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A method to determine the orientation of the upper arm about its longitudinal axis during dynamic motions

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ABSTRACT

Inaccuracy in determining the orientation of the upper arm about its longitudinal axis (twist orientation) has been a pervasive problem in sport biomechanics research. The purpose of this study was to develop a method to improve the calculation of the upper arm twist orientation in dynamic sports activities. The twist orientation of the upper arm is defined by the orientation of its mediolateral axis. The basis for the new method is that at any angle in the flexion/extension range of an individual's elbow, it is possible to define a true mediolateral axis and also a surrogate mediolateral axis perpendicular to the plane containing the shoulder, elbow and wrist joints. The difference between the twist orientations indicated by these two versions of the mediolateral axis will vary from one elbow angle to another, but if the elbow joint deforms equally in different activities, for any given subject the difference should be constant at any given value of the elbow angle. Application of the new method required individuals to execute sedate elbow extension trials prior to the dynamic trials. Three-dimensional motion analysis of the sedate extension trials allowed quantification of the difference between the true and surrogate mediolateral axes for all angles in the entire flexion/extension range of an individual's elbow. This made it possible to calculate in any dynamic trial the twist orientation defined by the true mediolateral axis from the twist orientation defined by the surrogate mediolateral axis. The method was tested on a wooden model of the arm.

1. Introduction

The calculation of the upper arm orientation about its own longitudinal axis ("twist orientation") often presents important difficulties. It is normally defined as the twist orientation of the underlying bone (humerus), but the bone is covered with soft tissues that obstruct it from view. Therefore, it is calculated through indirect methods. Errors in these methods produce errors in the twist orientation, and subsequently in other kinematic and kinetic parameters.

Two primary methodologies have been used in the past to determine the upper arm orientation. Both define it as the orientation of a local reference frame embedded in the segment, relative to a global reference frame or to an anatomical reference frame embedded in the scapula. The direction vectors of the local reference frame define its mediolateral, anteroposterior, and longitudinal axes. These will be referred to here as $\mathbf{X_{UA}}$, $\mathbf{Y_{UA}}$ and $\mathbf{Z_{UA}}$, respectively. In both methods, $\mathbf{Z_{UA}}$ points from elbow to shoulder. The methods differ in the calculation of the $\mathbf{X_{UA}}$ and $\mathbf{Y_{UA}}$ orientations.

The first method will be called here the "traditional joint centers method". It uses the shoulder, elbow and wrist joint centers to define the twist orientation of the upper arm. $\mathbf{X_{UA}}$ is the cross-product of a vector pointing from elbow to wrist with vector $\mathbf{Z_{UA}}$. It defines the mediolateral axis. The cross-product of $\mathbf{Z_{UA}}$ with $\mathbf{X_{UA}}$ defines the anteroposterior axis ($\mathbf{Y_{UA}}$). This method was used in studies of throwing and tennis serving (Feltner and Dapena, 1986; Fleisig et al., 1996; Bahamonde, 2000; Gordon and Dapena, 2006). It works reasonably well when the elbow is markedly flexed. However, as the elbow approaches full extension, small errors in the locations of shoulder, elbow and wrist produce large errors in the calculated twist orientation. An additional complication is that the longitudinal axes of the upper arm and forearm are not aligned at full elbow extension; they present a valgus angle known as the "carrying angle". With this method, the carrying angle adds a false external rotation as the elbow extends.

The second method, which will be called here the "marker based method", utilizes skin-mounted markers. The locations of markers opposite to each other across the upper arm near its endpoints are averaged to determine two points on the longitudinal axis. $\mathbf{Z_{UA}}$ is calculated from these points. A vector directed from a medially placed marker to a laterally placed marker defines the mediolateral axis ($\mathbf{X_{UA}}$). The cross-product of $\mathbf{Z_{UA}}$

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and $\mathbf{X_{UA}}$ defines the anteroposterior axis ($\mathbf{Y_{UA}}$). This method was used in studies of tennis (Van Gheluwe et al., 1987; Sprigings et al., 1994; Elliott et al., 1995; Elliott, 2000). Skin-mounted markers commonly produce two problems. Since the markers are near the longitudinal axis, small errors in their locations can produce large errors in the twist orientation. The second problem is that the skin-mounted markers do not necessarily follow the underlying bone's motions (Cappozzo et al., 1996; Reinschmidt et al., 1997; Gordon and Dapena, 2006).

At any angle in the flexion/extension range of an individual's elbow, it is possible to define a true mediolateral axis and a surrogate mediolateral axis perpendicular to the plane containing shoulder, elbow and wrist. The twist difference between these two versions of the mediolateral axis changes from one elbow angle to another. However, if we assume that the elbow joint does not deform differently in different activities, the twist difference will be constant at any given value of the "simple elbow angle" (the angle between the longitudinal axes of upper arm and forearm) for any given subject. If this twist difference were known for all angles in an individual's flexion/extension range, it would be possible to calculate for any human activity the twist orientation defined by the true mediolateral axis from the one defined by the surrogate mediolateral axis. This is the basis for the new method presented here ("corrected joint centers method").

2. Methods

2.1. Videotaping of trials

Nine male N.C.A.A. Division I varsity tennis players served as subjects. Permission was obtained from the Indiana University Human Subjects Committee; informed consent was obtained from the participants.

Each subject executed two elbow extensions. Both were performed at slow speed, with the upper arm kept in a neutral position of internal/external rotation. Thus, it was assumed that in these sedate trials the skin markers had negligible motion relative to the underlying bone.

The elbow extensions were executed with the elbow lifted laterally and the palm of the hand facing upward (Fig. 1). Location markers (22 mm diameter styrofoam balls) were attached to each subject. For the first extension, eight markers were attached. Two were directly anterior and posterior to the shoulder joint, and helped in the visual identification of the shoulder joint center. Four were attached to an inelastic Velcro band wrapped around the arm just proximal to the elbow. These markers were spaced at approximately 90° intervals, with one marker approximately aligned with the lateral humeral epicondyle. Two markers were attached to the ends of a hard wire that fit firmly around the wrist and was held in place by a rubber band (Miyanishi et al., 1996). The wire positioned these markers just lateral to the radial styloid and just medial to the ulnar styloid. The anterior marker of the Velcro band inhibited the initial amount of elbow flexion in the first extension. For the second extension, it was removed to allow full range of flexion/extension; all other markers remained in place.

Fig. 1. Placement of markers in the first sedate extension trial. The dashed white ring indicates the approximate location of the upper arm medial marker blocked from view. *Note*: To facilitate the identification of the visible upper arm markers attached to the Velcro band, a white graphical circumference has been added to the lateral marker, and black circumferences to the anterior and posterior markers.

The trials were videotaped with four cameras recording at 50 Hz. Two AVT Pike F-032C cameras were placed behind and to the left and right of the subjects; two Sony HVR-V1P cameras were placed in front of and to the left and right of the subjects.

2.2. Landmark digitization, and calculation of three-dimensional coordinates

The locations of the shoulder joint and of the styrofoam balls were manually digitized in each frame of each camera (SIMI Reality Motion Systems GmbH, Unterschleissheim, Germany). The three-dimensional (3D) coordinates of the landmarks relative to a global reference frame were calculated following the DLT method (Abdel-Aziz and Karara, 1971; Walton, 1981).

The 3D landmark coordinates obtained in the extension trials were used to determine three angles for each instant: (a) the simple elbow angle; (b) the orientation of the surrogate mediolateral axis, using the traditional joint centers method; and (c) the orientation of the true mediolateral axis, using a mathematical model of the 3D elbow flexion/extension.

2.3. Calculation of provisional upper arm reference frame

The data from the first trial were used to measure the position of the anterior marker relative to the other three, which allowed reconstruction of the location of the missing anterior marker throughout the second trial. This was the only use made of the data from the first extension trial. All further calculations used exclusively the second trial.

The 3D coordinates from the second extension trial were used to define an upper arm reference frame. After reconstructing the location of the anterior marker, the longitudinal axis of the upper arm ($\mathbf{Z_{UA}}$) was defined by a line pointing from the average of the four Velcro band markers to the shoulder joint. A second axis ($\mathbf{X_{UA}}$) was directed from the medial marker of the Velcro band to the lateral marker. The cross-product of $\mathbf{Z_{UA}}$ with $\mathbf{X_{UA}}$ defined the third axis ($\mathbf{Y_{UA}}$). To ensure orthogonality, $\mathbf{X_{UA}}$ was recalculated as the cross-product of $\mathbf{Y_{UA}}$ and $\mathbf{Z_{UA}}$. $\mathbf{X_{UA}}$ was considered a provisional orientation for the mediolateral axis of the upper arm. All 3D coordinate data were then transformed into this reference frame.

2.4. Calculation of elbow joint center

The location of the distal end of the ulna relative to the upper arm reference frame is determined by the subject's elbow joint structure and by the degree of elbow flexion/extension, while the locations of the distal end of the radius and of the wrist center depend in addition on the degree of pronation of the forearm. Because of this, the present method was based exclusively on the movements of the ulna.

The distal end of the ulna was located using the markers attached to the hard wire fastened to the wrist. The 3D locations of the marker centers, together with the known marker diameters, the measured distances from the marker surfaces to the skin (measured directly on the subject before the trial), and the distance from the skin to the distal ulna center allowed the determination of the distal ulna center location in all frames. The distance from the skin on the ulnar side to the center of the distal ulna center head was estimated at about 15% of wrist width, based on measurements taken from ten wrist x-rays obtained from Internet sources (Uwmsk.org, 1997; Anatomy.med.umich.edu, 2000; Missouristate.edu, 2005; Eatonhand.com, 2007; Pacificdentalimaging.com, 2007; Faqs.org, 2008; Dhmc.org, 2009; Learn-computer.org, 2009; Uptodateinc.com, 2009; Web.szote.u-szeged.hu, 2009; Wheelessonline.com, 2009).

The position of the distal ulna center, expressed in the upper arm reference frame, was calculated over the full range of elbow extension. A plane was then fitted to the 3D distal ulna center locations. Every distal ulna center location was subsequently projected onto this ulnar plane, and the center of the circular arc that best fit the projected points (ulna arc center) was calculated. The elbow center was defined as the point on the longitudinal axis of the upper arm nearest to a line normal to the ulnar plane and that passed through the ulna arc center. For each instant of the second extension trial, the longitudinal axis of the forearm ($\mathbf{Z_{FA}}$) was then defined by a vector pointing from the unprojected distal ulna center to the elbow center.