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Instantaneous helical axis estimation of glenohumeral kinematics: The impact of rotator cuff pathology

Rebekah L. Lawrence *, Matthew C. Ruder, Roger Zaul, Michael J. Bey

Bone and Joint Center, Department of Orthopaedic Surgery, Henry Ford Health System, 6135 Woodward Avenue, Detroit, MI 48202, USA

1. Introduction

Rotator cuff tears are common, affecting approximately 40% of individuals over age 60 (Milgrom et al., 1995; Yamamoto et al., 2010). The high prevalence of pathology is believed to be particularly problematic given the rotator cuff’s central role in shoulder function. Specifically, the rotator cuff contributes to two force couples which are believed to be necessary for glenohumeral joint function: the deltoid and the inferior rotator cuff (i.e., infraspinatus and teres minor) in the transverse plane (Burkhart, 1991; Inman et al., 1944; Lippitt and Matsen, 1993; van der Helm, 1994; Veeger and van der Helm, 2007). Technically, these relationships are not pure force couples because equal and opposite muscle forces are not produced. However, the term is frequently used to suggest the presumed physiological goal of balanced moments resulting in joint rotation without translation (e.g., Ackland and Pandy, 2011; Halder et al., 2001; Thompson et al., 1996).

Although the theory that the rotator cuff contributes to glenohumeral force couples is supported by in-vitro (e.g., Dyrna et al., 2018; Halder et al., 2001; Mura et al., 2003; Thompson et al., 1996) and musculoskeletal modeling studies (e.g., Steenbrink et al., 2009; Yanagawa et al., 2008), there is limited in-vivo evidence due to the difficulty estimating muscle forces. However, assessing glenohumeral kinematics may provide indirect evidence of rotator cuff function as it reflects, in part, the consequence of these muscle forces. For example, glenohumeral motion will theoretically approximate that of a ball-and-socket joint (i.e., pure joint rotation without translation) when both glenohumeral force couples are balanced (Burkhart, 1991; Inman et al., 1944). Therefore, any deviation in glenohumeral kinematics from ball-and-socket form would suggest an impairment of the glenohumeral force couples, which may provide important – although indirect – information regarding rotator cuff muscle function.

* Corresponding author.
E-mail address: rlawren2@hfhs.org (R.L. Lawrence).

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Numerous studies have sought to investigate the extent to which glenohumeral kinematics are altered in the presence of rotator cuff pathology (e.g., Baumer et al., 2017; Lawrence et al., 2014; Millett et al., 2016). Although these studies have expanded our knowledge of kinematics in the presence of rotator cuff pathology, the employed methodologies were not designed to assess potential alterations in ball-and-socket kinematics. For example, glenohumeral translations are typically described by tracking a landmark such as the humeral geometric center (e.g., Millett et al., 2016; Yamaguchi et al., 2000) or the estimated joint center of rotation (e.g., Lawrence et al., 2014). However, tracking a single landmark may result in incorrect descriptions of translations if the landmark does not lie along the joint’s axis of rotation. In this case, the landmark will move in an arc about the axis of rotation, which will be incorrectly interpreted as a joint translation. Consequently, traditional methods of describing joint kinematics such as Euler angles and joint translations may not be well-suited to assess potential alterations in ball-and-socket kinematics.

Helical axes are an alternative approach for describing joint motion that may be more well-suited to detect alterations in ball-and-socket kinematics. Specifically, a helical axis is defined as the 3D axis about which a segment rotates and along which it translates (e.g., Woltring, 1991; Woltring et al., 1994). The dispersion (i.e., variability) of the orientation and position of the helical axes during motion reflects the extent to which the joint motion can be reasonably characterized as having ball-and-socket form (Woltring, 1990; Woltring et al., 1994). Additionally, helical axes are defined directly from the motion that occurred and are therefore not affected by between-subject variations in anatomical coordinate systems, which may hinder the detection of potentially meaningful differences in kinematics. Despite these advantages, helical descriptions of motion are highly susceptible to measurement error (Ehrig and Heller, 2019; Woltring et al., 1994, 1985), which has precluded its broader use in kinematic analyses. However, biplane x-ray imaging has substantially improved the accuracy with which glenohumeral kinematics can be measured (Bey et al., 2006) and facilitates the use of helical descriptions of motion. Thus, the purpose of this study was to determine the extent to which rotator cuff pathology is associated with impaired ball-and-socket kinematics as defined by helical dispersion metrics. It was hypothesized that the severity of rotator cuff pathology will be associated with increased helical dispersion.

2. Methods

2.1. Participants

A retrospective sample of convenience was compiled using 51 participants from previous studies (Baumer et al., 2016; Bey et al., 2011). Symptomatic participants were at least 50 years old, had a full-thickness supraspinatus tear, and no history of shoulder trauma or surgery. Asymptomatic participants were at least 50 years old and had no history of shoulder trauma or surgery. Depending on the methods of the study for which participants were originally recruited, asymptomatic participants either had no current shoulder symptoms and were tested with their dominant shoulder (59%) (Baumer et al., 2016), or had a symptomatic full-thickness supraspinatus tear in one shoulder but had no symptoms in the contralateral shoulder (41%) (Bey et al., 2011). Because not all participants were tested bilaterally and to ensure independent groups for statistical analysis, data from only one shoulder was included for participants having bilateral data available. All participants underwent MRI or ultrasound imaging to screen for rotator cuff pathology and all examinations were interpreted by fellowship-trained musculoskeletal radiologists. Based on the presence/absence of symptoms and supraspinatus pathology severity, participants were classified into one of five groups: asymptomatic healthy, asymptomatic tendinosis, asymptomatic partial-thickness tear, asymptomatic full-thickness tear, symptomatic full-thickness tear (Table 1). All participants provided written informed consent prior to study participation.

2.2. Data collection

Three-dimensional bone models were created of the humerus and scapula from computed tomography (CT) scans (Mimics, Materialise NV; Leuven, Belgium). Anatomical landmarks were digitized on the scapular and humeral bone models for later processing. Specifically, scapular landmarks included the root of the scapular spine, posterior acromioclavicular joint, and inferior angle, and humeral landmarks included the geometric center of the humeral head and the medial and lateral epicondyles.

Glenohumeral kinematics were tracked during an approximately 2-second trial of coronal plane abduction (raising phase only) using a custom biplanar x-ray system (Bey et al., 2006) (Fig. 1). This system consists of two 100 kW pulsed x-ray generators (EMD Technologies CPX 3100CV; Quebec, Canada) and two 40 cm image intensifiers (Shimadzu Al5765HVP; Kyoto, Japan) (inter-beam angle: 60°, source-to-detector distance: 183 cm). Biplane images of the glenohumeral joint were collected using high-speed cameras (Phantom v9.1, Vision Research; Wayne, NJ, USA) optically coupled to the image intensifiers. Images were collected at 60 Hz with the cameras shuttered at 4 ms to reduce motion blur (radiographic parameters: 70–75 kVp, 320 mA, 2 ms pulse width). Three-dimensional scapular and humeral motion were quantified from the biplane x-ray images using procedures described previously (Bey et al., 2006).

2.3. Data processing

Data processing involved filtering landmark coordinate trajectories and calculating helical dispersion metrics, which was completed using a custom MATLAB code (The MathWorks Inc.; Natick, MA, USA).

Table 1

<table>
<thead>
<tr>
<th>Participant Demographics by Group.</th>
<th>Asympt. Healthy (n = 10)</th>
<th>Asympt. Tendinosis (n = 15)</th>
<th>Asympt. PTT (n = 10)</th>
<th>Asympt. PTT (n = 6)</th>
<th>Sympt. FTT (n = 10)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>58 ± 5</td>
<td>62 ± 9</td>
<td>61 ± 8</td>
<td>64 ± 10</td>
<td>60 ± 11</td>
<td>0.75</td>
</tr>
<tr>
<td>Sex (% female)</td>
<td>50%</td>
<td>60%</td>
<td>60%</td>
<td>50%</td>
<td>70%</td>
<td>0.93</td>
</tr>
<tr>
<td>Side tested (% dominant)</td>
<td>90%</td>
<td>79%</td>
<td>50%</td>
<td>67%</td>
<td>80%</td>
<td>0.33</td>
</tr>
<tr>
<td>Tear size (cm)</td>
<td>N/A</td>
<td>N/A</td>
<td>0.3 ± 0.5</td>
<td>1.0 ± 0.4</td>
<td>1.3 ± 0.7</td>
<td>0.37</td>
</tr>
<tr>
<td>Tear retraction (cm)</td>
<td>N/A</td>
<td>N/A</td>
<td>0.8 ± 1.0</td>
<td>1.0 ± 0.7</td>
<td>1.0 ± 0.7</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Demographic data are presented as mean ± SD or proportions, as appropriate. Groups were compared using two-sample independent t-tests or Chi-square tests for continuous and binary data, respectively. For tear size, only the groups with full-thickness tears were compared. Abbreviations: Asympt = asymptomatic, PTT = full-thickness tear, N/A = not applicable, FTT = partial-thickness tear, Sympt = symptomatic.
using an X-Z
(Woltring, 1990). The optimal pivot
tied between individuals.
However, the actual range of humerothoracic elevation likely var-

Fig. 1. Overhead view of the biplane radiographic system. Participants were positioned with the glenohumeral joint approximately at the intersection of the biplane x-ray beams. The x-ray systems were positioned with a 60° inter-beam angle and a source-to-detector distance of approximately 183 cm. Participants were instructed to complete the raising phase of coronal plane abduction in 2 s.

2.3.1. Filtering landmark coordinate trajectories
The time series of anatomical landmark coordinates during the motion trial were low-pass filtered with a 4th order Butterworth filter and a cutoff frequency of 4 Hz. This cutoff frequency was determined based on the results of a residual analysis (Winter, 2009; Yu et al., 1999). Filtered anatomical landmark coordinates were used to reconstruct anatomical coordinate systems (Ludewig et al., 2009; Wu et al., 2005). Next, transformation matrices representing glenohumeral kinematics were calculated at each frame of the motion trial as the humerus relative to the scapula.

2.3.2. Helical dispersion calculations
Instantaneous helical axes were calculated for each frame of the motion trial from the time series of glenohumeral transformation matrices (Woltring, 1990; Woltring et al., 1994). Each instantaneous helical axis can be fully described by a unit direction vector \( \mathbf{n} \) and position vector \( \mathbf{s} \). An instantaneous helical axis for a given frame of data was only considered for further analysis if the angular velocity about the axis \( \omega \) exceeded a subject-specific minimum threshold defined as a proportion of the maximum angular velocity across the trial \( \omega > 0.1 \omega_{\text{max}} \) (Woltring et al., 1994).

Before calculating the helical dispersion metrics, each participant’s data was subsequently reduced to include only the instanta-

\[\mathbf{Q} = \frac{1}{n} \sum_{i=1}^{n} \mathbf{Q}_i\]

where \( Q_i = I - \mathbf{n}_i \mathbf{n}_i^T \), \( Q = \frac{1}{n} \sum_{i=1}^{n} Q_i \), and \( n \) = the number of frames of data during the motion trial. Similarly, the optimal direction vector \( \mathbf{n}_{\text{opt}} \) passing through \( \mathbf{s}_{\text{opt}} \) was calculated as the vector that was maximally coincident with all instantaneous helical axes. Together, the optimal helical pivot point and axis represent a single approximately mean helical axis for the motion trial.

Next, root-mean-square estimations of the mean angular \( (X^{\text{rm}}) \) and positional \( (d_{\text{rm}}) \) dispersions from the optimal helical axis and pivot point were calculated (Woltring, 1990):

\[X_{\text{rm}} = \sin^{-1} \sqrt{\frac{1}{n} \sum_{i=1}^{n} \sin^2 \gamma_i}\]

\[d_{\text{rm}} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\mathbf{s}_{\text{opt}} - \mathbf{s})^T \mathbf{Q}_i (\mathbf{s}_{\text{opt}} - \mathbf{s})}\]

where \( \gamma_i \) = the angle between \( \mathbf{n}_{\text{opt}} \) and \( \mathbf{n}_i \). Conceptually, the mean angular dispersion estimates how much (on average) the orientation of each instantaneous helical axes deviates from the optimal axis (Fig. 2). Likewise, the mean positional dispersion estimates how far away (on average) each instantaneous helical axis is located from the optimal pivot point. In the case of a perfect ball-and-socket joint, all instantaneous helical axes would intersect a single point resulting in no positional dispersion. However, angular dispersion about the optimal helical axis may still occur as the joint is free to rotate (i.e., spin) around the single point. Instead, increased mean angular dispersions may indicate inefficient or uncoordinated angular motion during the abduction trial.

2.4. Statistical analysis
Prior to statistical analysis, the assumptions of normality and homogeneity of variance were assessed by inspecting data skew-
ness and kurtosis, and relative variance, respectively. Differences between groups in helical dispersions were tested using one-

factor ANOVAs. In the case of a significant main model, pairwise differences between groups were tested using Tukey’s HSD. Additionally, effect sizes were calculated to help interpret the strength of the effect \( (\eta^2 \text{ for ANOVA, Hedges’ } g \text{ and 95% confidence interval for pairwise comparisons}) \) (Torchiano, 2019). Hedges’ \( g \) statistic was calculated instead of Cohen’s \( d \) as it has been shown to be less biased with small sample sizes (Cohen, 1988b). The interpretation of effect sizes followed the recommendations of Cohen \( (|\eta^2|): \)

- small = 0.01, medium = 0.06, large = 0.14;
- \( |g| \): small = 0.2, med-

3

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The mean angular dispersion about the optimal helical axis was not statistically different between groups ($p = 0.32, \eta^2 = 0.10$) (Fig. 3A). The magnitudes of effect sizes (\(|g|\)) for between-group comparisons ranged from 0.0 to 0.83 but none were statistically significant (Fig. 4).

The mean positional dispersion about the optimal helical pivot point was statistically different between groups ($p = 0.02, \eta^2 = 0.22$) (Fig. 3B). Specifically, the positional dispersion was 1.6 mm greater in symptomatic participants with a full-thickness tear compared to asymptomatic participants with a healthy rotator cuff ($p = 0.01, g = -1.73, 95\% CI: -2.79, -0.68$) (Fig. 5), and 1.2 mm greater compared to asymptomatic participants with tendinosis ($p = 0.04, g = -1.19, 95\% CI: -2.08, -0.31$). The magnitudes of effect sizes (\(|g|\)) for the remaining between-group comparisons ranged from 0.13 to 0.92 but none were statistically significant (Fig. 6).

4. Discussion

The purpose of this exploratory study was to determine the extent to which rotator cuff pathology is associated with impaired ball-and-socket kinematics, which was assessed using estimates of helical axis dispersion. The results of this study partially support our hypothesis: individuals with a symptomatic full-thickness supraspinatus exhibit greater helical positional dispersion than individuals with a healthy rotator cuff or supraspinatus tendinosis; however, differences in angular dispersion were not statistically significant. By definition, a ball-and-socket joint rotates about a fixed center of rotation, or in the terminology of this study, has no positional dispersion about the optimal helical pivot. Therefore, the results of this study suggest individuals with a symptomatic full-thickness rotator cuff tear may have impaired ball-and-socket kinematics. Ultimately, these findings may offer new insights into rotator cuff function in healthy and diseased states.

The increased positional dispersion – or shifting – of the instantaneous helical axes in individuals with symptomatic full-thickness supraspinatus tears may indicate an impairment in one or both of the glenohumeral force couples. Although the current study was not designed to identify specific muscle impairments, the emergence of a dominant muscle within a synergistic force couple would theoretically shift the instantaneous helical axis towards the motion axis that would exist if the muscle were to act in isolation (Woltring et al., 1994). Therefore, the increased positional dispersion observed in individuals with a symptomatic full-thickness supraspinatus tear suggests the rotator cuff may be unable to consistently offset the actions of a dominant agonist(s). Presumably, this finding supports the classic theory proposed by Burkhart in which a loss of a stable fulcrum (i.e., pivot) for glenohumeral motion will occur due to an uncoupling of one or both of the glenohumeral force couples (Burkhart, 1991). For example, results of in-vitro studies suggest that rotator cuff tears require
increased deltoid muscle force to prevent abduction motion loss (Dyrna et al., 2018; Mura et al., 2003; Thompson et al., 1996). Therefore, the emergence of the deltoid as a dominant agonist may explain the axis shifting observed in this study. However, this remains speculative because muscle function was not directly assessed in the current study. Future research may benefit from assessing muscle function and helical dispersion concurrently so that the patterns and directionality of helical axis shifting can be interpreted relative to muscle impairment. Clinically, the results of those efforts may help guide therapeutic intervention to target specific muscle impairments based on an individual’s pattern of helical dispersion.
Preservation of the glenohumeral force couple has been theorized to be an important determinant of whether an individual with a full-thickness supraspinatus tear remains asymptomatic or experiences pain and dysfunction (Burkhart, 1991; Keener et al., 2009; Thompson et al., 1996). Although positional dispersion was not statistically different between asymptomatic and symptomatic individuals with full-thickness supraspinatus tears, it is possible that a potentially meaningful group difference went unde-
ected given the medium effect size ($g = −0.76$, CI = $−1.84$ to $0.32$, Fig. 6). Furthermore, it is likely that additional factors not assessed in this study influence an individual's symptom state. For example, the duration for which the tear has been present, the individual's activity level, involvement of the rotator cable, presence of fatty degeneration, and psychosocial aspects of pain may all be important factors (e.g., Halder et al., 2002; Mesiha et al., 2013; Pinkowsky et al., 2017; See et al., 2015; Yoon et al., 2018). Collectively, these factors may help explain the large between-subject variability observed within pathology groups. Future research may benefit from investigating these factors in combination to better understand the determinants of symptom manifestation and shoulder function in the presence of rotator cuff pathology.

Unlike the analysis of positional dispersion, no statistical differences were observed between pathology groups in the angular dispersion. Because the orientation of the helical axis is defined solely by angular motion (Woltring et al., 1994), the angular dispersion about the optimal helical axis reflects variability in angular motion. Therefore, the findings of this study suggest that rotator cuff pathology may not significantly alter the variability in angular kinematics during planar arm raising. This finding may seem to contradict previous studies that have reported decreased glenohumeral elevation or altered scapulothoracic rhythm in individuals diagnosed with rotator cuff pathology (e.g., Kolk et al., 2017; Lawrence et al., 2014; Mell et al., 2005; Yamaguchi et al., 2000). However, these studies quantified the relative magnitude of angular motion whereas the current study captured the variability in angular motion. This is an important distinction and suggests that while a symptomatic full-thickness supraspinatus tear appears to be associated with altered kinematic strategies (e.g., increasing scapular contribution to compensate for a loss of glenohumeral elevation), the ability to control these strategies – at least from an angular perspective – appears to remain largely intact. Taken together with the findings regarding positional dispersion, this may suggest that the primary source for aberrant glenohumeral motion associated with symptomatic full-thickness supraspinatus tears is the displacement of the humeral head as a result of a shifting helical axis.

As hypothesized, asymptomatic individuals without rotator cuff pathology exhibited kinematics most consistent with a ball-and-socket joint. However, a small amount of position dispersion was observed in this group (mean ± SD: $1.8 ± 0.7$ mm, range: $0.7–2.9$ mm) suggesting that true ball-and-socket kinematics – and therefore balanced glenohumeral cuff force couples – may not consistently occur even in the absence of rotator cuff pathology. This finding is interesting as it challenges a classic assumption about “optimal” shoulder function. However, some uncertainties exist that need to be better understood before dismissing this assumption and indeed, interpreting the results of this study as a whole. First, glenohumeral helical dispersions have not been widely investigated making it challenging to interpret absolute magnitudes and group differences. Second, this study only included older adults (>50 years). Therefore, it is possible a small amount of positional dispersion may be part of healthy shoulder aging and that younger subjects without rotator cuff pathology may still exhibit kinematics more consistent with ball-and-socket kinematics (Temporiti et al., 2019). Ultimately, more research is needed to better understand the practical implications of aberrant glenohumeral motion characterized by increased helical dispersion.

Although helical axes are less frequently employed to describe joint kinematics than Euler angles and translations, they have been used in various forms to detect abnormal motion (e.g., Cattrysse et al., 2020; Cescon et al., 2014; Grip et al., 2008; Temporiti et al., 2019). However, comparing results across studies is often difficult due to differences in how the helical axes and dispersion metrics are calculated. For example, helical axes can be calculated either instantaneously or across a larger time (or motion) step (i.e., finite helical axis) (Ehrig and Heller, 2019; Woltring et al., 1985, 1994). When calculated instantaneously, the axes can describe motion trajectory (Woltring et al., 1994). In contrast, a finite helical axis is considered a theoretical axis because it describes the shortest 3D path between joint poses at two observation times, which may not necessarily reflect the actual motion trajectory that occurred (Ehrig and Heller, 2019). Therefore, helical dispersion metrics calculated from instantaneous axes may be more precise than those calculated using a finite approach. Additionally, while measures of angular dispersion are largely comparable across studies, significant variability exists in the calculation of positional dispersion. In addition to the metric used in this study, positional dispersion has also been calculated as the minimum area of a convex hull (Cattrysse et al., 2020; Cescon et al., 2014) and the average distance between helical axes at the point where they pierce a common plane (i.e., intersection points dispersion) (Temporiti et al., 2019). Regardless of the approach used, the results of these studies suggest helical dispersion metrics can provide a succinct assessment of abnormal kinematics in many joint systems.

This study has limitations to consider when interpreting the results. First, the small and unbalanced sample sizes likely impacted statistical power. In particular, the numerous medium-to-large effect sizes suggest potentially meaningful findings were not detected (Figs. 4 and 6). However, the effect sizes should be interpreted with caution given their wide confidence intervals. Second, only coronal plane abduction was studied and other motions, including with resistance, may further challenge the rotator cuff and be more sensitive to potential group differences. Third, although participants were instructed to perform the motion trial in $2\text{s}$, variability between subjects in motion speed may influence dispersion metrics. Fourth, this study investigated only glenohumeral kinematics, which serve as an indirect assessment of rotator cuff muscle function. Future research should employ a more direct assessment of muscle function in an effort to rigorously test the theories explored in this study. Finally, the study’s cross-sectional nature does not allow for the determination of cause-effect relationships between impaired ball-and-socket kinematics and rotator cuff pathology. Nevertheless, the results of this study may highlight opportunities for future research in an effort to better understand these temporal relationships.

The results of this investigation further our understanding of kinematic alterations in the presence of rotator cuff pathology. Individuals with a symptomatic full-thickness supraspinatus tear exhibit impaired ball-and-socket kinematics compared to individuals with tendinosis or a healthy rotator cuff. This finding is believed to be associated with a disruption of the glenohumeral force couples, suggesting the rotator cuff is unable to offset the action of a more dominant agonist(s). More research is needed to better understand the kinetic factors that may contribute to impaired ball-and-socket kinematics and whether these factors contribute to the development of rotator cuff pathology and/or occur as a result.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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