



The effect of elastic deformation and rigid displacement soft tissue artefact on glenohumeral axial rotation

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ABSTRACT

Measurement of axial rotation of the humerus using marker-based motion capture is compromised due to soft tissue artefact. The aim of this study was to quantify the elastic deformation of markers on the humerus and evaluate the combined effects of elastic deformation and rigid displacement of the markers on humeral kinematics during axial rotation. Thirteen wheelchair users performed active humeral internal rotation whilst a Vicon motion capture system tracked 12 *retro*-reflective markers placed on the arm. Elastic deformation was quantified using the Optimal Common Shape Technique (OCST) and Ordinary Procrustes Analysis (OPA). The combined effects of elastic deformation and rigid marker displacement were quantified by comparing kinematics derived from only the humeral markers to the kinematics derived using the forearm segment (benchmark measurement). Elastic deformation of the markers demonstrated a systematic variation in the deformation pattern across the arm where the proximal markers lagged and the distal markers proceeded the OPA fitted reference shape of the marker cluster. There was a significant 48.7° underestimation in the range of axial rotation ($P < 0.001$). A secondary analysis was performed utilising only the distal arm markers on the humerus. The underestimation in axial rotation range of motion reduced to 25.9° and was not significantly different to the benchmark measurement from neutral through to internal rotation. Systematic elastic deformation of markers was present across the upper limb segment that adversely affected the estimation of humeral axial rotation. Careful selection of marker position for the arm cluster is needed minimise the effect of soft tissue artefact.

1. Introduction

The measurement of upper limb kinematics is utilised to understand movement dysfunction associated with musculoskeletal and neurological conditions, assess effectiveness of treatment interventions and understand and improve performance in sport. The use 3-dimensional marker-based motion capture and protocols are available (Jaspers et al., 2011; Schwarz et al., 2019; Valevicius et al., 2018), however, adoption in clinical decision making is not wide spread with factors such as availability of standardised reference tasks and standardisation of protocols being barriers to implementation (Philp et al., 2022). An issue leading to a lack of standardised protocols is the yet unresolved question of how to best to overcome issues associated with soft tissue artefact, with different upper limb kinematic protocols adopting different approaches. Soft tissue artefact is defined as both the local elastic deformation of markers on a given segment violating the rigid body

assumption (Capozzo et al., 1997; Soderkvist and Wedin, 1993), and a rigid displacement of the markers relative to the underlying bone. Humeral axial rotation is a common movement observed in the analysis of upper limb kinematics as rotational deficits and/or changes are linked to shoulder injury (Johnson et al., 2018; Keller et al., 2018). Measurement of humeral axial rotation using skin-based markers, however, is highly susceptible to soft tissue artefact where up to a 35 % underestimation of the measured motion has been observed (Cutti et al., 2005; Ludewig et al., 2002). Analysis of soft tissue artefact of skin mounted markers with respect to bone pins suggests that elastic deformation accounts for 20 % and rigid displacement accounts for 80% of soft tissue artefact during axial rotation (Blache et al., 2017). Methods have been developed to reduce the effect of soft tissue artefact during axial rotation with the International Society of Biomechanics (ISB) describing two options for establishing the humeral local coordinate system (Wu et al., 2005). The first (H_1) utilises the lateral and medial epicondyles to define the Z

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axis (pointing laterally), the second (H_2) defines the Z axis as being perpendicular to the longitudinal axes of the humerus and forearm. The ISB recommends the use of H_2 as the relatively short distance between the lateral and medial humeral epicondyles causes the direction of the Z axis to be highly sensitive. Further to this, the H_2 method is less reliant on the position of the medial and lateral epicondyles to determine axial rotation as it utilises the plane formed by the long bones of the upper extremity and, therefore, largely independent of these anatomical locations. Multibody kinematic optimisation (MKO) or regression methods can reduce the effect of soft tissue artefact in measuring axial rotation of the humerus (Cao et al., 2007; Cutti et al., 2006; Duprey et al., 2017; Roux et al., 2002; Schmidt et al., 1999). The rigid joint constraints within these models, however, may oversimplify movement patterns. In addition, some models rely on the forearm and require elbow flexion being present to avoid linearity between the long axes of the humerus and forearm, thus making their use during some tasks impractical where full elbow extension is present.

Defining the humerus using the H_1 method requires accurate tracking of the medial and lateral epicondyles. Placing markers directly onto the landmarks can provide accurate tracking, but only when little elbow flexion/extension occurs (King and Yeadon, 2012), which is unlikely in many activities of daily living and sporting tasks. It is, therefore, suggested to avoid the use of markers placed over anatomical landmarks which may be susceptible to soft tissue artefact and instead utilise a technical marker set attached to the arm (Kontaxis et al., 2009). The location of the medial and lateral epicondyles are then determined with respect to the technical marker set during a calibration trial and then recreated during the dynamic trials based on their location with respect to the technical marker set. Correct location of the markers constituting the technical marker set is paramount when estimating humeral kinematics and they should be positioned where soft tissue artefact is minimal (Cappozzo et al., 1997). Whilst there is some evidence suggesting that the use of a technical marker set approach is comparable to an anatomical approach, where markers directly attached to the medial and lateral epicondyles (Boser et al., 2018), the assessment of marker location comprising the technical marker set has received little attention. Understanding the soft tissue artefact across the arm segment would allow for optimisation of marker location to improve validity of humeral kinematic measurements.

The aim of this study was to examine soft tissue artefact across the arm segment during humeral axial rotation. Specific objectives included; quantify the elastic deformation of markers placed along the arm, determine the combined effects of elastic deformation and rigid displacement on humeral axial rotation and determine if a refined marker set comprising the technical marker set based upon analysis of the elastic deformation improves humeral axial rotation measurements. The hypotheses are; humeral axial rotation will be underestimated and a refined marker cluster will reduce the underestimation of humeral axial rotation.

2. Method

2.1. Participants

Thirteen wheelchair users, three of which were recreationally active male wheelchair users and 10 (3 female and 7 male) were professional wheelchair tennis players, took part in the study (average age 30 years $\pm$ 10). All participants could actively internally and externally rotate their humerus unaided. The study was approved by the School of Health Sciences Ethics Committee and participants provided written informed consent prior to commencement of the study.

2.2. Data collection

Retroreflective markers were attached to the thorax on the sternal notch (IJ), xiphoid process (PX), C7 and T8 vertebrae and rigid marker

clusters consisting of three markers were attached bilaterally to the acromion (Warner et al., 2015; Warner et al., 2012). Markers were then attached bilaterally and directly on to the skin of the anterior, lateral and posterior aspects of the arm. Four markers were attached to each aspect of the arm spaced equidistant starting at the point of insertion of the deltoid muscle and ending approximately 3 cm proximal to the elbow joint line (Fig. 1). Four markers were also attached bilaterally to the wrist, one each on the dorsal aspect of the radial and ulna styloid and two markers approximately 3 cm proximal to the radial and ulna styloid. A wand was used to determine the location of the medial and lateral humeral epicondyles with respect to the arm marker cluster. Marker movements were captured using a Vicon T-series motion capture (Oxford, UK) system operating at 100Hz.

A three second static trial was captured with the participant's arm by their side and elbow fully extended. Participants then completed a circumduction movement to functionally determine the glenohumeral joint centre. Participants then completed three repetitions of humeral axial rotation with each arm; starting with their arm abducted to 90° and elbow flexed to 90°, participants actively internally rotated their arm until they reached their maximum.

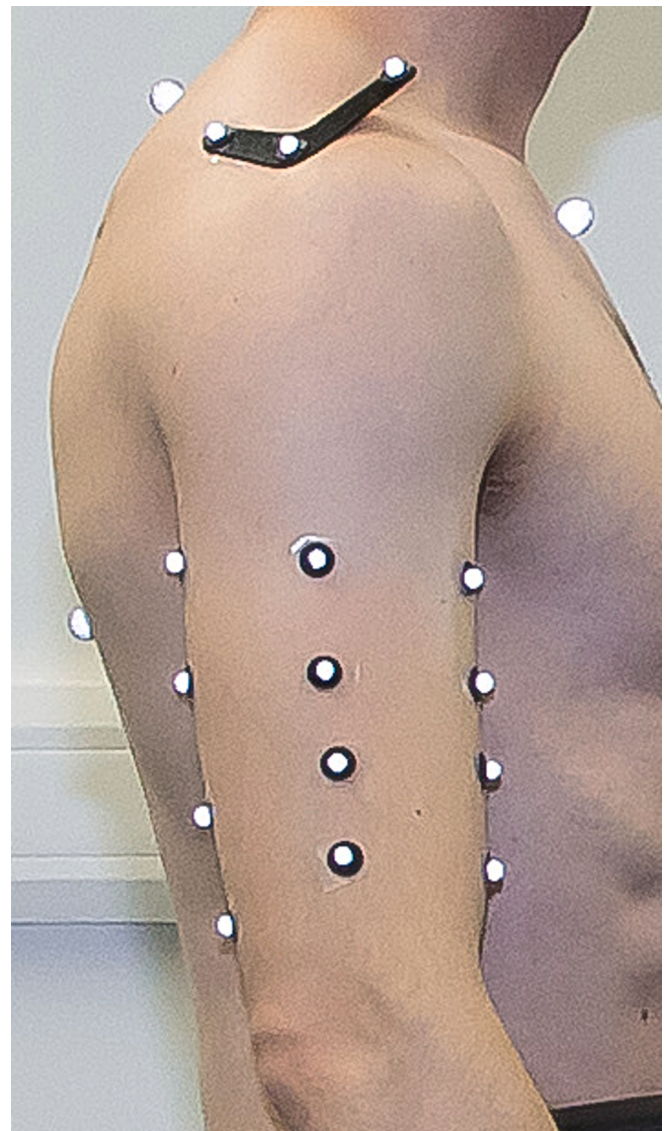


Fig. 1. Retro-reflective marker placement.

2.3. Determination of elastic deformation soft tissue artefact

The Optimal Common Shape Technique (OCST) was used to determine elastic deformation during the humeral axial rotation (Taylor et al., 2005). First, the average shape of a given set of markers is determined during a reference activity, in this case the static trial, using a Generalised Procrustes Analysis (GPA). Secondly, the rigid shape is mapped on to the captured markers during the dynamic activity, in this case humeral axial rotation, using an Ordinary Procrustes Analysis (OPA). To determine the amount of local deformation the Euclidian distance between each OPA fitted marker and its respective captured marker was calculated during the axial rotation movement. The displacement vectors of the captured markers with respect to the relevant OPA fitted markers was determined by defining a local coordinate system for the arm using the OPA fitted markers, where the X axis pointed forward, Y axis pointed superiorly and the Z axis pointed laterally when the arm was in its static position. The origin was placed at each OPA fitted marker in turn and the vector displacement of each captured marker was determined with respect to the local coordinate system. The Euclidian distances and vector displacements were time normalised through interpolation over 101 data points from the start of the axial rotation movement to the end. The data were then averaged across the three trials for each side, then averaged across all participants with left and right sides being combined resulting in 26 arms used for analysis. Following analysis of the elastic deformation, a secondary analysis was performed where only the most distal markers on the arm were used to form the arm cluster.

2.4. Determining rigid displacement soft tissue artefact on humeral axial rotation

The location of the humeral medial and lateral epicondyles were determined with respect to the OPA fitted markers. The location of the humeral anatomical landmarks were then reconstructed in the global coordinate system based on their known location with respect to the OPA fitted arm markers recorded during the axial rotation trials. This process was repeated for the revised arm marker cluster consisting only of the distal markers. The glenohumeral joint centre was determined between the acromion marker cluster and the arm marker cluster during the circumduction movement using the SCoRE technique (Asadi Nikooyan et al., 2011; Ehrig and Heller, 2019; Ehrig et al., 2006).

Joint kinematics for the humerus were determined through defining local coordinates systems for the thorax and humerus following International Society of Biomechanics (ISB) guidelines (Wu et al., 2005). The humerus was defined using both options (H_1 and H_2) as described by the ISB. A Euler rotation sequence of plane of elevation (Y), angle of elevation (X) and axial rotation (Z) was used to determine humerothoracic kinematics (Doorenbosch et al., 2003).

As the H_2 is less reliant on the location of the medial and lateral humeral epicondyles to determine the amount humeral axial rotation (Wu et al., 2005) it was considered as the benchmark to assess the effect of rigid displacement on glenohumeral axial rotation kinematics. To assess statistical significance between H_1 and H_2 at 5% intervals from the start to the end of the axial rotation movement a repeated measures ANOVA with main effects of ISB humeral option (2 levels) and percentage of movement (21 levels) was used. Post-hoc analysis involved the use of paired samples T-test with Bonferroni correction to determine which stage of the movement significant differences occurred. A repeated measures ANOVA with main effects of ISB humeral option (2 levels; H_1 and H_2) and marker configuration (2 levels; full marker cluster and revised marker cluster) was used to compare the range of axial rotation. Statistical analysis was undertaken using SPSS Statistics version 22 with significance levels set at 5%.

3. Results

The Euclidian distance of the arm markers with respect to the OPA fitted markers revealed large deviations between the captured and OPA fitted markers with the distal and proximal markers exhibiting the largest differences (Fig. 2). The most distal anterior marker and the most distal and proximal posterior markers increased in distance from the start of the movement (externally rotated) through to the end of the movement (internally rotated) (Fig. 2).

The vector displacement of the captured arm markers with respect to the OPA fitted markers revealed the most proximal anterior marker moved $17.0 \text{ mm} \pm 3.2$ laterally (Z axis) and the most proximal posterior marker moved medially (Z axis) $19.5 \text{ mm} \pm 4.3$ (Fig. 3). The most distal anterior marker moved $22.9 \text{ mm} \pm 4.7$ medially and the most distal posterior marker moved $16.9 \text{ mm} \pm 3.4$ laterally (Fig. 3). Given the location of the markers on the arm these data show the most proximal markers lagged the OPA rigid segment whereas the distal markers preceded the OPA rigid segment. See [Supplementary Material](#) for a 3D visualisation of how the captured markers move with respect to the OPA fitted markers. The most distal anterior marker was on average $10.5 \text{ mm} \pm 1.5$ more superior with respect to its OPA fitted marker, the other markers were on average $3.7 \text{ mm} \pm 1.5$ to $-12 \text{ mm} \pm 0.8$ superior to inferior with respect to their OPA fitted markers.

When examining the effect of rigid displacement on humeral kinematics the range of axial humeral rotation was significantly ($P < 0.001$) underestimated when utilising H_1 ($76.0^\circ \pm 14.7$) compared to H_2 ($124.7^\circ \pm 18.3$). Statistical analysis also showed a significant ($P < 0.001$) interaction effect between ISB humeral option and percentage of task ($P < 0.001$) with post-hoc analysis, using a Bonferroni adjusted significance level of 0.002, revealing a significant ($P < 0.001$) underestimation in external rotation from the start of the movement to 43% of the movement (Fig. 4). There was no significant difference between H_1 and H_2 at 40% ($P = 0.003$), 45% ($P = 0.216$), 50% ($P = 0.462$) and 55% ($P = 0.01$) of the movement. From 60% through 100% of the movement H_1 significantly ($P < 0.001$) underestimated axial rotation (Fig. 4).

Based on the analysis of elastic deformation a revised marker cluster consisting of only the distal markers on the arm were used to measure humeral kinematics. In this case, the H_1 method still significantly ($P < 0.001$) underestimated the range of axial rotation ($98.5^\circ \pm 16.1$) compared to H_2 ($124.4^\circ \pm 18.6$). There was again a significant ($P < 0.001$) interaction effect between ISB humeral option and percentage of task ($P < 0.001$) with post-hoc analysis revealing a significant ($P < 0.001$) underestimation in external rotation from the start to 50% of the movement. There were no significant differences between H_1 and H_2 beyond 60% of the movement where axial rotation passes through neutral and into internal rotation (Fig. 5).

4. Discussion

This study aimed to examine soft tissue artefact across the arm segment during humeral axial rotation to inform placement of markers to minimise the effect of soft tissue artefact in the estimation of humeral kinematics. The results revealed substantial soft tissue artefact across the arm both in terms of local elastic deformation of the marker cluster and rigid displacement of the marker cluster with respect to the underlying bone.

A systematic pattern of elastic deformation of the marker cluster was present across the arm where the proximal markers lagged the OPA fitted OCST reference shape while the distal markers preceded the OCST reference shape, resulting in a helical shaped distortion of the markers along the longitudinal axis of the arm. The errors between fitted reference and captured markers were largest at the end of ranges and smallest when the humerus was nearing a neutral internal rotation position. It was reported by Blache et al. (2017) that elastic deformation only accounts for 20% of soft tissue artefact, with 80% being related to rigid displacement. Although a direct comparison cannot be made due to

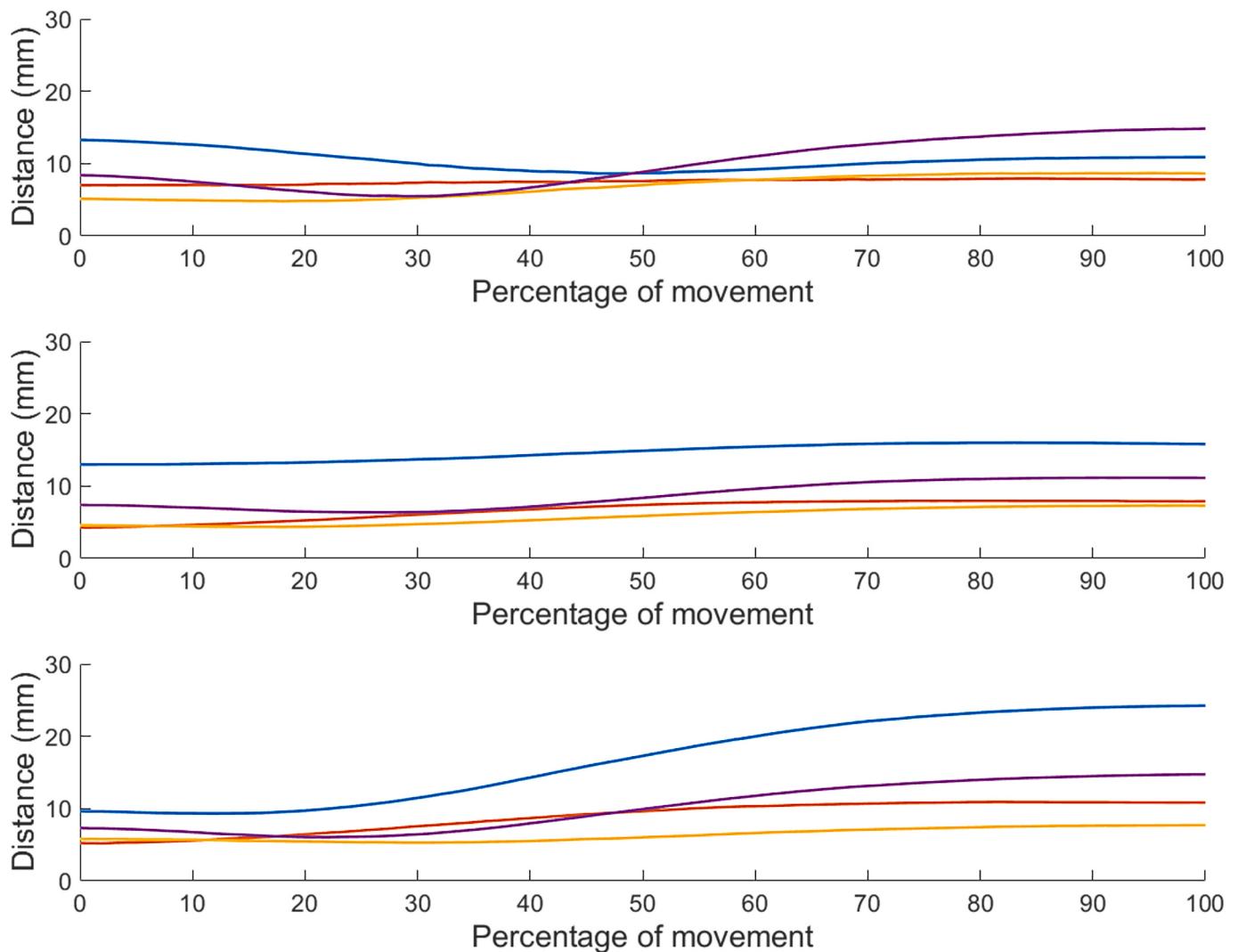


Fig. 2. Euclidian distance between OPA fitted and captured markers on the anterior (upper), lateral (middle) and posterior (lower) sides of the arm from the most proximal (blue) through to the most distal marker (red, orange and purple; respectively). Standard deviation omitted for clarity.

differing approaches to analysis, the analysis of the 3D displacements in this present study suggests that error associated with elastic deformation appears to be larger than previously reported. The lower contribution to soft tissue artefact observed by Blache et al. (2017), may be attributed to the use of bone pins inserted slightly distal to deltoid insertion. The pins can cause anchoring of the skin which would not allow for typical skin movement, particularly for the proximal markers near the insertion of pins, causing an underestimation of the local elastic deformation to the markers.

The findings of the present study suggest a systematic elastic deformation of the markers on the arm, i.e. the shape of the markers on the arm changed in a predictable manner with respect to the motion. Whilst studies, particularly in the lower limb, have suggested the contribution of elastic deformation to soft tissue artefact is minimal (Benoit et al., 2015; Bonci et al., 2015), the movements involved in these studies have typically been single planar with little axial rotation. The elastic deformation in these studies is likely due to random errors associated with measurement error, muscle contraction, impact, among other sources. The systematic elastic deformation observed in this present study demonstrates that certain movements cause predictable changes in the shape of the markers as the skin twists and stretches with the movement. The lagging of the proximal markers suggests a rigid displacement of these markers with respect to the underlying bone and contributed the significant underestimation of 48.7° in the amount of humeral axial

rotation. The amount of underestimation is accordance with previous literature who have observed similar underestimations (Cutti et al., 2005; Ludewig et al., 2002). Careful selection of marker placement and modelling approach to defining the arm is needed to minimise systematic error and rigid displacement to ensure accurate measurement of humeral kinematics.

When using only distal markers on the arm the underestimation of axial rotation decreased to 25.9° . It is, therefore, suggested that an arm marker configuration should consist only of markers placed on the distal end of the segment. When considering the specific location on the distal end, the marker on the anterior aspect of the arm was superiorly translated by 10 mm, which is likely caused by elbow flexion pushing the marker in a superior direction. It is therefore recommended that markers should not be placed on the distal anterior aspect of the arm.

Based on the findings of this study, it might seem logical to place markers directly on the medial and lateral humeral epicondyles, however, it has been recommended not to place markers on these landmarks due to soft tissue artefact (Kontaxis et al., 2009). More recent evidence contradicts this recommendation by suggesting there is minimal difference between an anatomical approach and marker cluster approach (Boser et al., 2018). The study of Blache et al. (2017) suggests that markers should be placed on the medial epicondyle and not the lateral due to the higher soft tissue artefact associated with the lateral side. However, it is not clear why there would be a disparity in deformation

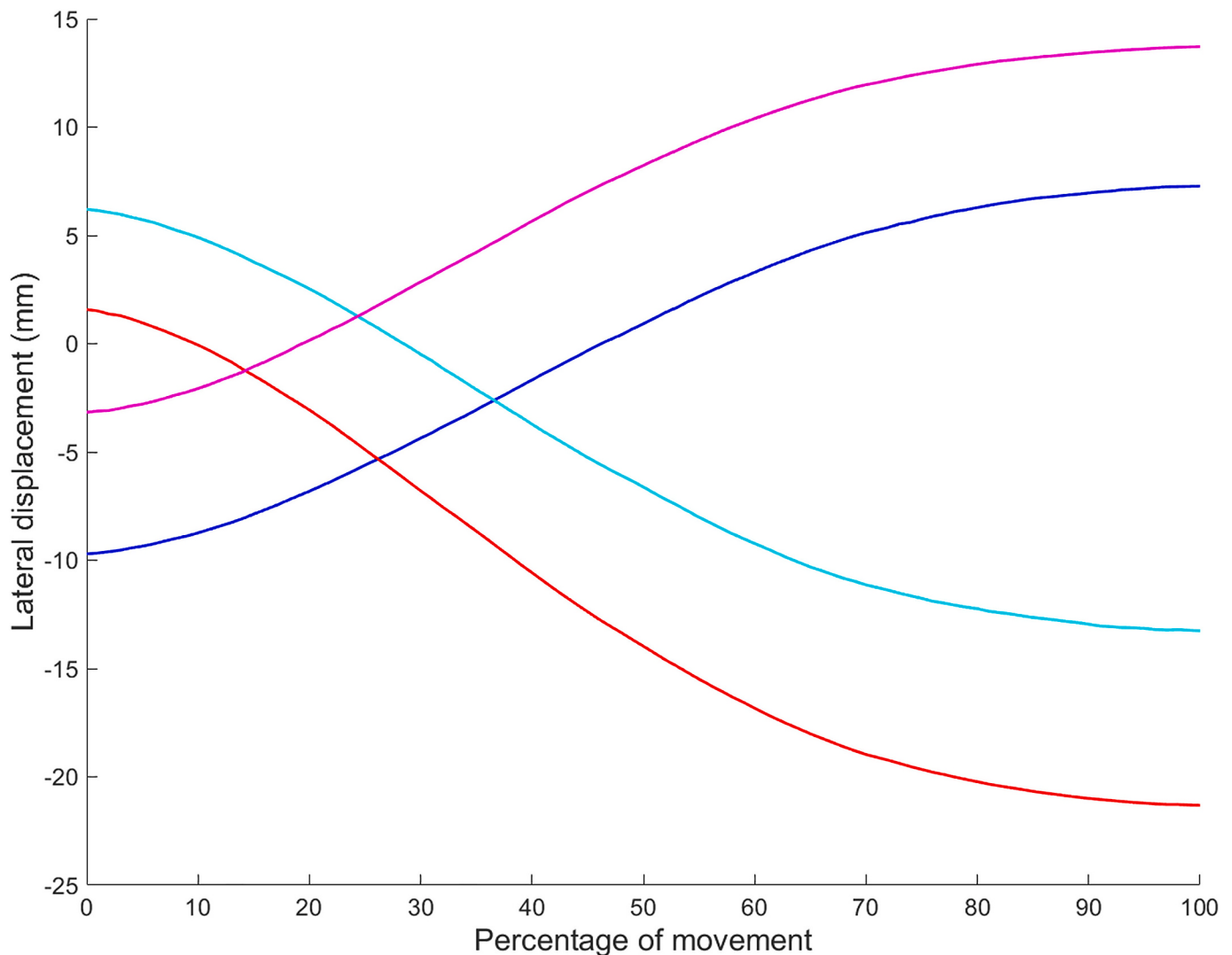


Fig. 3. Lateral displacement, denoted by a positive change in values, of the captured markers with respect to the OPA fitted markers for the most proximal anterior (blue) and posterior (red) and the most distal anterior (cyan) and posterior (magenta) markers.

between the medial and lateral side and further investigation is needed. The recommendation based on the findings of this study is that markers should be positioned on the lateral and posterior aspect of the arm at the distal end. The use of a local optimisation process, such the Optimal Common Shape Technique, applied to these markers can then aid in the reduction of elastic deformation associated with random errors and enforce a rigid shape to the markers on the humerus.

Although the above recommendation for marker placement is suggested as being optimal for humeral kinematics, one must also consider the identification of the glenohumeral joint centre, which is often dependant on markers attached to the arm when using a functional approach (Lempereur et al., 2010; Monnet et al., 2007; Nikooyan et al., 2011). The study of Campbell et al. (2009) suggests a proximal marker cluster, along with an acromion marker cluster, configuration is optimal for representing the glenohumeral joint centre during motion. Therefore, it is suggested the complete solution for determining upper limb kinematics will be a combination of markers located at the proximal end of the arm for accurate determination of the glenohumeral joint centre and the markers at the distal end to ensure accurate determination of axial rotation.

A few considerations must be made before adopting such an approach. Although the distal markers provided a substantial reduction in the underestimation of axial rotation, there was still large

underestimation in axial rotation when the humerus was in an externally rotated orientation through to a neutral orientation. The effect of elbow flexion must also be considered as it is likely that the distal markers will be affected by soft tissue artefact through large elbow flexion/extension movements. The humeral epicondyles are calibrated with respect to the arm cluster with the elbow in a flexed position to allow easy palpation of the landmarks. It is important to understand how humeral kinematics are affected by soft tissue artefact caused by elbow flexion/extension when calibrating the humeral epicondyles. Within this study elbow flexion was fixed during the movement so it was not possible to determine the effect of elbow flexion/extension on soft tissue artefact related errors associated with this marker position, further studies are needed to explore the effect of soft tissue artefact during dynamic movements.

The effect of rigid displacement on axial rotation was determined by comparing the H_1 and H_2 methods for defining the humerus, the latter being considered less susceptible to soft tissue artefact for axial rotation as it utilises the forearm vector to define the Z axis of the humerus. However, readers are advised of the issues associated with the H_2 method. Firstly, the position of the elbow joint centre is determined as the mid-point between the lateral and medial epicondyles, whose location is determined with respect to the arm cluster, which is susceptible to soft tissue artefact. Furthermore, even though there was no supination/pronation of the forearm during the axial rotation movement observed

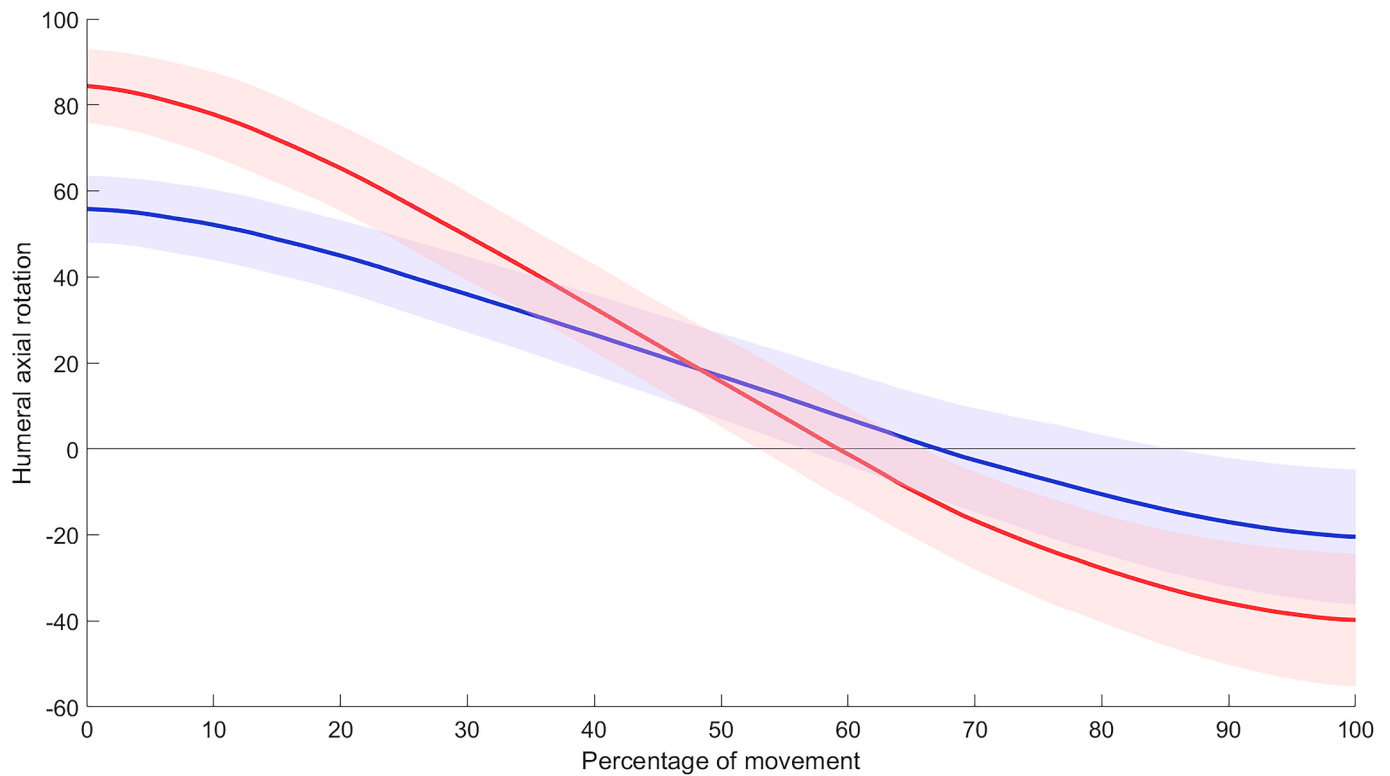


Fig. 4. Humeral axial rotation (degrees) utilising H_1 (blue) and H_2 (red) methods of defining the humerus coordinate system when utilising all markers attached to the arm.

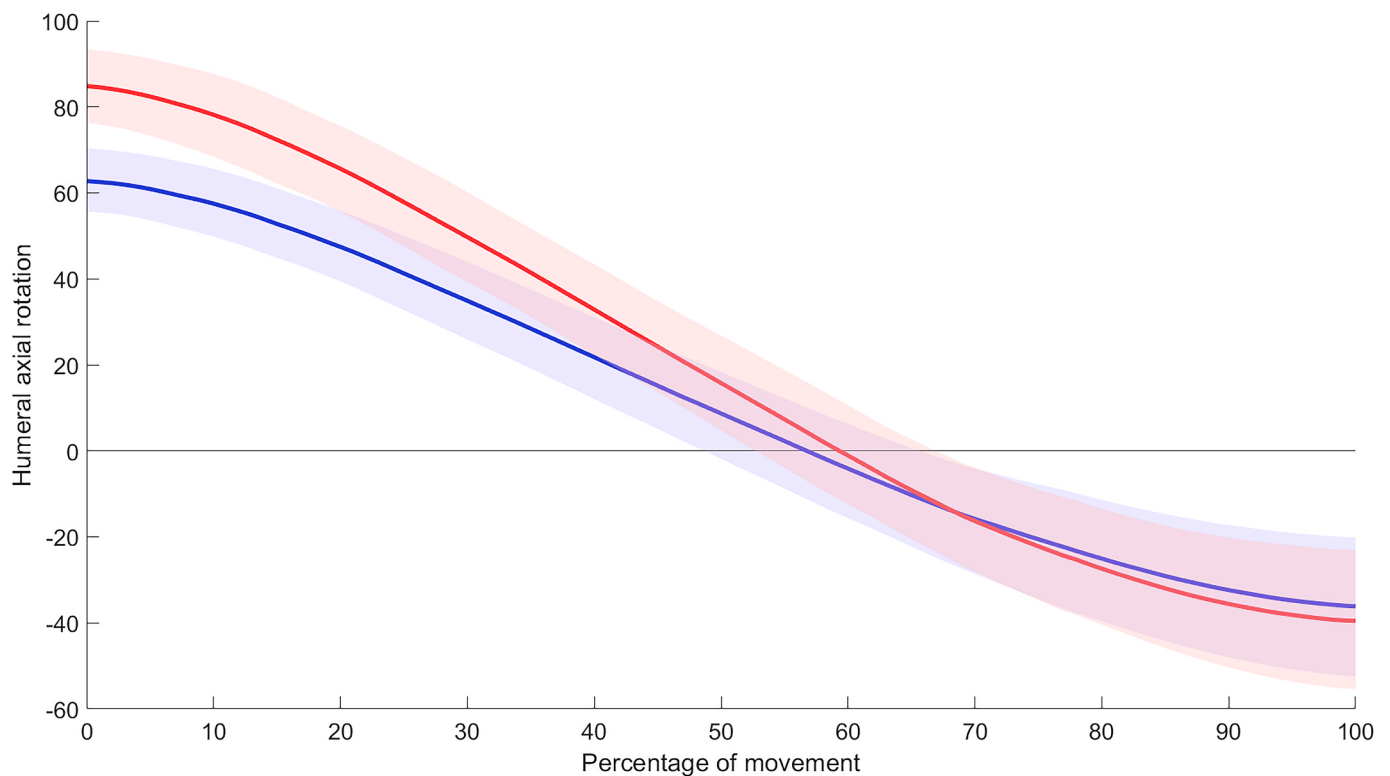


Fig. 5. Humeral axial rotation (degrees) utilising H_1 (blue) and H_2 (red) methods of defining the humerus coordinate system when only using distal markers.

in this study, local deformations and soft tissue artefact of the forearm markers could affect the longitudinal axis of the forearm. The H_2 method, therefore, cannot be considered completely independent of soft

tissue artefact in the arm and cannot provide a 'ground-truth' with which to measure humeral internal rotation. The use of bone pins or imaging studies provide a solution to determine the 'ground truth',

however, such approaches are susceptible to errors such as anchoring of the skin affecting normal soft tissue artefact or small capture volumes preventing both proximal and distal segments to be fully imaged. The use of the H₂ method, whilst not a ground-truth, provided an approach that demonstrated the substantial underestimation of humeral axial rotation when markers are attached proximally to the humerus.

5. Conclusion

Analysis of soft tissue artefact revealed a systematic elastic deformation and rigid displacement of reflective markers attached to the arm during humeral axial rotation. The underestimation of the axial rotation by the proximal markers suggests that markers should be placed on the distal end of the arm. Careful selection of markers that constitute the entire arm cluster is needed with consideration given to both glenohumeral joint centre and minimising soft tissue artefact.

CRedit authorship contribution statement

Martin B. Warner: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Markus O. Heller:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jbiomech.2025.112893>.

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