Assessment of the Glenohumeral joint's active and passive axial rotational range

A Humphries[1], S Cirovic[1], AMJ Bull[2] Anthony Hearnden[3], AF Shaheen[1]

[1] Centre for Biomedical Engineering, Duke of Kent Building, Department of Mechanical Engineering Sciences, University of Surrey, UK

[2] Department of Bioengineering, Imperial College London, UK

[3] Orthopaedics, Royal Surrey County Hospital, UK

Abstract

Background: Assessment of the range of axial rotation of the Glenohumeral joint will improve understanding of shoulder function, with applications in shoulder rehabilitation and sports medicine. However, there is currently no complete description of motion of the joint. The study aims to develop a reliable protocol to quantify the internal and external axial rotations of the Glenohumeral joint during active and passive motion at multiple humeral positions.

Methods: Optical motion tracking was used to collect kinematic data from 20 healthy subjects. The humerus was positioned at 60°, 90° and 120° of humero-thoracic elevation in the Coronal, Scapular and Sagittal planes. Internal and external rotations were measured at each position for active and passive motion, where intra-subject standard deviations were used to assess variations in internal-external rotations.

Results: The protocol showed intra-subject variability in the axial rotational range of less than 5° for active and passive rotations at all humeral positions. Maximum internal rotation was shown to be dependent on humeral position, where a reduced range was measured in the Sagittal plane ($p<0.001$) and at 120° elevations ($p<0.001$). Conversely, maximum external rotations were not affected by humeral position.

Conclusion: The results describe normal ranges of internal-external rotation of the Glenohumeral joint at multiple humeral positions. The protocol's low variability means it could be used to test whether shoulder pathologies lead to changes in axial rotational range at specific humeral positions.

Keywords: Glenohumeral joint, Kinematics, Shoulder, Reliability, Axial rotation, Active, Passive

Introduction

The range of axial (internal-external) rotation of the Glenohumeral joint (GHJ) is important in the assessment of shoulder function. For example, shoulder disorders such as posterior impingement[28,31,38], instability[8,20], rotator cuff tears[14] and SLAP lesions[39] exhibit increased internal rotations and decreased external rotation. Axial rotations of the GHJ are also used as an outcome measure in the evaluation of rehabilitation[11,15,30] and assist in the diagnosis of injuries and post-surgical outcomes such as rotator cuff repair[14]. Limitations to the range of internal and external rotation of the GHJ have been shown to influence overhead sports performance[2,9,21] and ability to complete activities of daily living[18,34]. Stability of the GHJ is provided primarily by the muscles of the rotator cuff during active motion and by a combination of capsular (ligamentous) and tendinous restraints during passive motion[5]. The limits of normal motion of the joint are defined by both active and passive restraints, leading to large variation in the range of axial rotation between individuals[25]. These restraints are susceptible to injury during maximum internal and external rotations[32], where a greater range of axial rotation of the GHJ can be associated with a greater risk of upper extremity injury[15,36].

Clinical assessments of internal and external rotations aim to assess passive axial rotational range of the GHJ by using the clinician’s judgement to define the end range of motion. However, this does not quantify the torque applied[38]; meaning assessments are subjective and have poor reproducibility[6]. Furthermore, the range of motion should be assessed at multiple elevation angles and elevation planes as the range of axial rotation at different humeral positions could be dependent on shoulder pathology. A number of studies in the literature report the axial range of motion of the GHJ, showing that the range is dependent on the elevation angle[17,37], elevation plane[17,29,37] and form of motion (active and passive rotations)[29]. However, these previous studies have not provided a comprehensive description of the normal range of axial rotation of the GHJ during active and passive motion when the humerus is positioned at multiple elevation angles and elevation planes.

The normal range of movement of the joint is currently not fully described for active and passive motion, mainly due to the large range of motion and multiple degrees of freedom of the shoulder. Previous studies have quantified the maximum humeral elevation in multiple planes, showing that healthy participants can achieve elevations of over 120° relative to the thorax[1,17]. They have also shown significant interactions between the elevation angle of the humerus and the angle of axial rotation, meaning the humeral elevation affects the internal and external rotations of the shoulder[17]. The interaction between the degrees of freedom, the translation of the scapula and soft tissue artefacts have led to large variations in the measured internal and external rotations of the GHJ[4,29].

The study aims to establish the differences between active and passive axial rotational range at multiple humeral elevation angles and elevation planes. Consequently, the study will establish a baseline for the normal active and passive axial rotational range of the GHJ. To measure the rotations of the shoulder, the study also develops an improved, protocol with low variability for quantifying the axial rotational range of the GHJ.

Materials and Methods

Data collection

This diagnostic study of the axial rotations of the GHJ in a non-pathological group was granted ethics approval by the University of Surrey ethics committee and all subjects gave informed consent.

Kinematic data of the scapula and humerus was collected from ten male and ten female subjects (age: 27± 6 years; weight: 70 ± 18kg; forearm length: 33 ± 7cm) who had no history of shoulder pathology or instability. Internal and external rotations of the GHJ were measured for the subject's dominant arm as arm dominance has no significant effect on the axial rotations of the GHJ in a non-pathological group[4,32]. Internal-external rotations were measured when the humerus was elevated at 60°, 90° and 120° in the Coronal, Scapular and Sagittal planes relative to the thorax. The Scapular plane was defined as 30° anterior to the Coronal plane. The order of humeral elevations and elevation planes used in the protocol was randomised to avoid bias.

The experimental setup used in the study is shown in Figure 1. A tripod was used to maintain the plane of elevation and humeral elevation angle during axial rotation of the humerus. A splint was attached securely to the arm using Velcro straps which flexed the elbow at 90° to allow the humero-thoracic elevation angle and elevation plane to be controlled and to ensure passive and active rotations occurred along the axial rotation axis of the humerus. The tripod supported the splint on a pin joint at the distal end of the humerus, ensuring the humerus' axis of rotation passed through the GHJ. A three-point harness and lateral supports restrained the thorax whilst the subject was seated. An inclinometer (SignalQuest, Lebanon, NH, USA), attached to the splint was used to measure the angle of rotation about two axes, representing the elevation angle and the axial rotation angle of the humerus, relative to the direction of gravity (±3°). The inclinometer's measure of the elevation angle was displayed in real-time to allow the observer to set the humeral elevation to the required angle; whilst floor markers were used to define the plane of humeral elevation.

At each humeral position, data was collected for three cycles of active and passive internal-external rotation, starting with the forearm directed anteriorly. Subjects practiced internal and external rotations at each humeral position before data was collected to precondition the internal structures of the shoulder and thus reduce variability in the measured range[37].

During active rotations, subjects were instructed to rotate their arm as far as possible without feeling discomfort. They selected a comfortable speed of active rotation at the start of the protocol, which was maintained for all humeral positions using a metronome as a guide[14].

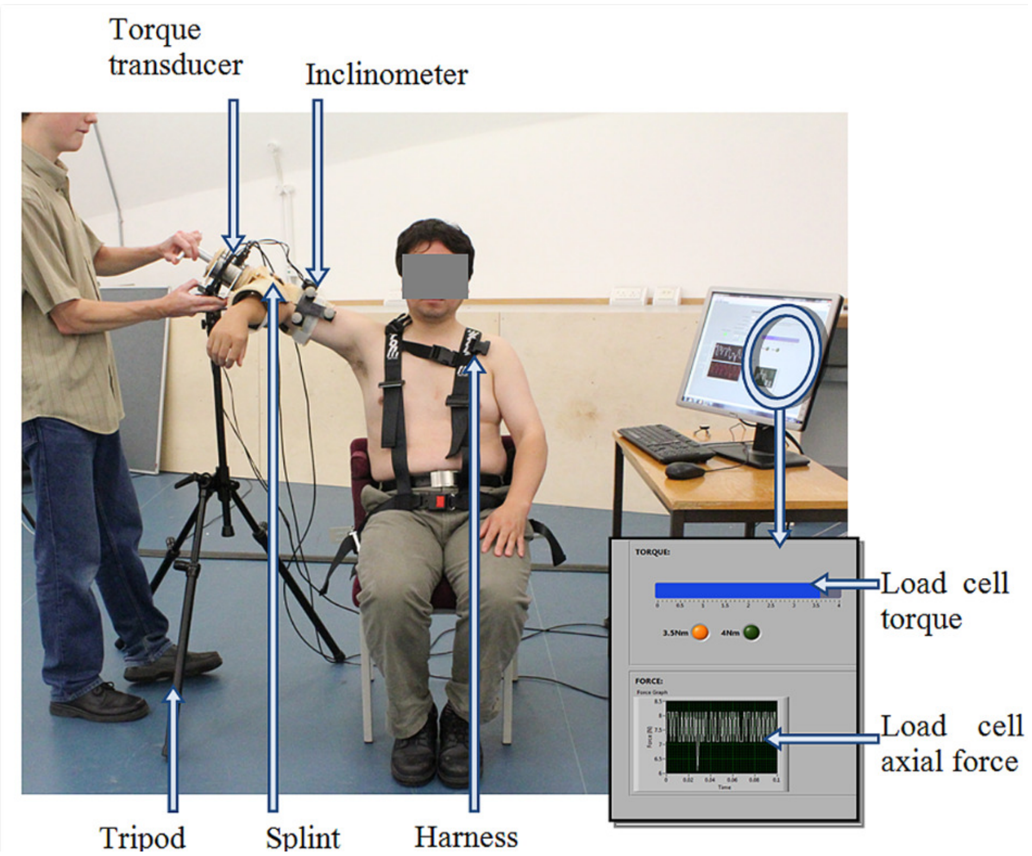

Figure 1: Data collection during passive axial rotations at 120 humeral elevation in the coronal plane, showing manual torque application and the real-time display of the computed torque applied to the humerus.

Passive axial rotational range was evaluated when a torque of up to 4Nm was applied to the humerus internally and externally in order to define a threshold value for the end range of motion[26,29]. The torque was applied manually and slowly increased from zero to 4Nm unless the subject expressed discomfort, in which case the applied torque was not increased any further. A load cell (Applied Measurements Ltd., Aldermaston, UK) attached to the distal end of the splint was used to measure the applied torque. LabVIEW (National Instruments, Newbury, UK) was used to compute the torque applied to the GHJ using the load cell measurements and the inclinometer readings for the axial rotation angle to correct for the torque caused by the weight of the forearm. The resulting torque was displayed in real-time in LabVIEW (Figure 1) to allow the observer to view the torque applied at the GHJ, ensuring it did not exceed the 4Nm threshold. The load cell also recorded the force applied along the humeral axis, which was displayed in real-time to ensure the compressive force was minimal (less than 0.3N); hence would not adversely affect the axial rotational range[27].

An optoelectronic system (Qualisys, Gothenburg, Sweden) consisting of 11 cameras, running at 200 Hz, was used to track the motion of the scapula and humerus. Markers were placed at palpated landmarks on the humerus and scapula during static subject calibration, allowing their local coordinate systems to be defined[40]. The glenohumeral centre of rotation was estimated using least squares to define the humerus coordinate frame[16]. The scapula landmarks were measured using the Scapula locator[24]; whilst the motion of the scapula and humerus were tracked using technical clusters. The scapula cluster was positioned at the junction between the acromion and the scapula spine to minimise the effects of skin artefact[35]. The locations of the technical clusters were defined relative to the local coordinate systems of the humerus and scapula at each humeral position[13,33].

Following static calibration, data was collected during three cycles of internal and external rotation of the humerus. Each cycle started from the neutral position when the forearm was directed anteriorly in Coronal and Scapular plane movements or medially in the Sagittal plane.

Evaluating the variation in internal-external rotations

The intra-subject standard deviations for the range of axial rotation were used to assess the variation in the internal- external rotations. This was determined using the three repeat cycles of internal-external rotation collected at each humeral position.

The intra-session and inter-session variability were also evaluated for the axial rotational range. Data collection at each humeral position was repeated in the same session for ten subjects at the end of the data collection protocol. This allowed the intra-session variability to be quantified. The remaining ten subjects attended a repeat data collection session, two weeks after their initial session. The protocol was repeated during the second session, allowing the inter-session variability to be evaluated.

The axial rotational range of the GHJ

Angles of rotation of the humerus relative to the scapula were computed using Euler sequence YX'Y''[40] to quantify the internal and external rotations of the GHJ, allowing the active and passive motion to be compared at each humeral position. A three-factor repeated analysis of variance (ANOVA) was used to establish if there were significant differences in the internal and external rotations at different humeral elevations (60°, 90° and 120°), elevation planes (Coronal, Scapular and Sagittal) and forms of motion (active and passive). Where differences were found, a Posthoc test with Bonferroni correction was applied in order to establish the significance of each of the independent factors. The significance level was set at $p=0.05$.

Axial rotations of the Glenohumeral joint

The humero-thoracic angles of axial rotation were also computed using Euler sequence YX’Y’’[40], allowing the humero-thoracic and glenohumeral angles of rotation to be compared in order to determine how the rotations of the scapula affected the quantified axial rotations of the shoulder.

Results

Evaluating the variation in internal-external rotations

We developed a protocol to quantify active and passive axial rotations of the GHJ and determined the effect of humeral plane and elevation angle on the range of axial rotation. Intra-subject variability in the active axial rotational range was less than 5° and passive rotational range was less than 4° for all humeral positions. The intra-session and inter-session variability of the axial rotational range were also shown to be low as these were less than 6° for active and passive rotations.

The axial rotational range of the GHJ

Assessment of the active and passive rotations illustrated how the internal and external rotations were affected by the humeral elevation angle and plane. The results showed that the axial rotational range at 120° elevation was significantly lower than at 60° and 90° elevations ($p<0.001$). The range was also significantly lower in the Sagittal plane ($p<0.001$) compared to the other two planes; whilst there was no significant difference between the range achieved in the Coronal and Scapular planes. Furthermore, the passive axial rotational range was shown to be significantly greater than the corresponding active rotation at all humeral positions ($p<0.001$), as illustrated in Figure 2.

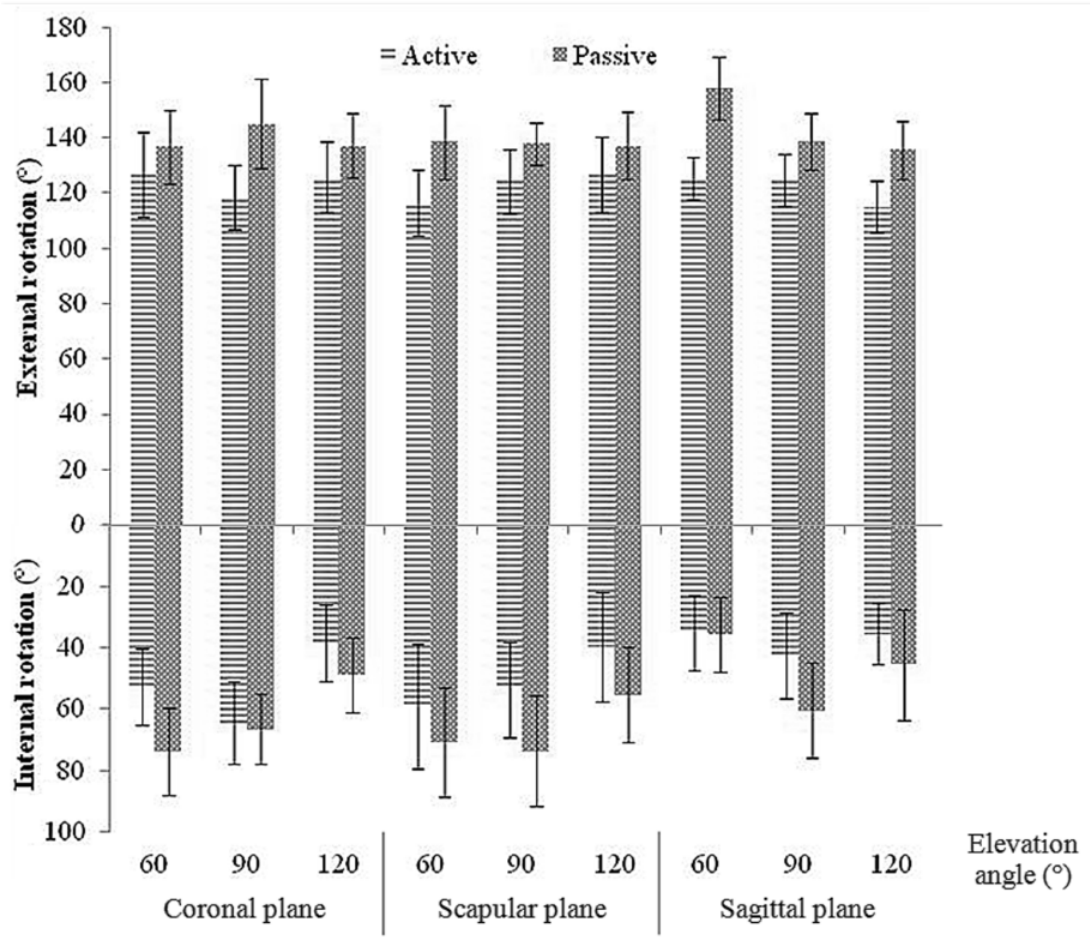

Figure 2: A plot of the mean internal and external GHJ rotations for active and passive motion, with the intersubject standard deviations at each humeral position. Internal-external rotations are defined relative to the neutral position, when the forearm was directed anteriorly or medially.

Internal rotations of the GHJ were also shown to vary with humeral position, where these differences were comparable to those observed for the axial rotational range. The results showed that internal rotations in the Sagittal plane were significantly smaller than those in the Coronal and Scapular planes ($p<0.001$); whilst there was no significant difference in the internal rotations achieved in the Coronal and Scapular planes. Furthermore, a significantly reduced internal rotation was achieved at 120° humeral elevation ($p<0.001$); whilst there was no significant difference in the internal rotations achieved at 60° and 90° elevation.

Furthermore, internal rotations achieved during passive motion were significantly greater than those achieved during active motion ($p<0.001$). This shows that the elevation plane, elevation angle and motion (active and passive) have significant influence on the internal rotation of the GHJ, which subsequently has a significant influence on the axial rotational range. Maximum internal rotation at 60° humeral elevations in the Sagittal plane were however not achieved whilst the subject was seated.

Conversely, humeral elevation plane and elevation angle were shown to have no significant influence on the external rotation of the GHJ, although, passive rotations were shown to lead to a significant increase in the external rotation compared to the active external rotation ($p<0.001$). A summary of the variation in internal and external rotations of the GHJ are illustrated in Figures 2 and 3 and a summary of the p-values for the independent factors when quantifying the axial rotational range are shown in Table I.

The motion of the scapula was shown to affect the quantified rotations of the shoulder, since humero-thoracic internal rotations were more than 10° greater than the quantified glenohumeral axial rotations ($p<0.05$) at all humeral positions. Conversely, external rotations were not affected by scapula motion as no significant differences were found ($p>0.64$).

Discussion

Quantifying the internal and external rotations of the GHJ is important in order to improve understanding of shoulder motion. This study develops a protocol with low variation to quantify the axial rotational range of the GHJ to establish how humeral plane and elevation angle affect the maximum internal and external rotations during active and passive motion. The internal and external rotations quantified using the protocol are then used to describe the normal range of motion of the GHJ.

Evaluating the variation in internal-external rotations

As the variability was less than 4% and 2% of the axial rotational range for active and passive rotations respectively, the protocol can be considered reliable for quantifying the axial rotational range of the GHJ. Internal rotations were however limited for all subjects in the study when the humerus was elevated at 60° in the Sagittal plane as they were in the seated position. Consequently, there was significantly lower variation and no considerable difference between the active and passive internal rotations at this position. Similarly, internal rotations at 90° elevation in the Sagittal plane were limited for two subjects as a result of greater forearm length.

Most subjects were comfortable with 4Nm of torque application. One subject expressed discomfort at 3.5Nm, although it was assumed the subject had achieved maximum rotation when 3.5Nm was applied[26]. However, one subject expressed discomfort at 2.5Nm when the humerus was elevated at 120° in the Sagittal plane meaning this may have affected their maximum internal and external rotations. Shoulder impingement could be a potential contributor towards discomfort, meaning this observation could benefit clinical diagnosis of shoulder disorders.

The variation in the internal-external rotations was reduced by re-calibrating the cluster location at each humeral position, to account for the effects of skin artefact as the humeral elevation and plane angles were changed[13,33]. The humeral cluster was attached to the rigid splint, which was securely strapped to the arm; this used the common assumption that the splint provided secure rotational stability[3].

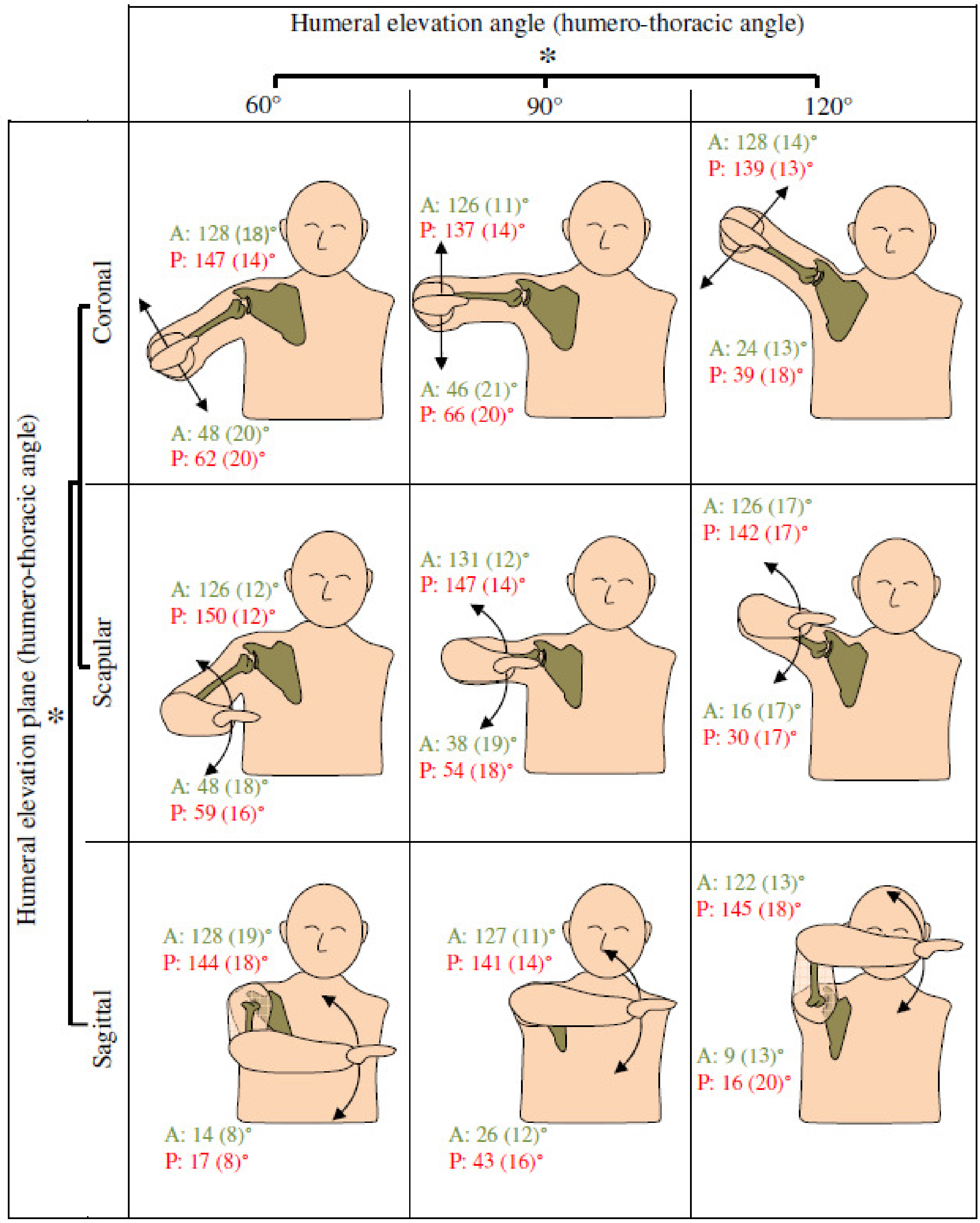

Figure 3: An illustration of the average and intersubject variation of the maximum internal and external rotations of the GHJ for active and passive motion at each humeral position. Angles are defined as rotations of the humerus (relative to the scapula) from the neutral position (when the forearm was directed anteriorly or medially).

Table 1: P values for the independent factors in quantifying the maximum axial rotations of the GHJ

	Factor						
	Elevation	Plane	Motion	Plane × Elevation	Elevation × Motion	Plane × Motion	Plane × Elevation × Motion
Internal rotation	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.7	**0.014**	**<0.001**
External rotation	**0.018**	0.359	**<0.001**	**<0.001**	**0.013**	**0.041**	**<0.001**
Axial range	**<0.001**	**<0.001**	**<0.001**	**0.001**	0.066	0.092	**0.046**

The torque application during passive rotations further reduced the variation in the maximum internal-external rotation; whereas maximum active rotations were affected by the subject's perception of their maximum range. The reduced variability for passive rotations could be because the subject's muscles were relaxed. Although the muscle activity was not monitored during motion, subjects practiced passive internal-external rotation prior to data collection and were reminded to remain relaxed throughout the motion.

Subjects were seated during the protocol to allow the thorax to be restrained and humero-thoracic elevation and plane angle controlled. Restraining the thorax and controlling the position of the humerus reduced the degrees of freedom of the GHJ and was shown to significantly reduce the thorax translations and rotations; improving consistency and reducing variation in the quantified axial rotations of the GHJ. However, the restraint chair was shown to limit the maximum internal rotation at some humeral positions and the range of humero-thoracic elevation that could be achieved. This meant the humeral elevation angle could not be less than 60°; whilst the range of motion of the shoulder meant the maximum elevation that could be achieved in the three elevation planes was 130° [17].

The protocol developed in this study could benefit clinical assessments, since the inclinometer provides a simple, fast method of measuring the axial rotation and elevation of the humerus relative to gravity. The kinematic data showed that the inclinometer defined the elevation of the humerus to within 3° of the true humero-thoracic angle of elevation and measured the range of axial rotation to within 3° of the true humero-thoracic angle of axial rotation. The inclinometer's measurements relative to gravity were comparable to the kinematic angles measured relative to the thorax as the lateral restraints maintained the thorax position to within 3° in the medial-lateral direction and 1° in the anterior-posterior direction. The setup would therefore enable both active and passive rotations to be assessed at multiple humeral elevation angles and elevation planes, although the reliability of the setup in clinic needs to be assessed. This could provide a novel approach to measuring the axial rotational range of the humerus in clinic, allowing the range to be compared at multiple humeral positions. It could therefore provide a technique for the assessment of shoulder disorders, as specific pathologies could lead to differences in the normal range of axial rotation at specific humeral positions.

The axial rotational range of the GHJ

The assessment of the active axial rotations of the GHJ illustrates that the range is significantly influenced by the humeral plane and elevation angle[17]; which is also shown for passive axial rotations. Previous studies have also reported that a reduced axial rotational range is achieved in the Sagittal plane[17,29] and at 120° humeral elevations[17,37] and confirm this is dominated by the angle of internal rotation. Meanwhile, McCully *et al.* confirm that passive axial rotational range is greater than the corresponding active range[29].

Clinical assessments of the shoulder measure the humero-thoracic angles of axial rotation, meaning the measured axial rotations are affected by the translations and rotations of the scapula. The results showed that the humero-thoracic internal rotations were significantly greater than the quantified rotations of the GHJ, demonstrating how the motion of the scapula enables a greater range of shoulder motion to be achieved[22].

Although there are a relatively small number of participants in the non-pathological group, this is shown to be comparable to previous studies investigating the kinematics of the shoulder[4,17]. Participants were however recruited from a younger age group, meaning the range of motion baseline may not be able to be extrapolated to older age groups. The quantified angles of axial rotation from the kinematic data were assumed to represent the true angles of rotation of the humerus relative to the scapula, as skin artefact and translations and rotations of the scapula were considered to have negligible effect on the measured rotations of the GHJ following re-calibration of the marker locations at each humeral position. Consequently, the kinematic data can be used to quantify the internal-external rotations of the GHJ whose variation could be a result of differences in bony and ligamentous constraints. To further develop understanding of the mechanisms responsible for limiting the axial rotations of the GHJ, future studies should consider the capsular and ligamentous constraints of the joint and quantify the axial rotations of the GHJ for specific shoulder pathological conditions, such as rotator cuff injuries.

Rotator cuff muscle forces are primarily responsible for maintaining stability by compressing the GHJ[12] during active rotations. This limits the translations of the humeral head on the glenoid[19,25], meaning joint conformity is likely to limit the active axial rotational range. During passive rotations the humeral head can translate on the glenoid at the extremes of motion, allowing a greater axial rotational range to be achieved[25]. Therefore, the length and elasticity of the Glenohumeral ligaments[10,25] and bony constraints such as the humeral tuberosity and the acromion[1,7] are likely to limit the passive axial rotational range. These constraints are also likely to affect the range that can be achieved at multiple humeral positions. For example, the reduced passive axial rotational range at 120° humeral elevation could be because shoulder ligaments are stretched more at higher elevations[37]. Meanwhile, the reduced active axial rotational range at higher humeral elevations could be due to joint conformity and contact between the humeral tuberosity and the acromion[1]. Similarly, the reduced range of internal-external rotation in the Sagittal plane may be due to a reduced contact area of articular cartilage at the GHJ[23]. Consequently, differences in joint conformity could lead to variation in active rotational range between individuals; whilst differences in bone geometry and ligament length could be responsible for the variation in the passive rotational range[25].

Conclusion

The protocol used in this study evaluates the axial rotational range of the GHJ with low variation; providing a greater understanding of shoulder motion for a normal subject group and how its range of motion is dependent upon humeral position during active and passive motion. Quantifying the axial rotational range of the GHJ at multiple humeral positions demonstrated that there were reduced internal rotations at higher humeral elevation angles; whilst internal rotations were also significantly reduced in the Sagittal plane. The results of the study can be used to describe the normal range of internal-external rotation of the GHJ in a normal population. This benefits understanding of shoulder pathologies which affect the structures of the shoulder, as these can affect the stability and range of the GHJ. Furthermore the study proposes a method of assessing the axial rotational range of the GHJ in clinic, providing a novel approach to diagnosing clinical disorders.

References

1. An KN, Browne AO, Korinek S, Tanaka S, Morrey BF. Three dimensional kinematics of glenohumeral elevation. *J Orthop Res*. 1991; 9:143-9.
2. Astolfi MM, Struminger AH, Royer TD, Kaminski TW, Swanik CB. Adaptations of the shoulder to overhead throwing in youth athletes. *J Athl Training*. 2015; In press. doi: 10.4085/1062-6040-50.1.14.
3. Barnett ND, Duncan RDD, Johnson GR. The measurement of three dimensional scapulohumeral kinematics – a study of reliability. *Clin Biomech*. 1999; 14:287-90.
4. Beardsley CL, Howard AB, Wisotsky SM, Shafritz AB, Beynnon BD. Analyzing glenohumeral torque–rotation response in vivo. *Clin Biomech*. 2010; 25:759-64. doi:10.1016/j.clinbiomech.2010.06.006.
5. Bigliani LU, Kelkar R, Flatow EL, Pollock RG, Mow VC. Glenohumeral stability. Biomechanical properties of passive and active stabilizers. *Clin Orthop Relat R*. 1996; 330:13-30.
6. Bovens AM, van Baak MA, Vrencken JG, Wijnen JA, Verstappen FT. Variability and reliability of joint measurements. *Am J Sports Med*. 1990; 18:58-63.
7. Browne AO, Hoffmeyer P, Tanaka S, An KN, Morrey BF. Glenohumeral elevation studied in three dimensions. *J Bone Joint Surg Br*. 1990; 72:843-5.
8. Burkhart SS, Morgan CD, Kibler WB. The disabled throwing shoulder: spectrum of pathology Part I: pathoanatomy and biomechanics. *Arthroscopy*. 2003; 19:404-20. doi:10.1053/jars.2003.50128.
9. Crockett HC, Gross LB, Wilk KE, Schwartz ML, Reed J, O’Mara J, Reilly MT, Dugas JR, Meister K, Lyman S, Andrews JR. Osseous adaptation and range of motion at the glenohumeral joint in professional baseball pitchers. *Am J Sports Med*. 2002; 30:20-6. No doi.

10. Culham E, Peat M. Functional Anatomy of the shoulder complex. *J Orthop Sport Phys*. 1993; 18:342-50.
11. Dipaola MJ, Jazrawi LM, Rokito AS, Kwon YW, Patel L, Pahk B, Zuckerman JD. Management of Humeral and Glenoid Bone Loss Associated with Glenohumeral Instability: Results with Anatomical Bone Grafting. *Bulletin of the NYU Hospital for Joint Diseases*. 2010; 68:245-50. No doi.
12. Ebaugh DD, McClure PW, Karduna AR. Three-dimensional scapulothoracic motion during active and passive arm elevation. *Clin Biomech*. 2005; 20:700-9. doi: 10.1016/j.clinbiomech.2005.03.008.
13. Blinded for review purposes. Eftaxiopoulou T, Gupte CM, Dear JP, Bull AM. The effect of digitisation of the humeral epicondyles on quantifying elbow kinematics during cricket bowling. *J Sports Sci*. 2013; 31:1722-30. doi: 10.1080/02640414.2013.803582.
14. Ellenbecker TS, Elmore E, Bailie DS. Descriptive Report of Shoulder Range of Motion and Rotational Strength 6 and 12 Weeks Following Rotator Cuff Repair Using a Mini-Open Deltoid Splitting Technique. *J Orthop Sports Phys*. 2006; 36:326-35. doi:10.2519/jospt.2006.2191.
15. Ellenbecker TS, Roetert EP, Bailie DS, Davies GJ, Brown SW. Glenohumeral joint total rotation range of motion in elite tennis players and baseball pitchers. *Med Sci Sport Exer*. 2002; 34: 2052-6. doi: 10.1249/01.MSS.0000039301.69917.0C.
16. Gamage SSHU, Lasenby J. New least squares solutions for estimating the average centre of rotation and the axis of rotation. *J Biomech*. 2002; 35:87-93. doi:10.1016/S0021-9290(01)00160-9.

17. Haering D, Raison M, Begon M. Measurement and description of three-dimensional shoulder range of motion with degrees of freedom interactions. J Biomech Eng. 2014; 136(8). doi: 10.1115/1.4027665.
18. Hall LC, Middlebrook EE, Dickerson CR. Analysis of the influence of rotator cuff impingements on upper limb kinematics in an elderly population during activities of daily living. *Clin Biomech*. 2011; 26:579-84. doi: 10.1016/j.clinbiomech.2011.02.006.
19. Harryman II DT, Sidles JA, Clark JM, McQuade KJ, Gibb TD, Matsen III FA. Translation of the humeral head on the glenoid with passive glenohumeral motion. *J Bone Joint Surg Am.* 1990; 72A:1334-43.
20. Hess SA. Functional stability of the glenohumeral joint. *Manual Ther*. 2000; 5:63-71.
21. Hurd WJ, Kaplan KM, Eiattrache NS, Jobe FW, Morrey BF, Kaufman KR. A profile of glenohumeral internal and external rotation motion in the uninjured high school baseball pitcher, part I: motion. *J Athl Training*. 2011; 46:282-8. No doi.
22. Inman VT, Saunders JB, Abbott LC, 1996. Observations of the function of the shoulder joint. 1944. Clin Orthop Relat Res; 330: 3-12.
23. Jobe CM, Iannotti JP. Limits imposed on glenohumeral motion by joint geometry. *J Shoulder Elb Surg*. 1995; 4:281-5.
24. Johnson GR, Stuart PR, Mitchell S. A method for the measurement of three dimensional scapular movement. *Clin Biomech*. 1993; 8:269-73.
25. Karduna AR, Williams GR, Williams JL, Iannotti JP. Kinematics of the glenohumeral joint: influences of muscle forces, ligamentous constraints, and articular geometry. *J Orthop Res*. 1996; 14:986-93.
26. Kuhn JE, Bey MJ, Huston LJ, Blasier RB, Soslowsky LJ. Ligamentous restraints to external rotation of the humerus in the late-cocking phase of throwing. A cadaveric biomechanical investigation. *Am J Sports Med*. 2000; 28:200-5.

27. Lippitt SB, Vanderhooft JE, Harris SL, Sidles JA, Harryman II DT, Matsen III FA. Glenohumeral stability from concavity-compression: A quantitative analysis. *J Shoulder Elb Surg*. 1993; 2:27-35.
28. Manske RC, Grant-Nierman M, Lucas B. Shoulder posterior internal impingement in the overhead athlete. *Int J Sports Phys Ther*. 2013; 8:194-204. No doi.
29. McCully SP, Kumar N, Lazarus MD, Karduna AR. Internal and external rotation of the shoulder: effects of plane, end-range determination, and scapular motion. *J Shoulder Elb Surg*. 2005; 14:602-10. doi:10.1016/j.jse.2005.05.003.
30. Moore SD, Laudner KG, Mcloda TA, Shaffer MA. The Immediate Effects of Muscle Energy Technique on Posterior Shoulder Tightness: A Randomized Controlled Trial. *J Orthop Sport Phys*. 2011; 41:400-7. doi: 10.2519/jospt.2011.3292.
31. Myers JB, Laudner KG, Pasquale MR, Bradley JP, Lephart SM. Glenohumeral range of motion deficits and posterior shoulder tightness in throwers with pathologic internal impingement. *Am J Sports Med*. 2006; 34:385-91. doi: 10.1177/0363546505281804.
32. Novotny JE, Beynnon BD, Nichols CE. Modeling the stability of the glenohumeral joint during external rotation. *J Biomech*. 2000; 33:345-54.
33. Blinded for review purposes. Prinold JAI, Shaheen AF, Bull AMJ. Skin-fixed scapula trackers: A comparison of two dynamic methods across a range of calibration positions. *J Biomech*. 2011; 44:2004-7. doi: 10.1016/j.jbiomech.2011.05.010.
34. Rundquist PJ, Obrecht C, Woodruff L. Three-dimensional shoulder kinematics to complete activities of daily living. *Am J Phys Med Rehab*. 2009; 88:623-9. doi: 10.1097/PHM.0b013e3181ae0733.

35. Blinded for review purposes. Shaheen AF, Alexander CM, Bull AMJ. Effects of attachment position and shoulder orientation during calibration on the accuracy of the acromial tracker. *J Biomech.* 2011; 44:1410-3. doi: 10.1016/j.jbiomech.2011.01.013.
36. Shanley E, Rauh MJ, Michener LA, Ellenbecker TS, Garrison JC, Thigpen CA. Shoulder Range of Motion Measures as Risk Factors for Shoulder and Elbow Injuries in High School Softball and Baseball Players. *Am J Sport Med.* 2011; 39:1997-2006. doi: 10.1177/0363546511408876.
37. Blinded for review purposes. Southgate DFL, Hill AM, Alexander S, Wallace AL, Hansen UN, Bull AMJ. The range of axial rotation of the glenohumeral joint. *J Biomech.* 2009; 42:1307-12. doi: 10.1016/j.jbiomech.2009.03.007.
38. Tyler TF, Nicholas SJ, Roy T, Gleim GW. Quantification of posterior capsule tightness and motion loss in patients with shoulder impingement. *Am J Sport Med.* 2000; 28:668-73.
39. Tzannes A, Murrell GAC. Clinical Examination of the Unstable Shoulder. *Sports Med.* 2002; 32:447-57. No doi.
40. Wu G, van der Helm FC, Veeger HE, Makhsous M, Van RP, Anglin C, Nagels J, Karduna AR, McQuade K, Wang X, Werner FW, Buchholz B. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion–Part II: shoulder, elbow, wrist and hand. *J Biomech.* 2005; 38:981-92. doi: 10.1016/j.jbiomech.2004.05.042.