The quantitative analysis of the humeral translation at different rotational velocities: synchronizing with cine MRI and video camera to identify the shoulder rotation angle

（異なる回旋運動速度下での上腕骨頭変位の定量的解析: Cine MRI とビデオカメラの同期による肩関節回旋角度の同定）

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主論文の要旨

緒言

　肩甲上腕関節は広い表面積の上腕骨頭と浅く狭い表面積の関節窩により構成される形態的に不安定な関節である．回旋筋腱板と三角筋による協調された筋収縮タイミングは関節窩上に上腕骨頭を留めるだけではなく，関節窩への求心力をもたらし上腕骨頭の位置に影響を与えることが示されている．

　日常生活や仕事，スポーツ活動中における挙上動作では，肩甲上腕関節の回旋運動が多く含まれる．これまでの肩関節回旋運動中の画像解析は，関節窩に対する上腕骨頭変位に注目されているが，上腕骨頭と肩関節の回旋肢位を同期した解析をしていないため，理学的検査における上腕骨頭変位の所見と先行研究の上腕骨頭変位との関係は希薄である．肩甲上腕関節での協調された筋のコントロールが低下した場合には，異なる肩関節自動回旋運動速度や収縮様式での上腕骨頭や回旋軸の逸脱した運動がみられるが，この肩関節回旋運動速度の違いが関節内運動へおよぼす影響は明らかにされていない．以上のことから，臨床家の徒手から得られる動的安定性の理学的検査所見を支持する客観的エビデンスを明らかにする研究が必要である．

　本研究の目的は，異なる肩関節回旋速度において健常な肩関節の上腕骨頭がどのように制御されているかを関節運動方向や角度に注目した解析をおこない臨床的な動的安定性を定量的に明らかにすることである．

対象および方法

頸椎，胸椎，肩関節に現病歴・既往歴を有さない健常成人 10 名（男性 8 名，女性 2 名，20 肩， 平均年齢 27.80 ± 6.05 歳）を対象とした．MRI 撮像前に対象者の肩関節は構造的不安定性と動的不安定性に該当しないことを理学的所見で予め確認した．

0.4T オープン型 MRI 装置 (Aperto Eterna， 日立メディコ)を用いて肩関節回旋運動中の肩甲上腕関節を軸位断上で撮像した．撮像条件はモディファイドグラディエントエコー法，繰り返し時間 4.4 ms，エコー時間 2.2 ms，フリップアングル 90°，スライス厚 1.7 mm，バンド幅 160 kHz，撮像領域 32 cm × 32 cm，マトリクス 256 × 256 ピクセルとした．撮像速度は 1 画像につき 0.5 秒とした．

対象者はオープン型 MRI 装置内にて背臥位，0°外転位をとり，外旋位から開始して最大内旋位の後に最大外旋位に戻るまでの連続した肩関節回旋運動を実施した．肩関節回旋運動速度は，低速 (15 回/ 分)，中速 (37.5 回/ 分)， 高速 (52.5 回/ 分)の 3 種類としてデジタルメトロノーム音に合わせて最大自動可動域での回旋運動を実施した．回旋運動速度は，先行研究において日常生活での肩関節回旋運動速度が 30° / 秒以下であったこと，ならびに予備実験において肩関節不安定症患者が実施可能な最大速度と最低速度をもとに決定した． MRI 撮像と同時に対象者頭側よりビデオカメラ撮影と MRI 撮像画像を同期することで肩関節の回旋角度を明らかにした．

得られた MRI 画像より上腕骨頭の変位として上腕骨頭中心を関節窩上へ投影した関

節窩中心からの距離とした．上腕骨頭中心は matlab 2016b (Mathworks Inc)を用いて上腕骨頭の関節表面の座標より最小二乗法により算出した．3 速度間の上腕骨頭の位置と変位は二元配置分散分析を用いて比較した．なお，本研究の計測方法である MRI 撮像とビデオカメラの同期と画像データ解析は，予備実験において計測精度ならびに再現性が高いことを確認した．

結果

上腕骨頭の位置と変位は 3 速度間において有意差はみられなかった．肩関節回旋運動中の上腕骨頭は関節窩中心より，後方 0.42 ± 1.82 mm から前方 1.91 ± 1.69 mm の範囲に位置した．上腕骨頭は前方 0.65±1.64mm から後方 0.64±1.84mm（低速），前方 0.74±1.92mm から後方 0.75±0.17mm（中速），前方 2.62±2.19mm から後方 1.51±1.60mm（高速）の範囲で変位した．

考察

本研究では肩関節自動回旋運動中の健常な肩関節の上腕骨頭を MRI により撮像し，被験者の肩関節を MRI と同期したビデオカメラにより撮像した．健常青年の動的に安定した肩関節は，肩関節回旋運動速度・肢位に影響されず，上腕骨頭の有意な変位はないことが明らかとなった．動的安定性の参考値として，上腕骨頭には関節窩中心よ

り後方 0.42 mm から前方 1.92 mm の範囲での生理的な遊びがみられた．この結果は臨床家が徒手から主観的に正常と判断する上腕骨頭変位を定量的に解析した参考値である．動的不安定性のみられる有病者の上腕骨頭位置と変位は，本研究の参考値である肩関節回旋運動中の上腕骨頭位置の分布範囲や上腕骨頭変位量から逸脱しているかもしれない．ここで得られた結果は異なる回旋運動速度下での健常な肩関節の上腕骨頭の変位を定量的に示し，臨床的な動的不安定性を検出するための基礎データになる．

結語

異なる肩関節回旋運動速度下での肩甲上腕関節の関節内運動を検証したところ，動的に安定した肩甲上腕関節は回旋運動速度に影響されず急激な変位はみられなかった．動的に安定した肩甲上腕関節は約 2 mm 程度の関節の遊びの範囲で生理的な安定性が得られていることが明らかになった．上腕骨頭の位置と変位は，生理的な関節の遊びとその範囲での変動であり，臨床家が徒手から主観的に正常と判断するための参考になると考えられた．

Abstract of Main study

Introduction

The glenohumeral joint is a morphologically unstable joint, which articulates the large surface of the humeral head with the shallow and small surface of the glenoid fossa. An appropriate onsets of rotator cuff muscles and deltoid muscles maintaining the humeral head on the glenoid fossa and compressing force towards the center of the glenoid fossa. An in vivo study proved that muscle contraction influenced the humeral head.

The glenohumeral joint during arm elevation involves shoulder rotation at various speeds in daily activities, at work, and in sports. In vivo studies provided data on humeral translation only during shoulder rotation. The relationship between clinical findings of humeral translation and the findings of previous studies dilute as rotation positions of the humeral head did not synchronize with the shoulder rotation position. The deviation of the humeral head and the rotation axis was observed via active shoulder rotation at various positions in the different types of contraction patterns and motion velocities when coordinated muscle control of the glenohumeral joint was dysfunction. Several imaging studies pertaining to variation of shoulder rotation velocities to analyze glenohumeral intraarticular movements have not revealed consistent findings. A study is needed to clarify quantitative evidence supporting the findings of dynamic glenohumeral stability obtained from clinicians' hands-on findings.

The purpose of this study was to analyze how the humeral head in a normal shoulder is under control among different rotation velocities, and to quantitatively clarify 'clinical' dynamic stability of the glenohumeral joint.

Methods

Both shoulders of ten healthy adults (mean age group between 27.80 ± 6.05 years) were used in this study. Prior to MRI scan, structural and dynamic glenohumeral stability was confirmed by physical examination.

A 0.4T open MRI scanner (Aperto Eterna, Hitachi Medical Corporation, Japan) was used to capture shoulder rotation on an axial plane every 0.5 s with a T2/T1 weighted image. The scanning sequence in a modified coherent gradient echo technique was used, with time repetition at 4.4 ms, time echo at 2.2 ms, flip angle at 90º, slice thickness at 1.7 mm, and a bandwidth of 160 kHz. The field of view and matrix were set at 32 cm by 32 cm and 256 by 256 pixels, respectively.

The participants were in supine position and asked to rotate their shoulder at three angular velocities (low, medium and high velocities), with the arm by the side of the body by real-time cine MRI. Their shoulder rotation velocities were synchronized with a digital metronome sound. One shoulder rotation cycle was defined as starting with external rotation position to internal rotation position and then end with external rotation position. The rotation velocities were determined the rotation velocity by which shoulder rotation was less than 30°/s in daily activity in a previous study, and by which a patient with unstable shoulder was able to undergo as quick as or as slow as possible in a preliminary study. Shoulder rotation angle during MR scan was identified by synchronizing with video camera data capturing from above a participant's head.

Translation of the humeral head was measured the distance between on the coordinate projected from the center of the humeral head perpendicularly and the center of the glenoid fossa on the golenoit fossa. The center of the humeral head was computed using the least mean square using matlab 2016b (Mathworks Inc). The position and translations of the humeral head between three rotation velocities were compared using two-way analysis of variance. The synchronization with MR scanning and video camera recording, the measuring technique of this study, and image analysis were confirmed high accuracy and reproducibility in a preliminary study.

Results

There were no statistical differences of the humeral head position and translation among three rotation velocities. The humeral head positioned 0.42 ± 1.82 mm posteriorly to 1.91 ± 1.69 mm anteriorly from the center of the glenoid fossa. Translation of the humeral head was distributed from 0.65 ± 1.64 mm anteriorly to 0.64 ± 1.84 mm posteriorly at low velocity, from 0.74 ± 1.92 mm anteriorly to 0.75 ± 0.17 mm posteriorly at middle velocity, and from 2.62 ± 2.19 mm anteriorly to 1.51 ± 1.60 mm posteriorly at high velocity.

Discussion

This study captured the humeral head during active shoulder rotation using an MRI, and the shoulder using a video camera synchronizing with the MRI device. The main results of this study demonstrated that translation of the humeral head is not affected by shoulder rotation velocity or position in dynamic glenohumeral stability of healthy adults. Healthy shoulder has regular width fluctuation so that the humeral head translates ranged 0.42 mm posteriorly to 1.92 mm anteriorly from the center of the glenoid fossa as reference value for dynamic stability assessment. The reference value of humeral translation provided what clinicians have believed from their hands-on findings of dynamically stable joints was analyzed quantitatively. The results of this study suggest that the possibility of dynamic glenohumereal instability during active shoulder rotation when the deviation from the distribution of the humeral head position or exceeded translation of the humeral head was observed. It could render clinically fundamental information for dynamic glenohumeral stability to evaluate the intraarticular movement of the glenohumeral joint at different velocities during shoulder rotation.

Conclusions

Translation of the humeral head was shown to undergo no significant change throughout the ranges of internal and external rotation, or among different rotational velocities in dynamic stability of the glenohumeral joint. The results of this study revealed that the glenohumeral joint with physiologically stable has approximately 2 mm joint play.

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I. PRELIMINARY STUDY

The Reliability and Validity of Motion Analysis using a cine MRI

I-1. Introduction

A Magnetic Reasoning Imaging (MRI) is a non-invasive instrument, is designed for detecting the abnormal findings of human tissue in supine lying position. Recent MR imaging studies challenged to scan continuous movement using three dimensional (3D) imaging (Sahara et al. 2007) and cine MRI technique (Pierrart et al. 2014). The imaging analysis requires an examiner's knowledge and skills and has potential human error. Knowing the reproducibility of image processing proves the reliability and validity of image analysis. It is fundamental data to assess numerous MR imaging.

Another issue of motion analysis using an MRI is a motion artifact (Smith and Nayak 2010) as the image is blurred in exchange for providing a valuable intraarticular finding. Scanning a joint with the least effect of motion artifact is inevitable to assess subtle translation of intraarticular movement.

The analysis of the humeral translation during active shoulder rotation is worth for dynamic instability evaluation. Tracking shoulder rotation angle with MR imaging and video camera imaging is a solution to link clinical findings of shoulder position and the intraarticular movement from imaging studies. Previous studies have not reported the intraarticular movement according to shoulder rotation position.

Verifying an MR scanning technique and an examiner's skills is an indispensable data prior to the quantitative analysis of the humeral translation using cine MRI. The purpose of this study thus was to investigate, (1) the reproducibility of MR imaging analysis by an examiner, (2) the validity and reliability of MR imaging using a phantom, and (3) the synchronizing with MR imaging and video camera data.

I-2. Methods

MR Scanning sequence and image analysis

Table 1 shows the scanning sequence using cine MRI. The acquisition time in the sequence was determined as 1 image /0.5s from 1 image/ 0.3s, 1 image /0.5s and 1image /1.0s, so that MR imaging can be recognized visually in imaging analysis. This scanning sequence was used in preliminary and main studies. MR imaging was analyzed using matlab 2016b (Mathworks Inc., Massachusetts, USA) in preliminary and main studies.

I-2-1. Reproducibility of MR imaging analysis by an examiner

The rotation angle on MR imaging was analyzed from 100 MR images chosen at random from ten shoulders (five healthy males, mean age 27.60 ± 4.39 years old). The rotation angle of the humeral head was measured as the angle between the line from the bicipital groove and the center of the humerus, and the line between the anterior and posterior edge of the glenoid.

An intraclass correlation coefficient (ICC(1, 2)) for the reliability of the examiner measuring rotation angles on the MRI was assessed in which one hundred scans of MRI were randomly selected and analyzed from the MR images of the participants. These MRI scans were analyzed again after a period of one week. Interpretation of ICC was judged according to four grades, poor (less than 0.5), moderate (0.5 to 0.75), good (0.75 to 0.90), and excellent (more than 0.90) (Koo and Li 2016).

I-2-2. Validity and reliability of MR imaging using a phantom

I-2-2-1. Validity of MR imaging at different angle

A phantom was fixed in the MRI horizontally which was confirmed using a level meter (Fig. I-1). The phantom imaging was captured at every 5° of rotation angle between 0 and 180° in static MRI and cine MRI after the angle of the phantom was set at a goniometer (Fig. I-1).

I-2-2-2. Reliability to analyze MR imaging at different angular velocities in vivo

Three healthy adults (6 shoulders) with a mean age of 29.00 ± 5.57 years old participated in this study. They were asked to rotate their shoulder at the arm by side of the body at three rotation velocities the same as main study (low: 15 cycles/ min, medium: 37.5 cycles/ min, and high: 52.5 cycles/ min). The static image was scanned to compare with the images during shoulder rotation. The radius and area of the humeral head was computed from the images scanned. The radius of the humeral head in this study was defined as the radius of the articular surface using the least mean square methods. The radius and the area of the humeral head in four rotation velocity conditions (static image, low, medium, and high velocities) were compared using one-way analysis of variance.

I-2-3. Synchronization with MR imaging and video camera data

Ten healthy males (20 shoulders) with a mean age of 27.80 ± 6.05 years old were asked to rotate their shoulders with their arms by the side of their body in an open MRI. The same MR technique and the same data analysis were used in the main study to compute the center of the humeral head. The rotation angle of the humeral head was measured using the same procedure as that used to assess the examiner's reliability. The external rotation angle of the shoulder at 0° adduction was measured as the angle between the line of gravity and the midline of the forearm. Subjects were asked to wear an arm brace in order to measure the midline of the forearm for shoulder rotation angle (Fig. II-1b). Pearson's correlation coefficient was performed to compare with rotation angle on MRI and video camera.

I-3. Results

I-3-1. Reproducibility of MR imaging analysis by an examiner

Reproducibility of the data was excellent, with an ICC of 0.98. The correlation was in Fig. I-2.

I-3-2. Validity and reliability of MR imaging using a phantom

I-3-2-1. Validity of MR imaging at different angle

There were no significant differences between the angle (p = 0.274298), the radius (p = 0.1106), and the area of phantom (p = 0.038211) using static and cine MRI. The rotation angle of phantom using static and cine MRI shows in Table I-1. The difference between the angle on MRI and true value was ranged -3.04° to 1.49° in static MRI and -3.08° to 2.54° in cine MRI, respectively. The radius and the area of the phantom showed in Fig. I-3a and 3b.

I-3-2-2. Reliability to analyze MR imaging at different angular velocities in vivo

There were no statistical differences of the radius (p = 0.999222) and the area (p = 0.992105) of the humeral head between four conditions (Fig. I-3c and 3d).

I-3-3. Synchronization with MR imaging and video camera data

Correlations of rotation angles at the three angular velocities were 0.90 for low velocity, 0.84 for medium velocity, and 0.77 for high velocity, respectively. The correlation of rotation angles between MR imaging and a video camera data for each participants appear in the scatter plot graph (Table I-2).

I-4. Discussion

I-4-1. Reproducibility of MR imaging analysis by an examiner

An excellent reproducibility was shown in imaging analysis by the examiner. There is certain reliability of imaging analysis between MR imaging when numerous image analysis was carried out over few days. The results indicated that the translation of the humeral head was able to be measured in chronological order. The imaging analysis in this study can be carried out with high reliability. The influence of motion artifact is discussed in I-4-2 and I-4-3.

I-4-2. Validity and reliability of MR imaging using a phantom

The methodology of this study was able to scan the shoulder images with the less effect of motion artifact. The radius increased in proportion to rotation velocity. However, the area of humeral head in high velocity decreased although there was no statistical difference between motion velocities. This subtle difference might be due to the blurred images. In high velocity, the area of humeral head could decrease as the outline of small circles in the phantom was blurred. On the contrary to the results of phantom image, the radius and area of humeral head at three rotation velocities was less different. The contrast between humerus and surrounded tissue was stronger than the handmade phantom. An image at fast velocity was able to be scanned up to 52.5 cycles/ min at this methodology.

I-4-3. Synchronization with MR imaging and video camera data

Shoulder rotation angle of the MRI correlated highly with that of the video camera at all angular velocities. There was a tendency to decrease the correlation between two imaging data in proportion to increase of shoulder rotation velocity. This might be because of the differences of image acquisition speed. The motion artifact could affect in both image of MRI and video camera data. However, the results demonstrated good correlation (Koo and Li 2016). The methodology of this study was eligible to link shoulder rotation position and the position of the humeral head.

I-5. Conclusion

The methodology of this study was verified in vivo and using a phantom. The results of this preliminary study demonstrated that the accurate analysis of the humeral translation was able to be carried out during active shoulder rotation. The examiner in this study showed reliable skills and knowledge for imaging analysis for main study. Image analysis in high velocity showed good data in MR imaging and video camera data.

II. MAIN STUDY

The quantitative analysis of the humeral translation at different rotational velocities: synchronizing with cine MRI and video camera to identify the shoulder position

II-1. Introduction

The glenohumeral joint is a morphologically unstable joint, which articulates the large surface of the humeral head with the shallow and small surface of the glenoid fossa. Hence, dynamic stability of the glenohumeral joint requires maintaining the humeral head on the glenoid fossa by appropriate onsets of rotator cuff muscles and deltoid muscles (Favre et al. 2012) and by the resulting compressing force towards the center of the glenoid fossa (Lippitt and Matsen 1993) during active shoulder motion. An in vivo study demonstrated that muscle contraction influenced the humeral head (Robert-lachaine et al. 2015). This study revealed that evaluation of intraarticular movement during active movement is vital in the assessment of dynamic stability.

The glenohumeral joint undergoes a wide range of motion at various speeds in daily activities, at work, and in sports. Translation of the humeral head during shoulder rotation has provided quantitative evidence in vivo studies (Bey et al. 2008; Dal Maso et al. 2014, 2015; Kozono et al. 2017). In those vivo studies provided data on humeral translation only during shoulder rotation (Bey et al. 2008; Kozono et al. 2017). The relationship between clinical findings of humeral translation and the findings of previous studies dilute as rotation positions of the humeral head did not synchronize with rotation positions of the glenohumeral joint.

The glenohumeral joint is subjected to opposing forces when the direction of shoulder motion is changed, accelerating and decelerating to make the movements. Physical evaluation for coordinated muscle control thus involves various motion velocities (Magarey and Jones 2003). The deviation of the humeral head and the rotation axis was observed during active shoulder rotation at various positions in the different types of contraction patterns and motion velocities when coordinated muscle control of the glenohumeral joint was dysfunction (Magarey and Jones 2003). Such evaluation is vital as altered muscle onset timing has been revealed in the unstable shoulder (Rajaratnam et al. 2013). Several imaging studies pertaining to variation of motion velocities ranging from 27.5°/s to 32.5°/s to analyze glenohumeral intraarticular movements have not revealed consistent findings (Bey et al. 2008; Kozono et al. 2017). Quality of movement is affected in slow motion (Arzi et al. 2014), pain can be provoked with quick active movement (Gross 1989), and apprehension is seen with quick passive movement (Milgrom et al. 2014) in unstable shoulder. To my knowledge, the effect of varying motion velocity on translation of the humeral head has not been evaluated although direction and distance of humeral head translation has been analyzed in real time in normal shoulders (Bey et al. 2008; Kozono et al. 2017). The purpose of this study was to analyze how the humeral head in a normal shoulder is under control among different rotation velocities, and to quantitatively clarify 'clinical' dynamic stability of the glenohumeral joint.

II-2. Methods

II-2-1. Study design and Participants

The observational and experimental study was conducted at Nobuhara Hospital in Japan. Ten healthy adults (eight men and two women, ten pairs of shoulders, average age 27.80 ± 6.05 years old) with no current or past history of cervical, thoracic, or shoulder disorder participated in this study. Physical examination of joint instability was done prior to MRI scan and we confirmed that the shoulders were structurally and dynamically stable. They were subject to exclusion if they had general magnetic resonance imaging (MRI) contraindications (Dill 2008).

II-2-2. Instrumentation

A 0.4T open MRI scanner (Aperto Eterna, Hitachi Medical Corporation, Japan) was used in this study. Shoulder rotation on an axial plane was captured every 0.5 s with a T2/T1 weighted image. The axial plane in this study was defined as where the scanning plane passed through the maximum width of the glenoid. The scanning sequence in a modified coherent gradient echo technique using an MRI device was in Table 1.

II-2-3. Procedure

The subject was asked to lie supine in an open MRI and to rotate the shoulder with the arm by the side of the body. A 30 degree elbow flexed position was maintained on the wedge shaped stand to enable sliding of the forearm during shoulder rotation (Fig. II-1a). This position was determined in a preliminary study to avoid the hand of subject hitting the coil of the MRI. Active rotation was controlled by a digital metronome at low (15 cycles/ min), medium (37.5 cycles/ min), and high (52.5 cycles/ min) speeds. The three rotational velocities were determined the rotation velocity by which shoulder rotation was less than 30°/s in daily activity in a previous study (Dal Maso et al. 2015), and by in a preliminary study of measuring maximum (i.e. high velocity) and minimum (i.e. low velocity) angular velocities during active shoulder rotation in patients with minor instability and pain. Medium velocity was defined as the middle of high and low velocities. One shoulder rotational cycle of repetitive shoulder rotational movement in this study was defined as shoulder rotation starting from maximum internal rotation, reaching maximum external rotation, and returning to maximum internal rotation. Each subject was instructed to perform shoulder rotation through maximum active range of motion for 20 seconds. An examiner measured range of shoulder rotation of each subject beforehand and checked via a video camera monitor whether or not the subject reached the end of internal or external rotation. Images were captured once the subject mastered the technique of the rotation movements required for the three rotation velocities. They were able to do that with a few minute practices which has been done prior to every shoulder image scanning.

A digital clock, synchronized with the time of capturing open MRI images, was displayed on the screen of an open MRI terminal. The shoulder rotation movements were captured using a digital, full high-definition video camera (resolution 1920 by 1080 pixels) (Fig. II-1c). The digital clock on the screen of the open MRI terminal was recorded in the visual field of the monitor camera so that the MRI images and shoulder rotation positions could be synchronized. Neutral rotation for this study was defined as when the forearm reached a full vertical position.

II-2-4. Data analysis

All imaging data of the MRI and video camera were analyzed after the initial six seconds in order to exclude the transitional period from resting position. The humeral head position and rotation angles on MR imaging and video camera were measured using Matlab 2016b (Mathworks Inc., Massachusetts, USA) before computing the translation of the humeral head (Fig. II-1d). The translation of humeral head was then measured the distance between the center of humeral head projected on the glenoid fossa and the center of the glenoid fossa (Fig. II-1d). All the data analyses were undertaken by one examiner. The reliability of data analysis was proven in a preliminary study (see Preliminary study).

II-2-4-1. Center of humeral head on MRI

The center of the humeral head was estimated as the center of a circle fitted to curvature of the head by the least squares method (Fig. II-1d). The sum of the difference of the square of the radius, *r*, in a circle is zero. The center of the humeral head, *HC* (*HCx, HCy*), was calculated from the articular surface of the humeral head, *HoHi* (*HoHxi, HoHyi*), was given by,

$$\Sigma\{r^2 - (HoHxi - HCx)^2 - (HoHyi - HCy)^2\} = 0$$

Hence, the center of the humeral head, *HC* (HCx, HCy) was given by,

$$HCx = (\Sigma HoHxi)/HoHi$$

$$HCy = (\Sigma HoHyi)/HoHi$$

The center of the glenoid was determined by bisecting a line between the anterior and posterior edges of the glenoid. Translation of the humeral head was defined in this study as the distance between the center of the glenoid and the perpendicular intersection at the glenoid of a line from the center of the humeral head (Fig. II-1d).

II-2-4-2. Shoulder rotation angle on video and MRI

The external rotation angle of the shoulder with the arm by the side of the body was measured as the angle between vertical and the orientation of the forearm (Fig. II-1c). A non-constraining brace was put on the forearm to aid in discerning the orientation of the forearm (Fig. II-1b). The orientation of the forearm was not affected by pronation or supination when the brace was applied in a pilot study. The rotation angle of the humeral head was the angle formed between a line connecting the bicipital groove to the center of the humeral head and a line parallel to a line connecting the anterior and posterior edges of the glenoid fossa that crossed the center of the humeral head (Fig. II-1d). The three angular velocities of rotation were computed.

The range of external and internal rotation with the arm by the side of the body was measured beforehand so that the rotation cycle of the shoulder position for each subject could be computed in terms of *shoulder rotation angle/ maximum rotation angle*. Excursion in one rotation cycle (from full external rotation to full internal rotation and back to full external rotation) was expressed as a percentage. A rotation from 0% to 100% and from 100% to 0% represents external rotation and internal rotation. This rotation cycle was used to normalize the slackened capsuloligamentous area in shoulder rotation range. Translation of the humeral head was computed as change in position of the humeral head every 20% of the rotation cycle, using linear interpolation.

II-2-5. Statistical analysis

The rotation arc at three rotation velocities was compared using one-way analysis of variance. Repeated measures two-way analyses of variance and Tukey-Kramer tests were used to analyze changes in position of the center of the humeral head among three rotational velocities during the rotational cycle. Statistical significance in analysis of variance was set at 0.05.

To judge sample size of this study, we performed a power analysis from the data of maximum translation of the humeral head in low and high velocities using Cohen's d, since humeral translation at different motion velocities has not previously been investigated in healthy shoulders. Interpretation of Cohen's d was judged according to three grades: small (0.2), medium (0.5), and large (0.8) (Lakens 2013).

II-3. Results

There were no statistically differences of rotation arc among the three rotation velocities ($p > 0.05$). The angular velocities in this study ranged from 36°/s to 117°/s. The effect size of this study showed medium power ($d = 0.50782$).

Position of the humeral head center was shown in scatter plot graphs and in line graphs at a given position using the least square methods in the rotation cycle at each of the angular velocities (Fig. II-2). The humeral head positioned 0.42 ± 1.82 mm posteriorly to 1.91 ± 1.69 mm anteriorly from the center of the glenoid fossa.

The course of humeral translation is shown in Table II-1. There were no statistically significant differences of humeral head position or of humeral translation among the three rotation velocities ($p > 0.05$). Translation of the humeral head was distributed to 0.67 ± 2.00 mm posteriorly from 1.44 ± 2.45 mm anteriorly at low velocity, to 0.75 ± 2.1 mm posteriorly from 0.74 ± 1.92 mm at medium velocity and to 1.51 ± 1.60 mm posteriorly from 2.62 ± 2.19 mm anteriorly at high velocity.

II-4. Discussion

II-4-1. What this study can add

This study captured the humeral head during active shoulder rotation using an MRI, and the shoulder using a video camera synchronizing with the MRI device. The results provide, in normal shoulders, there were no statistically significant differences in the position and translation of the humeral head among the three angular velocities. This demonstrated an aspect of dynamic glenohumeral stability of healthy adults in which humeral translation was not influenced by slow or quick motion velocities. Healthy shoulder has regular width fluctuation so that the humeral head positions ranged 0.42 mm posteriorly to 1.92 mm anteriorly from the center of the glenoid fossa as reference value for dynamic stability assessment. The reference value of humeral translation provided what clinicians have believed from their hands-on findings of dynamically stable joints was analyzed quantitatively in this study. The results of this study suggest that the possibility of dynamic glenohumeral instability during active shoulder rotation when the deviation from normal humeral distribution, or exceeded humeral translation of the humeral head was observed. The quantitative analysis of humeral translation in the healthy shoulder could render clinically fundamental information for dynamic stability of the glenohumeral joint. It provides some evidence to detect abnormal humeral translation by comparing with normal translation of the humeral head among the different rotation velocities as the humeral head cannot position in the center of the glenoid during active rotation velocity in patients with dynamic instability of the shoulder. The methodology in this study offers visualization of normal intraarticular movement of the glenohumeral joint at various motion velocities for comparison with shoulder dysfunction initially detected by the clinician manually.

II-4-2. Precision of methodology

Active rotation range of motion did not statistically differ among the three angular velocities, ranged from 65.18 ± 14.76° to 68.23 ± 17.73°. These findings demonstrate that intraarticular movement was assessed with essentially the same precision of shoulder rotational position and active shoulder range of motion at all three angular velocities. The rotation angle in this study was close to that in previous studies (Bey et al. 2008; Dal Maso et al. 2014). In terms of possible rotation angle difference, the results showed that the value of standard deviation of rotation arc was less than 20°. Even 10 % of rotation cycle shows that possible angle difference was 2°. Hence, this study judged the differences of rotation angle between each subject were not serious issue since the nature of this difference is close to step length between people. Although there was possible different distribution of humeral head position and different range of humeral translation can be seen in lower and higher rotation velocities in this study, the rotation velocities were appropriate. This was because the rotation velocities were determined on basis of whether patients with pain and dynamic instability of the shoulder tolerate to rotate the shoulder as possible as quick or slow.

Sample size was determined according to previous MRI studies (Bey et al. 2008; Pierrart et al. 2014; Sahara et al. 2007). A 3D MRI study recruited four to seven participants to measure active shoulder elevation (Pierrart et al. 2014; Sahara et al. 2007). Five shoulders in post-surgery of rotator cuff reconstruction were compared the humeral translation with that of the contralateral shoulders (Bey et al. 2008). This study recruited sufficient sample of healthy shoulders with medium power in Cohen's d. In future study, our results of dynamic glenohumeral stability is comparable data with dynamic glenohumeral instability.

II-4-3. Position of humeral head

The distribution of humeral head position at low velocity was close to previous study (Bey et al. 2008). The distribution of humeral head could be joint play during shoulder rotation. Our results might demonstrate that measuring glenohumeral intraarticular movement was able to scan with the same procedure as Bey et al. (2008). On the other hand, shift in humeral position from internal to external rotation at low velocity differed from previous studies (Bey et al. 2008; Kozono et al. 2017). The main methodological difference was that shoulder rotation in this study was repetitive shoulder rotation. The humeral head might have positioned itself differently for repetitive continuous shoulder rotation as internal rotation started immediately after external rotation in this study. The humeral head position at low velocity remained anterior to the center of the glenoid fossa, although the subject's supine position might have been a factor to mechanically translate the humeral head posteriorly. This result implies that the humeral head at low velocity positioned near the center of the glenoid by appropriate muscle control in conjunction with the mechanical conditions of gravity and inertial force during shoulder rotation. The humeral head in dynamic instability might deviate from the distribution of humeral head position in this study.

II-4-4. Translation of humeral head

Translation of the humeral head in this study suggests that there would be physiological fluctuation during ordinary shoulder motions in a normal shoulder. Consider how the humeral head is subjected to accelerations, decelerations and changes direction of shoulder rotation. Near the beginning of rotation, the humeral head might be influenced by sudden muscle contraction that first generates the rotational motion. Changing the direction of rotation involves appropriate muscle activation to decelerate one joint movement and then generate the opposite joint movement while maintaining a stable intraarticular environment.

The effect of the relatively slack shoulder tissues of opposite side might influence fluctuation of humeral translation as the contraction by agonist rotator muscles extrudes the humeral head. In a cadaveric study, this phenomenon was attributed to capsular tightness on the contralateral side (Harryman et al. 1990). During active shoulder rotation, extrusion of the humeral head is thus more likely toward the side contralateral to that of the sudden contracting muscles if uncoordinated muscle control.

II-4-5. Advantage of methodology in this study

An advantage of MR scanning in this study is the non-invasive nature of the instrument and no need to prepare for the analysis. The number of subjects was restricted due to radiation exposure in fluoroscopic and biplane studies (Bey et al. 2008; Matsuki et al. 2012; San Juan et al. 2013) or to markers mounted into bone in a motion capture study (Dal Maso et al. 2014, 2015). The scanning time for one elevation requires 4 seconds in a 3D MRI study (Pierrart et al. 2014). Although cine MRI contains less information than 3D MRI, it can scan the shoulder at higher velocity with 114°/s than angular velocities observed in previous studies (Bey et al. 2008; Matsuki et al. 2012; San Juan et al. 2013; Pierrart et al. 2014). The methodology of this study might be useful for detecting, during rotary movement, abnormal humeral translation due to macro or micro trauma in daily activities.

II-4-6. Future application of this study

The methodology of this study could detect abnormal humeral deviation in movement impairment syndrome. The rotation velocities were sufficient as the rotation velocities was designed to scan dynamic instability of the shoulder for future study. That is, the shoulder rotation velocities in this study were determined so that patients with unstable shoulder and pain tolerate to rotate their shoulder during scanning intraarticular movement of the glenohumeral joint. Patients with multidirectional instability (MDI) and rotator interval lesion (RI) including inferior instability due to the laxity of capsular (Chechik et al. 2010; Lee et al. 2013; Muto et al. 2015), requires the improvement of coordinated muscle control in physiotherapy intervention. The methodology might visualize the instant deviation of the humeral head or rotation axis that palpation detects. The scanning technique of this study could detect such dynamic glenohumeral instability, especially, in mid-range of shoulder rotation where coordinated muscle control provides dynamic stability. A humeral head was unable to be centered if muscle control was impaired as the static stability by capusuloligamentous structure is the least in mid-range of shoulder rotation. By comparing with normal value provided, the methodology of this study could be a diagnostic tool for functional impairment. This methodology could be of a great benefit to the other joints with motor control deficit. Low back disorder associated with instability due to delayed muscle onset timing of primary motor muscle (Selkow et al. 2017), a catching sensation (Hipp et al. 2015; Press 2015; Denteneer et al. 2016) and positive finding of active straight leg raise test (Liebenson et al. 2009) might be detected motor control deficit. Similarly, cervical pain provokes motor control deficits (Meisingset et al. 2015). It would be outcome measure for physiotherapy intervention if this methodology could visualize such dynamic instability.

II-4-7. Limitation of this study

A limitation of this study was that the motion analyzed was restricted to a single rotatory plane. This is a far cry from continuous functional shoulder movements such as combing hair or reaching for an object. Future research is required to confirm the role of varying shoulder rotational speed in analyzing dynamic instability of the glenohumeral joint to achieve enhanced performance of activity in the shoulder.

II-5. Conclusions

The reference value of humeral translation provided what clinicians have believed from their hands-on findings of dynamically stable joints was quantitatively analyzed in this study. Intraarticular movement of the glenohumeral joint was validated at different rotation velocities using cine MRI synchronized with a video camera. The results revealed that, in the dynamically stable glenohumeral joint, humeral head position and translation did not significantly differ among three rotation velocities of active shoulder rotation. This study showed that a physiologically stable glenohumeral joint has approximately 2 mm joint play.

III. Nomenclature

MRI: Magnetic Resonance Imaging

TR: Time Repetition

TE: Time Echo

ICC: Intraclass Correlation Coefficient

ROM: Range of Motion

IR: Internal Rotation

ER: External Rotation

3D: three dimensional

r: Radius of humeral head

HoHi: coordinate of an articular surface of the humeral head

HC: Center of humeral head

IV. Competing interest

The authors declare that there was no competing interest in this study.

V. Ethics approval and consent to participate

The ethics committee of Nagoya University (14-504) approved this study. All subjects gave informed consent in a document prior to participating in this study.

VI. Acknowledgement

All work for this study was conducted under the direction of Professor Yasushi Uchiyama. This study was one of my goals how to visualize the hands-on findings of the intraarticular movement by manual therapists. I especially would like to express my gratitude to Professor Yasushi Uchiyama who supervised the experimental design and procedure and contributed to the manuscript draft. I was given the considerable advice and learnt how to build and verify my hypothesis and explain my opinion with logical expression. I also would like to express the deepest appreciation to the members of the examination committee for my dissertation, Professor Eishi Sugiura and Professor Kazuhiro Shimamoto. Both of them gave me thoughtful comments and constructive suggestions to improve my dissertation after examination.

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I deeply appreciate my old friend, Mr. Haruo Imamura who passed away in 1996. It is unforgettable and irreplaceable memory that Haruo amd me often discussed about physiotherapy in our school days. This encounter with him was one of opportunities that I decided to study in higher education. I wish he could have a read my dissertation.

Finally, I thank my family, my wife, Namie, and children, Aimi, Narika, Yuri, and Lion born around the end of August. I was unable to complete the dissertation without their support.

VII. Tables

Table 1. Scanning sequence using cine MRI in this study

The following sequence in using an MRI device was used in preliminary and main studies.

MRI scanning sequence	Parameter
Scanning technique	Modified coherent gradient echo technique
Scanning plane	Axial plane
Time repetition	4.4 ms
Time echo	2.2 ms
Flip angle	90º
Slice thickness	1.7 mm
Bandwidth	160 kHz
Field of view	32 cm × 32 cm
Matrix	256 × 256 pixels
Acquisition time	0.5 s / image

Table I-1. Angle of the phantom using static and cine MRI comparing with true value (Deg).

True value	Static MRI	cine MRI	True value	Static MRI	cine MRI
0	-2.69	-1.63	95	95.22	94.61
5	5.67	5.85	100	98.59	98.20
10	9.81	9.37	105	105.38	104.49
15	14.14	16.01	110	108.60	108.41
20	18.81	20.19	115	113.00	114.05
25	25.90	25.97	120	118.39	119.23
30	29.19	29.95	125	123.50	124.12
35	33.45	34.21	130	127.92	127.28
40	40.21	39.04	135	133.02	133.62
45	43.29	45.26	140	138.96	136.92
50	47.48	49.19	145	143.53	143.38
55	55.23	55.71	150	150.53	150.40
60	61.49	60.53	155	153.66	154.35
65	64.77	67.55	160	158.30	158.35
70	68.96	68.89	165	164.73	165.57
75	74.20	72.09	170	169.27	167.93
80	77.77	82.04	175	171.96	172.75
85	84.64	83.74	180	178.20	178.94
90	87.98	87.86			

Table I-2 Correlation of rotation angles between MR imaging and a video camera data in each participants (Rt: right shoulder, Lt: left shoulder).

	Low velocity		Medium velocity		High velocity	
Participants	Rt	Lt	Rt	Lt	Rt	Lt
A	0.94	0.76	0.74	0.75	0.88	0.86
B	0.67	0.85	0.91	0.86	0.63	0.82
C	0.96	0.73	0.86	0.81	0.86	0.70
D	0.81	0.95	0.76	0.82	0.66	0.70
E	0.97	0.92	0.86	0.88	0.73	0.66
F	0.97	0.93	0.82	0.87	0.61	0.91
G	0.97	0.98	0.97	0.77	0.88	0.97
H	0.96	0.91	0.68	0.83	0.66	0.68
I	0.82	0.99	0.96	0.97	0.95	0.66
J	0.98	0.98	0.62	0.98	0.65	0.89
mean	0.90	0.90	0.82	0.85	0.75	0.78
	0.90		0.84		0.77	

Table II-1 Anterior translation of the humeral head from the center of the glenoid fossa at every 20% of the rotation cycle (mean ± SD mm)**.** IR: Internal Rotation, ROM: Range of Motion, ER: External Rotation, 0%: Full IR, 100%: Full ER.

Movement	Position		Low	Medium	High
ER motion	Far ER	0-20%	0.65 ± 1.30	0.74 ± 1.92	2.62 ± 2.19
	Near ER	20-40%	0.32 ± 2.55	0.60 ± 2.03	-0.01 ± 1.66
	Mid ROM	40-60%	-0.57 ± 1.63	0.05 ± 1.78	-0.03 ± 1.43
	Near IR	60-80%	-0.21 ± 1.24	-0.33 ± 1.98	-1.17 ± 1.44
	Far IR	80-100%	-0.67 ± 2.00	-0.75 ± 2.17	0.30 ± 0.62
IR motion	Far IR	100-80%	1.44 ± 2.45	0.14 ± 2.49	0.93 ± 1.85
	Near IR	80-60%	0.65 ± 1.64	0.31 ± 1.42	0.34 ± 1.84
	Mid ROM	60-40%	-0.65 ± 1.84	0.07 ± 1.35	-0.15 ± 1.37
	Near ER	40-20%	-0.46 ± 1.49	-0.51 ± 1.18	0.31 ± 2.67
	Far ER	20-0%	0.39 ± 1.81	-0.63 ± 1.81	-1.51 ± 1.60

VIII. Figures

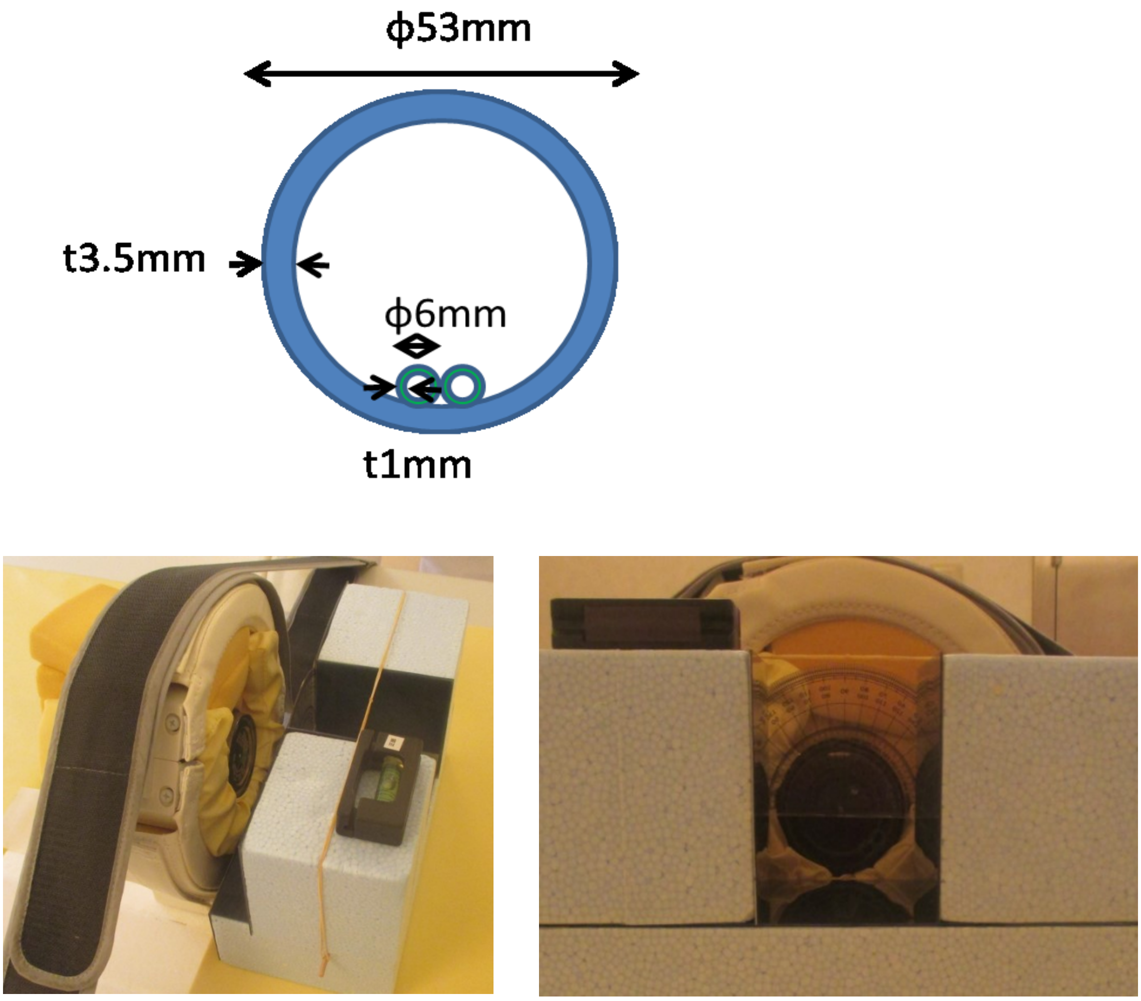

Fig. I-1. Experimental imaging using a phantom in MRI device. The size of the phantom (Fig. I-1a: top). Phantom was fixed horizontally by referring a level meter (Fig. I-1b: left bottom). The rotation angle of the phantom was determined according to a goniometer (Fig. I-1c: right bottom).

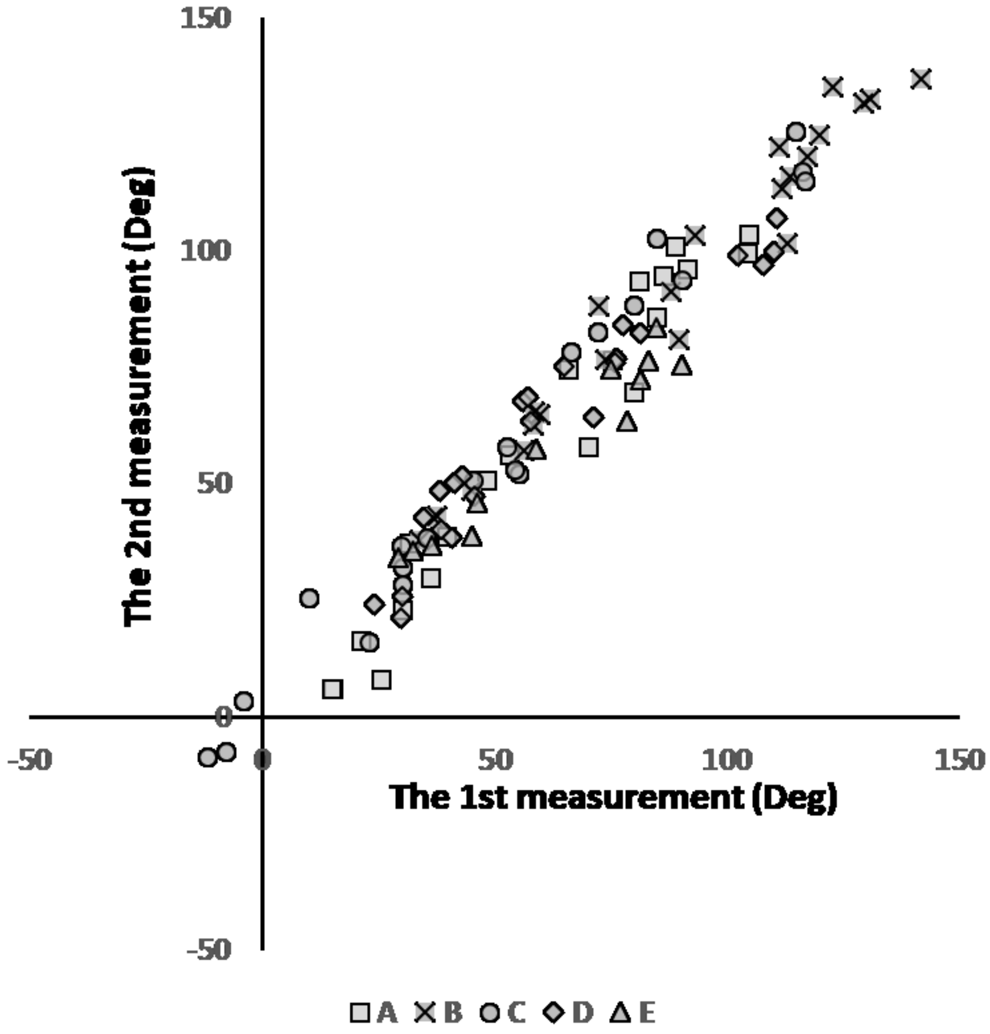

Fig. I-2 Reproducibility of the rotation angle in the first and the second measurement. A to E represents the participants.

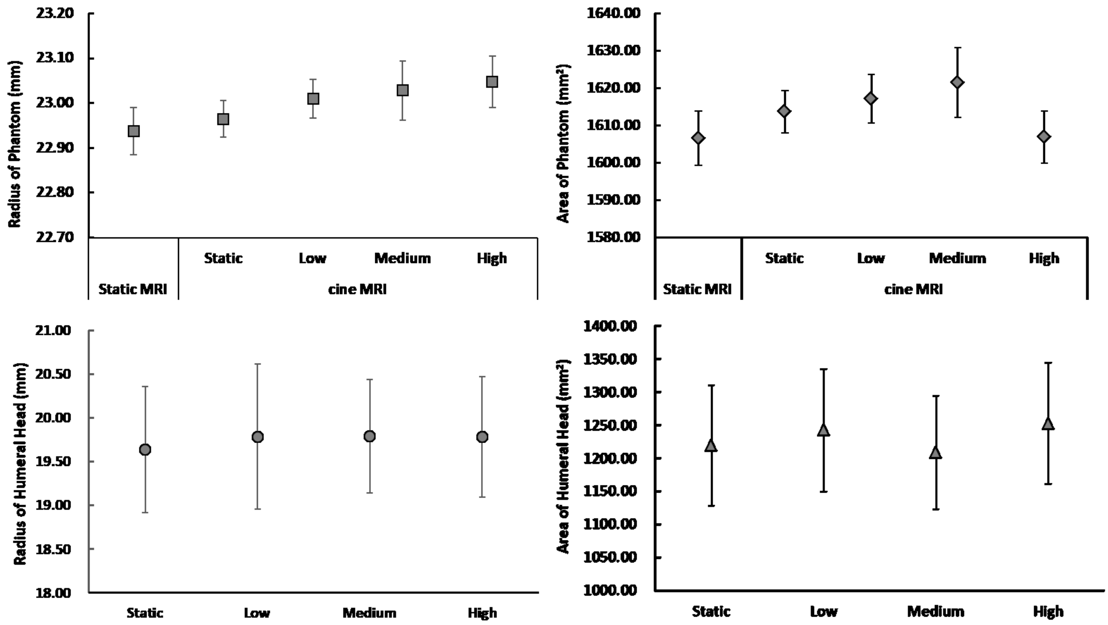

Fig. I-3. Size of phantom and humeral head imaging (Static: static imaging, Low: low velocity, Medium: medium velocity, High: high velocity, Error bar: 95% confidence interval). Square marker represents the mean value of the radius of phantom imaging (Fig. I-3a: left top). Diamond marker represents the mean value of the area of phantom imaging (Fig. I-3b: right top). Circle marker represents the mean value of the radius of the humeral head (Fig. I-3c: left bottom). Triangle marker represents the mean value of the area of the humeral head (Fig. I-3d: right bottom).

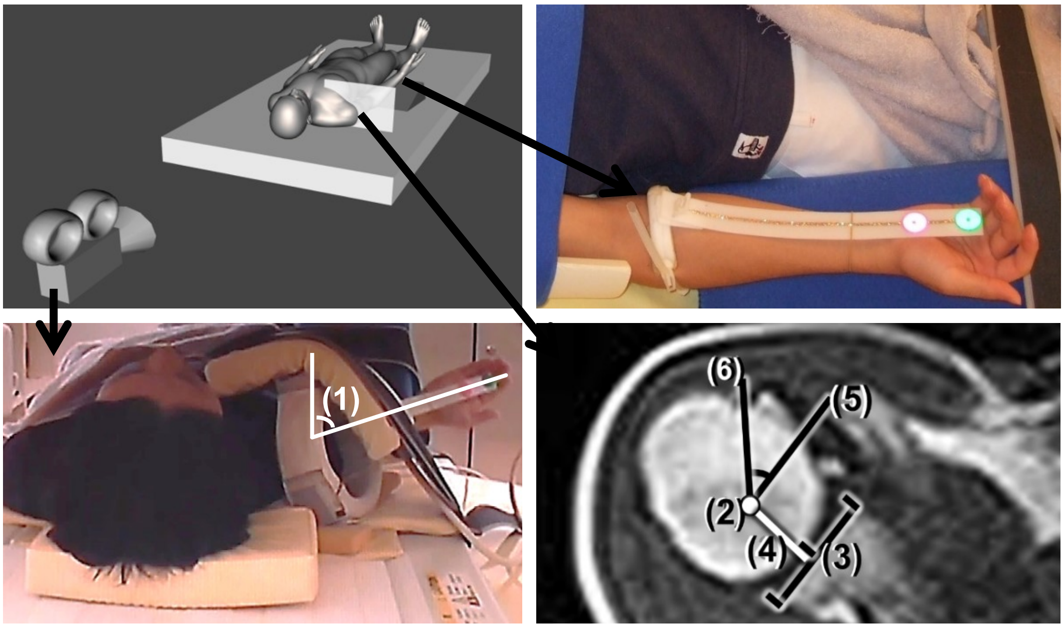

Fig. II-1 Experimental imaging. Fig. II-1a (left top) shows the view of the video camera that was synchronized with the MRI. Fig. II-1b (right top) shows a non-constraining brace applied to the subject's forearm. The position of the brace was not affected by pronation or supination of the forearm. Fig. II-1c (left bottom) is a frame captured by the video camera, showing (1) the shoulder rotation angle. Fig. II-1d (right bottom), taken from an MRI scan, shows how translation of the humeral head and rotation angle on MRI are defined. (2) Center of the humeral head. (3) Center of the glenoid fossa. (4) Line from the center of the humeral head perpendicular to the glenoid. Translation of the humeral head is defined as the distance between (3) and (4). (5) Line parallel to a line connecting the anterior and posterior edges of the glenoid and crossing the center of the humeral head. (6) Line connecting the bicipital groove to the center of the humeral head. The rotation angle of the humeral head is defined as the angle between (5) and (6).

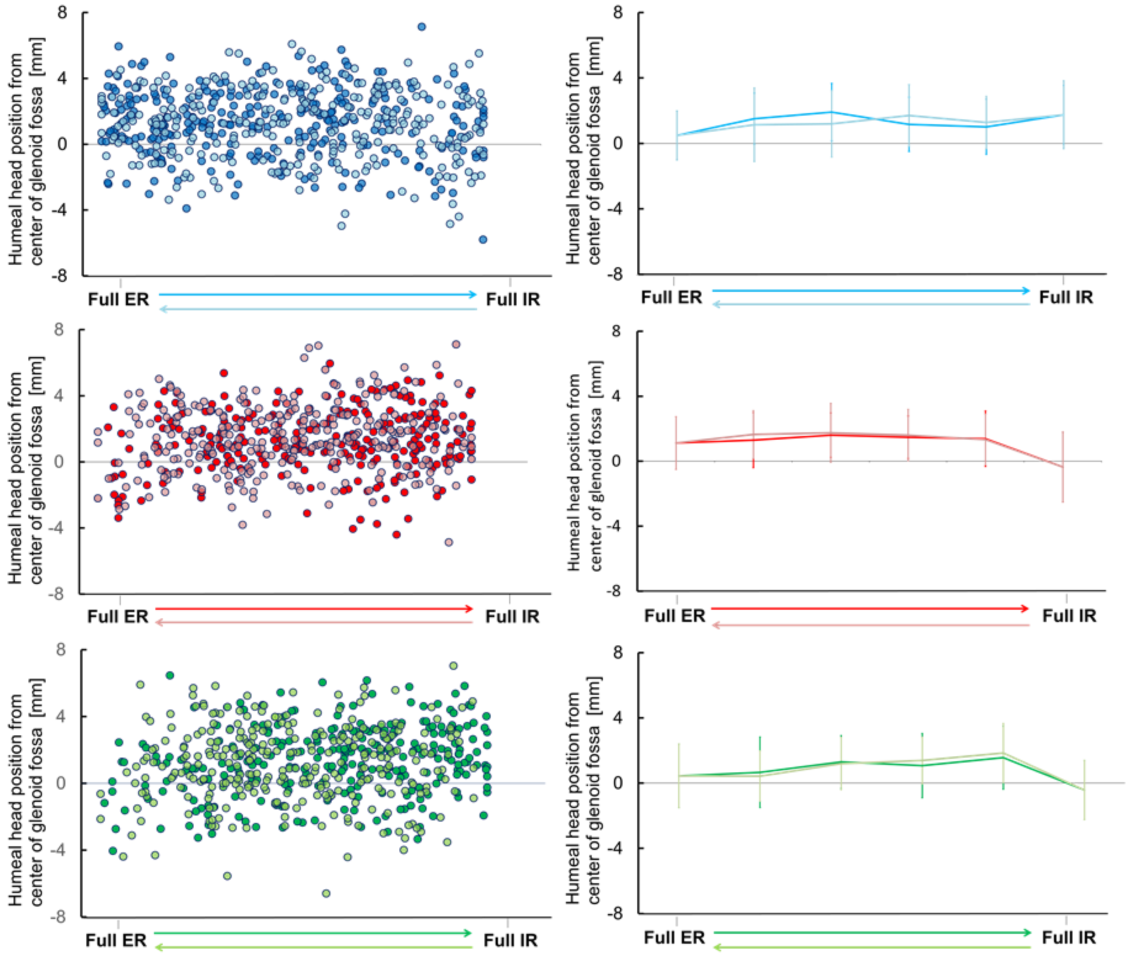

Fig. II-2 Distribution of humeral head position (the left scatter plot graphs) and mean value of humeral head position (the right line graphs). X-axis represents shoulder rotation (Full IR: Full internal rotation; Full ER: Full external rotation). Y-axis represents the humeral head position from the center of the glenoid fossa (mean ± SD mm). Blue markers (top row) are for low velocity. Red markers (middle row) are for medium velocity. Green markers (bottom row) are for high velocity. The darker markers and lines represent IR and the lighter markers and lines represent ER.

IX. References

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