Kicking Performance in Young U9 to U20 Soccer Players: Assessment of Velocity and Accuracy Simultaneously

Luiz H. P. Vieira¹,², Sérgio A. Cunha³, Renato Moraes¹,², Fabio A. Barbieri⁴, Rodrigo Aquino¹,², Lucas de P. Oliveira¹, Martina Navarro⁵,⁶, Bruno L.S. Bedo¹,², Paulo R. P. Santiago¹,²

¹FMRP Faculty of Medicine at Ribeirão Preto, University of São Paulo, Ribeirão Preto, Brazil. ²LaBioCoM, School of Physical Education and Sport of Ribeirão Preto, University of São Paulo, Brazil. ³Laboratory of Instrumentation for Biomechanics, UNICAMP, Campinas, Brazil. ⁴Human Movement Research Laboratory, Physical Education Department, São Paulo State University, Bauru, São Paulo, Brazil. ⁵Federal University of São Paulo, Department of Ophthalmology and Visual Sciences, São Paulo, Brazil. ⁶Faculty of Human Sciences, Institute of Sport Science, University of Bern, Bern, Switzerland.

Correspondence address: Paulo Roberto Pereira Santiago, PhD. University of São Paulo, School of Physical Education and Sport of Ribeirão Preto, Av. Bandeirantes 3900, Monte Alegre – Ribeirão Preto/SP, Brazil. Postal code: 14040-907. E-mail: paulosantiago@usp.br

Abstract

Purpose: To compare the kicking performance in young soccer players of U9 to U20 age-groups. Method: Three hundred and sixty-six Brazilian players were evaluated on an official pitch, using 3-D kinematics to measure (300 Hz) ball velocity (Vball), foot velocity (Vfoot), Vball/Vfoot ratio, last stride length, and distance between support foot and ball. Simultaneously, a 2-D procedure was also conducted to compute (60 Hz) the mean radial error, bivariate variable error, and accuracy. The possible age-related differences were assessed through 1-way ANOVA and magnitude-based inferences. Results: Ball velocity increased 103% (p < 0.001; η² = 0.39) from the U11 (48.54±8.31 km/h) to U20 (98.74±16.35 km/h). Foot velocity presented a 59% increase (p < 0.001; η² = 0.32) from the U11 (49.08±5.16 km/h) to U20 (78.24±9.49 km/h). This was due to improvement in the quality of foot-ball impact (Vball/Vfoot ratio) from U11 (0.99±0.13 a.u.) to U20 (1.26±0.11 a.u.; p < 0.001; η² = 0.25). Parameters such as mean radial error and accuracy appear to be impaired during the growth spurt (U13–U15). The last stride length is correlated, low to moderately high, with the ball velocity in all age-groups (r = .36-.79). Conclusions: In summary, we conclude that simple Biomechanical parameters of kicking performance present distinct development. These results suggest that different training strategies specific for each age-group could be applied. We provide predictive equations in order to aid coaches in the long-term monitoring process to develop the kick in soccer or search for talented young players.
Development of the computational sciences (e.g., computer vision and image processing) has improved the analysis techniques and measurement systems applied to human movement research. These advances have allowed expansion of the knowledge about 3-D kinematic and kinetic characteristics in soccer kicking (Lees, Asai, Andersen, Nunome, & Sterzing, 2010). Kicking performance has been widely reported in previous studies with youth players (Anderson & Sidaway, 1994; Barnett, van Beurden, Morgan, Brooks, & Beard, 2010; Berjan Bacvarevic et al., 2012; Juarez, Lopez de Subijana, Mallo, & Navarro, 2011; Kapidzic, Huremovic, & Biberovic, 2014; Katis, Kellis, & Lees, 2015; Wilson et al. 2016; Wong, Chamari, Dellal, & Wisloff, 2009), varying from six (Teixeira & Teixeira, 2008) to twenty years of age (Apriantono, Nunome, Ikegami, & Sano, 2006). However, only a limited number of works aimed to verify the effects of age on direct measures of kicking performance and these included a small range of age-groups (Berjan Bacvarevic et al., 2012; Cerrah et al., 2015; Katis, Kellis, & Lees, 2015, Teixeira & Teixeira, 2008).

Kicking is the defining action in soccer (Lees et al., 2010) and searching for performance indicators that help to achieve success in this skill is one of the most commonly raised issues of applied biomechanics in soccer. Ball velocity and accuracy are considered the main factors that contribute to a successful kicking outcome (van den Tillaar & Ulvik, 2014; Vieira et al., 2016). In the past, it has been shown that short-term training (10 weeks) may be sufficient to achieve a typical pattern of proximal-distal coordination improving kicking performance, but in young adults (Anderson & Sidaway, 1994). In recent years, the process of talent identification and development has become a very important issue in the football context and research. Yet, the results obtained in studies that focused on clarifying the evolution of kicking performance with advancement in chronological age are still discordant. For instance, some studies found that kicking is not an age-dependent skill, especially in terms of accuracy, which does not demonstrate change with age (Malina et al., 2005; Malina, Ribeiro, Aroso, & Cumming, 2007; Rosch et al., 2000; Vaeyens et al., 2006). A different framework was noted when analyzing ball velocity, where increases were seen (Berjan Bacvarevic et al., 2012; Cerrah, Şimşek, Soylu, Ertan, & Nunome, 2015; Katis et al., 2015).

An important literature review on this topic pointed to the existence of a gap between research on sports biomechanics and the teaching-learning-training process (Lees et al., 2010). In this sense, velocity and accuracy were not considered simultaneously in the majority of the studies that we reviewed. These parameters have been analyzed in isolation in youth soccer (Juarez et al., 2011; Kapidzic et al., 2014; Katis et al., 2015; Malina et al., 2005; Malina et al., 2007; Rosch et al., 2000; Teixeira & Teixeira, 2008; Vaeyens et al., 2006; Wilson et al. 2016; Wong et al., 2009). The prioritization or selection of only one parameter (e.g., velocity) may represent a significant loss of the other (e.g., accuracy), since a prior study reported the presence of a speed-accuracy trade-off when kicking with the dominant limb (van den Tillaar & Ulvik, 2014). Also, many authors used different types of technology [e.g., speed radar (Berjan Bacvarevic et al., 2012; Wong et al., 2009), videogrammetry (Juarez et al., 2011; Kapidzic et al., 2014; Katis et al., 2015; Teixeira & Teixeira, 2008), microphones (Navarro et al., 2013)]. Low acquisition frequency to investigate the kicking task is an important limitation of some previous work [e.g., 60 Hz; (Anderson & Sidaway, 1994; Orloff et al., 2008; Teixeira & Teixeira, 2008)]. In addition, radars provide limited information about lower limb movements. Target size and location, type of kick performed, ball used, footwear, collection environment, number of trials, and instructions were not standardized among previous studies. It is difficult to directly compare the data of previous cross-sectional studies in youth players, in order to understand performance evolution as a function of chronological age.

Young players from different countries on different continents around the world, and with distinct mean ages [e.g., Asia: Japan (20 years; Apriantono et al., 2006), China (U14; Wong et al., 2009); Oceania: Australia (16.8 years; McLean & Tumilty, 1993); Europe: Spain (16.1 years; Juarez et al., 2011), Turkey (12–17 years; Cerrah et al., 2015), Netherlands (19.1 years; Navarro et al., 2013), Bosnia (13 years; Kapidzic et al., 2014), Serbia (12.2–15.3 years; Berjan Bacvarevic et al., 2012); and North America: USA (20.2 years; Orloff et al., 2008)],
or uninformed locations (e.g., 15.1 years; Katis et al., 2015) have already been evaluated. The place in the world may contribute to possible differences, depending on the models of introduction to the sport, training process, and specialization (Vieira et al., 2017). For instance, when analyzing maximal kicks in age-matched players (13 years old), different mean ball velocities were found by Kapidzic et al. (2014) (~75.42 ± 8.86 km/h) and Berjan Bacvarevic et al. (2012) (~89.68 ± 6.64 km/h). Data on the population of young South American players are still unknown. Understanding the development of kicking could have practical applications for talent identification and training prescription, finding critical and sensitive periods to develop specific performance parameters. Thus, the purpose of the study was to compare kick performance in young trained soccer players of U9 to U20 age-groups from a large sample. Our hypothesis was that increases in some kicking performance parameters would be found, mainly velocities (ball velocity, foot velocity and ratio between them) while the error rates (accuracy measures) would simultaneously show decreases with age advance.

Methods

Experimental Design

The experimental protocol was conducted on an official pitch with natural grass (FIFA-standard, 100 x 70 m; goal dimensions: 7.32 x 2.44 m) in the presence of sunlight (09:00–10:30 am and 4:00–5:30 pm). The data were collected from June/2014 to December/2016. All players wore the equipment (i.e., footwear and clothing) usually adopted for training sessions and official soccer competitions. First, the anthropometric parameters were measured: weight (digital scale Sb623 DLK Sports® - São Paulo, Brazil; sensitivity = 0.1 kg), height (PRIME MED stadiometer - São Paulo, Brazil; sensitivity = 0.1 cm), and time to peak height velocity [PHV = -7.999994 + (0.0036124 x (Age x Height))] (Moore et al., 2015). Prior to the kick protocol, a general warm-up of 10 minutes was performed, composed of moderate-intensity running, ballistic stretching, and specific kick exercises to warm the body and avoid injury during the test phase (van den Tillaar & Ulvik, 2014; Vieira et al., 2017). Each participant then performed penalty kicks using the dominant lower limb, with a distance of 11-m between the initial ball position and goal plane, to hit a 1 x 1 m target (Figure 1(C)) positioned in the goal center (van den Tillaar & Ulvik, 2014). Identification of the dominant lower limb was obtained by self-report (Vieira et al., 2016). The participants were given the following instruction: "kick with maximum ball velocity as possible and hit the center of the target" (Apriantono et al., 2006; Milioni et al., 2016; van den Tillaar & Ulvik, 2014; Vieira et al., 2016), with an instep kick type. Standardized balls (PENALTY® brand, FIFA-approved) were used according to the norms of the São Paulo Football Federation (Brazil), regarding dimensions and weight for each age group, size 4 in the U9 and U11 groups (65 cm Ø; 375 g) and size 5 for the U13 to U20 (70 cm Ø; 430 g). Each participant performed three trials (Berjan Bacvarevic et al., 2012; Vieira et al., 2016), and no restrictions were imposed on the number of steps, approach angle, or interval, which were auto-selected (Barbieri, Gobbi, Santiago, & Cunha, 2015; Lees, Kershaw, & Moura, 2005).

Participants

Three hundred and sixty-six (N = 366) young male Brazilian soccer players participated in this study. Participants were included in specific groups according to their age: U9 (n = 11, 8.6 ± 1.1 years, 30.1 ± 5.7 kg, 131.3 ± 4.4 cm; PHV = -4.02±0.35), U11 (n = 73, 10.4 ± 0.5 years, 38 ± 5.3 kg, 149.6 ± 6.3 cm, PHV = -2.19 ± 0.41), U13 (n = 80, 12.3 ± 0.5 years, 50.8 ± 10.7 kg, 160.2 ± 9.6 cm; PHV = -0.70 ± 0.85), U15 (n = 105, 14.2 ± 0.6 years, 62.6 ± 9.2 kg, 173.5 ± 8.7 cm, PHV = 1.23 ± 0.44), U17 (n = 78, 15.9 ± 0.6 years, 66.9 ± 6.1 kg, 175.8 ± 7 cm, PHV = 1.49 ± 0.81), and U20 age-groups (n = 19, 18.4 ± 0.9 years, 74.5 ± 6.9 kg, 180.6 ± 5.4 cm, PHV = 3.48 ± 0.89). To participate in this study, participants were required to have initiated formal training at the age of 6 years-old (Teixeira & Teixeira, 2008). Participants were excluded if they had a professional contract, to train and/or compete at their age level. All procedures were approved by the local Human Research Ethics Committee, in accordance with the Code of Ethics of the World Medical Association (approved by the Ethics Advisory Board of Swansea University). All participants signed a written consent form confirming in writing their participation as a volunteer and players aged less than 18 years-old only participated if their guardians also signed a consent form. Players U9–U13 participated in 3 days of training a week [1 conditioning session of stretching and running drills without ball; 1–2 sessions of isolated
technical skills; and 2 specific sessions including simulated match-play and technical-tactical exercises such as small-sided, conditioned games, and game sub-phases (e.g., 1 vs. 1 + goalkeeper)]. The U15–U20 age-groups undertook 4–5 days of training a week consisting of 1–2 conditioning sessions without ball (focused on stretching, running and strength development), 1 session of isolated technical skills, and 3–4 specific sessions in the field (similar content than those described for younger players). All players trained for approximately 90 minutes per day plus one competition match at weekends.

Kinematic Procedures

The experimental protocol was monitored by four digital video cameras positioned at specific points on the field. Two cameras (Casio Exilim Highspeed EX-F1; CASIO® Computer Co. Ltd. – Tokyo, Japan) were allocated laterally (Figure 1(A)), with a distance of 3 m from the penalty mark, forming an angle of 90° between them and 45° with the ball adjusted to an acquisition frequency of 300 Hz (NTSC standard; shutter speed of 1/2000 s, 512 X 384 pixel resolution). For the spatial calibration, an orthogonal triad (1 x 1 x 1 m) containing ten markers with known absolute positions on the x, y, and z axes (Milioni et al., 2016) was used. The z axis was defined as vertical (pointing up), the y-axis as anteroposterior (pointing to the center of the goal and orthogonal to z), and the x-axis obtained by the vector product of y by z (pointing laterally). The sequences were transferred to the computer and the commands run (Barbieri et al., 2015; Milioni et al., 2016; Vieira et al., 2016) for (a) synchronization by a beep that was issued when all the cameras were turned on, (b) a calibration frame definition (c) frame marking (Figure 1(A) – (C)), and (d) 3D-DLT (Direct Linear Transformation) reconstruction using DVIDEOW software (Figueroa, Leite, & Barros, 2003). Data matrix containing the 3-D spatial coordinates of each measured marker were obtained for each shot performed (N = 1098 trials). An accuracy test was carried out (Barbieri et al., 2015; Milioni et al., 2016; Vieira et al., 2016) and the experimental uncertainties for this study were low (precision = 1 cm, bias = 0.9 cm, accuracy = 1.4 cm).

Dependent Variables

The following dependent variables were calculated for each trial: last stride length (LSL) (Kapidzic et al., 2014; Lees et al., 2005)–defined as the Euclidean distance between the place where the dominant foot lost contact with the ground and the calcaneus of the non-dominant foot when it landed on the ground during the last stride; distance between support foot and ball (D_{support-ball}) (Kapidzic et al., 2014; McLean & Tumilty, 1993; Orloff et al., 2008)–defined as the Euclidean distance between the centroid of the support foot and the centroid of the ball at the instant of impact; foot velocity (V_{foot}) (Barbieri et al., 2015; Juarez et al., 2011)–measured from the displacement of the marker on the distal phalanx of the fifth metatarsus of the dominant foot; and ball velocity (V_{ball}) (Katis et al., 2015; Milioni et al., 2016)–measured from the displacement of the ball centroid (Figure 1(C)). We also computed the V_{ball}/V_{foot} ratio as a dependent measure.

Data treatment and calculations were conducted using written routines in Matlab® environment (The MathWorks Inc., Natick, USA). Kinematic data (i.e., 5th metatarsal trajectory) were filtered by the LOESS-quadratic fit function (Barbieri et al., 2015) with smoothing parameter (span = 0.7) selected after residual analysis. To smooth the ball trajectory, the horizontal components were considered linear and calculated as the first derivative of the linear regression lines, adjusted to their unfiltered displacements. The vertical component was considered as the second degree and calculated as the first derivative of a quadratic regression line with its second derivative set as equal to -9.8 m.s^{-1} and adjusted to its non-filtered displacement in the airborne frames. Ten frames were considered before contact with the ball to calculate the average 3-D foot velocity and ten frames after foot contact with the ball to calculate the average 3-D ball velocity (Barbieri et al., 2015; Milioni et al., 2016; Vieira et al., 2016).

Mean Radial Error, Bivariate Variable Error and Accuracy
Two auxiliary cameras (GoPro® Hero 3+ Black Edition, Woodman Labs Inc. - USA) were used to determine kicking accuracy. One was placed frontally, 17 m from the goal line, and the other at the intersection of the goal line with the goalkeeper's area line, to identify the moment the ball crossed the goal line (Figure 1(D)). Both were set at 60 Hz (superview mode 1920 x 1080 pixel resolution, NTSC standard) (Milioni et al., 2016). The radial distortion was previously corrected (Vieira et al., 2016). Next, the ball centroid at the moment it crossed the goal line was digitized in 2-D by an operator, similar to the kinematic procedures and using the same software. By means of specific routines, the distance from the ball to the center of the target ($D_{target}$) (Barbieri et al., 2015) was calculated, and from this value the dependent variables: mean radial error (MRE), bivariate variable error (BVE), and accuracy (ACUR) (Vieira et al., 2016) were calculated according to the following equations 1–4:

\[ D_{target} = \sqrt{(x_{target} - x_{ball})^2 + (y_{target} - y_{ball})^2} \]  

\[ MRE = \frac{1}{N} \sum_{i=1}^{N} |D_{target}| \]  

\[ BVE = \sqrt{(SD_{x-coordinate})^2 + (SD_{y-coordinate})^2} \]  

\[ ACUR = \sqrt{(\text{MRE})^2 + (BVE)^2} \]

where $D_{target}$ = Euclidean distance between ball centroid and target center; $(x, y)_{target}$ = 2-D coordinates of target center point; $(x, y)_{ball}$ = 2-D coordinates of ball centroid when it crosses the goal line; $N$ = number of trials; $SD_{x-coordinate}$ = standard deviation of $x_{ball}$ coordinates in the three trials; $SD_{y-coordinate}$ = standard deviation of $y_{ball}$ coordinates in the three trials.

**Statistical Analysis**

The normal distribution of the data was verified using the Kolmogorov-Smirnov test. The data are presented as mean ± standard deviation and confidence interval (95%). The analysis of variance (1-way ANOVA), followed by Tukey-Kramer post hoc, was used to compare kicking performance between age groups. Pearson's product-moment correlation test was used to verify possible associations between ball velocity, age and all other dependent variables. Linear regressions were performed to estimate the contribution of chronological age to the variation in kicking performance ($R^2$). The significance level was set at $p < 0.05$. For each ANOVA, the *partial eta squared* ($\eta^2$) was calculated. For all comparisons we also calculated the Cohen’s $d$. Effect size limit values of $d$ were > 0.2 (small), > 0.5 (medium), and > 0.8 (large); $\eta^2 > 0.01$ (small), > 0.06 (medium), and > 0.15 (large); and $R^2 > 0.02$ (small), > 0.13 (medium), and > 0.26 (large) (Cohen, 1988). Using a 95% confidence interval, we also calculated whether the chances of true differences (unknown) between two groups exhibiting lower, similar, or higher values [i.e., higher than the smallest practically important effect, or smallest worthwhile change, SWC (0.2 multiplied by the between-subject deviation, based on the Cohen’s $d$ principle)]. The quantitative chance (QC) was interpreted as: ≤ 1% almost certainly not, > 1–5% very unlikely, > 5–25% unlikely, > 25–75% possibly, > 75–95% likely, > 95–99% very likely, > 99% almost certain. If the likelihood of higher or lower differences were both > 5%, the true difference was reported as unclear. Otherwise, we interpreted this change as the observed difference (Hopkins, Marshall, Batterham, & Hanin, 2009). Statistical analyzes were performed on IBM SPSS Statistics v.20 (Armonk, NY-USA) andMicrosoft Excel® spreadsheets (available in the domain http://www.sportsci.org/).

**Results**

In Table 1 the results for all variables are presented according to age group. The ANOVA revealed that $V_{ball}$ was significantly different ($F(5, 360) = 45.49, p < .001$, $\eta^2 = 0.39$) between age groups. *Post-hoc* comparisons indicated statistical difference ($U20 > U17$, $U15 > U13 > U11$, $U9$; $100/0/0$ *almost certain*, $d = 0.71$–3.87), except between $U9$ and $U11$ ($p = .33$, $75/17/8$ *unclear*, $d = 0.96$), and between $U15$ and $U17$ ($p = .29$, $97/3/0$ *likely*, $d = 0.28$). Statistical analysis for the $V_{foot}$ identified significant differences between groups, similar to what was observed for the $V_{ball}$ ($U20 > U17$, $U15 > U13 > U11$, $U9$; $d = 0.76$–3.82). Significant differences were found ($F(5,$
360) = 34.03, p < .001; η² = 0.32) with increases as a function of age. Again, the absence of differences occurred between the U9 and U11 (p = .66, 92/6/2 likely, d = 0.75) and U15 and U17 (p = .22, 66/34/0 possibly, d = 0.76). The QCs were almost certain for the majority of comparisons (100/0/0) except for U17 vs. U20 (98/2/0 very likely, d = 0.91) and those mentioned above. Similarly, the V<sub>ball</sub>/V<sub>foot</sub>ratio presented progressive increases (F(5, 360) = 24.23, p < .001; η² = 0.25), from U9 to U20. However, in the post hoc comparisons, some near age groups did not differ significantly. This was the case in U9 vs. U11 (p = .12, 54/35/11 unclear, d = 0.66), U11 vs. U13 (p = .64, 55/44/1 possibly, d = 0.27), U15 vs. U17 (p = .98, 25/72/4 unclear, d = 0.1), and U17 vs. U20 (p = .09, 67/28/5 unclear, d = 0.67). Remaining comparisons were likely to almost certain (d = 0.76–2.24).

**** Table 1 near here ****

The LSL also presented differences (F(5, 360) = 19.92, p < .001; η² = 0.22), which suggests increases as a function of age. Some groups, generally near, did not present significant statistical differences, although QCs were observed. This was the case for the post-hoc comparisons between U9 and U11 (p = .13, 99/1/0 very likely, d = 1.14) and U13 and U15 (p = .16, 86/14/0 likely, d = 0.33). In addition, supporting the significant statistical differences verified, very likely QCs (98/2/0, d = 0.89–1.62) were identified between the U9 and U13; U13 and U20; U15 and U20; the U17 and U20. In contrast, likely QC (91/9/0) between the U13 and U17 was obtained. Finally, there were no differences between the U15 and U17 age-groups (p = 1, 23/72/5 unclear, d = 0.05). The D<sub>support-ball</sub> presented a very distinct pattern of development (see Table 1). Although the analysis of variance pointed to an effect of age group (F(5, 360) = 4.30; p = .001; η² = 0.06), only differences between the U11 were observed with other groups (d = 0.5–0.61), i.e., versus U13 (99/1/0 very likely), U15 (93/7/0 likely), and U17 (99/1/0 very likely). In the comparison with U9 (p = .91, 13/28/59 unclear) and U20 (p = .11; 62/36/2 unclear) the difference was not identified (d = 0.42–0.88). The other post hoc comparisons, in addition to being non-significant, were unclear (d ≤ 0.35).

MRE (F(5, 360) = 6.92; p < .001; η² = 0.09) was greater for the U11 group (d = 0.57–1.04) than for the U15 (p = .001, 0/4/96 very likely), U17 (p < .001, 0/0/100 almost certain), and U20 (p = 0.003, 0/1/99 very likely). The U13 group also presented higher indices (d = 0.46–0.93) than the U15 (p = 0.017, 0/3/97 very likely), U17 (p = 0.006, 0/2/98 very likely), and U20 (p = 0.012, 1/11/88 likely). Other quantitative chances were unclear (d = 0.1–0.61), except between the U15 and U20 (1/14/85 likely, d = 0.48). With regard to the BVE (F(5, 360) = 3.55, p = .004; η² = 0.05), only the U11 group (d = 0.46–0.75) differed from the U15 (p = .008, 0/8/92 likely), U17 (p = .013, 0/9/91 likely), and U20 (p = .045, 0/5/95 very likely). Although similar to the U13 (d = 0.26–0.75), possibly QCs were identified when comparing the U11 (0/42/58), U15 (0/44/44) and U17 (1/48/52) and likely versus U20 (1/15/84). Finally, the results of the ACUR (F(5, 360) = 6.61, p < .001; η² = 0.08) revealed that the U11 (d = 1.03) was greater than the U15 (p < .001), U17 (p < .001), and U20 (p = .002, 0/2/98 very likely for all). In addition, the U13 (d = 0.52–0.89) was also greater than the U17 (p = .044, 0/5/95 likely) and U20 (p = .036, 0/8/91 likely). Relevant quantitative chances (d = 0.2–0.67) were noted between (i) the U9 with U11 (94/6/1 likely) and U20 (2/12/86 likely); (ii) U13 with U11 (1/50/49 possibly); and U15 (0/24/76 likely).

Correlations between the V<sub>ball</sub> and the dependent variables analyzed ranged from no correlation to high correlation. However, the magnitude of these correlations varied across age groups (Table 2). Chronological age also showed moderately high correlations with V<sub>ball</sub> (r = .68) and V<sub>foot</sub> (r = .67), moderate correlations with the V<sub>ball</sub>/V<sub>foot</sub> ratio (r = .54) and LSL (r = .50), low correlations with MRE (r = -.27) and ACUR (r = -.26), and no correlation with D<sub>support-ball</sub> (r = .18) and BVE (r = -.18). The linear regressions between chronological age and V<sub>ball</sub>/V<sub>foot</sub> ratio, V<sub>ball</sub>/V<sub>foot</sub> ratio, LSL, and a third-order polynomial model with the MRE, including the predictive equation, as well as the contribution estimates for the total variance (R²) and standard error of the estimates are also described (Table 3). Small (i.e., MRE), medium (i.e., LSL), and large (i.e., V<sub>ball</sub>/V<sub>foot</sub>/V<sub>ball</sub>/V<sub>foot</sub> ratio) coefficients of determination were found.

**** Table 2 near here ****
Discussion

The main purpose of the present study was to compare kick performance in young trained soccer players of U9 to U20 age-groups from a large sample—with reference to some biomechanical parameters ($V_{ball}$, $V_{foot}$, $V_{ball}/V_{foot}$ ratio, LSL, $D_{support-ball}$) and accuracy measurements (MRE, BVE, ACUR) during soccer kicks. The main findings were that the ball velocity, foot velocity, last stride length, $V_{ball}/V_{foot}$ ratio, and magnitude of correlation between $V_{ball}/V_{foot}$—indicators of foot-ball impact quality, increase linearly with increasing age. Moreover, accuracy parameters appear to be impaired in adolescence, near to the growth spurt (i.e., peak height velocity age equal to zero).

The parameters $V_{ball}$ and $V_{foot}$ presented moderately high correlation with age ($r = .68$). To explain these changes, we rely on the Ecological perspective [i.e., Dynamic Systems Approach; Kugler, Kelso, and Turvey (1982)], applied to motor development that considers the interrelationship between individual, environmental, and task constraints. Firstly, with reference to the constraints of the individual, among the factors that contributed to the results presented herein, one of them is certainly related to the increasing capacity to produce muscular strength in the lower limbs. Parker, Round, Sacco, and Jones (1990) studied the development of strength through maximal isometric voluntary contractions (MIVC) of the quadriceps in children and adolescents ($n = 267, 5–17$ years of age) and also identified a trend of linearly adjusted increase across the age groups. In another study, Barber-Westin, Noyes, and Galloway (2006) using an isokinetic dynamometer (ID) ($n = 224; 9–17$ years of age), identified that peak torque of knee extension increases progressively from 9 (U9–present study) to 14 years of age (U15–present study), and then stabilizes between 14–17 years. We identified a very similar picture for kicking performance (i.e., $V_{ball}$ and $V_{foot}$), with increases from U9 to U15 and signs of stabilization in increases around this age (U15–U17; $p = .22–.29; d = 0.28–0.76; possibly to likely$). However, variables from MIVC evaluations (e.g., peak force) and ID (e.g., peak knee extension torque) may reveal only limited kicking information due to differences in task etiology (kick vs. MIVC and ID) (McLean & Tumilty, 1993; Milioni et al., 2016; Vieira et al., 2016). In this way, the development of the muscular system, as previous evaluated, only partially explains kick development. Also, according to a literature review, there would be a positive transference of strength training to kicking performance, however isolated muscle strength gains could lead to stagnated or possible impaired kicking skill (Young & Rath, 2011).

The increased practice time from the younger group to the older groups is a factor that could contribute in itself to the improvement in velocity (Anderson & Sidaway, 1994). It is also possible to suggest an influence of maturation state of the players on kicking performance according to the results of Malina et al. (2007) which revealed that maturity predicted ($R^2 = 0.21–0.29$) a composite skill score [i.e., a sum of performances (Z scores) in ball control, slalom dribbling, passing, and shooting tests]. However, when the authors performed the analysis separately, advanced biological maturity status was associated with slightly better performance in shooting test (adjusted $R^2 = 0.05–0.08$) (Malina et al., 2005). Furthermore, our results indicate for the first time that while ball velocity exhibits increases that ranged from 15.2–21.4% between close groups (except U15 to U17), foot velocity demonstrates smaller increases, 7.7–14.3% for the same comparisons. Davids, Lees, and Burwitz (2000) argued that attempts at theoretical modeling of the process of coordination and control of kicking in soccer require an understanding of coordination between the movement system and the ball (i.e., constraints of the individual-task), rather than only understanding the coordination between the components of the isolated system. In addition, for the first time, our results point out that the magnitude of the correlation between ball velocity and foot velocity—assumed as an indirect indicator of impact quality (Apriantono et al., 2006)—increased from the U9 (moderate correlation; $r = .66$) to U17 (high correlation; $r = .89$), with a simultaneous increase in another impact quality indicator (i.e., $V_{ball}/V_{foot}$ ratio; U9: 0.99 ± 0.13 – U20: 1.26 ± 0.11 a.u.), and conversely, a decrease in the magnitude of correlation of the $V_{ball}/V_{foot}$ ratio and ball velocity (U9: $r = .82$ – U17: $r = .61$). This indicates that increasing foot velocity alone does not explain the consequent increases in ball velocity with increasing age. Thus, the factor that contributes to this
increase in $V_{ball}$ is mainly related to the improvement in the quality of the foot-ball interaction at ball impact through the age groups. In other words, older players are more able to transfer higher momentum rates from foot to ball during impact than younger players. Interestingly, the kicking performance values of the older group investigated in the present study (U20) are greater compared to age-matched (63 ± 7.92 – 67.68 ± 5.4 km/h) (Navarro et al., 2013) and older NCAA Division III players (20.2 years old; 81.72 ± 11.16 km/h) (Orloff et al., 2008), being also similar to those of Brazilian elite professional players ($V_{ball}$: 99.74 ± 8.45; $V_{foot}$: 82.31 ± 7.93 km/h) (Vieira, et al., 2016). Additionally, the U20s showed greater correlation between $V_{ball}$ and $V_{foot}$ than reported in a study for adult males (e.g., moderate correlation; $r = .57$–Apriantono et al., 2006), indicating that by this age players already have a fairly mature pattern of movement to achieve high kicking performance.

A limited number of previous studies have investigated kicking performance in very young U9, U11, and U13 players and reported values of $V_{foot}$ (U9: ~ 29.24–32.73, U11: 33.23–36.56 km/h) (Teixeira & Teixeira, 2008) slightly lower than ours. In the U13, $V_{ball}$ was either within the range or moderately lower (58.54–82.06 km/h) (Berjan Bacvarevic et al., 2012; Kapidzic et al., 2014; Wong et al., 2009) and inversely, $V_{foot}$ was higher than that reported previously (~48.46 km/h) (Kapidzic et al., 2014). The majority of the studies in the literature evaluated above U15 (e.g., Apriantono et al., 2006; Juarez et al., 2011; McLean & Tumilty, 1993; Navarro et al., 2013; Orloff et al., 2008). For the U15, our findings were slightly greater than those of a past study ($V_{ball}$: ~60.37–66.26 km/h) (Berjan Bacvarevic et al., 2012). Regarding the U17 group, our data are either, below ($V_{ball}$: 108.22–109.19 km/h; $V_{foot}$: 87.95 – 88.92 km/h) (Juarez et al., 2011) or above some references ($V_{ball}$: 64±5–79±6 km/h) (McLean & Tumilty, 1993). Changes in coordination patterns between lower limbs resulting from different angular adjustments in the joints, for each age group, may be responsible for producing the above results. However, a small number of investigations are found on this topic with a limited range of age groups (Cerrah et al., 2015; Katis et al., 2015; Teixeira & Teixeira, 2008), and our data do not allow inferences to be made in this line. Katis, et al. (2015) compared two groups of players, one young (15 years old) and one adult (25 years old) during the instep kick, with only one stride prior to impact. They found that adjustments in the final stages of kicking, in hip (> flexion), knee (> angular velocity), and ankle joints (> plantar flexion, < inversion and > angular velocity) favored the adults. Nevertheless, the authors themselves report as a limitation that multi-step approaches prior to impact, in addition to increasing performance, may reveal more differences between age groups (Katis et al., 2015). Taking this into account, we opted in the present study to allow a multi-step approach as necessary to each participant before the kicks. Additional research should contribute to the understanding of how the improvement presented here occurs in the quality of foot-ball impact, from childhood to adulthood, as well as the development of proximal-distal transference and kinematic aspects in a variety of age groups.

Unlike the velocity, the last stride length (LSL) (Kapidzic et al., 2014; Lees et al., 2005) and the distance between the support foot and the ball ($D_{support-ball}$) (Kapidzic et al., 2014; McLean & Tumilty, 1993; Orloff et al., 2008) have been little explored to date in young players. In this way the development of these components was not clear up to this point. Regarding LSL, only one study presented values, which were similar to ours (in the U20: 1.73±0.15 m) (Lees et al., 2005). Also, in this study (Lees et al., 2005) it was reported that LSL influenced the velocity of the ball in the U20 age group, although with a smaller coefficient ($r = 0.42$, see Table 2). In the present study, this parameter was identified as correlated, low to moderately high, with the development of ball velocity in all age groups (Table 2) and also demonstrated increases as a function of age (Table 1). The LSL is important to allow greater range of movement of pelvic retraction, which then provides greater pelvic protraction, in the forward rotation on the kicking side (Lees et al., 2010). Therefore, considering this variable in addition to $V_{ball}$, $V_{foot}$ and $V_{ball}/V_{foot}$ ratio in battery-testing, during the teaching-learning-training process and in subsequent studies it is recommended for all age groups from U9 to U20, as well as to identify if players are suitable for transition to another older group. In contrast, differences in $D_{support-ball}$ according to age do not follow the other parameters ($V_{ball}$, $V_{foot}$, $V_{ball}/V_{foot}$ ratio, LSL). McLean and Tumilty (1993) and Orloff et al. (2008) reported a $D_{support-ball}$ close to ours, in U17 (~0.37±0.03–0.39±0.04 m) and U20
(0.31±0.09 m), respectively. In contrast, Kapidzic et al. (2014) found lower values and inverse correlations with the \( V_{ball} \) (U13–U15: 0.14±0.07 m; \( r = -0.45 \)). However, attention is needed in U13–U17 groups where an excessively small \( D_{support-ball} \) could produce slower kicks due to low to moderate correlations with \( V_{ball} \) (Table 2). The absence of correlations between error measurements and \( V_{ball} \) (e.g., no correlation in U13–U17) was in line with the current literature (Navarro et al., 2013; Vieira et al., 2016). Moreover, there was an exception for MRE, which showed moderate inverse correlations in U9, U11, and U20, indicating that achieving higher \( V_{ball} \) is not necessarily accompanied by poor ball placement on a target when kicking.

From the calculations of MRE, BVE, and ACUR, we identified that these indicators, which represent measures of error during the kick, follow different dynamics of changes in function of chronological age. These data are not comparable with previous work as they used indirect measures to assess accuracy in young players (Malina et al., 2005; Malina et al., 2007; McLean & Tumilty, 1993; Rosch et al., 2000; Vaeyens et al., 2006; Vieira et al., 2017; Wilson et al. 2016). Criticism of this type of approach has been pointed out earlier by Berjan Bacvarevic et al. (2012), and we followed their recommendations for the design of the present study. The main results were that MRE, BVE, and ACUR appear to be impaired in the U11 (MRE, BVE, and ACUR, > than U15 to U20), U13 (MRE: > than U17, U20; ACUR: > than U17 and U20), with a likely extension up to U15 (MRE > than U20), and improvements are observed only in the older U17 and U20 groups. During the first pubertal phase (growth spurt; 12–13 to 14–15 years old) there is a marked increase in muscle mass, at the same time as muscular strength, and additionally, a rapid increase in height and weight, usually leading to a decrease in coordinative capacity, in that control of movements can become compromised. Movements without "precision" are typical at this age (Weineck, 1990). This premise seems also to apply to the ability to kick. Considering that the U9 group did not present the same differences as the older groups, it is possible to suggest that the increased indicators of kicking error suffer from a negative influence of the pubertal period as mentioned above (i.e., PHV time), especially in the U13, possibly extending up to U15. Thus, in order to refine kicking accuracy, we recommend that some specific training sessions should focus on instructions such as "hit the center of the target" instead of "kick the ball as fast as possible and try to hit the center of the target "or other instructions focusing mainly on velocities (van den Tillaar & Ulvik, 2014) often demanded in practical settings.

The main limitations of the present study were the choice to perform the kick without the presence of a goalkeeper, which represents a closed motor skill. According to the theoretical base accumulated in recent years (Vieira et al., 2017), the mere presence of a static goalkeeper (Navarro et al., 2013) is a task constraint that actually distracts and affects kicking performance during a penalty. This indicates that caution is required in attempting to transfer the findings to a competitive official match. Furthermore, the U9 and U20 age groups presented reduced sample sizes due to the inclusion and exclusion criteria established and logistical difficulties (e.g., mandatory necessity of both younger players and their guardians to sign the consent form). In Brazil, due to limited financial resources of several soccer teams to contract new players, U20s are generally also part of professional squads– and we opted not to include them. In addition, future studies with longitudinal approaches are necessary to confirm the occurrence of adaptations in kicking parameters, and investigate nondominant limb performance. Up to this point, mechanical factors during kicking have not been assessed during play, mainly due to practical difficulties (Apriantono et al., 2006). Considering that there is still a gap from analysis of the kick to coaching process (Lees et al., 2010), we try to provide real contributions to professionals, translating the results into practical terms. To our knowledge, this was also one of the first studies on kicking performance to use an integrated analysis approach, applying conventional statistics and magnitude-based inferences, which are contemporary trends (Cohen, 1988; Hopkins et al., 2009) added to which, the current literature examines a much smaller number of participating young soccer players, even in comprehensive work [e.g., \( N = 106 \)–Berjan Bacvarevic et al. (2012)].

Conclusion

In summary, responding to the original questions of this study, using 3-D and 2-D kinematic procedures in a large sample, we conclude that some biomechanical parameters of kicking performance present differentiated development. Ball and foot velocities present
increases as a function of the increase in chronological age, in a practically linear way, being moderately highly correlated with age. Football velocity transfer rate and last stride length before the kick followed a similar pattern (showing moderate correlations with age). Accuracy parameters presented impairment mainly during the growth spurt period, although there are no–bivariate variable error–to low correlation magnitudes–mean radial error and accuracy–with age. These results suggest that different specific training strategies should be applied for each age group.

What Does This Article Add?

From the results of the present study, we showed that some kicking performance measures ($V_{\text{ball}}$, $V_{\text{foot}}$, $V_{\text{ball}}/V_{\text{foot}}$ ratio, and LSL) have moderate to moderately high correlations with individual’s age, presenting sensitivity to the development from childhood (8 years) to the beginning of adulthood (19 years), which is expected to be a very important component during training sessions in youth soccer academies, although between U15–U17 less pronounced gains are expected. Coaches should consider that during the peak period of growth velocity (growth spurt, U13–U15) accuracy variables are negatively affected, in contrast to the current paradigm (Malina et al., 2005; Malina et al., 2007; Rosch et al., 2000; Vaeyens et al., 2006). Activities that prioritize hitting a target may be beneficial to these age groups. In U13–U17, very small $D_{\text{support-ball}}$ during impact could produce slower kicks. The LSL does not require highly advanced motion capture and measurement systems to be measured and was identified as correlated, low to moderately high, with kicking performance in all groups. Thus, training focused on increasing the range of motion when kicking is also recommended. Coaches should be aware of the reference values and predictive equations (Table 3) for the long-term monitoring process to develop the soccer kick. The promotion of young talent to an older age group, a common practice among coaches, could also consider whether players exhibit kicking performance that allows this transition.

References


### Table 1. Mean ± standard deviation (95% confidence limits) for kicking performance variables according to age (n = 366).

<table>
<thead>
<tr>
<th>U9</th>
<th>U11</th>
<th>U13</th>
<th>U15</th>
<th>U17</th>
<th>U20</th>
</tr>
</thead>
<tbody>
<tr>
<td>V(ball) (km.h⁻¹)</td>
<td>48.54 ± 8.31 a,b,c,d</td>
<td>57.87 ±10.93 e,f,g,h</td>
<td>66.70 ±13 k,l,j,k</td>
<td>76.92 ±15.58 l</td>
<td>81.35 ±16.04 m</td>
</tr>
<tr>
<td></td>
<td>(42.96; 54.12)</td>
<td>(55.32; 60.42)</td>
<td>(63.81; 69.60)</td>
<td>(73.90; 79.93)</td>
<td>(77.74; 84.97)</td>
</tr>
<tr>
<td>V(foot) (km.h⁻¹)</td>
<td>49.08 ±5.16 a,b,c,d</td>
<td>53.79 ±7.25 e,f,g,h</td>
<td>60.54 ±8.77 i,j,k</td>
<td>65.17 ±10.43 l</td>
<td>68.44 ±11.83 m</td>
</tr>
<tr>
<td></td>
<td>(45.62; 52.55)</td>
<td>(52.10; 55.48)</td>
<td>(58.58; 62.49)</td>
<td>(63.15; 67.19)</td>
<td>(65.77; 71.10)</td>
</tr>
<tr>
<td>V(ball) / V(foot) ratio</td>
<td>0.99 ± 0.13 a,b,c,d</td>
<td>1.07 ± 0.11 e,f,g,h</td>
<td>1.1 ± 0.11 i,j,k,l</td>
<td>1.18 ± 0.1 l</td>
<td>1.19 ± 0.1 m</td>
</tr>
<tr>
<td></td>
<td>(0.90; 1.07)</td>
<td>(1.05; 1.10)</td>
<td>(1.07; 1.12)</td>
<td>(1.16; 1.20)</td>
<td>(1.16; 1.21)</td>
</tr>
<tr>
<td>LSL (m)</td>
<td>1.09 ± 0.14 a,b,c,d</td>
<td>1.25 ± 0.14 e,f,g,h</td>
<td>1.36 ± 0.19 k</td>
<td>1.43 ± 0.23 l</td>
<td>1.44 ± 0.2 m</td>
</tr>
<tr>
<td></td>
<td>(1.00; 1.18)</td>
<td>(1.21; 1.28)</td>
<td>(1.32; 1.40)</td>
<td>(1.38; 1.47)</td>
<td>(1.39; 1.48)</td>
</tr>
<tr>
<td>D(support-ball) (m)</td>
<td>0.33 ± 0.07 a,m</td>
<td>0.3 ± 0.07 e,f,g,h</td>
<td>0.34 ± 0.06</td>
<td>0.34 ± 0.06</td>
<td>0.34 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>(0.28; 0.37)</td>
<td>(0.29; 0.32)</td>
<td>(0.33; 0.35)</td>
<td>(0.33; 0.36)</td>
<td>(0.33; 0.36)</td>
</tr>
<tr>
<td>MRE (m)</td>
<td>1.4 ± 0.49 a,b,c,d</td>
<td>1.65 ± 0.6 e,f,g,h</td>
<td>1.59 ± 0.59 i,j,k</td>
<td>1.34 ± 0.48 l</td>
<td>1.29 ± 0.5 m</td>
</tr>
<tr>
<td></td>
<td>(1.07; 1.73)</td>
<td>(1.52; 1.79)</td>
<td>(1.46; 1.72)</td>
<td>(1.24; 1.43)</td>
<td>(1.18; 1.40)</td>
</tr>
<tr>
<td>BVE (m)</td>
<td>1.26 ± 0.58 a,b,c,d</td>
<td>1.47 ± 0.73 e,f,g,h</td>
<td>1.30 ± 0.57</td>
<td>1.18 ± 0.51</td>
<td>1.17 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>(0.87; 1.65)</td>
<td>(1.31; 1.64)</td>
<td>(1.17; 1.43)</td>
<td>(1.08; 1.27)</td>
<td>(1.06; 1.28)</td>
</tr>
<tr>
<td>ACUR (m)</td>
<td>1.93 ± 0.64 a,b,c,d</td>
<td>2.25 ± 0.84 e,f,g,h</td>
<td>2.09 ± 0.72</td>
<td>1.81 ± 0.62</td>
<td>1.77 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>(1.50; 2.36)</td>
<td>(2.06; 2.45)</td>
<td>(1.93; 2.25)</td>
<td>(1.69; 1.93)</td>
<td>(1.63; 1.92)</td>
</tr>
</tbody>
</table>

Note: a = U9 x U13; b = U9 x U15; c = U9 x U17; d = U9 x U20; e = U11 x U13; f = U11 x U15; g = U11 x U17; h = U11 x U20; i = U13 x U15; j = U13 x U17; k = U13 x U20; l = U15 x U20; m = U17 x U20. Confidence limits = (lower; upper bound). V(ball) = ball velocity; V(foot) = foot velocity; V(ball) / V(foot) = ball velocity / foot velocity ratio; LSL = last stride length; D(support-ball) = distance between support foot and ball; MRE = mean radial error; BVE = bivariate variable error; ACUR = accuracy. Significance level of post hoc comparisons: V(ball): a,e p < .01; b,c,d,e,f,g,h,i,j,k,l,m p < .001. V(foot): i p < .05; a,m p < .01; b,c,d,e,f,g,h,i,j,k,l p < .001. V(ball) / V(foot) ratio: a,l p < .05; b,c,d,e,f,g,h,i,j,k p < .001.
Table 2. Correlation coefficients between ball velocity and dependent variables according to age.

<table>
<thead>
<tr>
<th></th>
<th>U9</th>
<th>U11</th>
<th>U13</th>
<th>U15</th>
<th>U17</th>
<th>U20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{foot}$</td>
<td>0.66</td>
<td>0.83</td>
<td>0.85</td>
<td>0.89</td>
<td>0.89</td>
<td>0.86</td>
</tr>
<tr>
<td>$V_{ball} / V_{foot}$</td>
<td>0.82</td>
<td>0.72</td>
<td>0.68</td>
<td>0.62</td>
<td>0.51</td>
<td>0.73</td>
</tr>
<tr>
<td>LSL</td>
<td>0.36</td>
<td>0.57</td>
<td>0.70</td>
<td>0.79</td>
<td>0.70</td>
<td>0.59</td>
</tr>
<tr>
<td>$D_{support-ball}$</td>
<td>-0.12</td>
<td>0.06</td>
<td>0.40</td>
<td>0.33</td>
<td>0.24</td>
<td>0.12</td>
</tr>
<tr>
<td>MRE</td>
<td>-0.46</td>
<td>-0.49</td>
<td>0.01</td>
<td>-0.04</td>
<td>-0.19</td>
<td>-0.46</td>
</tr>
<tr>
<td>BVE</td>
<td>0.07</td>
<td>-0.21</td>
<td>-0.04</td>
<td>-0.12</td>
<td>-0.04</td>
<td>0.23</td>
</tr>
<tr>
<td>ACUR</td>
<td>-0.24</td>
<td>-0.39</td>
<td>-0.01</td>
<td>-0.08</td>
<td>-0.15</td>
<td>-0.21</td>
</tr>
</tbody>
</table>

Note: Criterion for judgment on correlation coefficients: $r < .2$ (no correlation), $.2 \leq r < .4$ (low correlation), $.4 \leq r < .6$ (moderate correlation), $.6 \leq r < .8$ (moderately high correlation), $r \geq .8$ (high correlation); $V_{foot}$ = foot velocity; $V_{ball} / V_{foot}$ = ball velocity / foot velocity ratio; LSL = last stride length; $D_{support-ball}$ = distance between support foot and ball; MRE = mean radial error; BVE = bivariate variable error; ACUR = accuracy.

Table 3. Linear and a polynomial third-order regressions models between chronological age and dependent variables, including the predictive equations ($n = 366$).

<table>
<thead>
<tr>
<th>Factor</th>
<th>$R^2$</th>
<th>Predictive equation</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{ball}$</td>
<td>0.47</td>
<td>$V_{ball} = (5.0743 \times \text{Age}) + 3.8195$</td>
<td>1.77</td>
</tr>
<tr>
<td>$V_{foot}$</td>
<td>0.39</td>
<td>$V_{foot} = (3.0105 \times \text{Age}) + 22.262$</td>
<td>1.90</td>
</tr>
<tr>
<td>$V_{ball} / V_{foot}$ ratio</td>
<td>0.28</td>
<td>$V_{ball}/V_{foot} = (0.0264 \times \text{Age}) + 0.7845$</td>
<td>2.05</td>
</tr>
<tr>
<td>LSL</td>
<td>0.25</td>
<td>$LSL = (0.0446 \times \text{Age}) + 0.7766$</td>
<td>2.10</td>
</tr>
</tbody>
</table>
MRE 0.07

MRE = (0.0012 × \text{Age}^3) - (0.0495 × \text{Age}^2) + (0.6143 × \text{Age}) - 0.7223

0.53

Note: SEE = standard error of the estimate. \( V_{\text{ball}} \) = ball velocity; \( V_{\text{foot}} \) = foot velocity; \( V_{\text{ball}} / V_{\text{foot}} \) = ball velocity / foot velocity ratio; LSL = last stride length; MRE = mean radial error.
Figure 1. Experimental setup, including target illustration, in order to obtain (A) the last stride length, (B) distance between support foot and ball, (C) foot velocity and ball velocity, and (D) view of the camera that recorded the distance between ball centroid and center of the target, and lateral camera which detected when the ball crossed goal line.