.03	(0.09)	4.64	(0.08)
Time of peak deformation from initial ball contact (ms)	3.6	(0.2)	3.7	(0.1)	3.6	(0.2)	3.4	(0.1)	3.4	(0.1)
The ratio of the peak deformation(%)a	42.7	(2.5)	45.0	(2.0)	44.9	(2.0)	43.5	(0.9)	45.4	(1.2)

[a] The ratio of the peak deformation of the ball occurrence time to the ball contact time

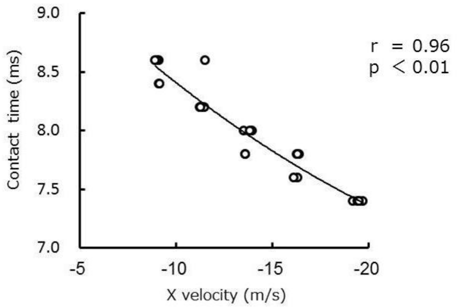

Figure 1: The relationship between the ball contact time and the ball X velocity

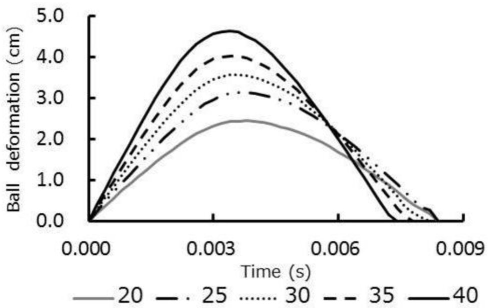

Figure 2: The average change of ball deformation during ball contact in trial ball of each velocity conditions.

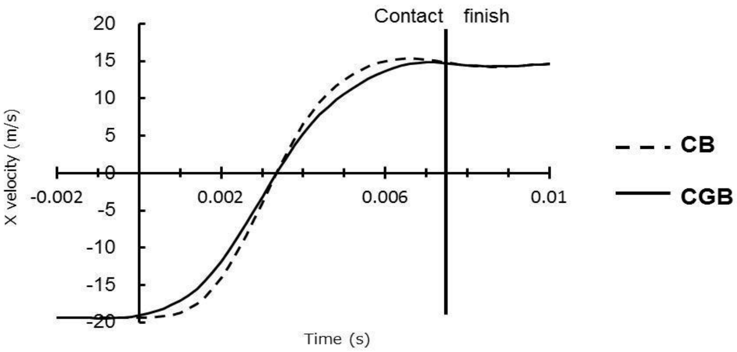

Figure 3: The average change of the linear velocity of the center of the ball(CB) and of the center gravity of the ball (CGB) just before, during, and just after ball contact in the fastest velocity condition (19.46±0.18m/s).

velocity condition (19.46±0.18m/s). There is an apparent discrepancy for the velocity changes between CB and CGB. During the ball deforming phase, the CGB velocity begun to increase from the initial ball contact while that of the CB had an apparent delay of its onset. After that, the both ball velocity changes overlapped around the maximal ball deformation. Likewise, reflected changes were observed for both velocity changes during the ball recoiling phase. Selected values related to force are summarized in Table 2. The average CGB forces were closer to that of D force. In contrast, the average CB forces were substantially larger than that of D force. These discrepancies for the magnitude tended to be larger in higher ball velocity conditions. On the other hand, the values of CB impulse, CGB impulse and D impulse were well matched with the theoretical value in all velocity conditions.

Table 2: Selected values related to force

	Mean(SD)									
Trial number	1		2		3		4		5	
Ball reaction force (N)										
CB	1760	(85)	2277	(74)	2803	(77)	3533	(137)	4405	(118)
CGB	1585	(71)	1985	(57)	2398	(58)	2967	(118)	3598	(88)
force platform	1565	(52)	2003	(54)	2416	(39)	2937	(82)	3553	(93)
The impulse of contact(N･ms)										
CB	6.9	(0.1)	8.8	(0.1)	10.4	(0.3)	12.3	(0.1)	14.5	(0.3)
CGB	6.9	(0.1)	8.7	(0.1)	10.3	(0.3)	12.1	(0.8)	14.3	(0.3)
force platform	7.0	(0.1)	8.5	(0.1)	10.3	(0.2)	11.8	(0.1)	13.9	(0.3)
Theoretical value	7.0	(0.1)	8.8	(0.1)	10.5	(0.3)	12.4	(0.2)	14.6	(0.3)

DISCUSSION: In the present study, an attempt was made to provide a reference of soccer ball reaction force. Theoretical value of the impulse computed from the ball momentum before and after ball contact and the impulse measured by a force platform were well matched. Therefore, it can be considered that the force change directly measured by the force platform is a reliable reference. Thus, the peak force was compared with those estimated from ball velocity changes (CB force and CGB force). In the procedure of Shinkai et al. (2009), a linear regression line was fitted to the slope of ball velocity change around the peak ball deformation to yield the peak acceleration of the ball. However, as shown in Figure 3, the CB velocity slope around the peak deformation was apparently overestimated because the CB model did not account for the ball deformation. The present study indicated that the model of CB most likely yield substantially larger peak force magnitudes while CGB forces were closer to the reference force in all velocity conditions. Only a few studies reported the peak magnitude of ball impact force. Asai et al. (2002) reported approximately 2500N by a computer simulation, and Shinkai et al. (2009) reported 2926N from the movement of the centre of the gravity of the ball being deformed. Of these, the study of Shinkai et al. (2009) can be used for comparison because their study used the same cinematographic procedure as is used in the present study. In their study, subjects were instructed to perform maximal instep kicking of stationary ball thereby producing the initial ball velocity of 29.3±1.7m/s and the peak ball reaction force was estimated as 2926N on the average. For a fair comparison, we focused on the amount of change of the ball velocity just before and after ball contact and trials that showed a similar change of ball velocity (approximately 30m/s) were chosen. In this condition, the average values of CGB force (2967N) and of D force (2937N) were quite comparable to that of the study of Shinkai et al. (2009). This result confirms that the cinematographic procedure proposed by Shinkai et al. (2009) is most likely a reasonable way to estimate the peak ball reaction force actually happened during soccer ball impact.

A longer foot to ball contact time has been thought by coaches/players to be an important factor of highly skilled footballers who can produce a faster ball velocity with good ball impact quality. However, the results of the present study are not consistent with this theory, even the contact time reduced curvilinear against the increase of the ball velocity and levelled approximately after 15m/s of the ball velocity. Shinkai et al. (2009) threw a doubt on the above mentioned practical theory by indicating the major factor to increase the ball velocity during the latter half of ball impact is ball recoiling. Besides, Nunome, Shinkai and Ikegami (2012) found only a weak, negative relationship between the ball contact time and resultant ball velocity. According to the foot to ball interaction during ball impact shown by Shinkai et al.(2009), the result of the present study seems very reasonable thereby reinforcing the result of these previous study.

Methodological limitation of the present study to mimic actual foot to ball impact are 1) a flat shape of the impact surface, 2) a rigid surface of the force platform and 3) a larger effective striking mass. In actual ball impact, it is assumed that the foot penetrates deeper into the ball and also the foot itself deformed by the ball reaction force. These factors might affect smaller ball deformation (up to 4.64cm) and shorter ball contact time (up to 7.4ms) observed in the present study. Further work needs to address those issues via the use of human like kicking machine with lighter and softer kicking foot.

CONCLUSION: It can be concluded that: 1) the model of ball centre of gravity can yield approximate peak force values while the model of ball geometric centre tend to overestimate the peak force magnitudes and 2) the cinematographic procedure of Shinkai et al. (2009) is most likely a reasonable way to estimate the peak ball reaction force actually happened during soccer ball impact.

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