DEVELOPMENT AND EVALUATION OF A METHOD TO QUANTIFY RUGBY PLACE KICK PERFORMANCE FROM INITIAL BALL FLIGHT DATA

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The purpose of this study was to develop and evaluate a method for quantifying rugby place kick performance using a metric that represents field-based performance but relies only on data typically available within a laboratory setting. A mathematical model was developed to predict the flight path of a rugby ball using equations of projectile motion and initial ball flight kinematics as inputs. The accuracy of the model predictions were then evaluated against empirical data collected from eight place kicks taken 22 m from the goalposts on a rugby pitch. The model estimated the position of the ball at the instant it reached the goalposts with a root mean square error of 0.65 m (2.9% of the range). It is intended that this method will provide an applied outcome measure that is relevant to players and coaches.

KEY WORDS: aerodynamics, drag, kicking, lift, Rugby Union, spin.

INTRODUCTION: In Rugby Union, place kicks provide an opportunity for teams to score points when a penalty is awarded or as a conversion following a try. Place kicks accounted for 45% of all points scored in 582 international Rugby Union matches between 2002 and 2011 (Quarrie & Hopkins, 2015). If the success percentage of the competing teams' place kicks had been reversed in each of these matches, 14% of the results would have changed, highlighting the importance of successful place kicking in international matches.

The success of a place kick is determined by the position of the ball when it crosses the try line; a successful kick must be above a crossbar (3.0 m above the ground) and between two upright posts (5.6 m apart). Once the ball leaves the kicking foot it must therefore possess appropriate velocity (both in terms of magnitude and direction) in order for the kick to be successful. It is straightforward to determine place kick success in a field environment. However, biomechanical analyses are often performed in a laboratory to allow more detailed measurement of technique-related variables and the tighter spatial constraints of a laboratory setting rarely allow the full flight path of the ball to be tracked.

Previous laboratory-based biomechanical research investigating rugby place kicking typically described performance based on the magnitude of the initial ball velocity (e.g. Bezodis et al., 2007; Sinclair et al., 2014). Bezodis et al. (2007) also measured the lateral displacement of the ball at a target 10 m away as a measure of kick accuracy. Whilst these measures quantify some of the initial ball flight characteristics, they do not provide outcome measures that are relevant to players and coaches.

When in-flight, it may be assumed that the path of the rugby ball is governed by equations of projectile motion based on the gravitational and aerodynamic forces acting on the ball. Mathematical modelling of ball flight has previously been undertaken for direct free kicks in soccer (Bray & Kerwin, 2003). A similar modelling approach would allow an applied measure of rugby place kick performance to be calculated from initial ball flight data collected in a laboratory. The aim of this study was therefore to develop and evaluate a method of quantifying rugby place kick performance using a metric that represents field-based performance but relies on data available within a laboratory setting.

METHODS: A mathematical model using equations of projectile motion was developed in Matlab (v.7.12.0, The MathWorks Ltd., USA) to predict the flight path of a rugby ball from initial flight conditions. The accuracy of this model was then assessed by comparing the model predictions to empirical data collected on a rugby pitch. The inputs to the model were immediate post-contact values for three-dimensional (3-D) ball position, 3-D linear ball

velocity, ball angle about the transverse axis and ball angular velocity about both the longitudinal and transverse axes. The position of the ball was updated for each time iteration (i, 0.0001 s) by double integrating the calculated 3-D accelerations which were determined by the forces acting on the ball. The acceleration of the ball in the medio-lateral (a_x), anterior-posterior (a_y) and vertical (a_z) direction was calculated using the following equations:

$$ax_{(i)} = - Fx_{(i)} / m \qquad (1)$$

$$ay_{(i)} = - Fy_{(i)} / m \qquad (2)$$

$$az_{(i)} = (Fz_{(i)} / m) - g \qquad (3)$$

Gravity (g; 9.81 m/s^2) and ball mass (m; 0.435 kg) were assumed to be constant. The spin, drag and lift forces (acting in the x, y and z directions, respectively, and termed F_x, F_y, F_z) were calculated at each time iteration using the following equations:

$$Fx_{(i)} = Cx_{(i)} \cdot \rho \cdot V^{2/3} \cdot 0.5 \cdot vx_{(i)}^2 \qquad (4)$$

$$Fy_{(i)} = Cy_{(i)} \cdot \rho \cdot A \cdot 0.5 \cdot vy_{(i)}^2 \qquad (5)$$

$$Fz_{(i)} = Cl_{(i)} \cdot \rho \cdot A \cdot 0.5 \cdot vz_{(i)}^2 \qquad (6)$$

The volume of the ball (V) was included as a constant (0.0048 m^3). The air density of the surrounding environment (ρ) was also constant (1.225 kg/m^3) based on the assumption of standard atmospheric conditions at the testing location (9 m above sea level) and a temperature of 15°C. The spin coefficient (C_x) was represented as a linear function of angular velocity about the longitudinal axis, assuming an average ball angle about the transverse axis of 45°, based on wind tunnel data presented by Seo et al. (2006). The drag and lift coefficients (C_y and C_z, respectively) were represented as eighth-order polynomial functions of ball angle about the transverse axis based on wind tunnel data presented by Alam et al. (2010). Ball angle about the transverse axis was determined for each time iteration based on the initial ball angle and the ball angular velocity (assumed constant) when in flight. The cross-sectional area (A) was included as a constant based on the projected frontal area of the ball when the longitudinal axis was parallel to the horizontal (0.029 m^2), consistent with that used by Alam et al. (2010) for the determination of C_y and C_z. The final terms in equations 4 to 6 are the linear velocities of the ball in the corresponding direction (v_x, v_y and v_z). The estimated 3-D ball position was updated for each time iteration until the ball had travelled 22 m in the y-axis. The estimated position of the ball in the x and z-axes in the final frame and the duration of flight were output from the model.

The accuracy of the model was evaluated through comparison of the estimated final ball position to measured values from field-based place kicks. One male participant (31 years, 1.79 m, 76.0 kg), proficient in place kicking, participated in the study which was approved by the local research ethics committee. Data were collected on an outdoor rugby pitch on a still, dry day (wind speed was measured at 0.39 ± 0.24 m/s during the trials). All kicks were taken from a kicking tee placed 22 m from the try line, perpendicular to the centre of the goalposts.

Two high-speed cameras (Phantom V5.2, Vision Research Inc., USA) synchronised to the nearest ms, recorded the initial 5 m of ball flight (1000 Hz). The raw video files were imported into Vicon Motus and the ball centre, one longitudinal end of the ball and the fifth metatarsalphalangeal joint, were digitised at full resolution (1280 × 800 pixels) and 2 × zoom. Given the importance of accurate initial linear ball velocities from these manual video data, each video clip was digitised 17 times, the number of repetitions which provided stable values within a bandwidth of ± 0.25 standard deviations either side of the mean (Taylor et al., 2015). The 3-D displacement time-histories of the digitised points were reconstructed using direct linear transformation (DLT), and a mean of the 17 repetitions was calculated. These data were down sampled to 240 Hz (the sampling frequency available in the laboratory) using an interpolating cubic spline. In order to identify ball contact and ball flight, ball and toe velocities were calculated from raw displacement data using the second central difference method. Ball contact was identified as the frame where peak toe velocity in the y-

axis was recorded. The first frame of ball flight was identified as the first frame that ball velocity in the y-axis decreased following movement onset. Subsequently, initial in-flight ball velocity was calculated in each principal direction by fitting a polynomial to the first four frames (at 240 Hz) of raw ball flight displacement data (first order for both horizontal directions, second order for vertical). Initial ball angle about the x-axis was identified from the first frame of ball flight and the average ball angular velocity about both its longitudinal and transverse axes was calculated across the first four frames of flight.

Two further high-speed cameras (Sony FX1000, UK) were positioned behind and to the side of the goalposts to record the ball's position as it crossed the try line (200 Hz). The frame in which the ball crossed the try line was identified from the side camera and the centre of the ball was digitised in the corresponding frame of the rear camera. For each trial, ball position was reconstructed from the rear camera data using two-dimensional DLT to provide criterion final ball positions. A further panning camera (Casio EX-FH20 camera, Casio Computer Co., Ltd., Japan) captured the complete ball flight at 210 Hz and was used to calculate flight time. The estimated final ball position from the model was compared to the measured final position for all trials and the root mean square (RMS) error was calculated. Estimated flight time was also compared to measured flight time and the RMS error calculated.

RESULTS: The mean initial resultant ball velocity across the eight trials was 22.59 ± 1.33 m/s at an angle of 30.6 ± 2.2° above the horizontal and 4.1 ± 2.0° in the medio-lateral direction. Mean flight time was 1.39 ± 0.10 s. Figure 1 depicts the estimated and measured final ball positions after 22.00 m (in the y-axis) for the eight kicks. The ball flight model yielded an RMS error in resultant (x-z) displacement of 0.65 m (2.9 % of y-axis displacement) and a maximum error of 1.12 m (kick 5) when compared with the measured positions in the field trials. An RMS error of 0.11 s (7.9% of total flight time) and a maximum error of 0.19 s (kick 5) was observed in ball flight times estimated by the model compared with measured values.
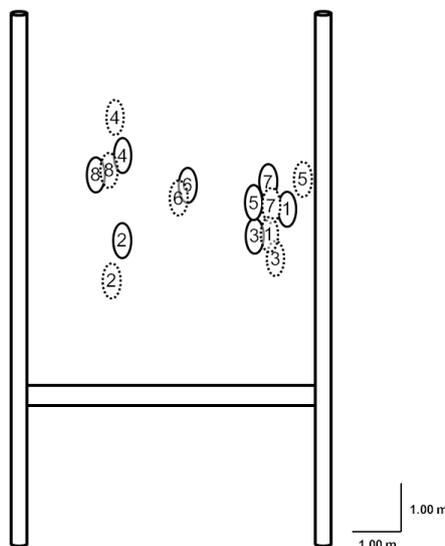
Figure 1. Positions of the measured final ball positions (solid lines) and estimated ball positions from the ball flight model (dotted lines) for all kicks (1-8).

DISCUSSION: This study developed a method for determining an outcome measure of rugby place kick performance which is relevant to players and coaches from data obtainable within a laboratory setting. Evaluation of the accuracy of the model against empirical data collected on a rugby pitch revealed an RMS error of 0.65 m (2.9% of the total y-displacement). Biomechanical analyses are typically performed in a laboratory to accurately quantify specific aspects of technique; the model therefore allows performance to be accurately and concurrently quantified in a way that is relevant to field-based performance. The model can be used to estimate the maximum distance from the goalposts that a place

kick could be taken from and still be successful (i.e. passing above the crossbar and between the goalposts) based on initial flight conditions. This measure provides players and coaches with a performance criterion that is meaningful in a practical setting. Using this measure with the initial ball flight data recorded in the current study, half of the kicks were limited by the medio-lateral displacement of the ball (kicks 1, 3, 5, 7) and half by the vertical displacement (kicks 2, 4, 6, 8). The model estimates that the kicker would have been successful from a mean distance of 30.0 m from the goalposts, slightly shorter than the mean kicking distance in international Rugby Union matches (32 m; Quarrie & Hopkins, 2015). The best kick was identified as kick 4 which would have been successful from any distance less than 38.4 m, whereas kick 5 was the worst, hitting or passing outside of the right upright post from any distance greater than 22.5 m.

Players are typically coached to kick through the ball in a straight line towards the target (Bezodis & Winter, 2014) and therefore not to impart sidespin on the ball. However, removing the medio-lateral forces from the ball flight model led to an increased mean RMS error of 1.04 m. Although the current data are from a single non-elite kicker, they suggest that it is important to consider the medio-lateral forces acting on the ball as some kickers may impart spin about the longitudinal axis of the ball in addition to about the transverse axis.

Future research should look to include additional trials from a range of distances and additional kickers. Additionally, the sensitivity of the model outputs to specific inputs which may vary depending on various rule-based or situational factors should be investigated. For example, the World Rugby Laws state that the ball must be between 0.41 and 0.46 kg and it is prudent to understand the effect that this may have on estimated place kick performance. Furthermore, international matches take place in venues such as Johannesburg, South Africa at an elevation of 1,753 m and Twickenham, UK at 15 m, and temperatures can also vary greatly between venues; the effect of air density (a constant within the model) is therefore also worthy of consideration.

CONCLUSION: This study developed and evaluated a method of quantifying rugby place kick performance from data typically obtained in a laboratory setting. The combination of experimentally-measured initial ball conditions with aerodynamic and gravitational forces acting on the ball throughout flight allowed the complete ball flight trajectory to be estimated with an acceptable level of accuracy. It is intended that this method will be used to provide an applied outcome measure that is relevant and meaningful for players and coaches.

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