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COMPARISON OF TWO METHODS FOR CALCULATING 3-DIMENSIONAL BALL SPIN, AND ITS APPLICATION TO SOCCER KICKING

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The aim of this study was to select an appropriate computational method for determining both spin axis direction, and spin rate during soccer ball flight. Calculation methods of Cross-Product (CP) and Singular Value Decomposition (SVD) were compared on a stationary spinning ball under laboratory conditions, using data collected from 10 Vicon MX cameras tracking 5mm hemispherical ball markers at 500Hz. When the ball was spun at 371 ± 15 RPM, spin axis orientation appeared close to 'real' values, yet CP showed greater error in RPM estimation. Comparison of the methods during a kick showed no significant difference for spin rate calculation, yet CP underestimated the x and y spin axes, and overestimated spin around the z axis. It was proposed that SVD is used in future to estimate ball spin parameters, especially during kicking where marker occlusion may be more prevalent.

KEY WORDS: kinematics, football, ball rotation, aerodynamics

INTRODUCTION: The ability to alter the path of a ball once it is airborne is achieved by applying spin. This altered trajectory can aid in deceiving opponents (goalkeepers), or evading interception (defensive wall) to gain an advantage. Spin applied to a spherical projectile will affect its flight path by a Magnus force applied to the surface of the ball due to a pressure differential. This force is applied perpendicular to the spin axis of the ball, yet as the force changes the flight path, similarly the direction of the spin axis is altered in a global setting. If players and coaches are to employ techniques to increase ball spin and orientation, it is necessary to know the size of this effect.

Several studies have attempted to quantify both the attitude of the spin axis, and the rate of ball rotation. Jinji and Sakurai (2006) used several ball markings and employed a cross product (CP) technique to determine the direction and rate of ball spin. Alternatively, singular value decomposition (SVD) can be applied to enable the calculation of ball spin parameters through the generation of a rotation matrix representative of the change in ball orientation that is summarised by an angle (θ) about an axis defined by the vector ŵ (Figure 1).

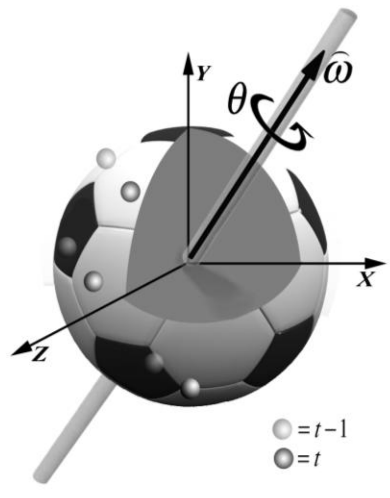

Figure 1: Ball spin parameters described using the SVD method by the angle of rotation (θ) about the spin axis vector (ŵ)

During soccer kicking baseline data exists for the rate of spin that a typical delivery may create (Whiteside et al., 2010) yet the accuracy, and consistency of the CP method has only been validated under controlled conditions from which its ecological validity has only been inferred (Whiteside et al., 2012). Therefore, the aims of this study were twofold. Firstly to ascertain under controlled conditions the respective validity of the CP and SVD methods to calculate both the rate and direction of spin, and, secondly, to investigate the robustness of these methods in calculating ball spin parameters under ecologically valid conditions through analysing ball flight during an actual soccer kick.

METHODS:

Experimental design: To investigate ball spin parameters under controlled and dynamic conditions, football kinematics were recorded at 500Hz using a ten camera Vicon MX motion analysis system (Vicon Motion Systems, Oxford, UK).

Ball spin parameters under controlled conditions were recorded using a mechanised, spinning ball simulator that incorporated a FIFA approved standard size football with 5mm, retroreflective markers affixed in a random configuration. For the purpose of this investigation, three different ball orientations were investigated at 371 ± 15 RPM, to approximate angular velocities associated with a football free kick (Whiteside *et al.,* 2012). For each orientation, the true spin axis and spin rate was established independent to the experimental methods under investigation to minimise the influence of bias. Within the horizontal plane, due to the sinusoidal path of each marker during a revolution, the RPM was defined based on the average wavelength and, the orientation of the spin axis was defined by the unit vector formed by two retroreflective markers affixed to opposite poles of the mechanical axis of the ball spinning simulator and expressed in relation to the global coordinate system (GCS).

To enable comparison of the experimental methods under dynamic conditions, kinematics of a FIFA approved size 5 ball being kicked under settings replicating a free kick were recorded five times using nine, 5mm retroreflective hemispherical markers affixed to the ball in a random configuration. To assimilate experimental challenges faced when recording ball flight kinematics, each method was evaluated based on the flight of the ball over 2m using the raw, broken marker trajectories.

Experimental methods: Calculation of ball spin parameters using each of the experimental methods required the translation of ball marker coordinates from the GCS into a ball local coordinate system (bLCS). The origin of the bLCS was calculated as the centre of the football via a sphere fitting algorithm established through minimisation as the unique solution that acknowledges the fixed relationship between the retroreflective markers on the surface of the ball and ball centre, with the axes of the bLCS in keeping with those of the GCS. To minimise error due to inaccuracy in defining the ball center, any sample ± 5% of the manufacturers stated ball radius was excluded from analysis.

Following the method outlined by Jinji & Sakurai (2006) the CP method was applied based on the understanding that the spin axis lies perpendicular to the path of a surface marker (p) as the ball revolves. Mathematically the orientation of the spin axis and the spin rate can therefore be established using a minimum of two markers based on the derived cross-product, however to minimise error was calculated using different marker perturbations and averaged.

In comparison to the CP method, rather than establishing ball spin characteristics through pairs of markers, the SVD method calculates ball spin parameters derived from a rotation matrix (R) that represents the change in ball orientation between t and t-1 as described by the marker positions through the matrices:

$$A = \left[p_{1_{t-1}}, \ldots\ldots, p_{n_{t-1}} \right], \quad B = \left[p_{1_t}, \ldots\ldots, p_{n_t} \right]$$

allowing R to be calculated as:

$$R = U diag(1, 1, \det(UV^T))V^T$$

where UV^T is the singular value decomposition of the matrix BA^T. Subsequently, both the orientation of the axis of rotation and the spin rate can be computed together using the angle-axis representation as outlined by Craig (2005).

Data processing and analysis: All data was processed using custom software created within LabVIEW 2011 (National Instruments, TX). To replicate experimental conditions under which ball spin parameters have been calculated previously by researchers, each experimental method under controlled conditions was calculated based on both 3 and 4 marker combinations whereby, for each orientation, three trials composed of three full revolutions were analysed. Under dynamic conditions, for each of the five trials, time-series changes in ball spin parameters were calculated using between 3 or 4 markers subject to marker occlusion. Each dynamic trial was processed three times using a random marker sequence to establish the reliability of each method.

Under controlled conditions, the validity of each experimental method was established based on the resultant RMSE in relation to the true spin axis and RPM under the controlled conditions. Ball spin data derived under dynamic conditions were used to establish the practical suitability of these methods. For each kick, calculated ball spin parameters were compared between experimental methods using the Bland-Altman method (1995), whereby significant differences ($p<0.05$) between methods was established within SPSS version 20 (IBM, NY) using paired t-tests based on each time sample.

RESULTS AND DISCUSSION:

Method validity: Table 1 depicts the RMSE between the known spin axis direction and spin rate, with those calculated by the two experimental methods, with minimal differences observed when calculating ball spin dynamics using either 3 or 4 markers. Between methods appreciable differences in both the magnitude and direction of spin were noted, with the SVD method demonstrating greater validity in calculating ball spin parameters compared to the CP method. RMSE associated with each experimental method within this study was greater than that reported within the CP method validation study by Whiteside et al. (2012), where at a similar spin rate reported an estimation error of 2 ± 1 RPM. However, this may be accounted for due to contrasting experimental designs, where experimental positions within this study were reflective of those imparted onto a kicked ball, which due to being multi-axial provides an indication of the robustness of the experimental methods in comparison to those chosen by Whiteside et al. (2012) who validated the CP method with the spin axis lying within the horizontal plane.

Table 1: RMSE associated with each experimental method under controlled conditions

Orientation	Number of markers	CP Method		SVD Method	
		Resultant Axis (º)	Spin Rate (RPM)	Resultant Axis (º)	Spin Rate (RPM)
1	3	2.49 ± 0.02	50 ± 1	1.8 ± 0.01	2 ± 1
	4	2.29 ± 0.01	43 ± 1	1.81 ± 0.01	2 ± 1
2	3	3.3 ± 0.03	21 ± 2	0.34 ± 0.03	2 ± 1
	4	6.29 ± 0.01	16 ± 2	0.4 ± 0.02	2 ± 1
3	3	0.47 ± 0.11	50 ± 4	0.28 ± 0.03	12 ± 5
	4	0.36 ± 0.08	42 ± 4	0.29 ± 0.03	12 ± 5

Method reliability: The reliability of each experimental method under investigation is summarised by the bias (mean error) and limits of agreement between experimental methods shown in Figure 2 for the spin axis. Whilst no significant differences ($p>0.05$) between methods were established for the spin rate, significant differences in the orientation of the spin axis for four of the kicks was observed. The CP method was found to typically underestimate the orientation about the x (mean difference = 1.43 ± 12.92 º) and y (mean difference = 9.42 ± 10.78 º) axes and overestimate the z axis (mean difference = 8.80 ± 13.43 º) in comparison to the SVD method.

This research is the first to investigate the reliability of methods used to calculate ball spin parameters under ecological constraints where marker occlusion frequently occurs. Whiteside et al. (2012) advocated the suitability of the CP method under dynamic conditions as being theoretically sound however only validated the method under static conditions where the influence of ball translation was not investigated. However, the CP method described by Jinji and Sakurai (2006), due to being calculated based on marker pairs demonstrated greater sensitivity towards marker reconstruction errors as manifested by the observed limits of agreement when compared to the SVD method. Findings from this research, advocate the application of the SVD under dynamic conditions due to establishing ball spin dynamics through a rotation matrix based on equally weighting all available coordinate data, therefore demonstrating greater robustness when data degrades due to marker occlusion.

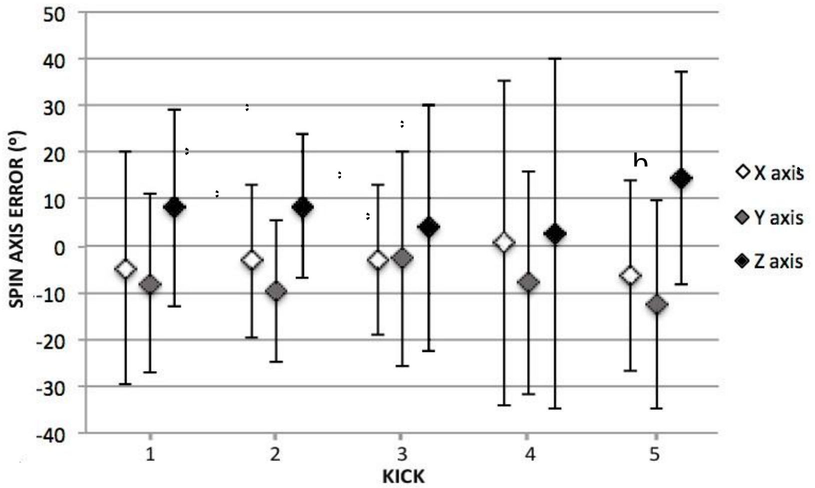

Figure 2: Spin axis estimation error (bias) between experimental methods (* denotes a significant difference (p<0.05) between methods

CONCLUSION: Findings from this investigation, demonstrated that both the CP and SVD method enable the calculation of accurate, controlled spin axes and rate of spin for measurement under laboratory conditions, and ecologically sound data from a real kicking action. From the two methods presented, the SVD displayed a reduced error in both ball spin rate, and the orientation of the spin axis that is robust under dynamic conditions. When being used in a soccer free kick setting where marker occlusion may be frequent, this would be the proposed method for calculating ball spin parameters

REFERENCES:

Bland, J &Altman, D (1995) Comparing methods of measurement: why plotting difference against standard method is misleading. *The Lancet,* 346,1085-1087.

Craig, J. (2005). *Introduction to robotics: Mechanics and control*. Pearson Prentice Hall, New Jersey, USA.

Jinji, T & Sakurai, S (2006). Direction of spin axis and spin rate of the pitched baseball. *Sports Biomechanics 5*(2), 197-214.

Whiteside, D., Alderson, J., & Elliott, B. (2010). Bend it like Beckham: Ball rotation in the curved football kick. In*: Proceedings of the XXVIII International Conference on Biomechanics in Sports.*

Whiteside, D., Chin, A. & Middleton, K. (2012) The validation of a three-dimensional ball rotation model. Proceedings of the Institution of Mechanical Engineers. Part P, Journal of Sports Engineering and Technology, 0 (0), 1-8.

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