Theoretical Study of Factors Affecting Ball Velocity in Instep Soccer Kicking

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The objective of this study was to investigate the factors affecting ball velocity at the final instant of the impact phase ($t_1$) in full instep soccer kicking. Five experienced male university soccer players performed maximal full instep kicks for various foot impact points using a one-step approach. The kicking motions were captured two dimensionally by a high-speed camera at 2,500 fps. The theoretical equation of the ball velocity at $t_1$ given in the article was derived based on the impact dynamics theory. The validity of the theoretical equation was verified by comparing the theoretical relationship between the impact point and the ball velocity with the experimental one. Using this theoretical equation, the relationship between the impact point and the ball velocity was simulated. The simulation results indicated that the ball velocity is more strongly affected by the foot velocity at the initial instant of the impact phase than by other factors. The simulation results also indicated that decreasing the ankle joint reaction force during ball impact shifts the impact point that produces the greatest ball velocity to the toe side and decreasing the ankle joint torque during ball impact shifts the impact point that produces the greatest ball velocity to the ankle side.

Keywords: ball impact, kinetics, impact dynamics theory, theoretical equation, simulation

In full instep soccer kicking, the ball is hit by the dorsal aspect of the kicking foot. Instep kicking is generally used when a faster shot or pass is required during a soccer match. The ball impact phase is important for determining the resultant ball behavior after impact.

Most studies of the impact phase for instep kicking have focused on kinematic aspects. It is well known that positive correlations exist between the foot velocity at the initial instant of the impact phase ($t_0$) and the ball velocity at the final instant of the impact phase ($t_1$) (Andersen et al., 1999; Asami & Nolte, 1983; Isokawa & Lees, 1988; Levanon & Dapena, 1998; Nunome et al., 2006b). Further, Asami & Nolte (1983) measured the angular displacement of the ankle and the metatarsophalangeal joint during ball impact and concluded that to kick a ball powerfully, the impact should be made closer to the ankle and not on the forefoot. Ishii et al. (2007) reported that the impact on the area surrounding the center of mass (COM) of the foot (the COM is located at 59.5% of the length of the foot from distal to proximal (Ae et al., 1992)) produced the greatest ball velocity and little angular displacement of the ankle during ball impact. As mentioned above, although it has been shown that the impact point is one of the factors affecting the ball velocity, the factors affecting the ball velocity have not been examined using the kinetic approach.

Although kinetic data such as the joint torques during the leg swing phase until $t_0$ have been reported for instep kicking (Nunome et al., 2002, 2006a; Putnam, 1991), no kinetic studies have been performed on dynamic phenomena occurring during ball impact. However, Ishii et al. (2007) and Ishii & Maruyama (2007) calculated the impact force from the ball deformation by applying the Hertz contact theory (Greszczuk, 1982; Timoshenko & Goodier, 1970). The ankle joint reaction force and ankle joint torque during ball impact can be calculated by an inverse dynamic analysis using the impact force. The ankle joint reaction force and ankle joint torque during ball impact are possible kinetic factors affecting the ball velocity. The theoretical equation of the ball velocity based on the impact dynamics theory related to these kinetic factors can be used to specifically investigate the factors affecting the ball velocity. Andersen et al. (1999) derived a simple equation to describe the ball velocity and examined the factors affecting the ball velocity; however, the kinetic factors and the impact point were not fully considered in their equation.
Although Sterzing & Hennig (2007, 2008) examined the effects of shoe features on the ball velocity in full instep kicking using unique experimental approaches, it would be difficult to examine the effects of specific variables (e.g., kinetic factors) on the ball velocity for various impact points. Asai et al. (2002, 2005) conducted finite-element simulations during ball impact based on kinematic data obtained experimentally. Although a finite-element analysis is useful for studying dynamic phenomena during ball impact and the resultant ball velocity at \( t_i \), the theoretical equation is considered better suited (necessary and sufficient) for studying the factors affecting the ball velocity for various impact points.

The objective of this study was to investigate the factors affecting the resultant ball velocity at \( t_i \) in full instep kicking using the kinetic approach. To accomplish this objective, the theoretical equation of the ball velocity was derived based on the impact dynamics theory concerning the simplified foot–ball impact model. Experimental data were substituted into the theoretical equation or were compared with the theoretical data to verify the validity of the theoretical equation. And then simulations of the ball velocity were conducted using the theoretical equation. It is thought that the theoretical understanding can help soccer players improve their kicking skills.

**Methods**

**Experiment**

Five experienced male university soccer players (age: 22.4 ± 1.9 years, height: 171.0 ± 6.2 cm, body mass: 62.5 ± 9.5 kg) who had more than 10 years of soccer practice participated in this study. They were informed of the purpose of the study and the procedures that would be used; these procedures were performed in accordance with the protocol approved by the Research Ethics Committee of the Tokyo Institute of Technology. A written informed consent was obtained from all subjects. The subjects were all right-footed kickers. The experiment and the kicking trials were then conducted.

The subjects were instructed to perform maximal full instep kicks using a one-step approach, toward a target on a goal net that was positioned 4 m away. The target was a rectangle with a height of 0.5 m (above the ground level) and a width of 1.0 m. In consideration of the two-dimensional analysis, the subjects were also instructed to swing their kicking leg through a vertical plane including the direction of the target. To obtain various foot impact points from the distal end of the metatarsal to the ankle along the longitudinal axis in the dorsal aspect, the height at which the ball was placed was changed from 0 to 12 cm at intervals of 2 cm by placing the ball on a support stand (a cardboard cylinder). The subjects performed three or four kicks for each height. A high-speed camera (Memrecam fx-K4, NAC Inc., Japan) was used to capture the kicking foot’s motion and ball behavior at 2,500 fps. The camera was placed perpendicular to the sagittal plane. Furthermore, a digital video camera was placed posterior to the subject to check the kicking motion and ball trajectory.

Markers having a diameter of 10 mm were secured on body landmarks of the kicking leg and shod foot, including the toe (digitus secundus), fifth metatarsal head, COM of the foot, heel, ankle (lateral malleolus), knee (lateral condyle), and intermediate cuneiform. The position of the COM of the foot was derived from the markers of the toe and heel based on the body segment inertia parameter reported by Ae et al. (1992); the COM was at 59.5% of the length of the foot from distal to proximal. Before the kicking trials, the position of the intermediate cuneiform marker was recorded against two tracking markers on the toe and fifth metatarsal head under static conditions. The intermediate cuneiform marker was removed after recording the relative position, and the kicking trials were then conducted.

**Data Processing**

Both the high-speed camera and the digital video images were confirmed, and the trial in which the instep kick was not conducted according to the instructions was excluded from the analysis. A digitizing system (Frame-DIAS II, DKH Inc., Japan) was used to digitize markers fixed on six body landmarks including the toe, fifth metatarsal head, COM of the foot, heel, ankle, and knee. Three points on the apparent circumference of the ball where the deformation was relatively small during ball impact (top, right edge, bottom) were also digitized. The impact phase was defined as the time period when the foot was in contact with the ball on the image.

The position of the intermediate cuneiform in the kicking trials was calculated by using the relative position of the intermediate cuneiform to the toe and fifth metatarsal head (Figure 1). The position of the center of the ball, which was considered to be located at an equal distance from the three digitizing points on the ball circumference, was obtained by calculating the intersection point of two perpendicular bisectors of two chords comprising the three points (Figure 1).

The coordinate data of the eight points (the toe, fifth metatarsal head, COM of the foot, heel, ankle, knee, intermediate cuneiform, and center of the ball) were digitally smoothed by a fourth-order Butterworth low-pass filter at a cut-off frequency (40–162 Hz) determined by using a residual analysis (Winter, 1990).

**Impact Point**

It was assumed that there was a contact surface of the foot on the line that extended from the toe to the intermediate cuneiform (calculated point). The contact point between the foot and the ball was calculated as the intersection point of the contact surface of the foot and the perpendicular line that dropped from the center of the ball to the
contact surface of the foot (Figure 1). The contact surface of the foot was a plane defined to calculate the contact point; however, the foot was not assumed as a plane that flatly deformed the ball. The impact point in each trial was calculated as the average of the distance from the COM of the foot (projected onto the contact surface) to the contact point in all frames during ball impact (Figure 2). The positive and negative values represented the ankle and toe sides, respectively. While the contact point is the intersection point in each frame, the impact point is the average distance during ball impact.

**Kinematic Analysis**

Each component of the ball velocity at $t_1$ and the foot (COM) velocities at $t_0$ and $t_1$ were derived from the first derivatives of regression equations fitted to their displacements in 10 frames before and after impact. The absolute magnitudes of the velocity vectors were calculated from the values of their components. The foot angular velocities at $t_0$ and $t_1$ were derived from the first derivatives of regression equations fitted to their angular displacements in 10 frames before and after impact. A positive value indicated counterclockwise rotation. Moreover, the coefficient of restitution in each trial was calculated using Equation 4.

**Inverse Dynamic Analysis**

The absolute magnitude of the impact force $|F_b|$ was calculated from the ball deformation $\beta$ by applying the Hertz contact theory (Figure 3). The methods for calculating the ball deformation and the impact force (Ishii et al., 2007; Ishii & Maruyama, 2007) are given in the Appendix.

The ball reaction force $F_f$ that was the impact force acting from the ball to the foot was assumed to act on the contact point in a direction opposite to the vector of the ball velocity at $t_1$. A rigid segment model of the foot was used to calculate the ankle joint kinetic data. The mass and moment of inertia of the foot were derived based on the body segment inertia parameter (Ae et al., 1992) with the addition of the shoe mass. The ankle joint reaction force and ankle joint torque during ball impact were obtained by solving Newton’s equations using an inverse dynamic technique (Winter, 1990). Moreover, the impulse of the ankle joint reaction force and the angular impulse of the ankle joint torque during ball impact for each trial were calculated by numerical integration.
Statistical Analysis

First, the measurement values of the ball speed at $t_1$ were normalized to the foot speed at $t_0$ to eliminate the influence of intertrial variance in the foot speed at $t_0$.

The experimental relationships between the impact point and several variables including the (normalized) ball speed at $t_1$, the impulse of the ankle joint reaction force, the angular impulse of the ankle joint torque, and the coefficient of restitution were expressed by quadratic regression curves for each subject. The correlation coefficients and the $p$-values for these quadratic regression curves were computed and the statistical significance was set at $p < .05$.

Theoretical Equation of Ball Velocity

For simplicity, it was assumed that the ball was hit by the vertical dorsal aspect and it was launched horizontally, as shown by the impact model in Figure 4. Because the movements of the ball and foot in the vertical direction were not considered, gravity was neglected here. The ankle joint reaction force was assumed to have only a horizontal component. Based on these assumptions, the following four equations were obtained for ball impact.

The impulse–momentum relationship for the foot is expressed as

$$\int_{t_0}^{t_1} R_{ax} dt + \int_{t_0}^{t_1} F_f dt = m_f (V_f - V_{f0})$$  \hspace{1cm} (1)

The angular impulse–momentum relationship for the foot is expressed as

$$\int_{t_0}^{t_1} T_a dt - k \int_{t_0}^{t_1} R_{ax} dt - l \int_{t_0}^{t_1} F_f dt = I_f \left( \omega_{f1} - \omega_{f0} \right)$$  \hspace{1cm} (2)

The impulse–momentum relationship for the ball is expressed as

$$-\int_{t_0}^{t_1} F_f dt = m_b V_{b1}$$  \hspace{1cm} (3)
The coefficient of restitution is expressed as

\[ e = -\frac{V_{b1} - (V_{f1} - l\omega_{f1})}{(V_{f0} - l\omega_{f0})} \] (4)

where \( R_{sX} \) is the ankle joint reaction force (horizontal component); \( T_s \) is the ankle joint torque; \( F_i \) is the ball reaction force; \( V_{f0} \) and \( V_{f1} \) are the foot velocities at \( t_0 \) and \( t_1 \), respectively; \( \omega_{f0} \) and \( \omega_{f1} \) are the foot angular velocities at \( t_0 \) and \( t_1 \), respectively; \( V_{b1} \) is the ball velocity at \( t_1 \); \( m_f \) and \( I_f \) are the mass and the moment of inertia of the foot, respectively; \( m_b \) is the mass of the ball; \( k \) is the distance from the COM of the foot to the ankle; \( l \) is the impact point (distance from the COM of the foot on the dorsal aspect).

The theoretical equation of the ball velocity at \( t_1 \) is obtained by solving Equations 1–4.

\[ V_{b1} = \frac{\left( lm_t k + I_f \right) \int_{t_0}^{t_1} R_{sX} \, dt - lm_t \int_{t_0}^{t_1} T_s \, dt + (1 + e) I_f m_t \left( V_{f0} - l\omega_{f0} \right)}{l^2 m_t m_b + I_f (m_t + m_b)} \] (5)

The impulse of the ankle joint reaction force, the angular impulse of the ankle joint torque, and the coefficient of restitution in Equation 5 were replaced for each subject by the quadratic regression equations (functions of the impact point \( l \)) observed as described in the preceding section. In addition, by substituting body data (\( m_f \) and \( I_f \) were derived as described above, \( k \) was obtained by experimental analysis) and the mean values of \( V_{f0} \) and \( \omega_{f0} \) for all trials of each subject into Equation 5, the theoretical relationship between the impact point and the ball velocity for each subject was obtained. The validity of the theoretical equation of the ball velocity was verified by comparing the theoretical relationship with the experimental one obtained as described in the preceding section.

Simulations of the ball velocity were conducted by independently varying (±10% from the measurement values) the foot mass, foot length, foot velocity at \( t_0 \), impulse of the ankle joint reaction force, and angular impulse of the ankle joint torque. Each pattern of the variable values is probable, although it is difficult for players to control the variable values exactly.

**Results**

The kinematic variables in the experiment for each subject are presented in Table 1. The mean duration of the impact phase was 9.6–10.7 ms. The minimum and maximum values of the normalized ball speed were 17.1–20.6 and 20.8–24.7 m/s, respectively. The mean foot speed at \( t_0 \) was 13.7–17.1 m/s. Examples of the time course of the ball deformation and the impact force are shown in Figure 5. The peak ball deformation was 29–65 mm and the peak impact force was 1,056–2,231 N. While the peak ball deformation increased as the impact point approached the toe, a greater peak impact force acted when impact was made on the area from 30 to 50 mm on the toe side of the COM of the foot.

The impulse of the ankle joint reaction force (horizontal component) and the angular impulse of the ankle joint torque were significantly correlated with the impact point for each subject (Table 2). As typical examples, the relationships of the impulse of the ankle joint reaction force and the angular impulse of the ankle joint torque to the impact point for Subject A are shown in Figure 6. The ankle joint reaction force and ankle joint torque during ball impact would act passively against the ball reaction force. The impact on the area from the COM of the foot to the ankle (the ankle was located 0.060 ± 0.005 m from the COM of the foot for each subject) produced a large ankle joint reaction force that acted in the forward direction (Figure 6a). The dorsiflexion torque increased as the impact point approached the toe (Figure 6b). Furthermore, there was a significant correlation between the impact point and the coefficient of restitution for each subject (Table 2).

Table 3 shows the variables of experimental and theoretical relationships between the impact point and the ball velocity for each subject. A significant correlation was found between the impact point and the ball velocity in the experiment for each subject. Typical experimental and theoretical relationships between the impact point and the ball velocity (Subject A) are shown in Figure 7. From the scatter plot of the ball velocity in the experiment, a greater ball velocity was observed when an impact was made on the area surrounding the COM of the foot. The impact point at the peak of the quadratic regression curve of the ball velocity in the experiment was in the range of –0.031 to –0.004 m (31 to 4 mm on the toe side of the COM). The theoretical relationship between the impact point and the ball velocity was in good agreement with the tendency indicated by the experimentally obtained scatter plot. The impact point at the peak of the theoretical curve of the ball velocity was in the range of –0.026 to 0.001 m (26 mm on the toe side of the COM to 1 mm on the ankle side of the COM). Furthermore, the peak ball velocity in the quadratic regression curve in the
Figure 5 — Examples of the time course of (a) the ball deformation and (b) the impact force.

<table>
<thead>
<tr>
<th>Subject</th>
<th>ID</th>
<th>Trial n</th>
<th>Impact Point (m)</th>
<th>Duration of Impact Phase (ms)</th>
<th>Normalized Ball Speed (m/s)</th>
<th>Foot Speed at Initial Instant of Impact Phase (m/s)</th>
<th>Foot Angular Velocity at Initial Instant of Impact Phase (rad/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean ± SD</td>
<td>Min.</td>
<td>Max.</td>
<td>Mean ± SD</td>
<td>Min.</td>
</tr>
<tr>
<td>A</td>
<td>23</td>
<td>–0.010 ± 0.038</td>
<td>–0.068</td>
<td>10.7 ± 0.7</td>
<td>9.2</td>
<td>19.6 ± 1.1</td>
<td>17.1</td>
</tr>
<tr>
<td>B</td>
<td>22</td>
<td>–0.015 ± 0.035</td>
<td>–0.059</td>
<td>9.7 ± 0.4</td>
<td>8.8</td>
<td>19.4 ± 1.0</td>
<td>17.4</td>
</tr>
<tr>
<td>C</td>
<td>27</td>
<td>–0.028 ± 0.033</td>
<td>–0.076</td>
<td>9.6 ± 0.4</td>
<td>9.2</td>
<td>22.4 ± 1.0</td>
<td>20.6</td>
</tr>
<tr>
<td>D</td>
<td>27</td>
<td>–0.008 ± 0.037</td>
<td>–0.056</td>
<td>10.6 ± 0.6</td>
<td>9.6</td>
<td>20.4 ± 1.0</td>
<td>18.3</td>
</tr>
<tr>
<td>E</td>
<td>26</td>
<td>–0.029 ± 0.030</td>
<td>–0.069</td>
<td>10.1 ± 0.5</td>
<td>9.6</td>
<td>22.6 ± 1.5</td>
<td>20.0</td>
</tr>
</tbody>
</table>

Table 1 — Selected kinematic variables in experiment
Figure 6 — (a) Relationship between the impact point and the impulse of the ankle joint reaction force (horizontal component) for Subject A. (b) Relationship between the impact point and the angular impulse of the ankle joint torque for Subject A.

Table 2 Correlation coefficients and p-values for quadratic regression curves between the impact point and the impulse of the ankle joint reaction force, the angular impulse of the ankle joint torque, and the coefficient of restitution

<table>
<thead>
<tr>
<th>Subject ID</th>
<th>Trial n</th>
<th>Impulse of Ankle Joint Reaction Force</th>
<th>Angular Impulse of Ankle Joint Torque</th>
<th>Coefficient of Restitution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>R</td>
<td>P-Value</td>
<td>R</td>
</tr>
<tr>
<td>A</td>
<td>23</td>
<td>0.945</td>
<td>***</td>
<td>0.982</td>
</tr>
<tr>
<td>B</td>
<td>22</td>
<td>0.866</td>
<td>***</td>
<td>0.981</td>
</tr>
<tr>
<td>C</td>
<td>27</td>
<td>0.883</td>
<td>***</td>
<td>0.981</td>
</tr>
<tr>
<td>D</td>
<td>27</td>
<td>0.817</td>
<td>***</td>
<td>0.990</td>
</tr>
<tr>
<td>E</td>
<td>26</td>
<td>0.958</td>
<td>***</td>
<td>0.977</td>
</tr>
</tbody>
</table>

***p < 0.001; **p < 0.01; *p < 0.05.

experiment (20.5–24.1 m/s) and the peak ball velocity in the theoretical curve (21.0–24.4 m/s) were also in good agreement. These suggested that the theoretical equation of the ball velocity could be used to express the tendency of the relationship between the impact point and the ball velocity.

Table 4 shows the variables of simulated relationships between the impact point and the ball velocity. As typical examples, the simulation results of the ball velocity for Subject A are shown in Figure 8. Independently lowering the foot mass or foot length decreased the ball velocity produced by the impact on the forefoot, and the impact point that produces the greatest ball velocity (IPgbv) shifted to the ankle side. However, these had minor effects on the ball velocity and IPgbv (Figures 8a and 8b). Decreasing the foot velocity at $t_0$ decreased the ball velocity produced by the impact for all impact points ranging from the forefoot to the ankle. Therefore, the IPgbv remained relatively consistent (Figure 8c). Independently decreasing the impulse of the ankle joint reaction force decreased the ball velocity produced by the impact on the area from the ankle to 0.03 m of the toe side. As a result, the IPgbv shifted to the toe side (Figure 8d). In contrast, independently decreasing the angular impulse of the ankle joint torque decreased the ball velocity produced by the impact on the forefoot. As a result, the IPgbv shifted to the ankle side (Figure 8e).

Discussion

The theoretical relationship between the impact point and the ball velocity was in good agreement with the experimental one (Table 3 and Figure 7). The limitations of the theoretical approach used in this study arise mainly from the simplifying assumptions of the impact model, as indicated in the Methods section. However, it was suggested that the theoretical equation of the ball velocity could be used to express the tendency of the relationship between the impact point and the ball velocity.

Although the impact point is a factor affecting the ball velocity, as described in previous studies (Asami & Nolte, 1983; Ishii et al., 2007), Equation 5 suggests that the ball velocity is affected by many factors other than the impact point. Furthermore, the IPgbv is considered to
converge on the area surrounding the COM of the foot as a result of a complex effect caused by many factors described in Equation 5. However, because of multiple effects caused by these factors, the IPgbv would not be strictly identical according to the subject or trial.

The simulation results of the ball velocity obtained by varying the foot mass or foot length (Figures 8a and 8b) were similar to those of Sterzing & Hennig (2008) that shoe mass does not influence the ball velocity significantly. Furthermore, it can be said that the simulation result of the ball velocity obtained by varying the foot velocity at $t_0$ (Figure 8c) supports a positive correlation between the foot velocity at $t_0$ and the ball velocity shown kinematically in previous studies (Andersen et al., 1999; Asami & Nolte, 1983; Isokawa & Lees, 1988; Levanon & Dapena, 1998; Nunome et al., 2006b). Decreasing the ankle joint torque during ball impact (Figure 8e) is thought to indicate a loosening fixation of the ankle.

From a comparison of the factors affecting the ball velocity (Table 4 and Figure 8), it was suggested that the ball velocity is affected more strongly by the foot velocity at $t_0$ than by other factors. Considering the factors affecting the IPgbv, it was suggested that the IPgbv is affected more strongly by the ankle joint reaction force and ankle joint torque during ball impact than by other factors.

The IPgbv of Subject C was located farther on the toe side of the COM compared with other subjects (Table 3). This result was considered to be attributed in part to the larger foot mass and larger foot length of Subject C (body mass: 78.6 kg, foot length: 29.0 cm) than of the other subjects (body mass: 53.0–63.0 kg, foot length: 24.0–26.5 cm). When the ball velocity simulation for Subject C was conducted by substituting both mean values of the foot mass and foot length for other subjects (mean body mass: 58.5 kg, mean foot length: 25.0 cm) into the theoretical equation, the IPgbv shifted to $-0.014$ m (14 mm on the toe side of the COM), which was a similar position to that of the other subjects.

When the ball is in contact with the ground as in the case of a free kick, it is difficult to make an impact on the area surrounding the COM of the foot because of the foot length. It is thought that an angled approach enables the

**Figure 7** — Experimental and theoretical relationships between the impact point and the ball velocity for Subject A.

### Table 3 Variables of the experimental and theoretical relationships between the impact point and the ball velocity

<table>
<thead>
<tr>
<th>Subject ID</th>
<th>Trial n</th>
<th>Quadratic regression curve of ball velocity in experiment</th>
<th>Theoretical ball velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Peak Value</td>
<td>Impact Point at Peak</td>
</tr>
<tr>
<td>A</td>
<td>23</td>
<td>0.901</td>
<td>20.5</td>
</tr>
<tr>
<td>B</td>
<td>22</td>
<td>0.856</td>
<td>20.7</td>
</tr>
<tr>
<td>C</td>
<td>27</td>
<td>0.654</td>
<td>23.0</td>
</tr>
<tr>
<td>D</td>
<td>27</td>
<td>0.798</td>
<td>21.2</td>
</tr>
<tr>
<td>E</td>
<td>26</td>
<td>0.835</td>
<td>24.1</td>
</tr>
</tbody>
</table>

***p < 0.001; **p < 0.01.
Figure 8 — Simulated relationships between the impact point and the ball velocity with varying (a) foot mass, (b) foot length, (c) foot velocity at initial instant of impact phase, (d) impulse of ankle joint reaction force and (e) angular impulse of ankle joint torque for Subject A.
Table 4  Variables of the simulated relationships between the impact point and the ball velocity

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak Value (m/s)</td>
<td>Relative Change of IP_{gbv} (m)</td>
<td>Peak Value (m/s)</td>
<td>Relative Change of IP_{gbv} (m)</td>
<td>Peak Value (m/s)</td>
<td>Relative Change of IP_{gbv} (m)</td>
<td>Peak Value (m/s)</td>
<td>Relative Change of IP_{gbv} (m)</td>
<td>Peak Value (m/s)</td>
<td>Relative Change of IP_{gbv} (m)</td>
</tr>
<tr>
<td>Foot Mass</td>
<td>+10%</td>
<td>21.1</td>
<td>-0.001</td>
<td>21.2</td>
<td>-0.001</td>
<td>23.4</td>
<td>-0.002</td>
<td>21.9</td>
<td>-0.001</td>
<td>24.5</td>
</tr>
<tr>
<td></td>
<td>-10%</td>
<td>20.9</td>
<td>+0.001</td>
<td>20.8</td>
<td>+0.001</td>
<td>23.0</td>
<td>+0.002</td>
<td>21.5</td>
<td>+0.001</td>
<td>24.2</td>
</tr>
<tr>
<td>Foot Length</td>
<td>+10%</td>
<td>21.0</td>
<td>-0.002</td>
<td>21.0</td>
<td>-0.001</td>
<td>23.3</td>
<td>-0.005</td>
<td>21.7</td>
<td>-0.002</td>
<td>24.4</td>
</tr>
<tr>
<td></td>
<td>-10%</td>
<td>21.0</td>
<td>+0.002</td>
<td>21.0</td>
<td>+0.002</td>
<td>23.1</td>
<td>+0.005</td>
<td>21.7</td>
<td>+0.002</td>
<td>24.3</td>
</tr>
<tr>
<td>Foot Velocity at Initial Instant of Impact Phase</td>
<td>+10%</td>
<td>22.6</td>
<td>+0.001</td>
<td>22.7</td>
<td>0.000</td>
<td>25.0</td>
<td>+0.003</td>
<td>23.3</td>
<td>+0.003</td>
<td>26.3</td>
</tr>
<tr>
<td></td>
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<td>19.4</td>
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<td>19.3</td>
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</tr>
<tr>
<td>Impulse of Ankle Joint Reaction Force</td>
<td>+10%</td>
<td>21.4</td>
<td>+0.006</td>
<td>21.4</td>
<td>+0.005</td>
<td>23.4</td>
<td>+0.005</td>
<td>21.9</td>
<td>+0.005</td>
<td>24.9</td>
</tr>
<tr>
<td></td>
<td>-10%</td>
<td>20.6</td>
<td>-0.006</td>
<td>20.6</td>
<td>-0.004</td>
<td>23.0</td>
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<td>-0.005</td>
<td>24.0</td>
</tr>
<tr>
<td>Angular Impulse of Ankle Joint Torque</td>
<td>+10%</td>
<td>21.1</td>
<td>-0.006</td>
<td>21.0</td>
<td>-0.003</td>
<td>23.4</td>
<td>-0.006</td>
<td>22.1</td>
<td>-0.008</td>
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</tr>
<tr>
<td></td>
<td>-10%</td>
<td>21.0</td>
<td>+0.005</td>
<td>21.0</td>
<td>+0.003</td>
<td>23.0</td>
<td>+0.006</td>
<td>21.5</td>
<td>+0.006</td>
<td>24.3</td>
</tr>
</tbody>
</table>

Note. Relative change of IP_{gbv} is the amount of change from the impact point at peak of the theoretical ball velocity. Positive and negative values of the relative change represent the ankle and toe sides, respectively.
foot to be tilted in the frontal plane, as skilled soccer players perform, and so facilitates an impact near the COM of the foot. Furthermore, because the ankle joint torque during ball impact was thought to act passively against the ball reaction force, it was suggested that the impact with the ankle in an insufficient plantar flexion makes the ankle fixation difficult and, thus, makes the ankle joint torque during the ball impact smaller. This shifts the IP_{gbv} to the ankle side (Figure 8e), and it becomes more difficult to make the impact on this point when the ball is in contact with the ground. To facilitate the impact on the IP_{gbv}, impact with the ankle in the full plantar flexion was also considered important.

This study derived the theoretical equation of the ball velocity for full instep kicking based on the impact dynamics theory including the kinetic factors and impact point. The variable values based on the experiment were substituted into the theoretical equation. The validity of the theoretical equation was verified by comparing the theoretical values with measurement values for various impact points. The simulations of the ball velocity were conducted by varying the variable values independently, and the effects of the variables on the ball velocity were investigated specifically. If the theoretical equation of the ball velocity at t_1 is extended in consideration of the ball velocity at t_0, it can be applied to the ball impact for additional sporting events (e.g., batting in baseball) other than just soccer.

Acknowledgments

The authors would like to express their sincere thanks to NAC Image Technology, Inc. for providing us with the high-speed camera used in this study.

References


Appendix: Ball Deformation and Impact Force

Tsaousidis & Zatsiorsky (1996) and Shinkai et al. (2009) calculated the ball deformation during ball impact from the position of a fixed point on the foot and ball in toe and instep kicking, respectively. However, because the foot posture and the contact point were variable during ball impact, it was thought that it was not appropriate to use the position of a fixed point on the foot to calculate the ball deformation in the normal direction to the contact surface in instep kicking. Ishii et al. (2007) calculated the time course of the ball deformation using the method in which this issue was considered. The ball deformation in the normal direction to the contact surface was calculated as the length by which the distance between the center of the ball and the contact surface (contact point) decreased after the beginning of the impact (Figure 3a).

Furthermore, Shinkai et al. (2009) calculated the peak acceleration of the COM of the ball in the sagittal plane from its velocity slope and estimated the peak impact force using Newton’s equation. However, because they estimated the position of the COM of the ball by the spherical shell model in which the ball was assumed to be flatly deformed, the peak acceleration of the COM of the ball and the peak impact force might be overestimated. In previous studies, the impact forces in the normal direction generated when heading the ball in soccer (Queen et al., 2003) and when getting hit by a pitch in baseball (Crisco et al., 1997) were calculated based on the Hertz contact theory (Greszczuk, 1982; Timoshenko & Goodier, 1970). Recently, the time course of the impact force in soccer kicking was calculated from the ball deformation during ball impact by applying the Hertz contact theory, as described in Ishii et al. (2007) and Ishii & Maruyama (2007). This method considered the issue mentioned above. The derivation process of the impact force equation is described below.

The normal impact force $F_n$ and the tangential impact force (frictional force) $F_t$ act on the ball during ball impact (Figure 3b). Based on the Hertz contact theory, the relationship between the normal impact force $F_n$ and the ball deformation $\beta$ is expressed as:

$$F_n = k\beta^{3/2}$$  \hspace{1cm} (A.1)

where $k$ is a coefficient defined by shapes, Poisson’s ratios, and Young’s moduli of the ball and foot; however, $k$ is not derived from these values in this study. On the other hand, assuming that the tangential impact force $F_t$ is approximately represented by the Amontons–Coulomb law, $F_t$ is given by

$$F_t = \mu F_n$$  \hspace{1cm} (A.2)

where $\mu$ represents the coefficient of friction, and it is assumed to be constant during ball impact in each trial. Furthermore, the value of $\mu$ is not obtained in this study. Using Equations A.1 and A.2, the absolute magnitude of the impact force $|F_b|$ is expressed as

$$|F_b| = \sqrt{F_n^2 + F_t^2} = \sqrt{F_n^2 + (\mu F_n)^2} = \sqrt{(1+\mu^2)F_n^2} = \sqrt{1+\mu^2} k\beta^{3/2}$$  \hspace{1cm} (A.3)

Because $\sqrt{1+\mu^2} k$ is the constant, this is replaced by $N$, and $|F_b|$ becomes

$$|F_b| = N\beta^{3/2}$$  \hspace{1cm} (A.4)

The impulse–momentum relationship for the ball in the ball impact is given by

$$\int_{t_0}^{t_1} N\beta^{3/2} dt = m_b V_{b1}$$  \hspace{1cm} (A.5)

$N$ is derived from Equation A.5.

$$N = \frac{m_b V_{b1}}{\int_{t_0}^{t_1} \beta^{3/2} dt}$$  \hspace{1cm} (A.6)

As noted from Equation A.6, $N$ results in a different value in each trial. We can obtain the equation of the absolute magnitude of the impact force ($|F_b|$) by substituting Equation A.6 into Equation A.4.
\[ |F_b| = \frac{m_b V_{b1}}{\int_{t_0}^{t_1} \beta^{3/2} \, dt} \beta^{3/2} \] (A.7)

The time course of the impact force for each trial was calculated using Equation A.7 in this study.

However, the calculation approach of the impact force has the following limitations. First, based on the Hertz contact theory, the viscosities of both the ball and the foot were not fully considered. Furthermore, the tangential impact force was assumed to be expressed by the Coulomb friction. Although these limitations influenced the time course of the impact force, they would have only a small influence. Therefore, it was considered that the impact force calculated by this approach could be used in the theoretical analysis for the purpose of this study.