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Dynamics of spin bowling: the normalized precession of the spin axis analysed with a smart cricket ball

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Abstract

As torque is imparted on a cricket ball before release, the spin vector precesses into the torque vector. Normalising the precession speed to the torque and the angular velocity yields the 'normalised precession', i.e. the angle between the spin vector and the torque vector. The maximal normalised precession was analysed in spin bowling, specifically in finger- and wrist spin, and topspin, sidespin and backspin deliveries. The data were recorded with a smart cricket ball and a Cortex motion analysis system. The maximal normalised precession at the beginning of the finger torque increased from topspin to backspin. The reason for this behaviour is that the motion of the bowling arm imparts a topspin on the ball, and therefore the spin axis does not have to change its direction if the fingers impart further topspin on the ball.

1. Introduction

The term 'precession' refers to the speed (angular velocity) of the moving (rotating) spin axis if a torque is imparted on a spinning object. The precession speed must not be confused with the spin rate, as the former corresponds to the speed of the spin axis, whereas the latter refers to the angular velocity of the rotating (spinning) object. The spin axis vector always moves ('precesses') into the torque vector [1,2], and the precession speed p (in

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rad/s) depends on the magnitude of the two vectors, torque T and angular velocity ω, on the angle θ between these two vectors, and on the moment of inertia I of the spinning object [1,2]

$$p = \sin\theta \frac{T}{\omega I} \tag{1}$$

In seam bowling, the rotation of the arm imparts topspin to the cricket ball, whereas the torque generated by the fingers causes the ball to be released with a backspin [2]. In backspin, however, the angular velocity vectors are located on the opposite side of the ball compared to the vectors in topspin. Therefore, when the fingers impart torque on the ball, the spin axis has to precess from one hemisphere of the ball to the other one (fig. 3b of [2]). The angle θ between angular velocity vector at the beginning of the precession and the torque vector at release was found to be 149° on average in the seam bowlers analysed by Fuss and Smith [2]. In fast bowling, the ball is always released with a backspin. In spin bowling, however, the ball can be released with any spin direction.

The aim of this research is to analyse the precession in spin bowling, by using Mark 2 of the RMIT Smart Cricket Ball. It is hypothesised that spin bowling deliveries released with backspin should precess more than the ones released with topspin. To confirm this hypothesis, the spin axis precessions of back- and topspin have to exhibit a statistically significant difference.

2. Methods

2.1. Definition of normalized precession and mathematical analysis

As the precession p depends on the torque T, angular velocity ω and moment of inertia I, according to Eqn (1), different precession speed can only be compared if normalised to T, ω and I. Accordingly,

$$p \frac{\omega I}{T} = \sin\theta \tag{2}$$

and $\sin\theta$, the sine of the angle θ between the vectors $\boldsymbol{\omega}$ and $\mathbf{T}$, corresponds to the normalised precession. In order to make the normalised precession p_n more understandable, $\sin\theta$ is expressed as the angle θ (in degrees):

$$p_n = \sin^{-1}\left(p \frac{\omega I}{T}\right) = \theta \tag{3}$$

The maximal p_n, i.e. θ_{max}, corresponds to the angle at the onset of the precession, i.e. when the spin vector $\boldsymbol{\omega}$ is forced to move towards the torque vector $\mathbf{T}$, once the fingers impart torque on the ball.

The precession speed p can be calculated from Eqn (1) where θ corresponds to

$$\theta = \cos^{-1}\left(\frac{\boldsymbol{\omega} \cdot \mathbf{T}}{|\boldsymbol{\omega}||\mathbf{T}|}\right) \tag{4}$$

or from the angle φ between two consecutive spin vectors

$$\varphi = \cos^{-1}\left(\frac{\boldsymbol{\omega}_i \cdot \boldsymbol{\omega}_{i+1}}{|\boldsymbol{\omega}_i||\boldsymbol{\omega}_{i+1}|}\right) \tag{5}$$

yielding p from

$$p = \dot{\varphi} = \frac{\Delta\varphi}{\Delta t} \qquad\qquad (6)$$

where Δt is the reciprocal of the recording frequency of the smart ball.

2.2. The smart cricket ball

The second prototype of the smart cricket ball incorporates three high-speed MEMS (micro-electro-mechanical systems) gyroscopes, a miniaturized circular PCB (printed circuit board) with a microcontroller, a battery, a flash memory, and electronic equipment for wireless data transfer (Bluetooth) and inductive charging. The ball is operated wirelessly via laptop or smart phone. The mass of the ball is 160 g and the ball is fully balanced. The electronics is protected by foam, a CNC-machined (computer numerical control) nylon6 shell and the ball is encased by the leather hemispheres of a cricket ball. The data sampling frequency of the ball is 815 Hz. The z-axis of the coordinate system is perpendicular to the seam, and the ball is held such that in right-/left-handers, the positive/negative z-axis points towards the palm in spin bowling. This convention ensures equal kinematics for right- and left-handers with respect to the ball's coordinate system. A software package was developed which processes the data, calculates the performance parameters and graphically displays them.

From the raw data of the gyroscopes, i.e. the components of the angular velocity vector, the following parameters are calculated: the angular acceleration, the torque, the precession, and the 4D vector diagram of the spin axis (with the colour-coded time as 4th dimension).

2.3. Experimental procedure

The smart cricket ball was equipped with three reflective markers, in order to define the orientation of the ball at release, i.e. the direction of the spin axis, with respect to the flight path of the ball. This orientation was derived from the Cortex motion analysis data recorded at 200 Hz. The following deliveries were recorded with the smart RMIT cricket ball and the Cortex motion analysis system: top-spin TS, top/side-spin TSS, side-spin SS, back/side-spin BSS, and back-spin BS, for both finger- and wrist-spin. All deliveries were bowled indoors by an ex-first class spin bowler, who is also a professional bowling coach, 6-15 times. The normalised precession p_n of the different deliveries was assessed with the t-test ($p < 0.05$) as to statistically significant differences.
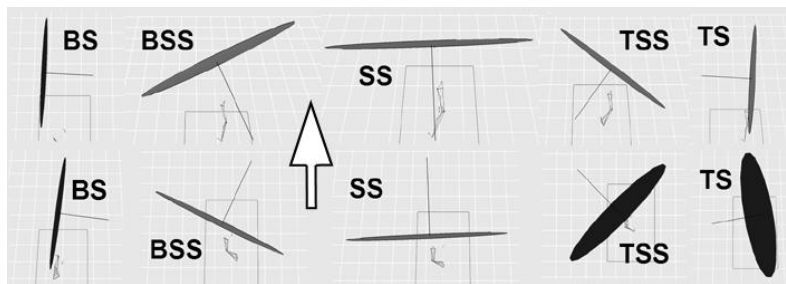

Fig. 1. Orientation of the spin axis with respect to the flight path (white arrow) of the ball in finger-spin (top row) and wrist-spin (bottom row) deliveries, analysed with the Cortex motion analysis system; TS = top-spin, TSS = top/side-spin, SS = side-spin, BSS = back/side-spin, and BS = back-spin; the plane of the seam is represented by a disc.

3. Results

In backspin and topspin deliveries, the spin axis at release points to the right and left, respectively (Figure 1). The orientation of the spin axis in sidespin deliveries depends on the type of spin (finger- or wrist spin) and on the handedness. In finger-spin deliveries, the spin axis points backwards in left-handers (Figure 1) and forwards in right-handers ('off-spin'); the opposite is true in wrist-spin deliveries.

Figure 2 explains how the maximum normalised precession θ_{max} at the beginning of the finger torque is determined. After the maximum, the normalised precession decreases and reaches a minimum after the torque peak. That minimum is the remaining angle between torque vector and spin axis.

Table 1 lists the averages and standard deviation of the normalised precession. The normalised precession decreases continuously from back spin BS to topspin TS (Table 1; Figure 3), which confirms the hypothesis mentioned in the Introduction. Moreover, the difference between BS and TS was highly significant ($p = 0$) as the data sets did not overlap. The differences of BS–BSS and of SS–TSS were not significant in finger-spin and wrist-spin deliveries. All other differences were significant (p-values between 0.03 and 0) within the finger- and wrist-spin subgroups, as well as between finger- and wrist-spin for the same deliveries. Wrist-spin deliveries exhibited smaller normalised precession angles than finger-spin deliveries ($20°$ on average, range: $10°$-$30°$).

Figure 4 shows the vector diagrams of angular velocity (spin axis) and torque. The positions of angular velocity and torque vectors at maximal normalised precession are identified, and θ_{max} is indicated.
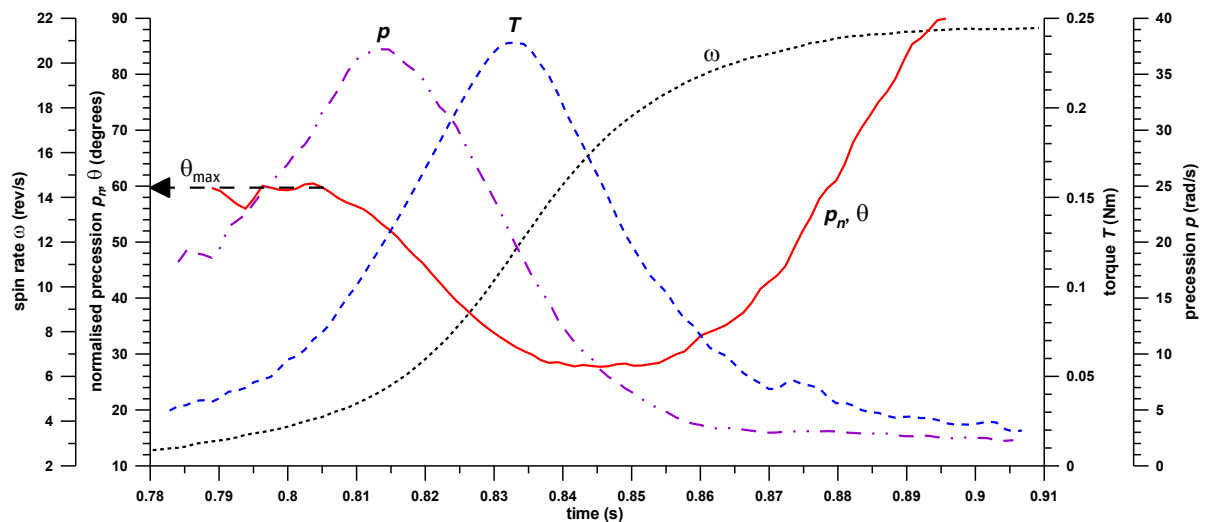

Fig. 2. Spin rate ω, torque T, precession p, and normalized precession (p_n, θ) of a finger-spin with sidespin delivery against time; θ_{max} = maximal normalized precession at which the spin axis moves towards the torque vector, before the normalised precession decreases.

Table 1. Averages and standard deviation of the normalised precession

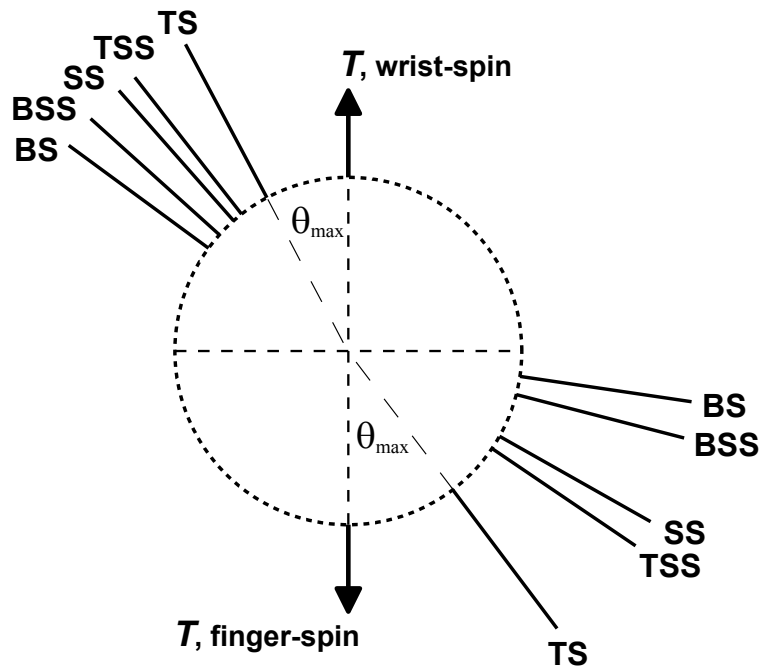| direction of spin	**finger-spin**, normalised precession (mean ± standard deviation; degrees)	**wrist-spin**, normalised precession (mean ± standard deviation; degrees)
backspin	81.6 ± 1.8	53.7 ± 9.8
back/side-spin	75.5 ± 9.7	48.0 ± 4.2
sidespin	60.6 ± 7.4	41.4 ± 2.9
top/side-spin	55.9 ± 5.7	38.0 ± 6.9
topspin	37.0 ± 4.8	28.0 ± 6.5

Fig. 3. Average spin axis vectors at maximal normalised precession θ_{max} of finger- (bottom hemisphere) and wrist-spin (top hemisphere) with respect to the torque vectors *T*; TS = top-spin, TSS = top/side-spin, SS = side-spin, BSS = back/side-spin, and BS = back-spin.
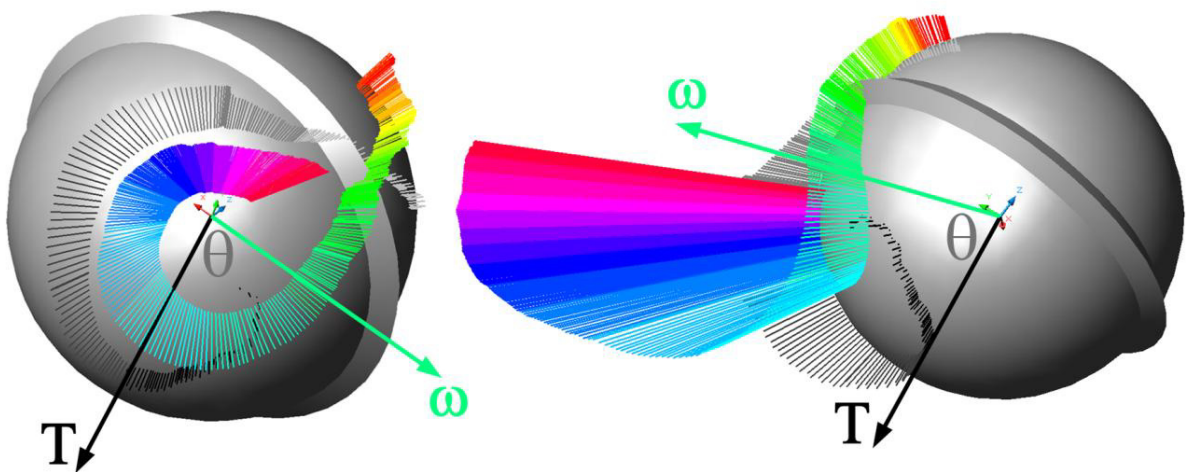

Fig. 4. Finger-spin sidespin delivery; angular velocity vector diagram (the time is colour coded / red-yellow-green-blue-magenta) and torque vector diagram (the time is grey-scale coded from black to light grey); θ = maximal normalised precession, ω = angular velocity vector at maximal normalised precession, T = torque vector at maximal normalised precession.

4. Discussion

As seen from Figure 2, θ_{max} is found before the precession peak. At that point, the torque T and the spin rate ω are still small. Subsequently, T and ω increase, but, as T causes the gain in ω magnitude, the ratio ω/T drops. This ratio is a component of Eqn (3), which explains that the normalized precession decreases as the spin axis vector closes in on the torque vector. After the finger torque peak, θ_{max} reaches its minimum, and then increases again once the aerodynamic torques start to have an effect on the ball. These torques are produced by drag forces at the seam, such that the torque vector is located parallel to the plane of the seam. The spin axis vector at release, however, is oriented perpendicularly to the plane of the seam and therefore the angle θ between spin and torque vectors reaches 90°. The precession, however, as that point is sufficiently small such that it does not substantially alter the direction of the spin axis, specifically if the spin rate of the ball is high.

The missing significant differences between BS and BSS deliveries, and SS and TSS ones, suggest that BSS is closer related to BS than to SS; and that TSS is closer related to SS than to TS. However, the number of data per delivery are relatively small (6-15) and a normal distribution is only assumed. It has to be explored in how far the normalised precession can be used for classification of spin bowling deliveries, by including hyper-topspin (doosra, googly) and hyper-backspin (flipper) into the statistical evaluation.

References

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[2] F.K. Fuss, R.M. Smith, Accuracy performance parameters of seam bowling, measured with a smart cricket ball. Procedia Engineering 72 (2014) 435–440.