A CASE STUDY ON THE EFFECTS OF THE UPPER ARM DEFINITION ON SHOULDER AND ELBOW KINEMATICS DURING THE BADMINTON SMASH

Harley Towler[1], Maurice Yeadon[1], Mark King[1]

School of Sport, Exercise and Health Sciences, Loughborough University, Loughborough, United Kingdom[1]

The aim of this case study was to identify the effect of the upper arm definition on shoulder and elbow kinematics during the badminton smash. A method was proposed that corrects the false external rotation when using the shoulder-elbow-wrist plane based on the carrying angle (*ISB-2C*) and compared to ISB recommendations for defining the upper arm (*ISB-1* and *ISB-2*). Differences were found in shoulder and elbow kinematics, in particular angular velocities. Both magnitude and the time history of the angular velocity were affected. In particular, use of the medial and lateral epicondyles was unable to detect a reasonable signal for pronation/supination. *ISB-2C* reduces some of the problems associated with *ISB-1* and *ISB-2* e.g. soft-tissue artifact, proximity of medial and lateral epicondyles to the humeral longitudinal axis and false external rotation caused by the carrying angle.

KEYWORDS: shoulder, upper arm, joint, racket

INTRODUCTION: A problem within biomechanics is defining the upper arm segment (Gordon & Dapena, 2013). Past methods have used markers placed at the distal end of the upper arm (medial and lateral epicondyles) as well as the shoulder joint centre, hereafter termed *ISB-1* (ISB 1st option; Wu *et al.,* 2005), which has been utilised previously in racket overhead motions (Elliott *et al.*, 1995), where the orientation of the upper arm with respect to the trunk can be determined by successive rotations representing flexion, abduction and external rotation (Yeadon, 1990). Wu *et al.* (2005) propose a 2nd option (*ISB-2*) which uses two vectors pointing from the elbow to shoulder joint centre, and from the ulnar styloid process to the elbow joint centre, previously used in overhead motions (Hirashima *et al.*, 2008; Gordon & Dapena, 2006). *ISB-1* is subject to several problems, including soft-tissue artifact (especially during rapid motions) and the proximity of the epicondyles to the longitudinal axis. *ISB-2* is subject to an apparent external rotation caused by the carrying angle (cubitus valgus), which becomes increasingly problematic as the elbow extends, posing a problem for overhead racket motions where the elbow extension angle reaches 166º on average (King *et al.*, 2020). *ISB-2* uses the shoulder, elbow and wrist joint centres to define the medio-lateral axis of the upper arm and assumes that there is only flexion when calculating this axis using the upper arm and forearm longitudinal axes which are initially aligned. As a consequence, the calculated direction of the medio-lateral axis is in error whenever there is abduction as in the case of the carrying angle. Both methods do not necessarily produce medio-lateral axes that are coincident with anatomical flexion/extension (Gordon, 2009). Gordon & Dapena (2013) proposed a correction to *ISB-2* that quantified the false external rotation due to the carrying angle for a range of simple elbow angles during a sedentary trial consisting of pure elbow flexion/extension and subsequently removed from dynamic trials. This was participant-specific and based on their anatomical structure. The present paper defines a method in which *ISB-2* is corrected based on a known carrying angle (*ISB-2C)* and makes a comparison with *ISB-1* and *ISB-2* by assessing the effects on shoulder and elbow kinematics during the badminton smash.

METHODS:

Participants: One elite male badminton player (age: 23 years, height 1.82 m, mass: 76.1 kg) was recruited, performing twenty forehand jump smashes from a feed representative of a lift during match conditions. Testing procedures were explained, and informed consent obtained.
Methodology for ISB-2C: The arm is defined by the shoulder (S), elbow (E) and wrist (W) joint centres. At full extension, the carrying angle is 2α, and the forearm (EW) rotates about axis X

through the elbow joint centre, where X is equally inclined to EW and the upper arm (ES) at an angle 90°-α. When fully flexed EW will lie along ES (Figure 1a). Let XYZ and xyz be right orthogonal triads with Z and z pointing at the reader, and y along SE. In frame XYZ:

$$E = (0,0,0), \quad S = (sin\alpha, -cos\alpha, 0), \quad W = (sin\alpha, cos\alpha, 0)$$

For simplicity, $|\overline{ES}| = |\overline{EW}| = 1$. If $\overline{EW}$ is rotated about X through ϕ, it will change from:

$$\overline{EW} = \begin{bmatrix} s\alpha \\ c\alpha \\ 0 \end{bmatrix} \; to \; \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\phi & -s\phi \\ 0 & s\phi & c\phi \end{bmatrix} \begin{bmatrix} s\alpha \\ c\alpha \\ 0 \end{bmatrix} = \begin{bmatrix} s\alpha \\ c\alpha c\phi \\ c\alpha s\phi \end{bmatrix} \quad (1)$$

The amount of internal rotation may be estimated as the angle between the arm plane (SEW) and the yz plane, which is the same as the angles between the normals of the planes, the angle between $\overline{EW} \times \overline{ES}$ and $\underline{x}$. The angle of internal rotation (ψ) can be obtained taking the dot product of unit vector $\underline{\hat{x}}$ and a unit vector parallel to $\overline{EW} \times \overline{ES}$.

$$cos\varphi = \hat{x} \cdot \frac{(\overline{EW} \times \overline{ES})}{|\overline{EW} \times \overline{ES}|} = \frac{c^2\alpha s\phi + s^2\alpha s\phi}{\sqrt{s^2\phi + s^2\alpha(1 + c\phi)^2}} = \frac{s\phi}{\sqrt{s^2\phi + s^2\alpha(1 + c\phi)^2}} \quad (2)$$

This value for φ, will be negative since the carry angle induces an apparent external rotation. If an apparent internal rotation angle is calculated for the direction of the normal to SEW, then the value may be corrected based on the simple elbow angle A (Equation 3) by adding $|\varphi|$. For a dynamic trial, Equation 3 can be rearranged to give ϕ based on knowing α and A at any given time point and inserting into Equation 2 to find ψ.

$$cosA = \overline{EW} \cdot \overline{ES} = \begin{bmatrix} s\alpha \\ c\alpha c\phi \\ s\alpha c\phi \end{bmatrix} \cdot \begin{bmatrix} s\alpha \\ -c\alpha \\ 0 \end{bmatrix} = s^2\alpha - c^2\alpha c\phi \quad (3)$$

To calculate the carrying angle, a functional elbow flexion/extension trial was performed where the upper arm was fixed. Two positions of the wrist joint centre with the arm flexed 90° (W_1) and the arm at its most extended (W_2) and one assumed position where the wrist joint centre lay on the longitudinal axis of the upper arm (W'), were expressed in a provisional upper arm reference (*ISB-1*). A plane was then defined using the W_1, W_2 and W', and a least squares circle fit was applied that represented the path of the wrist joint centre during flexion/extension. The angle between unit vectors $\widehat{ES}$ and $\widehat{EW}$, created from all locations of W on the circle, was calculated, and the greatest value represented full elbow extension, which the participant may not have achieved, allowing the carrying angle (2α) to be calculated (Figure 1b).

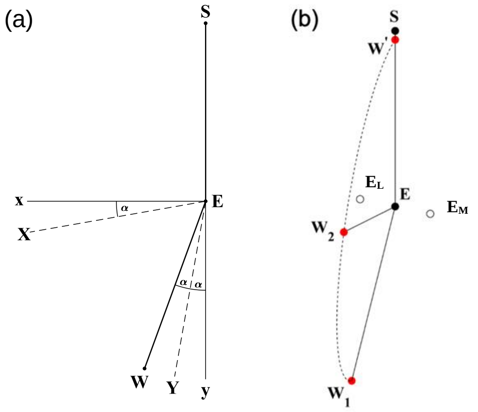

Figure 1. (a) The arm fully extended, with carrying angle (2α). Elbow flexion/extension occurs about X. (b) Calculation of the carrying angle. The dotted line represents the path of the circular least squares fit.

Data Collection and Processing: An 18-camera Vicon Motion Analysis System (OMG Plc, Oxford, UK) was used to collect 3D kinematic data of the participant, racket and shuttlecock at 500 Hz, consistent with King *et al.* (2020). Joint angles and angular velocities of the shoulder and elbow were calculated using *ISB-1, ISB-2* and *ISB-2C* segment definitions and shuttlecock speed was determined using a curve-fitting methodology (McErlain-Naylor *et al.,* 2020). Note that the wrist joint centre is defined as the distal ulnar centre, calculated similarly to Gordon (2009), as elbow flexion/extension is defined as motion of the ulna with respect to the humerus. Joint angles were calculated using the ISB recommended sequence for 'humerothoracic' and humeroulnar joints (Wu *et al.,* 2005) and joint angular velocities were expressed in terms of rates of change of the angles. Shoulder joint angular velocities were expressed in the upper arm reference frame. Elbow pronation/supination angular velocity was expressed about the forearm longitudinal axis, whilst flexion/extension was expressed about the upper arm mediolateral axis for *ISB-1* and *ISB-2*. For *ISB-2C* the elbow flexion/extension axis was defined by axis X, which has direction $(cos\alpha, 0, sin\alpha)$ in the upper arm reference frame xyz (Figure 1a). Time histories were normalised between the instant at which the racket head speed reached 5 $m \cdot s^{-1}$ from which the value did not decrease, and racket-shuttlecock impact.

RESULTS: Shuttlecock speeds were 76.8 ± 3.8 $m \cdot s^{-1}$ and the participant's carrying angle was 11.6º. Kinematic data about the two transverse axes of the shoulder and elbow extension axis were relatively similar between methods. Notable differences were present when assessing shoulder internal/external rotation and elbow pronation/supination kinematics (Figure 2).

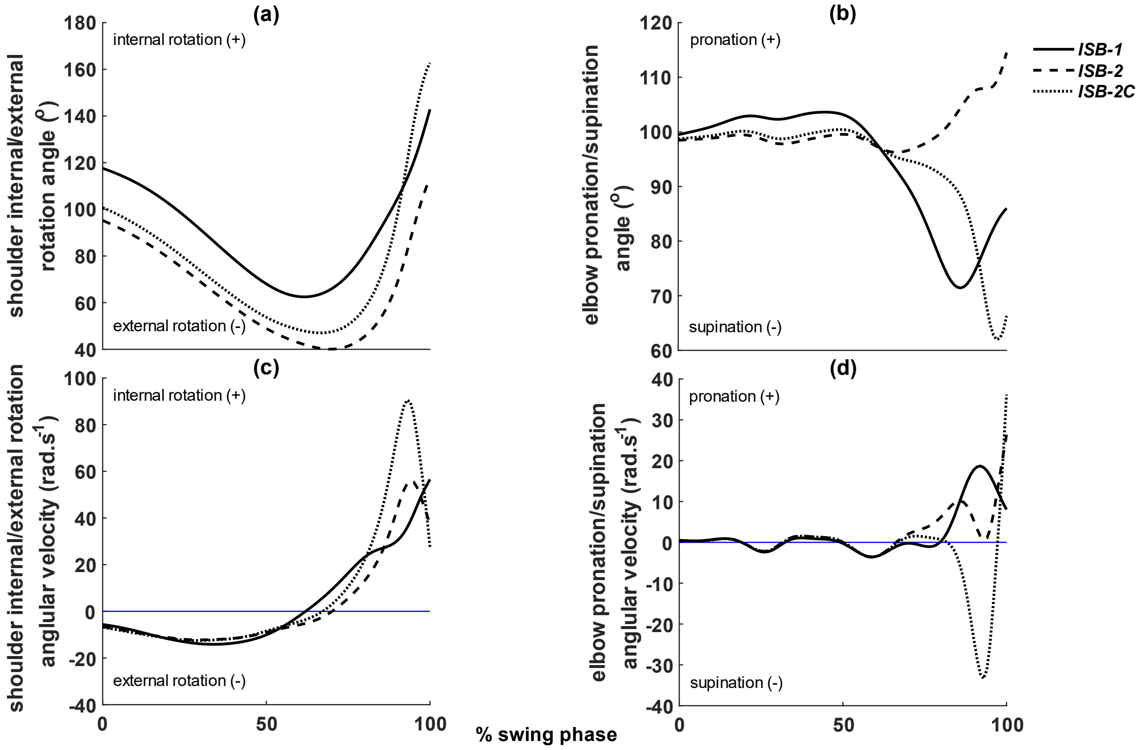

Figure 2. Shoulder and elbow kinematics for *ISB-1*, *ISB-2* and *ISB-2C*. Shoulder internal/external rotation angle (a), elbow pronation/supination angle (b), shoulder internal/external rotation angular velocity (c) and elbow pronation/supination angular velocity (d).

DISCUSSION: The carrying angle induces an apparent external rotation when using *ISB-2*, particularly as the elbow becomes more extended (Gordon & Dapena, 2013), on average 29.3º and 49.2º at impact compared to *ISB-1* and *ISB-2C* (Figure 2a). The shoulder internal/external rotation angle for *ISB-1* differed mostly near periods of external rotation (~60-80% of the swing phase), underestimating the external rotation by 38.5º and 23.2º, compared to *ISB-2* and *ISB-2C*, respectively. Whilst the general time history of the shoulder internal/external rotation angle were similar across methods, the angular velocities were very different, where both the *ISB-2* and *ISB-2C* methods peak prior to impact (~90% of swing phase) whilst *ISB-1* peaks at impact.

Additionally, the peak magnitude of *ISB-2C* is notably larger (34.6 rad·s^{-1} on average) than *ISB-2* (Figure 2c). Elbow pronation/supination angles varied after 60% of the swing phase (Figure 2b), where *ISB-2C* showed a much greater supination near impact. Most notable were the angular velocities in which *ISB-1* and *ISB-2* suggested little supination angular velocity. Perhaps more appropriately, *ISB-2C* showed a rapid supination followed by pronation (80-100% of swing phase; Figure 2d), consistent with previous work (Waddell & Gowitzke, 2000). *ISB*-2C requires an accurate carrying angle and locations of the shoulder, elbow and distal ulnar joint centres, especially near full elbow extension where small changes in the simple elbow angle will cause large effects on the correction angle. This method assumes that there is no forced abduction during a dynamic trial and that the use of the SEW plane will give greater precision than the use of medial and lateral epicondyles in defining the upper arm. Additionally, it is assumed that the forearm longitudinal axis will lie along the upper arm longitudinal axis when the elbow is fully flexed. Kapandji (1982) stated that the most common anatomical variation of trochlear groove (Type I) would cause the ulna to lay in the same plane as the upper arm at full flexion somewhat validating this assumption. The method could be further improved by more accurately locating the humeroulnar joint centre, which is distal to the humeral medial and lateral epicondyles.

CONCLUSION: This study presents a method in which the upper arm reference frame can be corrected based on the simple elbow angle and carrying angle, alleviating problems associated with *ISB-1* (soft-tissue artifact and marker-proximity to the longitudinal axis) and *ISB-2* (apparent external rotation due to the carrying angle). Method comparison found differences in shoulder and elbow kinematics, notably angular velocities. The method could be improved by more precisely defining the shoulder, elbow and distal ulnar joint centres and is limited by small marker location errors causing large correction angle changes as the elbow becomes more extended. The method has practical application to badminton and other sports such as tennis and cricket, where the elbow nears full extension.

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