A Marker-Based Mean Finite Helical Axis Model to Determine Elbow Rotation Axes and Kinematics in Vivo

Aaron Chin, David Lloyd, Jacqueline Alderson, Bruce Elliott, and Peter Mills

The predominance of upper-limb elbow models have been based on earlier lower-limb motion analysis models. We developed and validated a functionally based 2 degree-of-freedom upper-limb model to measure rotations of the forearm using a marker-based approach. Data were collected from humans and a mechanical arm with known axes and ranges of angular motion in 3 planes. This upper-limb model was compared with an anatomically based model following the proposed ISB standardization. Location of the axes of rotation relative to each other was determined in vivo. Data indicated that the functional model was not influenced by cross-talk from adduction-abduction, accurately measuring flexion-extension and pronation-supination. The functional flexion-extension axis in vivo is angled at 6.6° to the anatomical line defined from the humeral medial to lateral epicondyles. The pronation-supination axis intersected the anatomically defined flexion-extension axis at 88.1°. Influence of cross-talk on flexion-extension kinematics in the anatomical model was indicated by strong correlation between flexion-extension and adduction-abduction angles for tasks performed by the subjects. The proposed functional model eliminated cross-talk by sharing a common flexion axis between the humerus and forearm. In doing so, errors due to misalignment of axes are minimized providing greater accuracy in kinematic data.

Keywords: cross-talk, pronation-supination, upper limb

The upper limb is used to position the hand for a wide range of tasks in daily living. However, functionally the elbow enables much of this movement, with rotations about its two degrees of freedom (2 df): flexion-extension (F-E) and pronation-supination (P-S) (Chao & Morrey, 1978; Fornalski et al., 2003). As such, many studies have been conducted using methods such as radiostereometric analysis, electromagnetic and opto-electronic systems, to measure kinematics of the upper limb (Biryukova et al., 2000; Cutti et al., 2008; Ericson et al., 2003; Schmidt et al., 1999; Stokdijk et al., 1999; van Andel et al., 2008; Veeger et al., 1997a).

Previous biomechanical research investigating axes of rotation have fixed the upper-arm of cadavers and moved the forearm passively through various motions to define the elbow axes (Chao & Morrey, 1978; Johnson et al., 2000; Youm et al., 1979; Veeger et al., 1997a, 1997b). These in vitro studies generally showed that the forearm F-E axis passes through the center of the trochlea. In addition, the position of the P-S axis has also been investigated relative to anatomical landmarks, with general agreement that it passes from the distal portion of the ulna head to a position near the humeral lateral epicondyle (Veeger et al., 1997a; Youm et al., 1979). These studies assumed that there was not elbow articulation in adduction-abduction (Ad-Ab), but there was a fixed Ad-Ab offset or carry angle of the elbow.

Earlier studies using marker based measurement systems have relied on marker placement on anatomical landmarks. Schmidt et al. (1999) and Rau et al. (2000) calculated joint centers from static calibration trials, whereas offsets from selected markers were used to establish joint positions by Rab et al. (2002). This has led to the International Society of Biomechanics (ISB) proposing a standardized joint coordinate system (JCS) definition for the elbow (Wu et al., 2005) based on 3-df Grood and Suntay’s JCS of the knee (Grood & Suntay, 1983). This 3-df elbow JCS is based on a vector running between the markers placed on the lateral and medial epicondyles of the humerus, and due to the short inter-marker distance, the anatomical coordinate system (ACS) can be rotated from its true anatomical position, which can introduce errors in the resulting kinematic data. The result of incorrectly defining ACS axes through misalignment has been shown to produce kinematic cross-talk during longitudinal axis rotations of the knee (Piazza & Cavanagh, 2000). Recently, the ISB proposed JCS was shown to estimate different P-S and Ad-Ab kinematics.
when a pure 140° elbow F-E movement was performed in vitro (Cutti et al., 2006). From this it was suggested that careful interpretation of in vivo kinematic data are needed. To our knowledge, the effect of kinematic cross-talk from F-E axis misalignment on both P-S and Ad-Ab rotations at the elbow has not been assessed.

An alternative to using anatomical landmarks to define axes of rotation is to define these axes using functional methods, whereby instantaneous helical axes are calculated to describe the motion between two segments in terms of a rotation and translation (Woltring, 1994). This method has been reported to potentially reduce kinematic cross-talk (Besier et al., 2003). Functional movement about the elbow has been measured with electro-magnetic tracking systems (Biryukova et al., 2000; Veeger et al., 1997a). Using mean Finite Helical Axes (FHAs) for F-E and P-S, the cadaveric work by Veeger and colleagues (1997a) showed that the elbow could be modeled using a 2-df joint, with Ad-Ab motion constrained. Stokdijk et al. (1999; 2000) performed a similar study based on the methods of Veeger et al. (1997a), applying the methods in an in vivo setting. All these studies reported the location of the functional axes relative to anatomical landmarks, although the model used by Stokdijk et al. (1999, 2000) only consisted of F-E of the elbow, and therefore only the location of the F-E axis of rotation was reported.

Biryukova et al. (2000) developed an in vivo upper-limb model consisting of 7 df, with 2 df at the elbow. The model, validated by solving direct kinematics of reaching movements, indicated that the position and orientation of the F-E and P-S functional axes in relation to each other were similar to those reported by Veeger et al. (1997a). However, the location of the axes relative to anatomical landmarks was not reported and although this was performed in vivo, passive movements were also used to calculate the axes of rotation. Finally, using a functionally based 2-df joint may reduce the effects of cross-talk when compared with the 3-df joint, but this premise has never been examined at the elbow.

This paper had three aims while using a functional marker based method for calculating F-E and P-S kinematics of the elbow during movement tasks. The first aim was to develop and implement a functional 2-df upper-limb model based on the commonly applied rigid body assumption using the mean finite helical axis method (abbreviated to HAM model). The second aim was to perform in vivo examination of kinematic data obtained from a healthy population. In addition, the influence of kinematic cross-talk throughout dynamic tasks was investigated and it was hypothesized that the HAM model would eliminate the effects of cross-talk in both the mechanical and in vivo trials. As a result of the hypothesized reduction in kinematic cross-talk, it was also hypothesized that kinematics obtained from the functional model will have smaller differences in calculated angles when compared with known angles than the anatomically based model.

Method

Kinematic data were obtained from the functional and anatomically based elbow models, using a mechanical arm that replicated forearm motion (e.g., varying levels of Ad-Ab), and a series of movement tasks performed by 10 male cricketers (mean age = 23.5 years SD = 2.7, mean height = 180.5cm SD = 7.9). All human test protocols were approved by the University of Western Australia Human Research Ethics committee, and each participant’s written, informed consent was obtained before data collection.

The functional 2-df upper-limb model was compared with an anatomically based 3-df Cardan ZXY angle decomposition method model as proposed by the ISB (ANAT model). Both measurement models were validated and compared by analyzing kinematics of known magnitudes and ranges using a mechanically constructed arm. The mechanical arm could replicate possible forms of axis misalignment and was used to assess F-E cross-talk associated with P-S and Ad-Ab motion.

The arm was constructed to represent the upper-limb, with an elbow allowing the forearm 3 df: F-E, P-S and Ad-Ab (Figure 1). These three axes had known locations and orientation, bisecting each other at a known location, and the elbow could be fixed in certain postures. The forearm could be flexed through a range of 135° and had a P-S range of 180°. Two methods of forearm abduction (carry angle) were employed: (1) abduct the forearm such that the F-E axis of the elbow remained in the same orientation, and (2) allow the F-E axis to be completely abducted by 10° or 20°, thus giving the F-E axis an abduction (frontal plane) tilt.

The same marker set was used for both the mechanical arm and human trials. Position and orientation of the upper-arm, forearm and hand was determined using clusters of retro-reflective markers (16 mm in diameter) placed on each segment in an adoption of the “CAST” method (Cappozzo et al., 1995). Additional markers were placed at the wrist and shoulder (Figure 2), and a pointer device used to identify medial and lateral epicondyles of the elbow (ME and LE respectively), to allow the upper limb joint centers (JCs) to be determined. Static trials were then performed to establish each segment’s technical coordinate system (TCS) such that ACSs and JCs could be defined relative to these TCSs. The upper-arm TCS was constructed from the locations of a triad of markers placed bilaterally on the upper-arm (Figure 2). As suggested by Anglin and Wyss (2000) the forearm TCS was created from the location of markers placed on the distal end of the forearm, just above the wrist where the radius rotates the most around the ulna. The forearm triad consisted of markers mounted on a rigid aluminum T-bar to allow sufficient distance between markers placed on the lateral and medial aspects of the forearm.

In addition to the static trials already described, functional calibration trials were performed. In the F-E calibration trial, used to establish the elbow F-E axis,
the forearm was moved through a full F-E range of motion (ROM) five times (Figure 3) while remaining in the same neutral position. The neutral forearm position, midway between full pronation and supination, was selected analogous to the methods used by Stokdijk et al. (2000), in order that direct comparisons can be made to previous literature. Furthermore, research into the upper limb kinematics of everyday functional tasks has reported that the forearm remains in a relatively neutral position, while performing the tasks (van Andel et al., 2008). In the P-S calibration trial, from which the P-S axis was defined, the forearm was moved through its full P-S RoM five times (Figure 4) in a continuous motion with the elbow constantly flexed at 90°. When carrying out these calibration tasks, subjects attempted to control the movement such that only the specific rotation (F-E or P-S) was being performed.

To test how the ANAT and HAM models affected the recorded joint kinematics and the degree of cross talk, dynamic trials were collected for the humans (in vivo) and mechanical arm. For the human subjects the F-E and P-S calibration trials served as dynamic movement tasks. In addition, each subject performed six cricket bowling trials. For the mechanical arm dynamic trials were collected to establish the effect of joint configurations on
Figure 3 — Flexion-extension (F-E) task to obtain the F-E helical axis. Subjects started with the upper arm parallel to the floor, with the forearm in maximum flexion (1) and with their hand in a neutral position (at 90°). Subjects then extended the forearm to full extension (2–4) before returning to the starting position (maximum flexion) while keeping the forearm in the same neutral position. Five continuous cycles were performed.

Figure 4 — Pronation-supination (P-S) task to obtain the P-S helical axis. Subjects started with the upper arm parallel to the floor at shoulder width, with the forearm remaining at 90° flexion (1) and with their hand in maximum pronation. Subjects then moved the forearm through a full range of supination (2–4) before returning to the starting position (pronated). Five continuous cycles were performed.

The recorded joint kinematics. In these, the elbow of the mechanical arm was fixed in selected positions, while a series of different F-E and P-S tasks were performed (Table 1). F-E tasks were also performed with the forearm in varying abduction angles. P-S tasks were undertaken with the elbow in 90° of flexion and with varying degrees of forearm abduction.

All trials were recorded at 250 Hz using a 12-camera Vicon MX motion analysis system (Vicon, Oxford, UK). All marker movement data were smoothed using a quintic spline (Woltring, 1986), with the mean square error (MSE) selected based on a modified residual analysis and visual inspection. An MSE of 15 was used to smooth displacement data from the mechanical arm, while 20 was used in all human trials.

Elbow F-E and P-S axes were determined from the F-E and P-S calibration trials respectively, for both the mechanical arm and human subjects with the HAM model. A custom MATLAB program calculated F-E and P-S instantaneous FHAs for every time point and a
following subsequent time point where there was an angle step ≥ 25° from the first time point. The mean FHAs were then calculated from all instantaneous FHAs based on the protocols established by Besier et al. (2003). A minimum angle step of 25° was used as it has been shown that axis orientation errors dramatically decreased for angular displacements >22° (Cheze et al., 1998). Finally, as with any FHA method there are outliers produced that are caused by skin movement artifact and noise. Similar to previous FHA implementations (Stokdijk et al., 1999) any FHA with an orientation greater than 2 standard deviations (SD) from the mean were removed before a final mean FHA was calculated. The F-E axis was then defined relative to the upper-arm TCS, and the P-S axis was held in the forearm TCS, the latter formed using either ANAT or HAM elbow JCs, which are now described.

Different JC locations were defined dependent upon the upper limb model. Location of the shoulder JC (SJC) was the same in both models and was determined using markers on the acromion process and the anterior and posterior aspects of the gleno-humeral joint. The SJC was then calculated as the point where the perpendicular line dropped from the acromion marker bisected the line created between the two anterior and posterior shoulder markers. The ANAT elbow JC (aEJC) was defined as the midpoint between ME and LE that were located using a 6 marker pointer rod in a similar fashion to Cappozzo and colleagues (1995). HAM elbow JC (hEJC) was defined as the point along the mean F-E helical axis that intersected a plane that was normal to the transepicondylar line, midway between the epicondyles. Location of the wrist JC (WJC) was the midpoint between two markers placed on the lateral (LWR marker) and medial (MWR marker) aspects of the wrist, for both models.

Two different methods were used to define the upper-arm ACSs and four different methods for the forearm ACSs (refer to Table 2 for a summary of joint and segment definitions). Joint kinematic conventions were dependent on the model and movement measured. The ANAT model followed the ISB standard whereby the sequence of rotation was: F-E, Ad-Ab then P-S. For the HAM model, F-E motion was calculated from the position of FAHAM1 relative to UAHAM about the Z-axis of the coordinate systems. P-S motion was determined from the position of FAHAM3 relative to FAHAM2 about the Y-axis (P-S axis).

The models were evaluated by a range of methods. Direct kinematic comparisons between predetermined angles and measured ranges of the mechanical arm were performed. In vivo measurements of the position and orientation of the HAM F-E and P-S axes were compared with the anatomical based axes. The angle between the HAM F-E axis and the vector running through the elbow epicondyles was calculated along with the distance between the intersection of these two vectors with the ANAT XY (sagittal) plane of the upper-arm. The angle between the HAM P-S axis and forearm long axis was calculated, as well as its point of intersection with the transverse plane of the forearm formed by the ANAT XZ axes. The angle in which the HAM P-S axis intersected the anatomical and HAM F-E axis was also calculated. By determining the location of functional F-E and P-S axes, relative to anatomical landmarks, comparisons between the values of the developed model to that of previous literature were made.

The degree of cross-talk between F-E and Ad-Ab curves, and F-E and P-S curves was assessed by calculating the Pearson correlations (r) between each pairing for

<table>
<thead>
<tr>
<th>Trial</th>
<th>Tested Motion</th>
<th>Forearm Abduction Angle (°)</th>
<th>F-E Axis Abduction Angle (°)</th>
<th>Forearm Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F-E</td>
<td>0</td>
<td>0</td>
<td>Neutral</td>
</tr>
<tr>
<td>2</td>
<td>P-S</td>
<td>0</td>
<td>0</td>
<td>Neutral</td>
</tr>
<tr>
<td>3</td>
<td>F-E</td>
<td>10</td>
<td>0</td>
<td>Neutral</td>
</tr>
<tr>
<td>4</td>
<td>F-E</td>
<td>10</td>
<td>0</td>
<td>Supinated</td>
</tr>
<tr>
<td>5</td>
<td>P-S</td>
<td>10</td>
<td>0</td>
<td>Neutral</td>
</tr>
<tr>
<td>6</td>
<td>F-E</td>
<td>20</td>
<td>0</td>
<td>Neutral</td>
</tr>
<tr>
<td>7</td>
<td>F-E</td>
<td>20</td>
<td>0</td>
<td>Supinated</td>
</tr>
<tr>
<td>8</td>
<td>P-S</td>
<td>20</td>
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<td>Neutral</td>
</tr>
<tr>
<td>9</td>
<td>F-E</td>
<td>0</td>
<td>10</td>
<td>Neutral</td>
</tr>
<tr>
<td>10</td>
<td>F-E</td>
<td>0</td>
<td>10</td>
<td>Supinated</td>
</tr>
<tr>
<td>11</td>
<td>P-S</td>
<td>0</td>
<td>10</td>
<td>Neutral</td>
</tr>
<tr>
<td>12</td>
<td>F-E</td>
<td>0</td>
<td>20</td>
<td>Neutral</td>
</tr>
<tr>
<td>13</td>
<td>P-S</td>
<td>0</td>
<td>20</td>
<td>Neutral</td>
</tr>
</tbody>
</table>
both mechanical arm and human dynamic tasks. Since there was only one F-E and one P-S trials per human subject, to ensure the same analysis method across all dynamic tasks, one of the six cricket bowling trials was randomly selected from each subject for analysis. The average Pearson correlation coefficient was then calculated across all human subjects for each dynamic task for each of ANAT and HAM methods. For mechanical arm the Pearson correlations were calculated for each different joint configuration.

### Results

The HAM F-E axis obtained from the mechanical arm was on average 2.6° ($SD = 0.6°$) from the ANAT F-E axis. These axes also intersected the upper-arm sagittal plane at a mean of 4.8 mm ($SD = 2.3$) apart. The HAM P-S axis was an average of 3.8° ($SD = 1.7°$) from the long axis of the forearm, and these two vectors intersected on average 17.5 mm ($SD = 8.2$) apart in the transverse plane of the forearm. In the frontal plane, the HAM P-S axis intersected the HAM F-E axes at an angle of 88.9° in a proximal lateral to distal medial direction, compared with the HAM P-S and ANAT F-E axes at 90.4° in a proximal medial to distal lateral direction.

The average HAM F-E axis obtained in vivo from the 10 human subjects was inclined at a mean of 6.6° ($SD = 4.1°$) in the frontal plane in a proximal lateral to distal medial direction and intersected at a distance of 19.8 mm ($SD = 14.4$) apart. On average there was 7.4° ($SD = 4.5$) between HAM and ANAT P-S axes, and 38.9 mm ($SD = 24.3$) between where the axes intersected with the transverse plane. The HAM P-S axis intersected the ANAT F-E axis at an average angle of 88.1° ($SD = 2.6$) in the frontal plane in a proximal lateral to distal medial direction, and the average angle between the HAM F-E and P-S axes was 84.6° ($SD = 6.8$).

Similar elbow F-E kinematic curves were observed between the ANAT and HAM models for all tasks using the mechanical arm (Figure 5). ANAT and HAM models

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**Table 2  Upper-arm and forearm anatomical coordinate system (ACS) segment definitions used in the ANAT and helical axis method (HAM) models**

<table>
<thead>
<tr>
<th>ACS</th>
<th>Segment Name</th>
<th>Definition (1st, 2nd, 3rd)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Upper Arm</strong></td>
<td><strong>Definition (1st, 2nd, 3rd)</strong></td>
</tr>
</tbody>
</table>
| ANAT Model | UAAnatomical        | Origin: aEJC  
Y-axis: unit vector from aEJC to SJC (superior positive)  
X-axis: cross-product of Y-axis and unit vector from LE and ME (anterior positive)  
Z-axis: orthogonal to X-Y plane (positive left to right) |
| HAM Model  | UAHAM                | Origin: hEJC  
Z-axis: mean F-E helical axis (positive left to right)  
X-axis: cross-product of the unit vector from SJC to hEJC and Z-axis (anterior positive)  
Y-axis: orthogonal to the X-Z plane (superior positive) |
|         | **Forearm**          | **Definition (1st, 2nd, 3rd)**                                                           |
| ANAT Model | FAanatomical        | Origin: WJC  
Y-axis: unit vector from WJC to aEJC (superior positive)  
X-axis: cross-product between Y-axis and unit vector from LW to MW (anterior positive)  
Z-axis: orthogonal to the X-Y plane (positive right) |
| HAM Model  | FAHAM1               | Origin: WJC  
Z-axis: mean F-E helical axis (positive to right)  
X-axis: cross-product of Z-axis and vector from hEJC to WJC (positive anterior)  
Y-axis: orthogonal to X-Z plane (positive superior) |
|          | FAHAM2               | Origin: WJC  
Y-axis: mean P-S helical axis (superior positive)  
X-axis: cross-product of Y-axis and F-E helical axis (positive anterior)  
Z-axis: orthogonal to X-Y plane (positive superior) |
|          | FAHAM3               | Origin: WJC  
Y-axis: mean P-S helical axis (superior positive)  
X-axis: cross-product of Y-axis and unit vector from MW to LW (positive to right)  
Z-axis: orthogonal to X-Y plane (positive to right) |
recorded F-E ranges of 132.2° and 133.3° respectively compared with the known range of 135°. P-S kinematic curves were also comparable during pure P-S tasks. There were large differences observed between forearm longitudinal rotation from both models during F-E tasks (Figure 5) as the ANAT model recorded P-S and Ad-Ab, while the forearm was being flexed, even though no P-S and Ad-Ab movement was performed. Magnitude of Ad-Ab also increased as the F-E axis was moved from 0°, 10° and 20° abduction, with ranges of 2.5°, 16.5° and 30° being recorded for each of these abduction angles respectively.

In the mechanical arm trials, the correlation between F-E and Ad-Ab was higher with the ANAT model than with the functional approach (Table 3). The ANAT model F-E kinematics were effected to a greater extent by Ad-Ab cross-talk with higher correlations displayed, when the F-E was abducted by 10° (r = .99) and 20° (r = .99) in comparison with when the F-E was recorded with the forearm and upper arm aligned (r = .48). In addition, mean r values between F-E and Ad-Ab from all trials were greater for the ANAT model (r = .67 SD= 0.51) compared with the HAM model (r = .00 SD= 0.02).

Varying differences were observed between ANAT and HAM models for F-E and P-S tasks within the subjects. Whereas F-E curves were highly similar during a task of pure F-E with the mechanical arm, in vivo results indicate a smaller magnitude for the ANAT model, particularly at maximum elbow extension (Figure 6). Although subjects were keeping the forearm in the same position during these tasks, large ranges of P-S and Ad-Ab were observed during these tasks in comparison with the HAM model, which reported only small ranges of P-S and no Ad-Ab (Figure 6). Kinematics from the highly complex and dynamic bowling task also displayed dissimilar waveforms as indicated in Figure 7.

The in vivo cross-talk analysis revealed strong correlations (r = .6–.7) between F-E and Ad-Ab for all tasks with the ANAT model. Further analysis indicated strong (r = .7 ANAT; r = .6 HAM), moderate (r = −.5 ANAT; r = −.5 HAM) and small (r = .1 ANAT; r = .1 HAM) correlations existed between F-E and P-S for the F-E, P-S and bowling tasks respectively.

**Discussion**

This study developed and validated a functionally based 2-df elbow model to measure forearm rotations using a marker based motion analysis system. This model was validated by analyzing kinematic data to that of known angles and RoM. Furthermore, the functionally based model was compared with an anatomical model based on Cardan ZXY angle decomposition in vivo.
Table 3  Cross-talk by the anatomical and helical axis method (HAM) models for the various mechanical arm and subject trials

<table>
<thead>
<tr>
<th>Test Model</th>
<th>Tested Motion</th>
<th>Forearm Abd Angle (°)</th>
<th>F-E Axis Abd Angle (°)</th>
<th>Forearm Position</th>
<th>Anatomical Model</th>
<th>HAM Model</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>F-E and Ad-Ab cross-talk (r)</td>
<td>F-E and P-S cross-talk (r)</td>
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<tr>
<td>Mechanical Subject</td>
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<td>0</td>
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<td>0.99</td>
<td>0.81</td>
</tr>
<tr>
<td>Mean (SD)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.67 (0.51)</td>
<td>0.00 (0.72)</td>
</tr>
<tr>
<td>Human Subjects</td>
<td>F-E</td>
<td>N/A</td>
<td>N/A</td>
<td>Neutral</td>
<td>0.65</td>
<td>0.65</td>
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<tr>
<td>Bowling</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td>0.72</td>
<td>0.12</td>
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</table>
Figure 6 — Upper-limb kinematics of one subject performing a dynamic flexion-extension task for functionally (HAM) and anatomically (ANAT) based models. Ranges of pronation-supination and adduction-abduction are evident with the ANAT model despite the subject keeping the forearm in the same position as the task was performed.

Figure 7 — Upper-limb kinematics from one bowling trial from one subject for functionally (HAM) and anatomically (ANAT) based models. The curves move in the same direction however there is no constant similarity between angular outputs.
Validation of models in other studies has not been performed with the use of a mechanical linkage system with 3 df. Biryukova and coauthors (2000) validated their model by solving the direct kinematics problem for voluntarily performed reaching movements. Cutti et al. (2008) performed comparisons between two systems, while other mechanical linkage comparisons only consisted of 1 df (Stokdijk et al., 2000) or 2 df (Piazza & Cavanagh, 2000). The new model was able to calculate axes of rotation with very small differences in the position and orientation to the measured axes of the mechanical arm. Similar F-E axis differences between calculated and measured values for an artificial hinge F-E axis were reported by Stokdijk et al. (2000).

Even though the anatomical landmarks could be easily located on the mechanical arm, kinematic cross-talk errors at the elbow were reflected in the kinematic P-S and Ad-Ab data. This led to moderate to strong correlations between F-E and Ad-Ab and F-E and P-S during pure F-E tasks. While both ANAT and HAM models had similar shaped F-E waveforms for the pure F-E tasks performed with the mechanical arm, an offset existed between the two curves. Previous research by Piazza and Cavanagh (2000) reported high sensitivity in location of anatomical landmarks, whereby errors due to cross-talk in long axis rotations were evident in a mechanical linkage, akin to the P-S rotations in the current study.

The average location and orientation in vivo of the HAM F-E axis from the current study indicates that the elbow F-E is angled at approximately 7° to the anatomical vector between the lateral and medial epicondyles, similar to values reported in the study by Veeger et al. (1997a) and Stokdijk et al. (1999, 2000). The orientation of the HAM F-E axis supports previous qualitative descriptions in earlier studies by Chao and Morrey (1978) and Youm et al. (1979) of the F-E axis passing through the trochlea. In the current study, the angle at which the HAM P-S axis crosses the F-E axes (ANAT = 88.1°; HAM = 84.6°) is comparable with previous research reporting that the P-S axis intersects the F-E axis at approximately 89° (Biryukova et al., 2000; Veeger et al., 1997a, 1997b). The angle at which the HAM P-S axis intersects the HAM F-E axis is indicative of the carry angle and is assumed to be constant between these two axes in the HAM 2-df model.

Whereas the ANAT model reported less flexion than the HAM model by an average of 1° during mechanical arm trials, there were varying offsets in angle outputs when the models were applied in vivo between different subjects. The diversity of offsets between F-E curves is most likely due to the varying amounts of carry angle displayed between the individual subjects as a result of their differences in bone geometry. As a result, the influence of Ad-Ab cross-talk shows greater variation between subjects. However, regardless of forearm abduction, strong correlations were observed between F-E and Ad-Ab when the ANAT model was applied, thus influencing F-E kinematics. The proposed HAM model resolves this cross-talk issue by sharing the helical F-E axis (Z-axis) for both upper-arm and forearm CSs. In doing so, the forearm is aligned with the F-E axis of the humerus and eliminates Ad-Ab to measure a true F-E rotation.

Although P-S curves were identical for pure P-S tasks performed with the mechanical arm, the exact location of ME and LE, and therefore the F-E axis was easily identifiable. This may not be the case in human populations where errors in identifying ME and LE, and subsequently the definition of the F-E axis, will lead to erroneous F-E and P-S kinematics. The HAM model reduces this variability by not being dependent on accurate identification of these landmarks. Of note, the HAM model did reveal a correlation between F-E and P-S when subjects performed the F-E task (see Table 3), suggesting the forearm rotates about its long axis at the extreme ends of F-E motion, a relationship Chao and Morrey (1978) observed regardless of forearm positioning.

Measurement of the true elbow axes of rotation in vivo is difficult and inaccuracies may exist with functional methods. The use of clusters reduces skin movement artifact although the HAM model will still be influenced by skin movement artifact, particularly P-S. However, as the clusters of markers were firmly attached to the mechanical arm, the rotations during described for these tasks are independent from the influence of skin movement. Small actual P-S and F-E deviations while subjects performed F-E and P-S tasks may also have influenced the HAM model as although great care was taken by each subject to avoid rotating about the second axis when performing calibration tasks, this may be a possible source of inaccuracy. However, passively moving the forearm will not guarantee that this does not occur. As used by Stokdijk et al. (1999, 2000) the technique of calculating the mean axis from FHA’s defined throughout the cycle eliminates random measurement noise. Small angular differences between the known mechanical arm axes and those established by the HAM model indicate that the model is accurate and can be successfully used to analyze forearm motion.

In summary, functional axes and the HAM modeling approach suggests that accurate forearm motion can be measured using a 2-df elbow model. Comparison of kinematic data obtained from the model with that of known angles and ranges of the mechanical arm design parameters indicates that the proposed HAM model accurately measures forearm kinematics. The location and orientation of the functional axes supports previous qualitative and quantitative analyses on the in vivo location of the F-E axis. It is also evident that the P-S axis of the forearm lies at an angle between the distal head of the ulna to the LE of the humerus. Cross-talk from incorrectly defining the F-E axis influences F-E kinematics, when the forearm is modeled using an anatomical ZXY decomposition. Where precise location of the axes of rotation is necessary in making clinical decisions, using functional axes may also reduce errors associated with anatomical landmark identification, which is required in anatomically based models.
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References