This study addresses the utility of the kinematics of penalty takers for goalkeepers in association football. Twelve professional and semi-professional players shot to one side of the goal with (deceptive condition) or without (non-deceptive condition) simulating a shot to the opposite side. The body kinematics of the penalty takers were registered with motion-capture apparatus. Correlation and regression techniques were used to determine the relation between the shot direction and aspects of the penalty taker's kinematics at different moments. Several kinematic variables were strongly correlated with shot direction, especially those related to the lower part of the body. Some of these variables, including the angle of the non-kicking foot, acquired high correlations at time intervals that are useful to goalkeepers. Compound variables, here defined as linear combinations of variables, were found to be more useful than locally defined variables. Whereas some kinematic variables showed substantial differences in their relation to ball direction depending on deception, other kinematic variables were less affected by deception. Results are interpreted with the hypothesis of non-substitutability of genuine action. The study can also be interpreted as extending the correlation and regression methodology, often used to analyze variables defined at single moments, to the analysis of variables in a time continuous fashion.

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1. Introduction

In sports such as handball, basketball, or football, there are severe time constraints for athletes while perceiving and acting. In addition, players are pressured to achieve high levels of precision. A match event in which these spatial and temporal constraints are particularly evident is the penalty kick in association football (Lopes, Araújo, Peres, Davids, & Barreiros, 2008). One of the aspects of the penalty kick that has received attention concerns the information that goalkeepers use to anticipate the direction of the ball (Diaz, Fajen, & Phillips, 2012; Dicks, Button, & Davids, 2010a). With the current experiment we aim to contribute to the knowledge about this aspect of the penalty kick, focusing on the information available in the kinematics of the penalty taker and on the role of deception.

Before we describe the purpose of the experiment in more detail, we briefly review previous results. A crucial issue is the time at which goalkeepers commit themselves to a side. Dicks, Davids, and Button (2010) reported average ball flight times between 590 and 648 ms and average goalkeeper movement times between 750 and 1085 ms. Hence, goalkeepers who base the direction of their dives on the first part of the ball trajectory are likely to start moving too late, especially if one takes into account that a small perceptual-motor delay must exist. The findings reported by Dicks et al. (2010) therefore support the common claim that goalkeepers should initiate their movements before ball contact, which means that they should not rely exclusively on information from the ball trajectory (Dicks, Uehara, & Lima, 2011; Franks & Harvey, 1997).

As an alternative source of information, goalkeepers may use the kinematics of their opponent before ball contact to anticipate the direction of the shot. This gives rise to two questions. First, which kinematic variables are good predictors of ball direction? And second, which kinematic variables are actually used by goalkeepers? A substantial body of work has addressed the second question, using self-reports (Kuhn, 1988), occlusion paradigms (Dicks, Button, & Davids, 2010b; Smeeton & Williams, 2012), and, most particularly, gaze-registration methods (Button, Dicks, Haines, Barker, & Davids, 2011; Dicks et al., 2010a; Piras & Vickers, 2011; Savelsbergh, van der Kamp, Williams, & Ward, 2005). Areas that goalkeepers have been claimed to focus on include the penalty takers' hips, the non-kicking foot, and the region between the ball and the kicking leg (i.e., ‘visual pivot’; Piras & Vickers, 2011).

Less research has addressed the first question, about how useful the candidate kinematic variables actually are. Franks and Harvey (1997) analyzed videos of penalties in FIFA World Cup competitions. They concluded that several kinematic variables have a high reliability at or immediately before ball contact. These variables include the inward or outward knee rotation of the kicking leg and the point of contact on the ball. However, given the time constraints for goalkeepers, Franks and Harvey considered that variables should be detectable and have a high reliability a certain time interval before ball contact. This led them to consider the final placement (i.e., pointing direction) of the non-kicking foot as the most useful variable. They reported that this variable has a reliability of about 80% and that it can be detected from about 150–200 ms before ball contact.

Studies by Lees and Owens (2011) and Diaz et al. (2012) also concerned the information value of candidate kinematic variables. These studies were more sophisticated than the one reported by Franks and Harvey (1997) in the sense that motion-capture equipment was used to register the kinematics of the penalty takers, allowing more advanced methods to analyze the reliability of the candidate variables. The three studies (i.e., the ones by Franks & Harvey, Lees & Owens, and Diaz et al.) agree in pointing toward the orientation of the non-kicking foot as a relatively reliable source of information around 200–250 ms before ball contact. Lees and Owens also reported hip rotation (as projected on the horizontal plane) and hip and ankle flexion as significant indicators of shot type and shot direction. Diaz et al. presented results for several locally defined kinematic variables. In addition, they concluded that global or distributed information might be useful. At 200 ms before ball contact, for instance, one of the sources of distributed information considered by Diaz et al. had a reliability of 77%. An emphasis on distributed information is consistent with research in other sports (e.g., Abernethy, Gill, Parks, & Packer, 2001; Huys, Smeeton, Hodges, Beek, & Williams, 2008; Ward, Williams, & Bennett, 2002).
The experiments reported by Lees and Owens (2011) and Diaz et al. (2012), however, are not without shortcomings. First, penalty takers were asked to shoot the ball into a smaller-than-standard size goal (Lees & Owens) or into a small (2.43-m wide) canvas substituting a goal (Diaz et al.). Second, penalties were shot from a distance shorter than the regular 11 m. Third, no goalkeepers were present during the penalty kicks. The results of these studies can hence be generalized to penalty kicks in match situations only if one assumes that these aspects do not affect the kinematics of the kicks, or, more precisely, if one assumes that they do not affect the reliability of the considered variables as information sources. We think that the relevance of this assumption warrants further research. The importance of representative designs has also been emphasized in previous penalty kick studies (Button et al., 2011; Dicks et al., 2010a; Lopes et al., 2008; cf. Araújo, Davids, & Hristovski, 2006).

In addition, the experimental designs of Lees and Owens (2011) and Diaz et al. (2012) did not consider the issue of deception, even though deception was mentioned in the respective discussions as being an important issue (cf. Dicks et al., 2010b; Smeeton & Williams, 2012). Suppose that a goalkeeper relies on the orientation of the non-kicking foot. If penalty takers know this, they may try to deceive the goalkeeper by kicking the ball in the opposite direction of that to which the non-kicking foot is oriented. Some aspects of the kicking action, however, need to be established in order to kick the ball in a particular direction, meaning that it is likely that some higher-order or distributed kinematic variables remain specific to the kick direction intended by penalty takers. This is captured by the hypothesis of the non-substitutability of genuine action: In trying to produce an unnatural movement pattern, one may successfully produce some of the kinematic details of the genuine action, but typically not all the complexity of the action that is needed to convince the perceiver that the action is genuine (Richardson & Johnston, 2005; Runeson & Frykholm, 1981, 1983; for sports applications see Jackson, Warren, & Abernethy, 2006).

To summarize, the combined literature states that goalkeepers’ actions are at least partly based on the kinematics of the penalty takers before ball contact. To analyze the information contained in the available kinematic variables, and to analyze which variables are actually used, it seems indispensable to register the movements of penalty takers during penalty kicks. Useful work in this regard has been done by Lees and Owens (2011) and Diaz et al. (2012), but further advances may be achieved by performing experiments in more representative situations and by considering the issue of deception. We asked professional and semi-professional players to take penalties in a situation with a goalkeeper and with a standard-size goal. The penalty takers used deceptive and non-deceptive strategies and their movements were registered with an infrared movement-registration system.

A further aspect of our study that we consider a contribution with regard to previous work in the field of penalty kicks is our data analysis, which is inspired by work concerning variable use in other tasks (Jacobs, Runeson, & Michaels, 2001; Michaels & de Vries, 1998). We assess the information available in single kinematic variables with the correlations between the kinematic variable and ball direction, reasoning that more informative variables have higher correlations. Likewise, the information contained in combinations of variables (which may also be referred to as compound variables, higher-order variables, or distributed variables) is assessed with multiple regressions with ball direction as dependent variable. Our application of correlation and regression methodology has the particularity that the values of the kinematic variables change continuously during the approach of the penalty takers to the ball. Our analyses therefore extend the use of correlation and regressions analyses from applications with single-moment variables to temporarily extended variables (cf. Jacobs, Vaz, & Michaels, 2012). In addition to using ball direction as dependent variable, we performed correlation and regressions with dive direction as dependent variable, in order to estimate the variables used by goalkeepers to predict kick direction.

2. Methods

2.1. Participants

The penalty takers were twelve male professional and semi-professional players ($M_{age} = 21.2$ years; $SD = 4.6$ years). Eight penalty takers were senior players of a team in the Portuguese National Second
Division. Four penalty takers were junior players that played in the same team as the senior players or alternated between that team and the junior team. The junior team played in the Portuguese National Junior Second Division. In association football, the penalty kicks taken by a team are mostly taken by one or a few players. The primary penalty takers of the senior and junior teams participated in the experiment (Participants 6 and 8, respectively; Participant 9 often assumed the role of primary penalty taker of the senior team in matches without Participant 6). No information was collected about the number of practice sessions in which penalty kicks were trained or about the number of penalties that had been taken by each player in match situations. The goalkeepers were five young but experienced non-professionals of the same teams ($M_{\text{age}} = 17.4 \text{ years}; SD = 0.9 \text{ years}$). Two goalkeepers regularly trained with the senior team and three were goalkeepers of the junior team. All participants—penalty takers as well as goalkeepers—had played competition for six or more consecutive years. Participant information is presented in Table 1. Informed consent was obtained from the players and from their club, after the ethical approval of the study by a local university committee.

2.2. Materials

The experiment was performed indoors with a standard football goal ($7.32 \times 2.44 \text{ m}$). The penalty kick mark was located 11 m from the goal. Judo mats protected goalkeepers from injuries. A regular size and weight ball was used. To facilitate the instructions to the penalty takers, two pieces of a soft PVC fabric ($1.83 \times 2.44 \text{ m}$; one green and one red) were placed at the sides of the goal, immediately after the goal line and close to the posts (Fig. 1). A four-camera infrared system (with the frequency set at 150 Hz) was used to record the kinematics of the penalty takers (Qualisys AB, Gothenburg, Sweden). The software used for this registration was Qualisys Track Manager 2.3. The experiment was also recorded with a standard video camera (DCR-HC23; Sony Corporation, Tokyo, Japan). Camera positions are shown in Fig. 2. Penalty takers wore regular football shorts (not covering the knees), their own indoor shoes, and a swimming cap. Sixteen lightweight light-reflecting markers with a diameter of 40 mm were used. Ten markers were attached to the skin: on the shoulders (acromion), elbows (lateral epicondyle), wrists (ulnar styloid), hips (posterior superior iliac spine), and knees (near lateral meniscus). Four markers were attached to the shoes: one on the backside of each shoe (moved slightly outwards) and one on the outer side (near the fifth metatarsal bone). Two markers were placed on the swimming cap: on the back of the head, one left and one right. In addition, a small piece of reflective

<table>
<thead>
<tr>
<th>Participant description.</th>
<th>Age (years)</th>
<th>Kicking foot</th>
<th>Professional status</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Penalty taker</strong></td>
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<td>Semi-professional</td>
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<td>5</td>
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<td>12</td>
<td>26</td>
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<td>Semi-professional</td>
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<tr>
<td><strong>Goalkeeper</strong></td>
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<tr>
<td>1</td>
<td>17</td>
<td>Right</td>
<td>Amateur</td>
<td>Junior</td>
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<td>2</td>
<td>18</td>
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cloth was attached to the ball. Although this (approximately flat) piece of cloth was not detected as reliably as the real (round) markers, it was captured for all penalties, in the majority of cases until a few frames after ball contact.

Fig. 1. Goal used in experiment with green (G) and red (R) target areas. Also shown are the ball and the judo mats.

Fig. 2. Top view of experimental set-up. The trapezoid area around the penalty kick mark (black filled circle) represents the volume covered by the Qualisys cameras (Cam 1, Cam 2, Cam 3, and Cam 4). A standard video camera (Cam 5) recorded the trials from behind the penalty taker. The shown camera positions were the ones used for players who kicked with their right foot. For players who kicked with their left foot the positions were mirror-reversed.
2.3. Procedure

Before the actual experiment participants were asked to warm up. For the penalty takers the warm up included penalty kicks to the experimental target areas. During the experiment each penalty taker performed 60 penalty kicks. The goalkeepers participated in the trials depending on their availability.\(^1\) Due to technical problems with the standard video camera, the identification of the participating goalkeepers (as well as the determination of the ball coordinates at the goal line) was accomplished only for 706 of the 720 trials (98.1%). Goalkeepers 1–5 participated in 178, 194, 177, 122, and 35 of these 706 trials, respectively. A maximum run up distance of 3.5 m was allowed. Just before each trial, the researchers orally communicated one of the following instructions to the penalty taker: (1) “shoot to green without simulating”; (2) “shoot to red without simulating”; (3) “shoot to green but simulate shooting to red”; and (4) “shoot to red but simulate shooting to green”. Goalkeepers were not informed about the instructions to the penalty takers. Goalkeepers switched on goal from one penalty kick to the next, waiting for their turn on the sideline. All participants were allowed to pause when requested.

2.4. Data analysis

2.4.1. Data from standard video camera

The recordings from the standard video camera were used to code three variables: trial outcome, goalkeeper movement, and ball direction. Outcome was coded as: 1 = ball out of goal or struck post/crossbar; 2 = goalkeeper stops ball; 3 = goal despite goalkeeper touching ball; and 4 = goal without goalkeeper touching ball. The movement of the goalkeeper was coded as: 1 = dive to the left and 1 = dive to the right (as seen from the perspective of the penalty taker). Trials without dives were not included in the analyses on dive direction. To determine the ball direction for a particular trial, the video was stopped when the ball crossed the goal line, and the lateral and height coordinates were measured on the screen and converted to real-world measures. Only the lateral direction of the ball was used in the analyses.

Although the instructions concerning shooting direction were binary (green/left or red/right), the measured lateral direction was a continuous variable. Positive values were associated to balls to the right side of the goal and negative values to ball to the left side of the goal (again, as seen from the perspective of the penalty taker). Occasional trials that laterally missed the goal by more than 1 m were considered outliers and hence not included in the analyses. Finally, for trials in which the goalkeepers actually dove to one of the sides, the videos were also used to estimate the time between the moment of the first noticeable lateral movement of the goalkeeper and the moment at which the foot of the penalty taker contacted the ball (cf. Dicks et al., 2010b, 2010).

2.4.2. Movement-registration data

Data from the infrared movement-registration system were first processed with the Qualisys software. With this software we identified the three-dimensional trajectories corresponding to the 16 markers. The trajectories were gap-filled with an algorithm included in the software. All gap-filled trajectories were checked visually. The gap-filled data were exported to Matlab 9.0 (The Mathworks Inc., Natick, MA, USA). In Matlab, the frame of ball contact was determined with an algorithm based on the position of the kicking foot. This algorithm identified the frame before the moment at which the marker on the side of the kicking foot crossed the horizontal line 11.15 m from the goal line as the frame of ball contact. The results obtained with this algorithm were checked visually (and occasionally corrected) by inspecting if the previously observed frame matched the last frame where the ball marker (i.e., the piece of reflecting cloth on the ball) showed no movement.

\(^{1}\) Whereas the number of penalties per penalty taker was determined beforehand and strictly controlled, the number of penalties per goalkeeper was not. This was so because the focus of the experiment was on the kinematics of the penalty takers, because more penalty takers were available than goalkeepers, and because aiming to stop a large number of penalties is physically more demanding than shooting the penalties.
2.4.3. Candidate kinematic variables

Values of a substantial number of kinematic variables were computed from 1.5 s (225 frames) before ball contact until 0.5 s (75 frames) after ball contact. The computed variables included three-dimensional angles formed by groups of three markers within and across body regions, three-dimensional angles formed by two markers with respect to a standard orientation (i.e., with respect to the vertical axis), two-dimensional angles formed by markers projected on horizontal and vertical planes, as well as speeds and movement directions of single markers.

We selected the more interesting of the computed variables for presentation in this article. A first set of variables selected for presentation include: head angle, shoulder angle, hip angle, kicking foot angle, non-kicking foot angle, kicking foot movement direction, and the approach angle of the penalty taker to the ball. These variables were computed as projections on the horizontal plane. All these variables were computed so that a clockwise rotation in the angle or movement direction corresponds to an increase in the angle or direction. Also presented are results for the knee angle of the kicking leg (measured as the angle formed by the markers on the hip, knee, and back of the foot; knee further extended = larger angle) and the kicking foot speed (measured as the speed of the marker on the front part of the kicking foot).²

2.4.4. Correlation and regression analyses

Correlation and (linear) regression analyses were conducted to determine the relation of the candidate kinematic variables and the lateral direction of the ball. The correlations and the regression models were computed separately for each penalty taker and each deception condition, at each moment in time with respect to ball contact. This means that the parameters of the models were different for different individuals, conditions, and moments in time. There were 30 penalties per penalty taker and per condition, meaning that each regression model was computed with a maximum of 30 values. In the more relevant time windows (i.e., where the kinematic variables reveal predictive potential; Diaz et al., 2012; Lees & Owens, 2011), most markers were registered correctly, meaning that the actual number of values was relatively close to the maximum of 30 values (see captions of Figs. 4 and 5). With this number of observations the expected statistical power of the regression analyses was high. More precisely, according to a procedure described in Cohen, Cohen, West, and Aiken (2003, p. 92), with a significance criterion of $p = .05$, three independent variables, and an estimated multiple correlation of 0.7 the statistical power is about 0.99.

For the kinematic variables kicking foot speed and knee angle of the kicking leg, the correlations were expected to be (and found to be) the opposite for penalty takers who kicked with their left and right foot. For example, players who kick with their right foot kick faster to the left than to the right, giving rise to a negative correlation between the speed of the kicking foot and the lateral direction of the ball. In contrast, players who kick with their left foot kick faster to the right, giving rise to a positive correlation. Rather than averaging correlations that are negative for some players and positive for other players, we inverted the sign of the correlations for these variables (i.e., for the kicking foot speed and for the knee angle of the kicking leg) for the participants who kicked with their left foot before averaging the correlations over all participants. For the other variables the expected and observed direction of the correlations was the same for participants who kicked with their left and right foot.

We inspected the assumptions for the regression models computed at 150 ms before ball contact and for the models computed at ball contact, using techniques described in Cohen et al. (2003, chap. 4). In these checks we focused on the linearity of the relationship between the independent variables and the dependent variable, the collinearity of the independent variables, the constancy of the variance of the residuals, the independence of the residuals, and the normality of the distribution of the residuals. Our main concern raised by these checks is the independence of the residuals. For a substantial percentage of the models this assumption is violated because of a phenomenon called clustering: the residuals were different for penalties shot to the left and penalties shot to the right. This was most clearly visible.

² A disadvantage of our research (and of similar research) is that the choices about which variables are interesting to present are to some extent subjective. Relatedly, one cannot rule out that other variables may have higher correlations than the ones that we have analyzed.
for the models that did not predict shot direction very well; these models tend to predict penalties to the middle of the goal and hence show negative residuals for penalties to the left and positive residuals for penalties to the right. The violations of this assumption of independence means that the significance tests reported in our article should be interpreted with caution (Cohen et al., p. 120).

In addition to the relation between the kinematic variables and ball direction—which is the main focus of our article—we tentatively explored the relation between the kinematic variables and the dive direction of the goalkeepers. These latter analyses are reported only for Goalkeepers 1–4, because Goalkeeper 5 participated in too few trials. Using the number of trials reported above and using expected multiple correlations similar to the ones of the models reported below (around 0.3), the procedure described in Cohen et al. (2003, p. 92) indicates that the expected power of the regression models for the reported goalkeepers was higher than 0.80 (whereas the expected power for Goalkeeper 5 would have been lower than 0.30).

3. Results

In this section we consider (1) measures concerning penalty kick outcome, (2) correlations between single kinematic measures and penalty kick direction, (3) multiple regressions with several kinematic measures predicting penalty kick direction, (4) predictions of dive direction, and (5) percentages of correctly predicted penalty kick directions.

3.1. Outcome measures

Table 2 presents the percentages of penalty kicks that missed the goal, were stopped, were touched by the goalkeeper, or were scored without being touched. The percentages are presented overall and for the different deception conditions. They are presented for the individual penalty takers, the individual goalkeepers, and averaged. Averaged over all penalty takers, 67.5% of the penalty kicks were scored (61.9% without and 5.6% with the goalkeeper touching the ball). The remaining 32.5% of the penalty kicks were not scored (18.8% due to goalkeeper interception and 13.7% because the ball was kicked outside of the goal or onto the bars). To statistically compare the outcomes for the deceptive and non-deceptive conditions, we performed a repeated-measures multivariate analysis of variance (MANOVA) with deception condition (deception, no deception) as independent variable and with the percentages per penalty taker for the four coding categories as dependent variables. No significant differences were observed: $F(4, 8) = 1.1, p = .42$; Wilks’ $\Lambda = 0.65$, partial $\eta^2 = 0.36$.

As a further test of the effect of deception on the outcome statistics we compared the sums of Codes 3 and 4 for each penalty taker (i.e., the total percentage of scored penalty kicks) for the different instructions. A paired $t$ test indicated that this difference was not significant: $t(11) = -.41, p = .69$. In sum, we did not find that instructions concerning deception affected these outcome measures. This may indicate that the penalty takers’ average level of expertise in the execution of deceptive penalty kicks was not sufficiently high (look ahead to Footnote 5). Let us anticipate, however, that the penalties in the deceptive and non-deceptive conditions differed significantly on aspects other than the overall outcome scores.

To analyze a possible change over trials of the outcome of the penalties, we computed the proportion of the 12 penalty takers that scored their penalty for each trial from the first to the last experimental trial. The Pearson product-moment correlation between trial number and the proportion of scored penalties was $-0.05 (p > .69)$. Hence, overall, there was no consistent trend in the proportion of the scored penalties over trials. To analyze the results per penalty taker, we computed the point-biserial correlations (Cohen et al., 2003, p. 29) between the individual penalty kick outcome and trial number. These correlations ranged between $-0.23$ and 0.20 ($M = -0.02; SD = 0.14$). None of them reached significance (all $p > .08$). We conclude from these results that trial number was not related to success and hence that fatigue and learning were not important factors in the experiment.

We observed a dive of the goalkeeper to the left, as seen from the penalty taker, on 261 trials, and a dive to the right on 322 trials. For penalties kicked to the left, dives to the left were more frequent (178 vs. 126), and for penalties kicked to the right, dives to the right were more frequent (196 vs. 83). A $\chi^2$
test indicated that the relation between shot direction and dive direction was significant: \( \chi^2(1, N = 583) = 48.8, p < .001 \). The correlation between these dichotomous variables, sometimes referred to as phi-coefficient (Cohen et al., 2003, p. 30), was 0.29. These results are interesting because they rule out that the goalkeepers randomly chose a side, and, therefore, indicate that the dives were at least to some extent based on detected information.

For the analyses in the following subsections it is relevant to note the spread of the shots to each of the sides. For shots to the left, the mean distance to the middle of the goal was 2.41 m and the standard deviation of that distance was 0.74 m. For shots to the right these values were 2.28 and 0.88 m, respectively. Because of the relatively large standard deviations, merely classifying the shots as left and right would entail a loss of information. In the correlation and regression analyses, we therefore used the lateral direction of the shots as a continuous dependent variable, instead of using left versus right as a binary dependent variable.

3.2. Single kinematic variables and ball direction

To facilitate the interpretation of the correlation and regression analyses, Fig. 3 first presents two scatter plots for an individual player who kicked with his right foot, for kinematics registered at 150 ms before ball contact in the non-deceptive condition. The observed lateral ball direction is plotted against the non-kicking foot angle (left panel) and the kicking foot speed (right panel). Also shown are the linear fits and the correlations associated to the scatter plots with their significance levels. To interpret the direction of the correlations, recall that the measured ball direction was considered positive if the ball was directed to the right of the goalkeeper and that two-dimensional (ground plane) angles and directions had higher values if they were rotated further clockwise. The positive correlation in the left panel thus indicates that penalties on which the non-kicking foot is oriented further clockwise tend to be directed further to the right. The negative correlation in the right panel indicates that, for this kicker, penalties on which the kicking foot moves faster tend to be directed further to the left.

Fig. 4 presents the time evolution of the average correlations between ball direction and single kinematic variables, for the non-deceptive condition (solid curves) and the deceptive condition (dashed curves). The moment of ball contact is defined as 0.0 s (vertical line segments). The main groups of variables selected for presentation in this figure are: (1) variables with high correlations with ball direction during a time window before ball contact, (2) variables with high correlations at the moment of ball contact, and (3) variables with substantially different correlations in the deceptive and non-deceptive conditions. Before initiating the presentation of the results, it is worth mentioning

![Fig. 3](Image)
that in order to be useful as an information source for goalkeepers, a variable should not only be highly correlated with ball direction, but it should be so before a certain moment (after which goalkeepers can no longer use information due to temporal constraints). Remember from the introduction that 150 to 200 ms before ball contact has been considered an appropriate time window.

A general inspection of Fig. 4 indicates that earlier than about 0.5 s before ball contact, the relations between our candidate kinematic variables and ball direction were weak or nonexistent. Among the kinematic variables selected for presentation, non-kicking foot angle, knee angle of the kicking leg, and kicking foot speed (leftmost column in figure) showed highly positive or negative correlations a certain time window before ball contact. Kinematic variables that showed high correlation values at

Fig. 4. Time evolution of product-moment correlations between single kinematic variables and ball direction. Curves represent correlations computed per penalty taker and averaged over the twelve penalty takers. Asterisks indicate that the curves differ significantly ($p < .05$, for a $t$ test for paired samples on the $z$ scores of the twelve correlations). The maximum number of penalties per computed correlation was 30. In the most relevant parts of the curves the average number of penalties ($n$) used to compute the correlations was close to 30. For example, at $t = -0.15$ s, $n = 29.0$ ($SD = 1.1$), and at $t = 0$, $n = 28.6$ ($SD = 2.0$). Curves are not shown if for one (or more) of the penalty takers the number of valid trials was less than 10.
the moment of ball contact were: kicking foot angle, hip angle, and kicking foot movement direction (middle column in figure).\(^3\)

We next address the significance levels of the correlations. Of the correlations shown in the middle column (12 correlations per curve), which we categorized as being high at ball contact, 97.2% had a significance level of \(p < .05\) at ball contact. Of the correlations in the leftmost column—categorized as being high before ball contact—86.1% had a significance level of \(p < .05\) at 150 ms before ball contact. Concerning the observation that the correlations were low until about 0.5 s before ball contact, at that moment 33.3% of all correlations reached the \(p = .05\) level. At 0.5 s before contact, the highest percentages of significant correlations occurred for the deceptive condition of the variable head angle (75.0%) and for the deceptive conditions of the variables hip angle and shoulder angle (both 66.7%). Overall, the significant correlations at 0.5 s before ball contact occurred significantly more often in the deceptive condition than in the non-deceptive condition (45.4% vs. 21.3%; \(t(8) = 4.7, p < .01\)).

Regarding the influence of deceptive and non-deceptive strategies, the kinematic variables approach angle, shoulder angle, and head angle were found to be affected, as evidenced by the differences between the solid and dashed curves in the rightmost column of Fig. 4. Asterisks on the continuous curves indicate that, at the corresponding moments, the difference between the continuous and dashed curves was significant. Other variables that were affected by deception were the non-kicking foot angle, kicking foot angle, and hip angle. In contrast, the knee angle of kicking leg and kicking foot speed were not substantially affected by the penalty taker’s strategy. For the variables that correlated most highly with ball direction at the moment of ball contact (middle column), one may observe that the solid and dashed curves lie close to each other at the moment of ball contact. This indicates that although the deception affected these variables before ball contact, it did not do so at ball contact.

Having presented the potential information and susceptibility to deception of single kinematic variables, with correlation analyses, the next explore these issues for compound variables through multiple regressions.

### 3.3. Compound kinematic variables and ball direction

Fig. 5 presents results of regression analyses with the lateral direction of the ball as dependent variable. The regression analyses search the linear combinations of individual kinematic variables that best predict the direction of the ball. Regressions for the non-deceptive and deceptive conditions are presented in the left and right column, respectively. Following our criteria used in the analyses of the single kinematic variables, the groups of predictor variables that were used in the analyses were (from top to bottom in the figure): (1) variables with high correlations during a time window before ball contact, (2) variables with high correlations at the moment of ball contact, and (3) variables with substantially different correlations between deceptive and non-deceptive conditions (i.e., the ones susceptible to deception).

An overall examination of Fig. 5 reveals three trends. First, in many cases the continuous black curves indicating the multiple correlations of the models fluctuate at an approximately constant level of about 0.4 until about 0.5 s before ball contact, after which they increase to reach levels of about 0.8 or 0.9 at ball contact. Second, the curves for the multiple correlations often lie substantially higher than the ones for the individual variables, indicating that compound variables defined with several of the individual variables are in many cases better predictors of ball direction than the individual variables by themselves. Third, comparing the curves of the regression models in the left and right

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\(^3\) Earlier than about 200 ms before ball contact there start to be cases in which the kicking foot is still on the ground and therefore shows negligible movement. Because of this, the precision of our measurements of the movement direction of the kicking foot is sufficiently reliable only after that moment, meaning that the curves for this variable should be interpreted only after that moment. The interpretation of these curves before that moment is further complicated because of our angular measure. When the foot is on the ground, the measured angles show a range larger than 360°; as a consequence, the measured angles may have jumped from +180° to −180° and vice versa (i.e., when the negligible movement was straight backward). The range of the measured values was much smaller than 360° for this variable during the final phases before ball contact and for all other angular variables at all moments, hence justifying the use of linear correlations and regressions (see left panel of Fig. 3 for a representative example).
panels indicates that the multiple correlations were not substantially affected by deception. The lack of a strong effect of deception on the multiple correlations is noteworthy especially for the bottom row of panels, because the variables in these panels were selected precisely because they were affected by deception as individual variables.

Asterisks placed on the curves for the multiple correlations (i.e., a thickening of the curves) indicate that the regression model was significant for at least 7 penalty takers. The curves for the kicking foot speed were positive–negative inversed for illustration purposes, allowing a better visualization of its contribution to the multiple correlations. Curves are presented only if the regression analyses for each penalty taker were computed with at least 10 valid trials. To give an indication of the average number of trials (n) used to compute these curves: for \( t = -0.15 \) s, \( n = 28.9 (SD = 1.1) \), and for \( t = 0 \), \( n = 28.0 (SD = 2.6) \).

Fig. 5. Multiple correlations associated with linear regression models with ball direction as dependent variable together with the correlations of the individual variables included in the respective regression models, as a function of time. For each panel and each moment in time, the regression analyses were computed per penalty taker and then averaged over all penalty takers. Asterisks indicate that the regression model was significant for at least 7 penalty takers. The curves for the kicking foot speed were positive–negative inversed for illustration purposes, allowing a better visualization of its contribution to the multiple correlations. Curves are presented only if the regression analyses for each penalty taker were computed with at least 10 valid trials. To give an indication of the average number of trials (n) used to compute these curves: for \( t = -0.15 \) s, \( n = 28.9 (SD = 1.1) \), and for \( t = 0 \), \( n = 28.0 (SD = 2.6) \).
significant, and in 11.6% all three predictors were significant. The fact that more than one predictor was significant in 65.2% of the models supports the conclusion that compound variables are in many cases more useful than the variables that we considered as individual predictors. For completeness,

Table 2

<table>
<thead>
<tr>
<th>Overall</th>
<th>Deceptive</th>
<th>Non-deceptive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penalty takers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>11.7</td>
<td>23.3</td>
</tr>
<tr>
<td>2</td>
<td>5.1</td>
<td>15.3</td>
</tr>
<tr>
<td>3</td>
<td>5.0</td>
<td>23.3</td>
</tr>
<tr>
<td>4</td>
<td>13.3</td>
<td>21.7</td>
</tr>
<tr>
<td>5</td>
<td>18.3</td>
<td>20.0</td>
</tr>
<tr>
<td>6</td>
<td>13.3</td>
<td>13.3</td>
</tr>
<tr>
<td>7</td>
<td>21.7</td>
<td>15.0</td>
</tr>
<tr>
<td>8</td>
<td>15.0</td>
<td>18.3</td>
</tr>
<tr>
<td>9</td>
<td>13.3</td>
<td>16.7</td>
</tr>
<tr>
<td>10</td>
<td>15.0</td>
<td>16.7</td>
</tr>
<tr>
<td>11</td>
<td>23.3</td>
<td>16.7</td>
</tr>
<tr>
<td>12</td>
<td>10.0</td>
<td>25.0</td>
</tr>
<tr>
<td>Average</td>
<td>13.7</td>
<td>18.8</td>
</tr>
</tbody>
</table>

Goalkeepers

| Penalty takers |
| 1 | 12.4 | 21.3 | 7.3 | 59.0 |
| 2 | 17.0 | 11.9 | 6.7 | 64.4 |
| 3 | 10.2 | 22.0 | 4.5 | 63.3 |
| 4 | 16.4 | 19.7 | 3.3 | 60.7 |
| 5 | 11.4 | 17.1 | 5.7 | 65.7 |
| Average | 13.5 | 18.4 | 5.5 | 62.6 |

Note: Categories 1 (Out) and 2 (Save) represent missed penalties and Categories 3 (Touch) and 4 (Goal) represent scored penalties.

Table 3

Significance of individual predictors, expressed as the percentage of the significant overall regression models at 150 ms before ball contact for which the coefficients of the predictors differed significantly from zero ($p < .05$).

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>High correlation before contact</td>
<td></td>
</tr>
<tr>
<td>Non-kicking foot angle</td>
<td>50.0</td>
</tr>
<tr>
<td>Knee angle of kicking leg</td>
<td>54.2</td>
</tr>
<tr>
<td>Kicking foot speed</td>
<td>37.5</td>
</tr>
<tr>
<td>High correlation at contact</td>
<td></td>
</tr>
<tr>
<td>Kicking Foot Angle</td>
<td>52.4</td>
</tr>
<tr>
<td>Hip angle</td>
<td>81.0</td>
</tr>
<tr>
<td>Kicking foot mov. direction</td>
<td>81.0</td>
</tr>
<tr>
<td>Susceptible to deception</td>
<td></td>
</tr>
<tr>
<td>Approach angle</td>
<td>62.5</td>
</tr>
<tr>
<td>Shoulder angle</td>
<td>20.9</td>
</tr>
<tr>
<td>Head angle</td>
<td>87.5</td>
</tr>
</tbody>
</table>

Note: All multiple regressions were performed with the three predictor variables in the category of predictors.

significant, and in 11.6% all three predictors were significant. The fact that more than one predictor was significant in 65.2% of the models supports the conclusion that compound variables are in many cases more useful than the variables that we considered as individual predictors. For completeness,

4 These percentages correspond to the fixed models with all three predictor variables. In such models, the significance of a predictor refers to the unique contribution of the predictor beyond the contribution of the other two predictors. Although we did not systematically explore this, the percentages may be higher for models from which non-significant predictors are successively removed.
the percentages of the significant models in which the different individual predictors were found to be significant at 150 ms before ball contact are given in Table 3.

### 3.4. Kinematic variables and dive direction

Although our experiment was designed to analyze the relation between the kinematic variables and the lateral ball direction, it also allows us to tentatively address the relation between the kinematic variables and dive direction (analyzed as a binary variable: either left or right), and, thereby, to illustrate how correlation and regression techniques may be used in this regard. Fig. 6 gives the correlations associated to analyses that regress dive direction against the three variables that showed high correlations with ball direction before ball contact.

If a goalkeeper systematically detects and uses information from a particular moment during the approach, then one would expect the correlations between dive direction and the kinematic variables to be high and significant at that moment. For Goalkeeper 1 (upper left panel) the highest correlations are observed earlier during the approach than for Goalkeepers 2–4. One may hence suspect that Goalkeeper 1 used information detected earlier in the approaches than the other goalkeepers. Motivated by this tentative prediction, we analyzed the initiation times of the diving movements. The average initiation times for Goalkeepers 1–4 were $-0.69$, $-0.25$, $-0.49$, and $-0.41$ s, respectively, with standard deviations of $0.15$, $0.10$, $0.15$, and $0.14$ s. Hence, Goalkeeper 1 indeed seemed to initiate the dives earliest.

Fig. 6 also seems to point to differences in which variables were used. For instance, the non-kicking foot angle (continuous black curve) has an important contribution to the highest multiple correlations for Goalkeeper 2 (upper right panel), which occurred around ball contact. This, on the other hand, does not seem to be as much the case for Goalkeepers 3 and 4 (lower panels), even though these goalkeepers also show their highest correlations around ball contact.
3.5. Percentages of correctly predicted left–right directions

Previous work has presented results about the reliability of kinematic variables as the percentage of correctly predicted left–right directions per variable (e.g., Diaz et al., 2012; Franks & Harvey, 1997). To facilitate the comparison of our results with previous results we also computed such percentages. Fig. 7 shows these percentages for the regression analyses with ball direction as dependent variable and the three variables with high individual correlations before ball contact as predictors. The predicted percentages are based on a cut-off value: If the values of a predictor are higher than the cut-off value, then a penalty to right is predicted, and if the value of the predictor is lower than the cut-off value, then a penalty to the left is predicted. We computed the cut-off values that maximized the differences between the percentage of correctly predicted directions and the chance level (50%). Qualitatively, the percentage curves (Fig. 7) are similar to the corresponding correlation curves (upper panels of Fig. 5). Percentages higher than 90% are observed toward the end of the approaches.

4. Discussion

The aims of the present study were (1) to determine the information value of single kinematic variables, related to the movement of penalty takers, as predictors of the direction of the penalty kick, (2) to determine the information value of compound kinematic variables, and (3) to determine the effect of deception on the information value of these kinematic variables. In contrast to previous studies (Diaz et al., 2012; Lees & Owens, 2011), our experiment was performed with a regular-size goal and with a goalkeeper. The information contained in the single and compound variables was analyzed with correlation and regression analyses, respectively (cf. Jacobs et al., 2001; Michaels & de Vries, 1998).

Kinematic variables that correlated highly with ball direction in the time interval around 150 ms before ball contact include the non-kicking foot angle, the knee angle of the kicking leg, and the speed of the kicking foot. Kinematic variables that were found to have a high correlation at ball contact include the kicking foot angle, the hip angle, and the movement direction of the kicking foot. Hence, our findings indicate that the most highly correlating variables are related to the lower part of the body.

The finding that the non-kicking foot angle is useful before ball contact is consistent with the findings of Lees and Owens (2011) and Diaz et al. (2012). The precise form of the curves for this variable in our study, however, is different from the one reported by Diaz et al. In our study the correlations and hence the information value of this variable continue to increase until ball contact (upper left panel of Fig. 4; see also Fig. 7). In the study of Diaz et al., the correlation shows a peak around 250 ms before ball contact and then decreases (see the curve associated to the foot yaw of the non-kicking foot in their Fig. 3a).

Kinematic variables that, in our experiment, were affected by deception include the approach angle, shoulder angle, and head angle, and also the non-kicking foot angle and the hip angle. Significant predictors of ball direction were observed earlier in the deceptive condition than in the non-deceptive condition. In the deceptive condition at 0.5 s before ball contact, the correlations for the
shoulder angle, head angle, and hip angle were significant in more than 50% of the cases. To give a tentative summary of these findings, one could say that the variables most affected by deception are the ones that are not related to the lower part of the body, and that the ones that are least affected by deception are the ones related to the kicking leg. Several variables showed a trend from being affected by deception before ball contact to not being affected by deception at ball contact. This can be interpreted with the hypothesis of non-substitutability of genuine action (Richardson & Johnston, 2005; Runeson & Frykholm, 1981, 1983; cf. Jackson et al., 2006). While trying to accomplish a particular goal (i.e., left or right direction of the ball), penalty takers can act in such a way that local aspects of their body movements have a different correlation with ball direction. However, as the action unfolds toward the moment of ball contact, the inability to perform completely deceptive actions becomes evident. Whatever movement penalty takers perform when trying to deceive, they cannot avoid that some fundamental aspects of the kinematics must reflect the genuine action (i.e., the one that fits their intention).

The regression analyses showed that compound variables (or combined, higher order, or distributed variables) are often more useful than individual kinematic variables, and that compound variables are almost equally useful in deceptive and non-deceptive conditions. Hence, despite the attempted deception, the regression analyses revealed the intention of the penalty takers. The higher information value of compound variables as compared to local kinematic variables is consistent with the emphasis on distributed information by Diaz et al. (2012; cf. Huys et al., 2009, 2008). This implies a warning for research that considers only local kinematic variables (e.g., Lees & Owens, 2011): Such research may not be able to reveal the full information potential that is available to the perceiver. The human perceptual system has repeatedly been claimed to rely on distributed information (e.g., Abernethy et al., 2001; Gibson, 1979; Ward et al., 2002).

Our analyses applied correlation and regression techniques to reveal the information potential of variables whose values continuously changed over time, hence extending previous applications of such techniques (which used variables defined at single moments; e.g., Michaels & de Vries, 1998). Independently of whether one analyzes variables that change over time, we believe that a more extended use of correlation and regression analyses may be beneficial in the domain of sports research. It is interesting to note in this regard that such analyses are used more frequently in the more general area of perception-action research than in the more specific area of sports research (e.g., Cabe & Wagman, 2010; Fajen & Devaney, 2006; Jacobs & Michaels, 2006; Jacobs et al., 2001; Runeson, Juslin, & Olsson, 2000; Withagen & Michaels, 2005). A more speculative part of our analyses showed how correlation and regression analyses can be applied to analyze which variables are used by goalkeepers. Individual differences in variables use were observed, which is consistent with studies that addressed variable use with other tasks (Jacobs & Michaels, 2001; Withagen & van Wermeskerken, 2009). It is appropriate, however, to include a few critical remarks at this point. First, the analyses on variable use included only four goalkeepers. This is not sufficient to confirm the usefulness of the methodology and to generalize the results to a broader population. Second, penalty takers were instructed beforehand to which side of the goal to shoot. This means that diving early to one side did not include the risk that the penalty taker would react and shoot to the other side. Although the goalkeepers were not informed about this part of the procedure, we cannot rule out that they may have noticed this novel constraint in the course of the experiment and that they may have adapted their performance accordingly (Lopes, Araújo, Duarte, Davids, & Fernandes, 2012). Third, judged from their age category and professional status, the level of expertise of the goalkeepers was not as high as that of the penalty takers.

Interesting parallels can be noted between the results of our correlation and regression techniques and previous results obtained with gaze-registration techniques. For example, Button et al. (2011) provided time-continuous measures of where goalkeepers look during the approach of the kicker. They observed that at the beginning of the approach goalkeepers tend to direct their gaze predominantly to the head of the kicker while later during the approach the gaze is directed more to the ball.

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5 It may be useful at this point to recall the level of expertise of the participants in this study. All penalty takers were professional and semi-professional field players. Only a few of them, however, regularly took penalty kicks in match situation. Some caution may therefore be appropriate when generalizing our results to the population of expert penalty takers.
Such findings are consistent with our finding that, in the time-interval just before ball contact, the kinematic variables that correlate most highly with ball direction are found in the lower part of the body. They are also consistent with our observation that earlier in the approach kinematic variables related to the upper part of the body (e.g., head angle and shoulder angle) are more often significant predictors of ball direction (in the deceptive condition at least).

To summarize, in the time interval most relevant for the goalkeeper’s action, highly correlating sources of local information can be found especially in the penalty takers’ lower body. Sources of distributed information can be identified with regression models and their potential to predict ball direction is often superior to the predictive potential of local variables considered individually. Finally, in trying to deceive the goalkeeper, penalty takers are able to modify the predictive value of the local body kinematics to some extent, most particularly early in the approach, but for the majority of kinematic variables the deception is unsustainable at the final moments before ball contact, where players have to act genuinely in order to shoot the ball in the desired direction.

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