Reliability and accuracy of distance measurements between shoulder bony landmarks evaluated by ultrasound in asymptomatic subjects

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Attestation of Authorship

“I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.”

Marion Duerr

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Abbreviations

AC	Acromioclavicular
AGTD	Acromion - greater tuberosity distance
AHD	Acromiohumeral distance
CV	Coefficients of variation
CAL	Coracoacromial ligament
GH	Glenohumeral
HGD	Humeroglenoid distance
ICC	Intraclass correlation coefficient
RC	Rotator cuff
SEM	Standard error of measurement
SIS	Shoulder impingement syndrome
SRD	Smallest real difference
US	Ultrasound
USI	Ultrasound imaging

Abstract

Background: Assessment of the glenohumeral (GH) joint is an integral part of clinical physiotherapy practice. Changes of normal GH joint kinematics occur frequently in individuals with GH joint disorders. Faulty GH kinematics can involve abnormal resting position of the humeral head and abnormal translation of the humeral head on the glenoid in the superior-inferior and/or anterior-posterior direction. Ultrasound imaging (USI) is a versatile imaging technique, which is becoming increasingly available for clinical use in physiotherapy. USI allows for assessment of distances between the humeral head and scapular landmarks, such as the acromion and the glenoid in various shoulder positions. Currently, only a small number of studies have applied USI for the assessment of distances between the humeral head and scapular landmarks, and humeral head translation occurring GH movement. Well-described methodologies are scarce and there is insufficient evidence for the reliability of USI assessing distances and humeral head translation.

Objective: The main objective was to determine the intra-rater reliability and accuracy of USI distance measurements between the humeral head and scapular landmarks, i.e. the acromion and the glenoid in a neutral shoulder position and in passive and active GH joint abduction. Further objectives were to determine normal values of these distances in the three shoulder positions in healthy individuals, and to assess the distance changes that occur with GH joint movement. Another objective was to compare measurements between genders and between the dominant and non-dominant side, as well as to examine the relationships between participants' characteristics and distance values.

Study Design: Intra-rater (single assessor) reliability study using same individuals repeated measures test-retest design.

Methods and Measurement: The USI methodology was developed in a pilot study. In the main study, 40 healthy subjects without a history of shoulder pain or injury were recruited. In the superior-inferior direction, the acromiohumeral distance (AHD) and the distance between the acromion and the greater tuberosity (AGTD) were measured using a superior USI view. In the anterior-posterior direction, the humeroglenoid distance (HGD) was measured using a posterior transverse USI view. AHD, AGTD and HGD were determined in a neutral shoulder position. In addition, AHD and HGD were measured at 60º passive and active GH joint abduction. Two consecutive measurements of each distance were taken by one examiner in two sessions, which were five to seven days apart. Statistical analysis included the intraclass correlation coefficient (ICC) for single measures for assessing the within- and between-sessions intra-rater reliability, and a Bland-Altman analysis. Measurement error and accuracy were calculated using the standard error of the measurement (SEM) and the smallest real difference (SRD). Independent samples *t*-tests were used to compare differences between mean values of the AHD and HGD in the three shoulder positions; between men and women; and between the dominant and non-dominant side. Correlations between distance measurements and participants' characteristics, such as body weight, height, age and overhead sports activities were analysed using regression analysis.

Results: ICC values were high to excellent for all distance measurements. ICC values were lower between sessions than within sessions, particularly for the HGD measurement. Measurement errors were small for all measurements, including SRD values of 0.12 cm for the AGTD, 0.09 cm for the AHD and 0.05 cm for the HGD in the neutral shoulder position, and 0.05 cm for the AHD and 0.14 cm for the HGD in abducted shoulder positions. In session 1, mean values (± SD) of the AGTD and AHD were 1.45 (± 0.28) cm and 1.07 (± 0.18) cm respectively in the neutral shoulder position. In 60º passive and active abduction, mean values of AHD were 0.81 (± 0.21) cm and 0.78 (± 0.19) cm respectively. In neutral, 60º passive and active abduction, mean values of HGD were 1.34 (± 0.38) cm, 1.20 (± 0.41) cm and 1.08 (± 0.40) cm respectively. Distances in Session 2 were comparable. AHD and HGD mean values decreased significantly when the arm was moved from the neutral position into abduction, while distances did not change significantly between passive and active abduction. Distances were found to be smaller in women compared to men, but no difference was detected between the dominant and non-dominant side. Body weight was significantly correlated with AHD and HGD. Moreover, HGD measurements were correlated with height and age. Participation in overhead sports activities had no effect on measured distances.

Conclusion: The results show that the USI method that was developed and applied in this research is highly reliable for the repeated application by one examiner. Furthermore, the low measurement errors suggest that this USI method is accurate enough to detect a small difference between two measurements, which may well be clinically important. Of the two measurements used in the superior USI view, the AHD showed higher quality, as it proved applicable in both the neutral and the abducted position, whereas the AGTD was not useable in shoulder abduction. The significant reduction of the AHD and HGD with 60º abduction indicates that the humeral head translates in an anterior-superior direction with abduction in healthy shoulders. This research has developed a reliable and accurate USI method, which uses reproducible anatomical landmarks visible on the USI image, functionally relevant shoulder positions for acromio-humeral and gleno-humeral distance measurements in both the superior-inferior and anterior-posterior direction, and is achievable for inexperienced examiners. Future studies are warranted to establish the reliability of the USI method between several examiners and in other shoulder populations, and to further examine the role of these measurements in shoulder disorders.

Key Words: Ultrasound imaging, glenohumeral joint, humeral head translation, distance measurement, intra-rater reliability, acromiohumeral distance, humeroglenoid distance, shoulder abduction.

1 Introduction

Physiotherapists routinely assess, diagnose and treat individuals with disorders of the glenohumeral (GH) joint. As part of this assessment, Physiotherapists utilise subjective and objective tests, which can be complemented by the use of imaging techniques. Ultrasound imaging (USI) is one of these imaging tools, and has seen tremendous advancements regarding image resolution, fields of application and costs of equipment in recent years (Kane, Grassi, Sturrock, & Balint, 2004c). In musculoskeletal medicine, USI is routinely used for diagnostics, monitoring and intervention. In the GH joint, USI is a first-line imaging modality and commonly utilised by sonographers for assessment of the rotator cuff (RC) tendons and subacromial bursa to reach a structural diagnosis (Kane, et al., 2004c; Martinoli, Bianchi, Prato, Pugliese, Zamorani, Valle, et al., 2003).

There is increasing interest from clinical therapists in integrating USI into rehabilitation as an adjunct for assessment, treatment evaluation and research due to its various benefits (Whittaker, Teyhen, Elliott, Cook, Langevin, Dahl, et al., 2007). USI is safe, easy to use, portable and relatively low-priced (Kane, Balint, Sturrock, & Grassi, 2004a). As a dynamic imaging method, USI is suitable for examining tissues both statically and dynamically with the individual in various positions, and is generally more accessible than other imaging methods, such as magnetic resonance imaging (MRI) and radiography (Bureau, Beauchamp, Cardinal, & Brassard, 2006; Martinoli, et al., 2003). Moreover, less specific training and skills are required for the application of USI in the area of rehabilitation compared to USI used for diagnostics of tissue pathology (Whittaker, et al., 2007).

USI is used in musculoskeletal rehabilitation for evaluating features of muscle morphology and muscle contraction and as a biofeedback tool (Wallwork, Hides, & Stanton, 2007; Whittaker, et al., 2007). More recently, USI is used in shoulder assessment for the quantification of distances between the humeral head and bony landmarks of the scapula, such as the acromion and the posterior or anterior part of the glenoid (Azzoni, Cabitza, & Parrini, 2004; Borsa, Jacobson, Scibek, & Dover, 2005a; Cheng, Hulse, Fairbairn, Clarke, & Wallace, 2008; Cholewinski, Kusz, Wojciechowski, Cielinski, & Zoladz, 2008; Desmeules, Minville, Riederer, Cote, & Fremont, 2004; Girometti, De Candia, Sbuelz, Toso, Zuiani, & Bazzocchi, 2006; Jerosch, Marquardt, & Winkelmann, 1991; Krarup, Court-Payen, Skjoldbye, & Lausten, 1999; Martinoli, et al., 2003; Pijls, Kok, Penning, Guldemond, & Arens, 2010; Schmidt, Schmidt, Schicke, & Gromnica-Ihle, 2004; Silva, Hartmann, Laurino, & Biló, 2008; Yeap, McGregor, Humphries, & Wallace, 2003). Distances that have been investigated with USI include the width of the subacromial space in the superior-inferior direction and the distance between the humeral head and a scapular landmark in the anterior-posterior direction. USI has been used to determine the position of the humeral head in relation to these landmarks and to express humeral head translation in relation to these scapular landmarks based on distance changes.

Usually, physiotherapists use palpation to assess the position of the humeral head in relation to bony landmarks of the scapula and to track the change of the position of the humeral head during passive or active arm movements (McKenna, Straker, & Smith, 2009). However, this assessment is performed manually and rated subjectively. USI, on the other hand, allows objective evaluation of distances between the humeral head and scapular bony landmarks. However, currently there is no standardised USI methodology for measuring these distances. Furthermore, there is a dearth of reports on reliability of USI for quantification of distances between the humeral head and scapular landmarks.

Quantification of distances between the humeral head and scapular landmarks, and humeral head translation has the potential to contribute valuable information about GH joint kinematics in assessment, treatment evaluation and research of the GH joint. However, the exact USI methodology and its reliability need to be established. Therefore, the main objective of this thesis is to develop a reliable USI methodology for distance measurements between the humeral head and scapular landmarks in the superior-inferior and the anterior-posterior direction.

The following chapters will summarise the anatomy and biomechanics of the shoulder, followed by a literature review, specifically of studies that utilise USI for distance measurements at the GH joint. The thesis then moves on into the experimental part, involving the development of the USI methodology and a reliability study. The result section will present the outcomes of the data analysis comprising the reliability and accuracy of the USI method, values of the distance measurements and correlations between distances and participants' characteristics. This is followed by the discussion of the results, conclusions and outlook for further research.

2 Shoulder anatomy and biomechanics

2.1 Anatomy

The bony frame of the shoulder complex is formed by the scapula, the humerus and the clavicle. Three synovial joints are part of the shoulder complex, the GH joint, the acromiohumeral (AC) and the sternoclavicular joint. The GH joint is formed by the small and shallow glenoid cavity of the scapula and the large head of the humerus (McMinn, 2005). With the glenoid covering only about one third of the humeral head, the proportions between those two bony structures have been compared to a golf ball sitting on a golf tee, or a seal balancing a ball on its nose (Kibler & Murrell, 2008).

The glenoid labrum, a ring of fibrocartilage attaching to the margins of the glenoid cavity, substantially increases the size and depth of the glenoid cavity, thereby enhancing congruency between the glenoid and the head of the humerus (Ludewig & Borstead, 2005; Prescher, 2000). The GH joint is surrounded by a large and loose joint capsule, which is attached to the margin of the labrum and the humeral head. The capsule features multi-directional fibre orientation and is reinforced by the superior, middle and inferior GH ligaments as well as the coracohumeral ligament (Lugo, Kung, & Ma, 2008; Veeger & van der Helm, 2007).

Between the anterior third of the acromion and the coracoid process spans the broad triangular coracoacromial ligament (CAL) (McMinn, 2005). Together with its osseous fixations, the CAL builds the coracoacromial arch, which forms a roof overlying the humeral head (Figure 1). The space that is confined by the coracoacromial arch superiorly and the humeral head inferiorly is called subacromial space (Ludewig & Borstead, 2005; Neer, 1972) (Figure 2). The soft tissues embedded in the subacromial space are organised in a stratified manner. The most internal structure is the tendon of the long head of biceps brachii, followed by the joint capsule, the rotor cuff (RC) tendons (primarily the supraspinatus tendon), and the subacromial bursa (Prescher, 2000).

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Figure 1. **Coracoacromial arch.**
Lateral view of right shoulder. Adapted from “Anatomical basics, variations, and degenerative changes of the shoulder joint and shoulder girdle,“ by A. Prescher, 2000, *European Journal of Radiology*, 35, p.94.

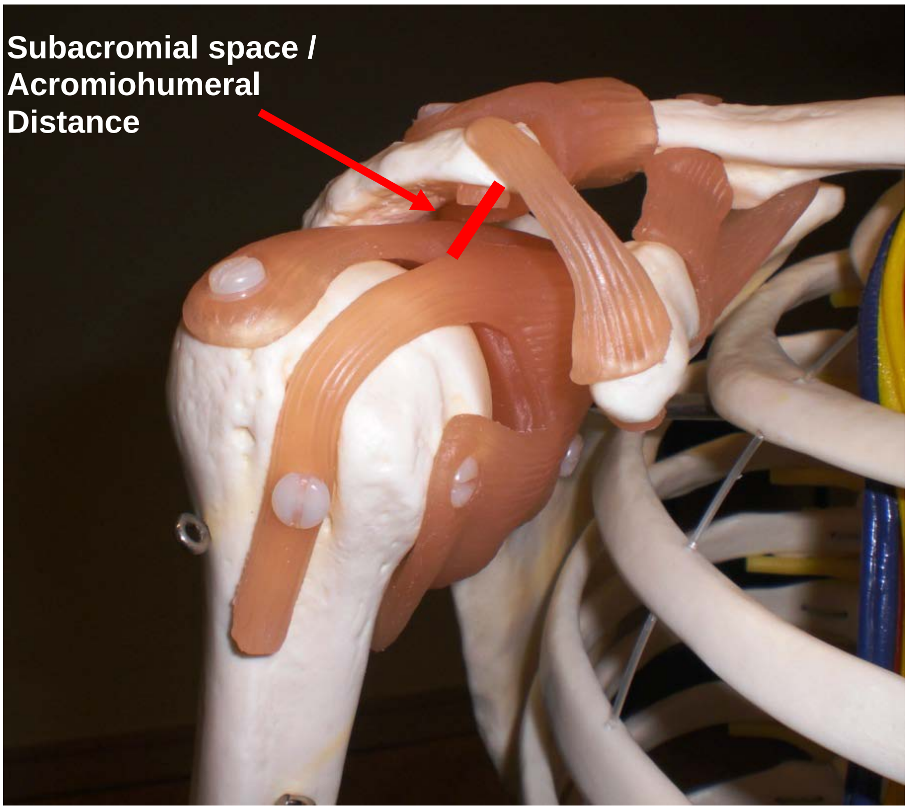

Figure 2. **Subacromial space / Acromiohumeral distance.**
Anatomic model of right shoulder.

The long head of biceps tendon arises from the supraglenoid tubercle and the superior part of the glenoid labrum, and passes over the humeral head through the GH joint cavity (Lugo, et al., 2008; McMinn, 2005). The subacromial bursa is large and thin-walled and lies underneath the coracoacromial arch, extending beyond the lateral border of the acromion. Its upper layer is firmly attached to the undersides of the CAL and the acromion (McMinn, 2005; Strizak, Danzig, Jackson, Resnick, & Staple, 1982). The subacromial bursa allows the subacromial structures to slide underneath the coracoacromial arch during shoulder abduction and external rotation (Prescher, 2000).

The GH joint is surrounded by a group of five muscles, converging from the scapula to the humerus: the supraspinatus, infraspinatus, teres minor, teres major and subscapularis muscles (McMinn, 2005). The supraspinatus, infraspinatus and teres minor pass from the posterior surface of the scapula and insert into the greater tuberosity of the humerus, while the subscapularis passes from the thoracic surface of the scapula to the lesser tuberosity (McMinn, 2005). The tendons of the supraspinatus, infraspinatus, teres minor and subscapularis muscles fuse to a musculotendinous cap, referred to as rotator cuff (RC), covering the GH joint from the dorsal, cranial and ventral side (Prescher, 2000).

The deltoid muscle, the main abductor of the GH joint, arises from the acromion, the spine of the scapula and distal clavicle, and inserts into the humerus, thereby covering the GH joint and RC like a cape (Ludewig & Borstead, 2005; McMinn, 2005). There are a number of scapulothoracic muscles passing from the thorax to the scapula and to the humerus respectively, thereby contributing to scapular and GH motion. The latissimus dorsi and pectoralis major are two important generators of adduction torques about the shoulder joint (Lugo, et al., 2008; McMinn, 2005).

2.2 Function and biomechanics

Functionally the GH joint is a ball and socket joint exhibiting three rotational and three translational degrees of freedom (McMinn, 2005). The design of the GH joint allows for a wide range of arm mobility, making the GH joint the most mobile joint in the human body (Ludewig & Borstead, 2005). Nevertheless, the wide range of movement of the upper extremity is in fact a result of both the movement of the GH joint and the gliding of the scapula on the thorax. The linkage between the scapula and the thorax is seen as a functional 'joint', because of its essential contribution to normal shoulder function (Kibler & Murrell, 2008; Ludewig & Borstead, 2005). The coordinated movement between scapula and humerus is known as scapulohumeral rhythm, with the ratio of GH joint movement to scapulothoracic 'joint' movement being approximately 2:1 during elevation (Kibler & Murrell, 2008; Lugo, et al., 2008). Upward rotation and posterior tilt of the scapula during overhead arm elevation amounts to approximately one third of full arm elevation (Ludewig & Borstead, 2005; Ludewig & Reynolds, 2009; Veeger & van der Helm, 2007).

Muscles that contribute to coordinated scapular motion are the trapezius and serratus anterior, which provide a stable position of the scapula against the chest wall and a synchronised upward rotation and elevation of the scapula with GH joint elevation (Kibler & Murrell, 2008; Ludewig & Borstead, 2005; Lugo, et al., 2008). Further muscles that contribute to a smooth, coordinated movement of the scapula are the rhomboids, levator scapulae, latissimus dorsi and the pectoralis minor muscles. These muscles work in coordinated force couples to control scapula movements in three dimensions (Kibler & Murrell, 2008; Ludewig & Reynolds, 2009; Lugo, et al., 2008).

Another functional articulation, the subacromial 'joint', refers to the unrestricted gliding of the subacromial structures and the humeral head underneath the coracoacromial arch with arm elevation (Ludewig & Borstead, 2005; Prescher, 2000). The movement of the subacromial 'joint' has been recognised as a crucial factor for normal GH joint function (Ludewig & Borstead, 2005). Overall, the wide range of motion of the upper extremity results from the synergy of the GH joint and the scapulothoracic and subacromial 'joints'.

2.3 Stability

The GH joint is mechanically unstable, because of the disproportion between the glenoid and the humeral head, and the lax joint capsule (McMinn, 2005; Veeger & van der Helm, 2007). The structures that ensure GH stability are categorised into static and dynamic stabilisers. Static stabilisers include articular structures of the GH joint, such as articulating surfaces, labrum, capsule and ligamentous structures. Dynamic stabilisers refer to musculature surrounding the shoulder joint (Abboud & Soslowsky, 2002; Ludewig & Borstead, 2005; Lugo, et al., 2008; Prescher, 2000).

The GH ligaments, as part of the capsule, have been described to function as checkreins. This means that the ligamentous constraints are lax through mid-ranges of GH motion and contribute insignificantly to GH stability. Towards the end-range of motion, the GH ligaments become progressively tauter, thereby preventing excessive GH motion and humeral translation at the extreme ranges of motion (Abboud & Soslowsky, 2002; Ludewig & Borstead, 2005; Lugo, et al., 2008). Each GH ligament limits a combination of GH motions, thus achieving stability of the GH joint in various positions (Lugo, et al., 2008). The superior GH ligament inhibits inferior dislocation of the humeral head and additionally restricts, along with the middle GH ligament, external rotation (Lugo, et al., 2008; Veeger & van der Helm, 2007). The anterior and posterior bands of the inferior GH ligament serve as primary stabilisers of the GH joint in the neutral, abducted and externally rotated position and restrict anterior, posterior, and inferior translation of the humeral head (Kibler & Murrell, 2008; Ludewig & Borstead, 2005; Prescher, 2000). Additionally, the strong coracohumeral ligament acts as a restraint for inferior and posterior translation of the humeral head (Lugo, et al., 2008).

The structures that contribute to stability during midrange GH motion include the shoulder muscles as the dynamic stabilisers, along with the shape of the articular surfaces, the labrum and intraarticular pressure (Abboud & Soslowsky, 2002; Prescher, 2000). Compression of the humeral head into the glenoid by the muscles surrounding the GH joint is crucial to maintain a centred position of the humeral head during GH motion. This dynamic stabilising force is mainly achieved through coordinated activation of the RC muscles, enabling the humeral head to pivot within the glenoid with GH movements (Dark, Ginn, & Halaki, 2007; Kibler & Murrell, 2008; Ludewig & Borstead, 2005). Additional factors playing a role in dynamic GH stabilisation include passive tension resulting from the bulk effect of the muscle, muscle contraction acting as a restraint for excessive humeral head translation and secondary tightening of capsuloligamentous structures with GH joint motion (Abboud & Soslowsky, 2002; Lugo, et al., 2008). The RC muscles counteract and balance the superiorly directed forces of the deltoid muscle during GH abduction by actively depressing the humeral head and compressing it into the glenoid cavity (Boettcher, Ginn, & Cathers, 2009; Dark, et al., 2007). Specifically, the synchronous activation of the subscapularis and infraspinatus muscles creates a force couple, providing humeral head stability throughout the midranges of elevation. Moreover, activation of infraspinatus and teres minor muscles can reduce strain of the anterior-inferior capsule and ligaments in external rotation and abduction, while the subscapularis muscle primarily stabilises the GH joint anteriorly in arm abduction and neutral rotation (Abboud & Soslowsky, 2002).

The long head of biceps tendon is another important contributor to GH stability. Owing to its attachment at the supraglenoid tubercle and its course over the humeral head, the long head of biceps tendon is capable of depressing the humeral head and creating compressive GH joint forces, as well as reducing stress of the inferior GH ligament. Thus, the long head of biceps tendon contributes to limit superior-inferior humeral head translation (Abboud & Soslowsky, 2002; Lugo, et al., 2008). With GH rotation, the orientation of the long head of biceps tendon changes with respect to the GH joint. In internal rotation, the long head of biceps tendon has been found to stabilise the humeral head anteriorly, while limiting posterior humeral head translation in external GH rotation (Abboud & Soslowsky, 2002; Lugo, et al., 2008). The function of the dynamic stabilisers is based on the neuromuscular control of the RC, deltoid and scapulothoracic muscles, as well as on the neural feedback of the capsuloligamentous structures. This means that the proprioceptive ability of the shoulder is crucial for appropriate reaction of the dynamic stabilisers (Kibler & Murrell, 2008; Ludewig & Borstead, 2005).

Overall, dynamic GH stability is reached through the complex interplay of the static and dynamic stabilisers. However, high demands on stability and mobility coupled with the intricate design of the shoulder complex leave the shoulder susceptible to injury, degenerative changes and instability (Gerber & Nyffeler, 2002; Kibler & Murrell, 2008; Ludewig & Borstead, 2005).

2.4 Altered shoulder kinematics

2.4.1 Epidemiology of shoulder disorders

Shoulder complaints are the third most common musculoskeletal problem encountered in primary clinical practice after neck and low back pain (Urwin, Symmons, Allison, Brammah, Busby, Roxby, et al., 1998; van der Heijden, 1999). In the general population, point prevalence of shoulder pain and associated disability ranges between 6.9% and 26%, and one-month prevalence can reach 45% (Luime, Koes, Heridriksen, Burdorf, Verhagen, Miedema, et al., 2004; Pope, Croft, Pritchard, & Silman, 1997; Urwin, et al., 1998). The lifetime prevalence of shoulder disorders in the general population is estimated to range between 10% and over 66% (Luime, et al., 2004; van der Heijden, 1999). Shoulder disorders are associated with impairment and disability, thus representing a significant health problem (van der Windt, Koes, de Jong, & Bouter, 1995).

Shoulder impingement syndrome (SIS), GH joint instability and adhesive capsulitis (‘frozen shoulder’) account for the majority of shoulder problems, with SIS being the most frequent diagnosis (Bigliani & Levine, 1997; Ludewig & Reynolds, 2009; Neer, 1972). Pathologies of the RC tendons, such as tendinopathy and tears, have been associated with SIS, and are seen as a major cause of shoulder pain, with RC tendinopathy found in as many as 85% of patients with shoulder pain presenting in primary care (Östör, Richards, Prevost, Speed, & Hazleman, 2005).

2.4.2 Pathogenesis of shoulder disorders

The pathogenesis of shoulder disorders is complex. Apart from anatomical and psychosocial factors, biomechanical factors, such as altered kinematics and biomechanics of the shoulder have been identified to be involved in the development of shoulder pain and dysfunction (Neer, 1972; van der Heijden, 1999). Altered shoulder kinematics includes changes in the scapulohumeral rhythm, such as decreased upward rotation and posterior tilting of the scapula (Kibler, 1998; Ludewig & Reynolds, 2009; Warner, Micheli, Arslanian, Kennedy, & Kennedy, 1992). This also includes changes in the movement of the humeral head on the glenoid fossa, for example excessive superior or anterior humeral head translation (Fu, Harner, & Klein, 1991; Poppen & Walker, 1976). Both scenarios may result in the humeral head adopting an abnormal position in relation to the glenoid or the acromion, leading for example to an excessively decreased subacromial space or a changed orientation of the coracoacromial arch, causing the subacromial structures to abut against the acromion during GH elevation (Lugo, et al., 2008; Michener, McClure, & Karduna, 2003).

Thus, altered shoulder kinematics may compromise physiological shoulder function, which may in turn make individuals susceptible to GH joint pathology (Fu, et al., 1991; Kibler & Murrell, 2008; Ludewig & Reynolds, 2009; Lugo, et al., 2008). Factors that have been associated with the development of altered shoulder kinematics include slouched thoracic posture, thoracic hyperkyphosis and altered muscle activation (Gumina, Di Giorgio, Postacchini, & Postacchini, 2008; Kebaetse, McClure, & Pratt, 1999). Altered muscle activation leading to changes in scapular kinematics has been linked to SIS, RC tendinopathy, RC cuff tears, GH instability, and adhesive capsulitis (Ludewig & Reynolds, 2009).

2.4.2.1 Shoulder Impingement Syndrome

SIS was originally described as encroachment and mechanical compression of the subacromial soft tissues against the coracoacromial arch, typically during overhead arm elevation (Neer, 1972). SIS most commonly involves the anterior edge and under-surface of the anterior third of the acromion, the CAL, and may include the AC joint (Burns II & Whipple, 1993; Neer, 1983). Furthermore, subacromial structures may get impinged on the posterior-superior edge of the glenoid in GH abduction and external rotation, which is often found in athletes performing overhead throwing motions (Bigliani & Levine, 1997). Signs and symptoms of SIS may include the presence of a painful arc of movement during shoulder abduction and/or flexion, positive clinical impingement signs, and pain and/or weakness in isometric external rotation or abduction (Calis, Akgun, Birtane, Karacan, Calis, & Tuzun, 2000; Lukasiewicz, McClure, Michener, Pratt, & Sennett, 1999; Michener, Walsworth, & Burnet, 2004).

A large number of factors have been suggested to be involved in the development of SIS. These factors can be categorised as intrinsic (factors within the RC tendons) and extrinsic (factors outside of the RC tendons), and they can be further characterised as primary and secondary (Fu, et al., 1991; Michener, et al., 2003). A primary etiology, which can be either intrinsic or extrinsic, is thought to cause the impingement process directly. A secondary etiology is theorised to be the result of another process, for example GH instability or neurological damage (Bigliani & Levine, 1997).

Intrinsic factors causing SIS include inflammation and thickening of the RC tendons or subacromial bursa. Inflamed and thickened subacromial structures are theorised to occupy increased volume in the subacromial space, thereby leading to friction of the subacromial structures against the coracoacromial arch (Bigliani & Levine, 1997; Bureau, et al., 2006; Neer, 1983). Overuse is considered as the primary cause of inflammation of the RC tendons or the subacromial bursa and is often related to forceful repetitive overhead tasks. Over time, this inflammatory process is thought to lead to degeneration and tears of the RC tendons (Fu, et al., 1991; Michener, et al., 2003; Neer, 1983). Subsequently, tendon degeneration and tears are believed to cause muscle changes, such as imbalances and weakness, and altered shoulder kinematics, which ultimately lead to SIS (Bigliani & Levine, 1997). Disturbed balance of muscle forces between the deltoid muscle and the RC muscles, resulting in superior migration of the humeral head, has been identified as one principal pathogenic element of SIS (Graichen, Bonel, Stammberger, Haubner, Rohrer, Englmeier, et al., 1999b; Graichen, Stammberger, Bonel, Englmeier, Reiser, & Eckstein, 2000).

Extrinsic impingement, on the other hand, suggests that subacromial tissues are compressed through an outside structure, such as the coracoacromial arch (Neer, 1972, 1983). This compression is believed to cause inflammation and degeneration of the subacromial structures (Bigliani & Levine, 1997; Fu, et al., 1991; Michener, et al., 2003; Neer, 1972). Extrinsic factors, such as hereditary variations or pathologies of the acromion and coracoacromial arch (e.g. hooked acromion, elongated coracoid process, bone spurs, and osteophyte formation), postural misalignment of the acromion, altered scapular or GH kinematics, and posterior capsule tightness have been identified as potential elements that may lead to mechanical extrinsic SIS. Hereditary abnormalities and variations are considered as primary causes for extrinsic impingement (Neer, 1972), whereas changes of GH kinematics and abnormal motions and positions of the scapula (scapular dyskinesia) are thought to be extrinsic factors that lead to SIS as a secondary phenomenon (Kibler, 1998; Warner, et al., 1992).

2.4.2.2 Glenohumeral instability

The GH joint is considered unstable, when it cannot maintain the centred position of the humeral head during movement. Reasons for GH instability may be due to changes of the integrity of the concavity of the glenoid or the coracoacromial arch and the passive and active forces that press the humeral head into the glenoid (Matsen, Chebli, & Lippitt, 2006). Instability of the GH joint can be traumatic or non-traumatic in origin. Further, the direction of the instability may be anterior, posterior, inferior or multidirectional (Gerber & Nyffeler, 2002; Kibler & Murrell, 2008; Ludewig & Reynolds, 2009; Matsen, et al., 2006). Non-traumatic GH instability or functional scapular instability can arise from repetitive microtrauma, which has been observed among young patients involved in throwing sports (Fu, et al., 1991; Kibler, 1998). Subtle GH instability has been suggested as the underlying diagnosis for SIS, particularly in young overhead athletes, despite the presence of subacromial bursitis (Bigliani & Levine, 1997).

2.4.3 Treatment of shoulder disorders

Exercise therapy and manual therapy techniques are widely used in the treatment of shoulder disorders. A combination of therapeutic exercise and manual therapy techniques has been demonstrated to produce the most favourable outcomes for SIS patients (Desmeules, Côté, & Frémont, 2003; Kachingwe, Phillips, Sletten, & Plunkett, 2008; Kuhn, 2009; Michener, et al., 2004). Moreover, treatment regimens comprising manual therapy and exercise proved superior to exercise programmes alone (Kachingwe, et al., 2008; Kuhn, 2009).

Mobilisations with Movement (MWM) is a relatively new manual treatment approach for musculoskeletal dysfunctions of extremity joints and the spine (Mulligan, 2003, 2006). MWM involves the application of a sustained manual glide combined with active or passive repeated physiological movements of the affected joint, which are performed by the patient or the therapist. This treatment approach puts emphasis on the restoration of a hypothetically restricted glide component to facilitate full pain-free range of motion. According to Mulligan (2006), slight misalignment of a joint, possibly following injury, can produce abnormal kinematics of the joint, which may result in dysfunction, loss of range of movement and/or pain. Mulligan (2006) put forward the 'positional fault hypothesis', and claimed that MWM may assist in normalising kinematics of a dysfunctional joint. Although, to date there is still insufficient evidence to explain this pathomechanical theory, an increasing number of studies support the clinical usefulness of MWM in the management of musculoskeletal disorders (Desantis & Hasson, 2006; Kuhn, 2009; Mulligan, 2003; Teys, Bisset, & Vicenzino, 2008; Vicenzino, Paungmali, & Teys, 2007). In the treatment of SIS patients, MWM combined with therapeutic exercises showed a higher percentage of change in decreasing pain, improving function and active flexion range of motion from pre to post treatment compared to GH mobilisations combined with exercise, exercise alone and the control group (Kachingwe, et al., 2008).

2.4.4 Acromiohumeral distance

It has been explained previously that altered GH kinematics can affect normal shoulder function. This underlines the importance of the assessment of GH kinematics and humeral head translation. As described in the previous sections, the subacromial space has been highlighted as a crucial component of normal shoulder function, and techniques to measure its size have been developed. A way to quantify the size of the subacromial space is by measuring the distance between the acromion and the most cranial part of the humeral head, which is referred to as the 'acromiohumeral distance' (AHD) (Figure 2, page 5). On radiographs, the measurement of the AHD proved to be the most reliable way to measure the superior migration of the humeral head compared to other measurements, such as the distance between the centre of the humeral head and the centre of the glenoid; the distance between the inferior margin of the humeral head and the inferior rim of the glenoid; and the distance between the centre of the humeral head and the spine of the scapula (Nagels, Verweij, Stokdijk, & Rozing, 2008). Normal values for the AHD have been reported in numerous studies using a variety of imaging methods, such as radiography, magnetic resonance imaging (MRI), computed tomography (CT), as well as measurements obtained from arthroscopy and cadaver studies (Graichen, et al., 1999b; Graichen, et al., 2000; Tillander & Norlin, 2002; Weiner & Macnab, 1970). AHD values in normal shoulders can range between 6 and 16 mm in a neutral shoulder position (Table 1) (Cotton & Rideout, 1964; Flatow, Soslowsky, Ticker, Pawluk, Hepler, Ark, et al., 1994; Petersson & Redlund-Johnell, 1984; Saupe, Pfirrmann, Schmid, Jost, Werner, & Zanetti, 2006; Tillander & Norlin, 2002; Weiner & Macnab, 1970).

Table 1. ***Acromiohumeral distance in healthy and pathologic populations.***

Author	**AHD Normal (abduction) (mm)**	**AHD Pathologic (mm)**	**Pathology type**	**Cut off point* (mm)**	**Imaging Method**
Cotton & Rideout (1964)	6-14[b] (0º)	1- 9[b]	RC tear	n/a	Radiography, cadavers
Flatow et al (1994)	11[a] (0º) 8[a] (60º)	n/a	n/a	n/a	Cadavers
Petersson & Redlund-Johnell (1984)	9.7[a] ± 1.5; 6.6-13.8[b] (0º)	n/a	n/a	<6 (for age group 55 years)	Radiography
Saupe et al (2006)	n/a	n/a	RC tear	≤ 7	Radiography, MRI
Tillander & Norlin (2002)	16[a]; 14-18[b]; (20º)	8[a]	SIS	n/a	During surgery
Weiner & Macnab (1970)	9.6[a]; 7-14[b] (0º)	6.6[a]; 1- 13[b]	RC tear	≤ 5	Radiography

Note.[a]: Mean values; [b]: Range, º: Degrees of shoulder abduction, *: Value suggested as threshold for normal AHD; AHD: Acromiohumeral distance; MRI: Magnetic resonance imaging; n/a: Not applicable; RC: Rotator cuff; SIS: Shoulder impingement syndrome.

2.4.4.1 Reduction of the acromiohumeral distance

A link between narrowing of the AHD and RC tears on radiographs was first described in the early 1960s (Cotton & Rideout, 1964). Since then, numerous studies have confirmed a relationship between a reduced size of the AHD and RC degeneration, RC tears and SIS (Deutsch, Altchek, Schwartz, Otis, & Warren, 1996; Petersson & Redlund-Johnell, 1984; Saupe, et al., 2006; Tillander & Norlin, 2002; Weiner & Macnab, 1970). Saupe et al (2006) found that the size of a RC tear had a significant influence on the decrease of the AHD. Furthermore, they reported a strong correlation between the degree of fatty degeneration of RC muscles, particularly the infraspinatus muscle, and a reduction of the AHD. In patients with full-thickness RC tears, AHD was found to be as small as 1 to 4 mm on radiographs (Cotton & Rideout, 1964). Weiner and Macnab (1970) reported AHD mean values of 6.6 mm in patients with RC tear. In another radiographic study, marked cartilage loss of the GH joint was associated with the reduction of the AHD in the neutral shoulder position and in active shoulder abduction (Umans, Pavlov, Berkowitz, & Warren, 2001).

Based on the average differences of the AHD between healthy individuals and patients with RC tears, cut-off points or threshold values for the AHD have been proposed in order to demarcate healthy shoulders from shoulders with RC tears (Petersson & Redlund-Johnell, 1984; Saupe, et al., 2006; Weiner & Macnab, 1970) (Table 1). Proposed cut-off points published in the literature vary between ≤ 5 and ≤ 7 mm. However, the presence of a reduced AHD as an indication of RC tears is not entirely reliable, because AHD reduction has also been observed in individuals with intact RC tendons (Cotton & Rideout, 1964).

Recently, studies have demonstrated a relationship between the AHD and shoulder function in SIS patients (Desmeules, et al., 2004; Mayerhoefer, Breitenseher, Wurnig, & Roposch, 2009). In one study, the score on a shoulder specific outcome measure, including measures of pain, daily living activities, shoulder range of motion and muscle strength, was related to the AHD in patients with SIS without RC tears (Mayerhoefer, et al., 2009). In this study, patients with an AHD of 7 mm or smaller on MRI images, reached significantly lower values on the shoulder score compared to those patients with an AHD larger than 7 mm (Mayerhoefer, et al., 2009). This suggests that in a SIS population without RC tears, the AHD appears to reflect the clinical condition and shoulder function.

In another study, functional improvement of SIS patients after a 4-week rehabilitation program showed a significant association with the narrowing of the AHD during active shoulder abduction (Desmeules, et al., 2004). This study found that those patients who showed improvement on a shoulder specific index, which included physical symptoms, sport / recreation, work, lifestyle and emotions, also demonstrated less AHD narrowing during active abduction after rehabilitation. In addition, the extent of AHD reduction (larger than 3 mm) with active shoulder abduction before the intervention was related with the functional improvement achieved after rehabilitation. The researchers concluded that a larger AHD reduction prior to rehabilitation had a potential predictive value for functional outcome.

2.4.5 Translation of the humeral head

2.4.5.1 Normal translation of the humeral head

During shoulder elevation, the humeral head moves towards the coracoacromial arch, thus causing a reduction of the subacromial space and the AHD (Graichen, et al., 1999b; Harryman, Sidles, Clark, McQuade, Gibb, & Matsen, 1990; Ludewig & Cook, 2002; Werner, Nyffeler, Jacob, & Gerber, 2004). A biomechanical study on cadaver specimens has shown that a reduction of the width of the subacromial space is most marked between 60º and 120º of abduction (Flatow, et al., 1994). The decrease of the AHD in healthy individuals during abduction has been explained as being partly due to the greater tuberosity approaching the acromion (Graichen, et al., 1999b).

During midrange shoulder movements, the humeral head is normally well centred in the GH joint and does not translate excessively (Deutsch, et al., 1996; Graichen, et al., 1999b; Harryman, et al., 1990; Howell, Galinat, Renzi, & Marone, 1988; Konrad, Markmiller, Jolly, Ruter, Sudkamp, McMahon, et al., 2006). Poppen and Walker (1976) reported superior humeral head translation of on average 1.1 mm for each 30º arc of motion from 0º to 150º active abduction in the scapular plane in a sequential set of radiographs. Similarly, an MRI study found a slight, non-significant superior humeral head translation of 1.3 mm with passive abduction from 60º to 90º, with mean AHD values of 6.7 mm at 60º abduction and 5.4 mm at 90º abduction (Graichen, et al., 1999b). However, Poppen and Walker (1976) observed that the largest amount of translation (approximately 3 mm) occurred at the beginning of abduction between 0° and 60°, while with further abduction, the humeral head either remained constant or translated only 1 - 2 mm superiorly or inferiorly for each successive position. Graichen et al (1999b), on the other hand, found significantly more superior humeral head translation with abduction from 90º to 120º compared to 60º to 90º, as the ADH decreased by 1.8 mm to a width of 3.6 mm.

Another study described the position of the midpoint of the humeral head relative to the centre of the glenoid in passive and active shoulder abduction using MRI (Graichen, et al., 2000). In 30º passive abduction, the humeral head was located slightly superiorly relative to the centre of the glenoid. From 30º to 150º abduction, the humeral head continuously translated inferiorly 1.2 mm on the glenoid, but still was located superior to the centred position. With active abduction, the humeral head adopted a more centred position on the glenoid at 90º and 120º compared to passive abduction. In a radiographic study, the humeral head was localised just below the centre of the glenoid (- 0.4 mm) at the start of abduction and translated less than 0.7 mm superiorly with active abduction from 0° to 120° in the scapular plane (Deutsch, et al., 1996).

With respect to anterior-posterior humeral head translation, anterior translation has been found to start approximately beyond 55º of flexion and posterior translation beyond 35º of extension (Harryman, et al., 1990). Graichen et al (2000) reported that at 30º and 90º passive abduction the position of the humeral head was located anteriorly to the centre of the glenoid, whereas at 150º abduction, it had translated posteriorly 1.62 mm. Comparing active to passive abduction at 60º and 90º, the same study found, that the humeral head was positioned more posteriorly and thus more centred in the glenoid. However, at 120º active abduction, the humeral head lost its centred position and translated further anteriorly than in passive abduction.

With end-of-range shoulder motion, humeral head translation beyond the centred position has been described. A cadaver study found anterior translation occurring with flexion and a radiographic study found posterior translation (approximately 4 mm) occurring with maximal horizontal abduction and external rotation (Harryman, et al., 1990; Howell, et al., 1988). These translations appeared to occur in an obligate manner, because they were not influenced by an oppositely directed force or concentric muscle activation. In the case of posterior translation, the humeral head was re-centred by moving the arm into flexion or neutral rotation, rather than by activation of the anterior shoulder muscles (Howell, et al., 1988). It has been theorised that normal humeral head translation occurring in the GH joint is mediated by mechanics influenced by capsule and ligamentous structures or articular congruencies (Harryman, et al., 1990; Howell, et al., 1988).

In summary, with passive and active shoulder movements, translation of the humeral head in superior-inferior and anterior-posterior directions has been described. However, there is no consensus with respect to the amount and direction of humeral head translation with given GH joint movements. The articles varied with respect to imaging methods and positioning of participants, which firstly may result in differences in distance measurements, and secondly makes comparison of results difficult. For example, Howell et al (1988) and Graichen et al (1999b; 2000) measured in supine lying and added a weight for active muscle contraction with abduction. Deutsch et al (1996) and Poppen and Walker (1976), on the other hand, used radiography in an upright position. However, those two articles differed with respect to the addition of a weight for active abduction and the alignment of the arm in the scapular plane. Therefore, studying the effect of passive and active abduction on humeral translation in a healthy population is relevant and worthy of consideration.

2.4.5.2 Abnormal translation of the humeral head

In contrast to small humeral head translation occurring in healthy shoulders, excessive humeral head translation has been reported in populations with shoulder disorders, such as RC disease, SIS and GH instability (Deutsch, et al., 1996; Graichen, et al., 1999b; Graichen, et al., 2000; Konrad, et al., 2006; Poppen & Walker, 1976). Previous GH injury, such as dislocation, RC tear, or significant shoulder pain have been associated with increased superior humeral head translation with shoulder abduction when compared to healthy individuals (Poppen & Walker, 1976). Similarly, a marked increase of superior humeral head translation with simulated active abduction has been reported with RC tears in cadavers using radiography (Konrad, et al., 2006). In addition, Konrad et al (2006) observed that, despite excessive superior translation with abduction, the humeral head may be inferiorly displaced at rest. The researchers suggested that this was caused due to unbalanced forces between the deltoid muscle and the RC muscles in patients with RC tear.

Deutsch et al (1996) found that patients with SIS, with and without RC tears, displayed significantly more superior displacement of the humeral head on the glenoid than healthy individuals (1.2 mm versus 0.7 mm), when the arm was actively abducted from 0° to 120°. In those patients with RC tears, the humeral head rose sharply in the first 20° of abduction. Furthermore, in the pathologic shoulders the humeral head position was located more superiorly at rest and during abduction than in healthy individuals. Another radiographic study compared healthy individuals to patients with symptomatic and asymptomatic RC tears (Yamaguchi, Sher, Andersen, Garretson, Uribe, Hechtman, et al., 2000). The groups with symptomatic and asymptomatic RC tears displayed significant humeral head superior translation with active abduction from 30° to 150° compared to the healthy shoulders, which showed a well-centred humeral head in the glenoid. In this study, significant superior translation of the humeral head was measured in several participants with asymptomatic RC tears. Although the sample size was quite small with ten subjects in each group, this may indicate that abnormal GH kinematics do not necessarily correlate with shoulder symptoms. This also implies that abnormal GH kinematics can concur with normal shoulder function.

Muscle fatigue has been demonstrated to lead to abnormal GH kinematics even in the absence of shoulder disorders (Chen, Simonian, Wickiewicz, Otis, & Warren, 1999). In this radiographic study, healthy volunteers displayed significantly more superior humeral head translation with abduction from 0° to 135° abduction, after the deltoid and the RC muscles had been fatigued with active exercises compared to the non-fatigued situation (0.3 mm versus 2.5

mm). In addition, in the fatigued situation, the humeral head displayed a statistically significant more inferior position (1.2 mm) at 0° abduction compared to the non-fatigued situation.

A cadaver study by Harryman et al (1990) identified tightness of the posterior GH joint capsule as another source of abnormal humeral head translation. In this study on cadavers, passive shoulder flexion led to an increase of anterior and superior translation by 3.48 mm and 1.78 mm respectively when posteriorly tightened and normal GH joint capsules were compared. Cross-body movement resulted in even larger increases of anterior and superior humeral head translation. Moreover, excessive translation occurred earlier in the range of motion (below 40º) compared to normal shoulders, or shoulders in which the GH capsule had been vented to simulate GH instability (Harryman, et al., 1990). These results suggested that a capsular constraint forces the humeral head to translate away from the limitation, and that this translation occurs earlier in the range of motion compared to normal capsuloligamentous conditions.

GH instability is another documented source of altered humeral head translation. Howell et al (1988) observed in 7 of 12 patients with anterior GH instability an increase of anterior translation of approximately 3.5 mm compared to normal shoulders with active horizontal abduction and external rotation. Similarly, GH instability that was simulated by a vented capsule in cadavers led to increased anterior translation with flexion (1.35 mm) and cross body movement (2.29 mm) compared to normal GH joint capsules (Harryman, et al., 1990).

Using anterior humeral head palpation in pathologic shoulders (SIS or RC disease), McKenna, Straker, and Smith (2009) found that the humeral head translated 5 mm more anterior with 90º passive abduction than when in a neutral shoulder position. The palpation measurement was reliable, and valid in comparison to measurements obtained by MRI. The measurement error was 2.2 mm and 3.0 mm for the measurement in neutral and abduction respectively. Based on these results and on previous literature providing measurements of anterior humeral head translation, McKenna et al (2009) proposed a pathologic threshold value of 5 mm as the average difference for anterior-posterior translation between pathologic and normal shoulders. In contrast to these findings, Hallström and Kärrholm (2006) found with dynamic radiometry, that an anterior glide that was seen in healthy individuals during 10-60º abduction did not occur in patients with SIS.

In summary, a range of shoulder disorders, as well as fatigued shoulder muscles have been associated with altered positions of the humeral head at rest and excessive humeral head translation during passive and active shoulder movements. The most common changes include increased superior and anterior humeral head translation with shoulder abduction. However, there are conflicting results regarding the direction and extent of the humeral head translation, which could be regarded abnormal or indicative for GH pathology. Based on the information that aberrations of the normal position of the GH joint, such as excessive humeral head translation can be associated with the development of shoulder problems, the significance of an objective measure of the humeral head position in relation to scapular landmarks becomes evident. Therefore, identifying and measuring the location of the humeral head in relation to scapular landmarks in the anterior-posterior and superior-inferior may be useful for assessment, diagnosis, and evaluation of patients with shoulder dysfunctions.

2.5 Shoulder imaging methods

Diagnostic imaging techniques, such as MRI, CT and radiography are commonly used for the assessment of the subacromial space and humeral head translation. Although valuable, these imaging methods have methodological limitations. Radiography, MRI and CT require a sustained arm position, frequently in supine lying with the arm along the side of the body (Shahabpour, Kichouh, Laridon, Gielen, & De Mey, 2008; Whittaker, et al., 2007). These positions may not adequately reproduce humeral head translation that would occur in functionally more relevant positions, such as sitting or standing. Besides, supine lying and a neutral arm position may not be provocative enough to elicit abnormal translation of the humeral head that would occur in an upright position with passive and/or active shoulder movements. Furthermore, in a horizontal position, gravity or muscle contractions might influence the position and translation of the humeral head in a different way than in a vertical position. These considerations are supported by McKenna et al (2009) who found that measurements of anterior humeral head position obtained in supine were not correlated to those acquired in sitting.

Another limitation of radiography is that measurement errors are common in this imaging method (Deutsch, et al., 1996). This may be due to radiography projecting the bone images onto a plane, which may compromise quantitative data by projection errors (Graichen, et al., 1999b). In one study, 20% of radiographs were unreadable despite careful positioning and alignment (Howell, et al., 1988). In particular, the projection of the acromion can be difficult due to its curved configuration and oblique position (Nagels, et al., 2008). Another obvious concern with radiography is that it exposes individuals to radiation. The risk of unnecessary exposure to radiation increases, when measurement errors might require repetitive radiographs.

2.5.1 Musculoskeletal ultrasound imaging

Sound waves with a frequency greater than 20,000 Hz are referred to as ultrasound (US) (Kane, Grassi, Sturrock, & Balint, 2004b). For USI, frequencies range between 3.5 to 15 MHz (Whittaker, et al., 2007). The application of USI as a medical diagnostic tool began in the late 1950s in surgery and obstetrics, being soon followed by the use of USI in the musculoskeletal field. For decades, musculoskeletal USI has been widely used as a qualitative diagnostic tool and has been mainly applied for distinguishing between normal and pathological anatomical structures (Kane, et al., 2004a). USI allows high-resolution, real-time imaging of articular structures. Compared to other common imaging techniques, USI is inexpensive, portable, and highly acceptable to patients. Moreover, USI displays very little associated risk and does not emit radiation (Kane, et al., 2004a). In particular, the visualisation of movement in real-time and the option of interaction with the patient during examination are considered a major advantage of USI (Whittaker, et al., 2007) .

In recent years, the usefulness of USI in quantitative assessment of the musculoskeletal system has become increasingly popular (Schmidt, et al., 2004; Whittaker, et al., 2007). In shoulder diagnostics, USI is commonly used to detect soft tissue disorders, and demonstrates high accuracy in identifying partial and full thickness lesions of the RC (Jacobson, Lancaster, Prasad, van Holsbeeck, Craig, & Kolowich, 2004). Although the reliability of diagnostic USI is associated with the experience of the examiner, it has been shown, that even with limited training, a high degree of agreement between examiners can be achieved (Kane, et al., 2004a). This applies particularly to the skills of landmark identification and distance measurements, which are more easily mastered than skills of structural diagnostics (Balint & Sturrock, 2001).

In a recent literature review, USI was assigned considerable diagnostic qualities compared to other imaging techniques (Shahabpour, et al., 2008). More precisely, MRI and USI showed high sensitivity and specificity for the detection of full-thickness RC tears, and USI appeared to be even more accurate than MRI for the detection of partial-thickness tears. Additionally, the authors emphasised, that USI is far more cost effective and available than MRI. Recent studies have also supported the validity of USI as a method for the assessment and quantification of humeral head translation. In comparison with stress radiography, which was used as a gold standard, USI showed high validity in the assessment of inferior, posterior and anterior humeral translation in asymptomatic shoulders ($r = 0.79$) (Borsa, et al., 2005a; Cheng, et al., 2008). Furthermore, USI has been demonstrated to be accurate compared to radiography for AHD measurements in patients with different stages of RC pathology ($r \geq 0.77$) (Azzoni, et al., 2004).

Another study, compared manual tracking of anterior humeral head translation in relation to the coracoid during medial rotation in 90º abduction with three-dimensional US analysis (Morrissey, Morrissey, Driver, King, & Woledge, 2008). In this study, manual assessment of translation proved only moderately valid in comparison with the US analysis. Additionally, the humeral head translation was systematically underestimated with the manual technique ($p = 0.03$). Based on those findings, USI appears to be a valid tool compared to radiography, MRI and manual palpation and may replace their use for the purpose of some clinical measurements.

3 Literature review of ultrasound imaging studies

3.1 Aim of literature review

The aim of this literature review was to identify articles that used USI to quantify distances between the humeral head and a part of the coracoacromial arch (i.e. the acromion, the coracoid process, or the coracoacromial ligament), or between the humeral head and the anterior or posterior glenoid. Furthermore, searches were performed for articles reporting on the reliability for these USI applications.

3.2 Search strategy

The electronic databases Scopus, (including 100% of MEDLINE), Sports Discus, Web of Science and CINAHL, were searched in two search processes (Figure 3). Additionally, the reference lists of all retrieved articles were searched for further eligible articles. To be included in the review, articles had to provide information on USI distance measurements or changes in distances between the humeral head and a part of the coracoacromial arch (e.g. the acromion or coracoid process), or between the humeral head and the anterior or posterior glenoid. In addition, studies reporting on reliability of these USI methods were included. Non-English studies were eligible for inclusion. Articles not discussing these parameters were excluded.

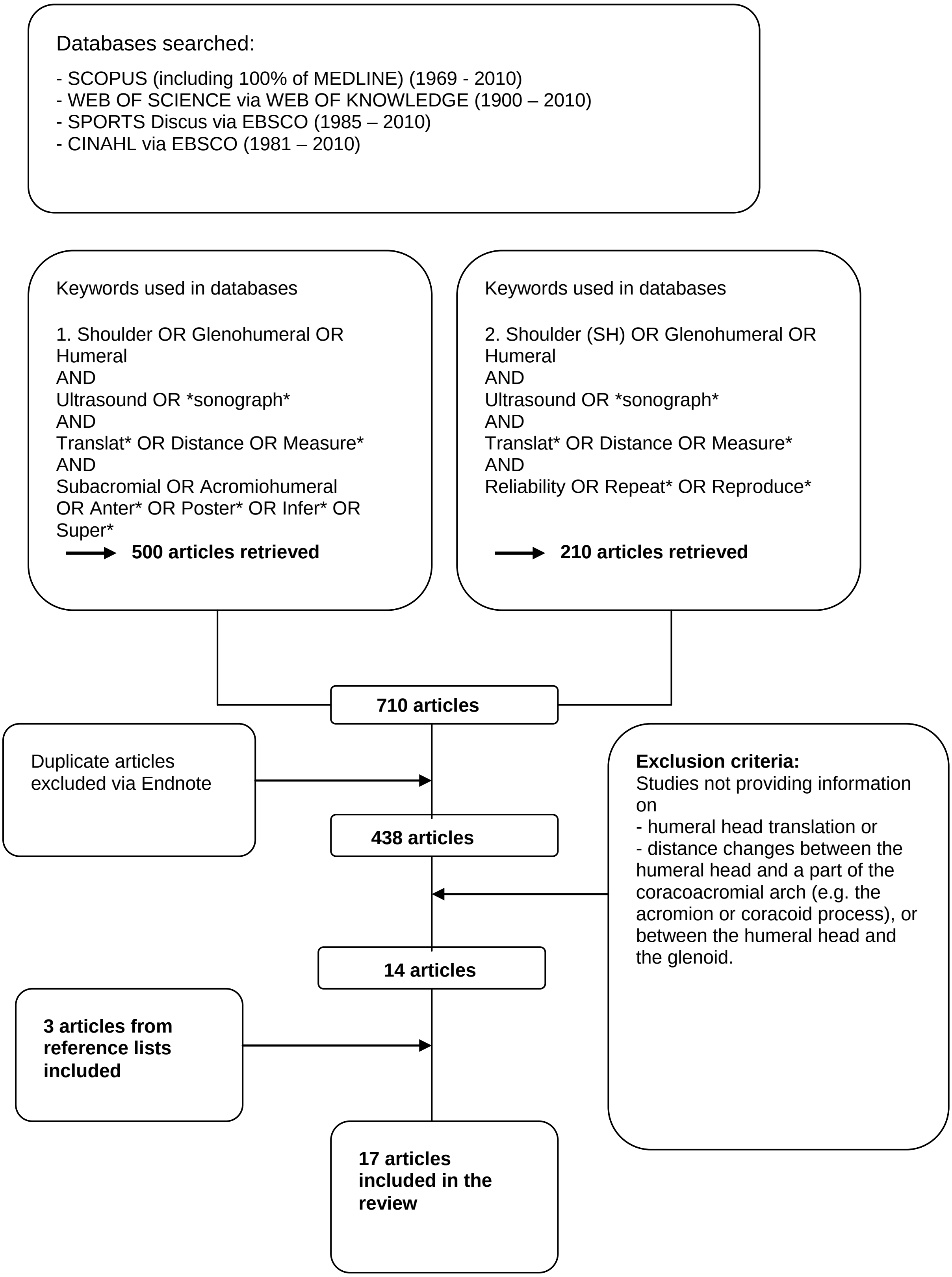

***Figure* 3. Search strategy for literature review**

Result of literature review

3.2.1 Selection of articles

After exclusion of duplicates, the literature search resulted in 710 articles. Fourteen articles were located after applying the exclusion criteria (Figure 3). A search through the reference lists of the sourced articles identified three further eligible articles. In total, 17 articles were included in this review (Figure 3).

3.2.2 Method of review

The articles that were located displayed a variety of methodologies, research designs and objectives, impeding a systematic approach of literature critique. Therefore, results of the literature review will be presented as narrative review according to topics of interest that have been identified previously by this author. Firstly, the USI methods will be presented and discussed. Secondly, distance measurement values obtained with USI in healthy and pathologic populations will be provided. Lastly, the reliability of the USI methods will be presented and evaluated.

3.2.3 Overview of selected articles

The USI methods that were utilised in the identified articles can be categorised into superior, anterior and posterior USI views, determined by the location of the USI transducer on the shoulder. With the superior USI view, images in the sagittal plane of the shoulder are obtained, allowing for distance measurements in the superior-inferior direction. The anterior and posterior USI views result in images of the shoulder in the transverse plane, allowing for distance measurements in the anterior-posterior direction. Each of the 17 articles provided information about distance measurements. In addition, ten studies published data on reliability of the utilised USI method. Fourteen articles provided data of distance measurement from healthy populations, and eleven articles presented results derived from pathologic populations.

3.2.4 Methods of superior imaging view

Eleven studies were located, which used a superior USI view for measuring the width of the subacromial space (Azzoni, et al., 2004; Cheng, et al., 2008; Cholewinski, et al., 2008; Desmeules, et al., 2004; Fremont, Desmeules, & Guimont C, 2000; Girometti, et al., 2006; Jerosch, et al., 1991; Pijls, et al., 2010; Schmidt, et al., 2004; Silva, et al., 2008; Wang, Lin, Pan, & Wang, 2005). The study of Fremont et al (2000) was published as an abstract and the results regarding reliability were described in the study of Desmeules et al (2004). Table 2 summarises the research purposes, USI methodologies, study populations and limitations of the studies.

Various research purposes were identified in the articles. Several authors evaluated the validity and/or reliability for USI used for measuring the width of the subacromial space and the AHD (Azzoni, et al., 2004; Cheng, et al., 2008; Desmeules, et al., 2004; Fremont, et al., 2000; Pijls, et al., 2010; Schmidt, et al., 2004; Wang, et al., 2005). Others determined the usefulness of USI for diagnosis and evaluation of shoulder disorders, as well as for distinguishing between healthy and affected shoulders (Azzoni, et al., 2004; Cholewinski, et al., 2008; Desmeules, et al., 2004; Girometti, et al., 2006; Jerosch, et al., 1991; Silva, et al., 2008; Wang, et al., 2005). One study provided standard reference values of the AHD in healthy individuals (Schmidt, et al., 2004). A linear array transducer with frequencies between 5 MHz and 12.5 MHz was used in all identified studies.

The literature review revealed methodological differences among the studies, for example in the description of transducer placement and the definition of landmarks (Table 2). Descriptions of the transducer placement on the shoulder included:

- Coronal axis view at greater tuberosity level. Long axis view of supraspinatus muscle (Azzoni, et al., 2004).
- Longitudinal view (Cholewinski, et al., 2008).
- Coronal plane, accompanying the major axis of the humerus (Silva, et al., 2008).

- Lateral surface of the shoulder, along longitudinal axis of the humerus. Most anterior part of the acromial arch and at 1 cm behind this measure (Desmeules, et al., 2004).
- Parasagittal plane, parallel to the longitudinal tendon axis (Girometti, et al., 2006).
- Midpoint of the lateral margin of the acromion (Wang, et al., 2005).
- Lateral shoulder, longitudinal 60º, cranial side of acromion (Schmidt, et al., 2004).
- Parallel to the humerus, anterior to the acromion, superior to the coracoid process and antero-superior to the humeral head (Cheng, et al., 2008).

In most of these studies, the transducer was placed either on the midpoint of the acromion process and along the longitudinal axis of the humerus; or along the anterior edge of the acromion and the longitudinal axis of the humerus to obtain a measurement of the AHD (Table 2). However, the description of the transducer placement was generally not described with enough detail to allow replication of the method (Table 2). Moreover, none of the studies defined reproducible anatomic reference points or adequately justified the transducer placement based on the anatomy of the subacromial space or the kinematics of the GH joint.

Instead, many authors used surface anatomy and palpation to determine the position of the transducer on the acromion (Cheng, et al., 2008; Desmeules, et al., 2004; Pijls, et al., 2010; Wang, et al., 2005). Silva et al (2008) defined the measurement position as the location at which the AHD displayed the smallest distance by moving the transducer around until the smallest distance was found. Desmeules et al (2004) derived from previous research that the shortest AHD is situated within the first two centimetres of the anterior part of the acromion. Based on this finding, the researchers measured the AHD at the most anterior part of the acromial arch and one centimetre posterior to this measure (Desmeules, et al., 2004). However, the researchers failed to explain, how the exact transducer position was achieved and reproduced. The acromion can display a variety of shapes and sizes between individuals (Prescher, 2000; Tillander & Norlin, 2002). Therefore, the method of Desmeules et al (2004) seems inappropriate for obtaining a reproducible USI location.

Table 2. ***Reviewed ultrasound imaging studies measuring superior-inferior humeral head translation.***

Author	Study purpose	USI view; Transducer placement (TP); Transducer type (TT); Participant position (PP)	Superior / inferior landmark (LM)	Participants	Limitations of study
Azzoni et al (2004)	- To compare the accuracy of USI to radiographic AHD measurements. - Verify variations of AHD in relation to morphology of acromion, age, sex and stage of RC pathology.	- Superior view; - TP: Coronal axis view of shoulder at greater tuberosity level (long axis view of supraspinatus muscle). - TT: 7.5 MHz linear transducer. - PP: Sitting, arm in extension, internal rotation.	- Superior LM: Most inferior echo from external, inferior edge of acromion. - Inferior LM: Nearest point of echo on humeral head surface. - Distance measured: Smallest distance between the two landmarks.	- Patients with shoulder pain, n = 200, grouped by USI into four stages of RC pathology. - Control group (contralateral shoulders), n = 200.	(-) - Reference point for transducer placement insufficiently described. - Largest distance of 3 measurements used. - No blinding during distance measurement. - No report of mean values and SEM. - Only range of AHD is presented.
Cheng et al (2008)	- To determine the level of agreement between dynamic USI and stress radiography for quantification of inferior translation of humeral head. - To determine the reliability of the USI method.	- Superior view; - TP: Parallel to humerus, anterior to acromion, superior to coracoid process and antero-superior to humeral head. - TT: 7.5 MHz linear transducer (6 cm wide) - PP: Sitting, arm in 10º extension.	- Superior LM: Surface of the transducer on skin. - Inferior LM: (1) Superior surface of coracoid process, (2) most cranial point on antero-superior surface of humeral head. - Distance measured: Relative distance change between landmarks and skin surface.	- Normal shoulders, n = 19, dominant side (18 right, 1 left).	(-) - No report on how blinding of examiners to their own data was achieved. - Values for intra-rater reliability between test sessions for the novice examiner not provided. - Transducer placement not described in detail. - Distance measurement from the skin surface down to the bony landmark possibly biased due to muscle bulk, and variable pressure on transducer.
Cholewinski et al (2008)	- Evaluation of usefulness of USI measurements (subacromial space width and RC thickness) for diagnosis and treatment of SIS.	- Superior view; - TP: Standard II longitudinal view. - TT: 8 MHz linear transducer (6 MHz, if subcutaneous fat) - PP: Sitting, arm in neutral rotation.	- Superior LM: Inferior-lateral edge of acromion. - Inferior LM: Apex of greater tuberosity. - Measured distance was termed AGT. - Bilateral scans.	- Patients with SIS, n = 57 - Asymptomatic control group, n = 72	(-) - Method insufficiently described for transducer placement and AGT distance measurement. - Number of measurements not reported. - Only median values and range provided.

Desmeules et al (2004)	- To establish inter-rater reliability of AHD measurement using USI. - Comparison of AHD variation during active abduction in patients with SIS and healthy subjects. - Evaluation of relationship between functional status and AHD variations before and after rehabilitation.	- Superior view; - TP: lateral surface of shoulder, along longitudinal axis of humerus. At most anterior part of acromial arch and 1 cm posterior to this point. - TT: 12.5-MHz linear transducer. - PP: Sitting, arm at 0º, 45º, 60º active abduction, 90º elbow flexion.	- Superior LM: Edge of acromion; - Inferior LM: Humeral head. - Distance measured: Shortest tangential distance between the two landmarks.	- Patients with SIS, n = 7 - Healthy subjects, n = 13	(-) - Transducer position poorly described (particularly superior landmark). - Abducted position against belt in frontal plane might have caused variable force generation between subjects and measurements. - Blinding of examiners provided for measurements between sessions, but not for measurements taken in same session. - Small subject number.
Fremont et al (2000)	- To establish test–retest and inter-rater reliability of AHD measurement using USI at rest and during active shoulder abduction.	- Superior view; - TP: Along longitudinal axis of humerus. At inlet of subacromial space. - TT: 6-10 MHz linear transducer (set at 8 MHz) - PP: Sitting, arm at 0º and 45º active abduction, elbow 90º flexion.	- Superior LM: Lateral tip of acromion; - Inferior LM: Surface of humeral head. - Distance measured: Tangential distance between the two landmarks.	- Healthy subjects, n = 10 (20 shoulders).	(-) - Results only published in abstract format - Small subject number.
Girometti et al (2006)	- USI evaluation of supraspinatus tendon morphology, AHD, and passive dynamic anterior impingement test. - Correlation of abnormal findings with pathologic model of secondary SIS (unilateral or multidirectional instability in young overhead athletes). - 1 senior sonographer (10 years experience). - Revision of hardcopy images by second radiologist.	- Superior view, - TP: “probe placed parallel to longitudinal tendon axis (paracoronal plane)”. - TT: 5-12 MHz linear transducer. - PP: sitting, arm behind back position (shoulder internal rotation, extension). - Bilateral scans	- Superior LM: Lateral to acromial shadow from tendon entry point perpendicular to humeral head; - Inferior LM: Humeral head	- Professional basketball players n = 10, (n = 4 with early stage SIS signs (non-traumatic instability, anterior shoulder pain/crepitus). - Non-athlete controls, n = 10. - All right handed	(-) - No data on reliability for revision of hardcopy images. - Low subject number, - Transducer placement not described in detail. - Arbitrary cut-off point (compromise between US preliminary data and MRI data) for AHD is crude measure and not adjusted to height of individual. - Cranial landmark (tendon entry point) fault prone due to lack of hyperechoic landmark.

Jerosch et al (1991)	- To measure AHD changes (inferior translation of humeral head) during passive inferiorly directed longitudinal force on humerus in normal subjects and subjects with multidirectional GH instability.	- Superior view, - TP: Cranio-lateral on shoulder, in 45º angle to humerus shaft. - TT: 5 MHz linear transducer. - PP: Sitting, arm in neutral.	- Superior LM: Caudal edge of acromion. - Inferior LM: Humeral head, supraspinatus tendon. - Distance measured: Vertical distance between landmarks.	- Normal shoulders, n = 150; - Multidirectional instability, n = 34 - Unidirectional instability, n = 23	(+) - Transducer placement well described. (-) - Marker placement on landmarks insufficiently described (only shown in a picture). - AHD at rest not reported for individuals with multidirectional instability.
Pijls et al (2010)	- To evaluate the inter- and intra-rater reliability and accuracy of AHD measurement using USI for both experienced and novice examiners in patients with SIS. - Measurement of AHD in neutral and 60º abduction.	- Superior view; - TP: At inlet of subacromial space, longitudinal with respect to supraspinatus tendon. - TT: 5-12 MHz linear transducer. - PP: Sitting, arm in neutral and 60º abduction in scapular plane.	- Superior LM: Acromion. - Inferior LM: Most superior aspect of humerus. - Measured distance: AHD as shortest distance between acromion and most superior aspect of humerus (with reference to Desmeules et al 2004).	- Patients with SIS, n = 43, (50 shoulders) 2 groups: - Group 1 measured in neutral: n = 21(24 shoulders). - Group 2 measured in 60º abduction: n = 22 (25 shoulders).	(+) - Examiners blinded to own and each others measurements; - Arm position well standardised and controlled. (-) - Poor definition of transducer position. Transducer was moved until the smallest AHD was found, recorded and measured. Unclear how this was achieved, because examiners were blinded during measurements. - Small subject number per group, no randomisation into groups, no information provided whether transducer was removed from skin between measurements.
Schmidt et al (2004)	- To define standard reference values for AHD to increase diagnostic accuracy.	- Superior view - TP: Lateral longitudinal 60º, cranial side of acromion. - TT: 10-5 MHz linear, transducer (45 mm wide). - PP: Sitting, arm in 60º internal rotation, 90º elbow flexion.	- Superior LM: Acromion. - Inferior LM: Humeral head. - Distance measured: Distance between humeral head and acromion.	Healthy individuals n = 102	(+) - Probe position well described - Large sample size (-) Information on reliability applied to complete USI shoulder examination, not for AHD measurement alone.

Silva et al (2008)	- To investigate the relationship between scapular dyskinesia and AHD in elite junior tennis players and non- athletes. - To determine the correlation between AHD and scapular dyskinesia during arm abduction.	- Superior view, - TP: Coronal plane, along major axis of humerus. - TT: 7-12 MHz linear transducer. - PP: Sitting, 0º and 90º abduction, internal rotation, forearm pronated.	- Superior LM: Acromion - Inferior LM: Humerus. - Distance measured: Measurement of smallest AHD.	- Elite junior tennis athletes, n = 53. - Non-athlete matched control, n = 20.	(-) - Patient position insufficiently described. No information whether active or passive abduction, frontal or scapular plane. - Landmarks insufficiently described.
Wang et al (2005)	- To define a spectrum of USI findings in shoulders of elite baseball athletes (with and without shoulder injuries) and healthy control group regarding subacromial structures and AHD in the frontal and scapular plane.	- Superior view; - TP: Midpoint of lateral margin of acromion. - TT: 5-10 MHz linear transducer. - PP: Sitting, in 0º and 90º abduction, in frontal plane (scapula retraction, no horizontal adduction) and scapular plane (scapula protraction, 30º horizontal adduction.	In 0º abduction: - Superior LM: Most lateral point of acoustic shadow of acromion, - Inferior LM: Highest point of greater tuberosity. In 90º abduction: - Superior LM: Most lateral point of acoustic shadow of acromion, - Inferior LM: Highest point of humerus.	- Elite baseball athletes (n = 54). 3 groups: - Injured athletes (n = 42) - Uninjured athletes (n = 12) - Non-athlete, asymptomatic control group (n = 16).	(+) - Groups characteristics not significantly different. - 2 experienced physicians conducted US and agreed upon measurement and interpretation. - Arm positions confirmed by goniometer. (-) - Superior landmark not described in detail. - Inferior landmark in 0º termed as greater tuberosity. However, the distance was measured on the surface of humeral head. - Retraction of scapula for frontal plane position does not equal upright posture. This might bias distance measurements. - Arm support in abduction not standardised. This might provoke muscle contraction.

Note. LM: Landmark; PP: Participant's position; TP: Transducer position; TT: Transducer type; (+): Positive aspect of methodology; (-): Limitation of study.

The majority of studies determined the width of the subacromial space in the sagittal plane by measuring the shortest distance between the bony landmarks of the acromion and the humeral head, which corresponds with the AHD (Azzoni, et al., 2004; Desmeules, et al., 2004; Girometti, et al., 2006; Jerosch, et al., 1991; Pijls, et al., 2010; Schmidt, et al., 2004; Silva, et al., 2008; Wang, et al., 2005). Jerosch et al (1991) first described this method in 1991. Reviewing the methods, differences were apparent regarding the description for reference points and calliper placement on the US image, particularly for the landmark of the acromion. Most studies applied the lateral and/or inferior edge of the sonographic shadow of the acromion as reference point (Azzoni, et al., 2004; Cholewinski, et al., 2008; Desmeules, et al., 2004; Jerosch, et al., 1991; Pijls, et al., 2010; Wang, et al., 2005). In contrast, Girometti et al (2006) measured from the entry point of the RC tendon lateral to the acromial shadow perpendicular to the humeral head. With this method, the bursa overlying the RC tendons would be neglected. Therefore, it is questionable whether this distance measurement appropriately represents the width of the subacromial space and AHD.

One article measured the distance between the acromion and the apex of the greater tuberosity of the humerus and called it AGT distance (Cholewinski, et al., 2008). Using a bony landmark on the humerus instead of measuring the smallest distance may help in obtaining more reproducible distance measurements. Similarly, Wang et al (2005) aimed at measuring the AHD in 0º shoulder abduction (neutral) from the lateral acromion to the highest point of the greater tuberosity and in 90º of abduction to the highest point of the humerus. However, on the US images of both shoulder positions, the AHD is represented by a vertical line between the acromion and the humerus. The researchers fail to explain how they identified the greater tuberosity on the US image in the neutral shoulder position and why they chose two different landmarks on the humeral head.

Cheng et al (2008) applied an unusual measurement method. In this study, the distance change between the superior part of the coracoid and the superior part of the humeral head during inferior translation of the humeral head was measured. This measurement was obtained by taking the distance from the surface of the skin down to the bony landmarks. This method may be less reliable and less accurate compared to the previously described methods, due to potentially changing muscle bulk and soft tissue overlying the bony landmarks, as well as variable pressure of the transducer on the skin between repeated measurements.

Overall, a lack in conformity was apparent in the USI methods for distance measurements of the AHD and superior-inferior translation of the humeral head. This might be due to different definitions of the AHD. Moreover, there might be disagreement about the most relevant location of USI regarding different shoulder pathologies. The literature review identified weaknesses of the superior USI method (Table 2). The placement of the transducer was poorly described in several studies. Surface anatomy, palpation of the shoulder and centimetre measures on the skin were used to define the placement of the transducer. These USI methods may result in varied and inaccurate transducer placement between measurements, leading to variation of measurements. Another weakness of several studies was the small subject number (Cheng, et al., 2008; Desmeules, et al., 2004; Fremont, et al., 2000; Girometti, et al., 2006).

The majority of AHD measurements were taken in a resting shoulder position (Table 2). The arm was either adducted to the side of the body and internally rotated (Azzoni, et al., 2004; Girometti, et al., 2006; Schmidt, et al., 2004; Silva, et al., 2008), or in neutral rotation (Cheng, et al., 2008; Cholewinski, et al., 2008; Jerosch, et al., 1991). Five studies additionally examined the AHD in shoulder abduction. Shoulder abduction was either held actively by the participant against the resistance of a belt (Desmeules, et al., 2004; Fremont, et al., 2000), or was not further specified (Silva, et al., 2008), or the arm was supported passively (Pijls, et al., 2010; Wang, et al., 2005). Measuring the AHD in active shoulder abduction potentially provides valuable insight in GH kinematics. However, in the studies of Desmeules at al (2004) and Fremont et al (2000), the amount of muscle activity might have changed between repeated measurements, which might have caused variation in AHD measurements. Wang et al (2005) did not describe how the arm was supported during the measurement in abduction. In this study, the arm seemed to be supported merely at the elbow. This might have led to involuntary muscle contraction and concomitant AHD changes, even if the participant were asked to relax.

3.2.5 Methods of anterior and posterior imaging views

Seven articles using USI to obtain an image of the GH joint in the transverse plane were identified. Three studies applied an anterior USI view (Court-Payen, Lee Krarup, Skjoldbye, & Lausten, 1995; Krarup, et al., 1999; Yeap, et al., 2003), and three studies utilised a posterior USI view (Borsa, et al., 2005a; Borsa, Scibek, Jacobson, & Meister, 2005b; Jerosch, et al., 1991). One article applied both USI views (Bianchi, Zwass, & Abdelwahab, 1994). Table 3 summarises the research purposes, USI methodologies, study populations and limitations of the studies. Six studies utilised linear array transducers, one research group used a curved transducer (Borsa, et al., 2005a; Borsa, et al., 2005b). USI frequencies ranged between 3.5 and 10 MHz.

3.2.5.1 Anterior imaging view

The method of imaging the shoulder from anterior to assess anterior translation of the humeral head with force application was described by a research team in 1995 (Court-Payen, et al., 1995). According to this technique, the edge of the coracoid process, the greater tuberosity of the humerus and the antero-superior part of the neck of the scapula, i.e. the anterior glenoid, are identified as hyperechoic bony landmarks on the US image. Those three landmarks should delineate an almost horizontal scanning plane, in order to obtain a reasonable measurement of the anterior translation of the humeral head (Court-Payen, et al., 1995). This method was used by two other studies to determine anterior humeral head translation with an anteriorly directed force in patients with and without GH instability (Krarup, et al., 1999), and in subjects with normal shoulders (Yeap, et al., 2003).

Several methodological issues were identified in these studies, such as imprecise description of landmarks and transducer placement and small sample sizes (Table 3). The exact location of the transducer has not been described in a reproducible manner. Even if the three landmarks (coracoid process, greater tuberosity and anterior glenoid) were visualised, there might be variation in transducer placement in the superior-inferior direction due to the dimensions of these bony prominences. Moreover, using surface palpation of the coracoid to determine the scanning location like Yeap et al (2003) did, might contribute to variation in the transducer placement.

Court-Payen et al (1995) and Krarup et al (1999) placed the participants' shoulders into internal rotation and adduction with a sling, which is a rather stable position for the GH joint. Yeap et al (2003) additionally obtained images in 90º shoulder abduction and external rotation, which might be a functionally more relevant position for the assessment of humeral head translation, for example in anterior GH instability.

Bianchi et al (1994) utilised an anterior USI view for the diagnosis of posterior shoulder dislocation or subluxation in supine lying. In this study, distances between the coracoid and the anterior glenoid were obtained by calculating the difference of the distances from the skin down to the bony landmarks. Variations of muscle bulk and soft tissue overlying the bony landmarks, as well as variable pressure of the transducer on the surface of the skin might be a source of error in this USI method. These factors might affect the reproducibility of distance measurements, as well as obstruct comparability of distances measured between the right and left body side, between individuals, and between repeated measurements over time.

3.2.5.2 Posterior imaging view

Four studies used the posterior USI view to determine the distance between the posterior humeral head and the posterior glenoid or a posterior aspect of the scapula in the transverse plane. Three studies measured the glide of the humeral head that occurred in an anterior-posterior direction with an anterior and/or posterior directed force (Borsa, et al., 2005a; Borsa, et al., 2005b; Jerosch, et al., 1991). The posterior USI method was first described by Jerosch et al (1991). The researchers chose the dorsal glenoid rim and the posterior edge of the humeral head as landmarks and measured the relative distance change between the two landmarks at rest and with an anterior or posterior directed glide, indicating an anterior or posterior translation of the humerus relative to the glenoid. Jerosch et al (1991) defined the transducer position as midway between the upper and lower glenoid edge. However, the upper and lower boundaries of the glenoid are not visible simultaneously on the US image and the researchers failed to provide a reproducible method for how to determine the correct location of the transducer.

Borsa et al (2005a) adopted this USI method by using a biaxial anatomical coordinate system for distance measurement, in which a flat part on the posterior scapula represented the x-axis, and a perpendicular line drawn to the posterior humeral head represented the y-axis. With this method, the location of scanning might be problematic to reproduce, because one defined flat part of the scapula does not exist. This might lead to inconsistent transducer placement. Bianchi et al (1994) measured from the posterior skin of the shoulder to the bony landmarks, which again poses difficulties on accuracy due to possibly variable bulk of soft tissue overlying the landmarks and variable pressure on the transducer on the skin. Bianchi et al (1994) took measurements while patients were actively moving their arm into a symptomatic position. Limitations of that study are that shoulder movements were not standardised and only five patients were examined.

Table 3. ***Reviewed ultrasound imaging studies measuring anterior-posterior humeral head translation.***

Author	**Study purpose**	**USI view; Transducer placement (TP); Transducer type (TT); Participant position (PP)**	**Landmarks (LM)**	**Participants**	**Limitations of study**
Bianchi et al (1994)	- Use of USI to diagnose posterior shoulder instability and subluxation by comparing affected and healthy side. Static and dynamic examination.	- Posterior and anterior transverse view. - TP: horizontal, at level of middle of GH joint, just under the spine of the scapula. - TT: 7.5 MHz linear transducer - Bilateral scans. PP: Sitting (posterior view); Supine (anterior view) in neutral (some subjects also in 90º flexion, abduction, external rotation).	In posterior USI view: - 1. LM: Posterior edge of glenoid, - 2. LM: Posterior edge of humeral head. In anterior USI view: - 1. LM: Coracoid process, 2. LM: Anterior edge of humeral head. - Distance measured: Distance from skin to the landmarks and calculation of their difference.	- Patients with history of shoulder trauma n = 10.	(-) - Distance measurement from skin to landmarks inaccurate due to muscle bulk and variable pressure on transducer. - Lack of information on neutral arm position (not reproducible). - Scanning in supine might influence position between landmarks due to gravity or muscle contraction (only three subjects were scanned in both the posterior and anterior USI view). - No information about actual distances measured, only differences between affected and non-affected side given. - Small sample size (results presented for 5 patients).

Borsa et al (2005a)	- To determine validity and reliability of posterior USI method for assessing GH laxity in non-symptomatic shoulders (stress radiography was reference standard for validity study).	- Posterior transverse view. - TP: referred to Jerosch et al (1991), Krarup et al (1999), and Court-Payen et al (1995). - TT: 5.0 MHz curved transducer. - PP: Sitting, arm fixed in 90º abduction, 60º external rotation. - Right shoulders assessed	- 1. LM: Flat segment of posterior scapula, - 2. LM: Posterior humeral head. - Distance measured: With biaxial anatomical coordinate system: x-axis: Plane of scapula, y-axis: Perpendicular line drawn from x-axis to point on humeral head.	- Validity study: Asymptomatic subjects n = 20. - Reliability Intra- and inter-rater study (test retest, 24 hours): Asymptomatic subjects n = 13. .	(+) - Image evaluation blinded and randomised. - One examiner placed markers on landmarks, other examiner measured displacement as difference of humeral head excursion between stressed and unstressed image (not blinded to stressed and unstressed). (-) - USI method not described in detail. - No report on how blinding and randomisation for image evaluation by two examiners was achieved. - Transducer placement insufficiently described (not reproducible). - Small sample size for reliability study.
Borsa et al (2005b)	- To quantify passive anterior and posterior humeral head translation in elite swimmers and non-swimming controls using USI under stressed (150 N) and non-stressed conditions. - To determine the influence of history of shoulder pain in swimmers on GH laxity.	- Posterior transverse view. - TP: referred to Jerosch et al (1991). - TT: 5.0 MHz curved transducer. - PP: Sitting, arm fixed in 90 abduction, 60 external rotation, scapular plane. - Bilateral scans.	Same landmarks and biaxial distance measurement system as in Borsa et al (2005a).	- Asymptomatic elite swimmers n = 42, (n = 27 with history of shoulder pain). - Asymptomatic control subjects n = 44.	(+) - Test order randomised - Distance measurement blinded and randomised. - Standardised force application and joint positioning. (-) - USI method not described in detail. - Transducer placement and scapular landmark (plane of scapula) not reproducible). - Scanning plane variable in vertical axis - Biaxial coordinate measurement system prone to errors due to possible changes of transducer angle. - No raw distances reported, only the differences between baseline and stressed condition.

Court-Payen et al (1995)	- Measurement of anterior humeral head translation with passive anteriorly directed force (90 N). - Evaluation of difference between stressed and non-stressed situation, and right and left shoulders.	- Anterior transverse view. - TP: Horizontal on anterior shoulder with horizontal alignment of greater tuberosity, anterior glenoid and coracoid process. - TT: 3.5 MHz linear transducer, 8 cm wide. - PP: Sitting, shoulder in internal rotation, elbow at body.	- 1. LM: Anterior edge of greater tuberosity; - 2. LM: Antero-superior part of neck of scapula, (anterior tip coracoid process for horizontal alignment).	- Asymptomatic shoulders, n = 20.	(+) - 5 scans and standardised force application, - Range of measurements (SEM up to 0.067, difference between measurements up to 0.41). (-) - No information about calculation of SEM and intra-rater reliability values. - Training level of sonographer not reported. - Transducer placement is not clearly defined by 3 bony landmarks. There is still variability in the vertical direction even if all 3 landmarks are visualised.
Jerosch et al (1991)	- Measurement of passive anterior and posterior humeral head translation in relation to dorsal glenoid (anterior and posterior drawer test) in normal shoulders and in shoulders with instability.	- Posterior transverse view. - TP: Probe on dorsal contour of shoulder, midway between upper and lower edge of glenoid, perpendicular to bony surface of posterior scapula (in both planes). - TT: 5 MHz linear transducer. - PP: Sitting, arm in neutral.	- 1. LM: Posterior glenoid, - 2. LM: Posterior humeral head. - Flat part of posterior scapula for transducer alignment.	- Asymptomatic: n = 150; - Multidirectional shoulder instability n = 34; - Unidirectional shoulder instability n = 23.	(+) - Clear description of landmarks and measurements. (-) - Transducer placement in vertical axis is variable and not reproducible (unclear is how the midline of posterior glenoid was defined, and how transducer position was reproduced on uneven surface of posterior scapula). - Subject characteristics insufficiently described.

Krarup et al (1999)	- Measurement of anterior humeral head translation during passive anteriorly directed force (90 N).	- Anterior transverse view; - TP: same as Court-Payen et al (1995) - TT: 3.5 MHz, linear transducer, 8 cm wide. - PP: Sitting, arm in internal rotation with elbow at side of body, (5 subjects: external rotation and neutral with elbow at body for test of influence of rotation). - Bilateral scans.	Same as Court-Payen et al (1995)	- Unilateral shoulder instability n = 20; - Asymptomatic control group n = 20.	(+) - Transducer placement and landmarks well described. - Standardised force application - 5 scans (-) - Transducer placement is variable in vertical axis. - No description how SEM was calculated. - No values for standard deviation. - Significant inter-rater variation, intra-rater values consistently higher for one examiner. - Training level of sonographer not reported.
Yeap et al 2003	- To establish inter-rater reliability for the measurement of anterior humeral head translation with an anteriorly directed force in a healthy population. - Anterior force of 90 N, 60 N, and pressure applied with thumb.	- Anterior transverse view; - TP: Anterior shoulder, at level of coracoid process. - TT: 10 MHz, 6 cm wide, linear transducer. - PP: 1. Sitting, arm in internal rotation with elbow at side of body. 2. Sitting, with arm in 90 abduction and external rotation	- 1. LM: Greater tuberosity of the humerus; - 2. LM: Anterior aspect of glenoid. - Coracoid process as landmark for transducer placement. - Distance measured: From anterior glenoid to most anterior aspect of humeral head.	Normal subjects n = 23; only right shoulders scanned.	(+) - Anterior force application standardised with a myometer in neutral and 60º abduction. (-) - Surface palpation used for landmark identification (coracoid process) and location for transducer placement. - Shoulder manually fixed during force application. - Blinding of measurements not evident (for 2 raters during USI, and blinding for one rater placing callipers and measuring distances on all pictures).

Note. LM: Landmark; PP: Participant’s position; TP: Transducer position; TT: Transducer type; (+): Positive aspect of methodology; (-): Limitation of study.

3.2.6 Distances measured with ultrasound imaging

3.2.6.1 Acromiohumeral distance in asymptomatic populations

Values for the AHD and humeral head translation that were reported for asymptomatic individuals using a superior USI view are summarised in Table 4. Mean AHD values at rest ranged between 0.56 cm and 1.34 cm. There seems to be a considerable variability within AHD values, which might have been influenced by true variation of the AHD between individuals, and by differences in the USI technique and positioning of participants. Although all measurements were obtained in sitting, two studies placed the arm in adduction and internal rotation (Girometti, et al., 2006; Schmidt, et al., 2004), whereas others adopted a neutral shoulder position (Cheng, et al., 2008; Cholewinski, et al., 2008; Desmeules, et al., 2004; Fremont, et al., 2000; Jerosch, et al., 1991; Silva, et al., 2008; Wang, et al., 2005). Interestingly, in four out of seven studies, mean AHD values ranged between 0.98 cm and 1.09 cm (Desmeules, et al., 2004; Fremont, et al., 2000; Schmidt, et al., 2004; Silva, et al., 2008). Girometti et al (2006) reported slightly lower mean values of 0.85 cm and 0.86 cm for the right and left side respectively. Compared to these results, one study found slightly higher mean AHD values averaging 1.34 cm (Jerosch, et al., 1991), whereas another study reported considerably smaller mean AHD values ranging from 0.56 cm (non-dominant side, frontal plane) to 0.74 cm (dominant side, scapular plane) (Wang, et al., 2005). Cholewinski et al (2008) did not measure the AHD, but the distance from the acromion to the tip of the greater tuberosity (AGT), and reported a mean AGT of 2.27 cm, which expectedly was larger compared to the AHD values described in the other articles.

Four studies investigated the influence of shoulder abduction on the AHD (Desmeules, et al., 2004; Fremont, et al., 2000; Silva, et al., 2008; Wang, et al., 2005). Three studies found a considerable and statistically significant decrease of the AHD between 0.15 cm and 0.23 cm when the arm was moved from neutral into 45º or 60º of abduction (Desmeules, et al., 2004; Fremont, et al., 2000; Silva, et al., 2008). In contrast, Wang et al (2005) reported no significant change of the AHD between 0º and 90º abduction. These differences might have been influenced by muscle contraction, because Desmeules et al (2004) and Fremont et al (2000) examined the AHD in abduction during active muscle contraction, whereas Wang et al (2005) supported the participants' shoulders in passive abduction. In addition, Wang et al (2005) reported the smallest AHD values across the studies. Therefore, differences in the measurement methods are likely to have played a role too. One study measured AHD values in the frontal and scapular plane, but did not observe significant differences between the two positions (Wang, et al., 2005).

Table 4. ***Acromiohumeral distance in asymptomatic populations.***

Author	Participants' characteristics	AHD Mean ± SD (range)	Shoulder position	Action
Cheng et al (2008)	Men, n = 19, age: 24.1 ± 4.4 years, height: 182.2 ± 7.7 cm, weight: 77.1 ± 9.5 kg.	Inferior translation: 0.44 ± 0.23 cm	Sitting, - shoulder in 10º extension	90 N caudal force (passive)
Cholewinski et al (2008)	Asymptomatic control group, n = 72 (♀: 22, ♂: 14), age: 57 (38-79) years	Median AGT distance *2.27 (1.83 – 2.94) cm* - Norm AGT distance: 1.91 – 2.84 cm (5^{th}-95^{th} percentile). - Norm difference for AGT distance between shoulders: 0.21 cm (excludes constitutional factors).	Sitting, - arm in neutral rotation	Rest
Desmeules et al (2004)	Healthy subjects, n = 13, age: 34 ± 9 years	*0º: 0.99 ± 0.15 cm* *45º: 0.83 ± 0.19 cm* *60º: 0.76 ± 0.17 cm* Mean maximal AHD narrowing from 0º to 60º: *0.25 ± 0.11 cm (15%)* AHD at 45º and 60º smaller than at 0º ($p \leq 0.001$).	Sitting, - arm in neutral, 45º and 60º abduction in frontal plane	- Rest in neutral; - Active abduction against belt in 45º and 60º.
Fremont et al (2000)	Healthy , n = 10 (20 shoulders)	*0º: 0.98 ± 0.15 cm*; (CI = 0.93 - 1.03) *45º: 0.83 ± 0.19 cm;* (CI = 0.76 - 0.90) Change of AHD between 0º and 45º significant ($p < 0.0001$)	sitting, - arm in neutral, and in 45º abduction in frontal plane.	- Rest in neutral, - Active abduction against belt in 45º and 60º.
Girometti et al (2006)	Asymptomatic non-athlete control group, n = 10, age: 21.6 (20-25) years	*0.860 ± 0.083 cm* (right side) *0.849 ± 0.086 cm* (left side) *Normal AHD defined as ≥ 0.7 cm*	Sitting, - arm adducted at trunk, internal rotation, extension	Rest

Jerosch et al (1991)	Asymptomatic subjects, n = 150, weight: 86.7 (77-88.5) kg, height: 1.90 (1.84-1.96) m, age range: 17-58 years.	*1.34 ± 0.21 cm (at rest)* Translation with caudal force: 0.24 (± 0.19) cm (dominant) 0.23 (± 0.22) cm non-dominant)		Sitting, - arm in neutral	Rest, and caudal force (manually applied)
Schmidt et al (2004)	n = 102, (♀: 54; ♂: 48), right handed n = 94, age: 38.4 years, height: 1.72 (1.56 – 1.98) m	*1.09 (0.59 – 1.96) ± 0.42 cm* (2 SD)		Sitting, - 60º internal rotation	Rest
Silva et al (2008)	n = 10 (♀: 11, ♂: 9), 20 shoulders, age: 14.6 (11 – 17) years, height: 161.9 cm, weight: 61.1 kg.	*0º: 0.98 ± 0.14 cm (0.76 – 1.39)* *60º: 0.762 ± 0.15 cm* (0.46 – 1.08) AHD reduction with abduction: *0.218 ± 0.11 cm* (0.01 – 0.55)		Sitting, - 0º and 60º abduction	Rest
Wang et al (2005)	Asymptomatic non-athlete control group, n = 16, age: 21.4 ± 1.2 years, height: 177.0 ± 3.7 cm, weight: 71.2 ± 14.1 kg, Positive physical examination results: n = 0.	0º, frontal plane *0.56 ± 0.15 cm* (dominant) *0.59 ± 0.21 cm* (non-dominant) 90º, frontal plane *0.62 ± 0.16 cm* (dominant) *0.73 ± 0.23 cm* (non-dominant)	0º, scapular plane *0.69 ± 0.16 cm* (dominant) *0.74 ± 0.28 cm* (non-dominant) 90º, scapular plane *0.67 ± 0.20 cm* (dominant) *0.72 ± 0.22 cm* (non-dominant)	Sitting, - 0º and 90º passive abduction - in frontal and scapular plane	Rest

Note.♀ Female; ♂: Male; 0º, 45º, 60º, 90º: Refers to degrees of shoulder abduction; CI: 95% confidence interval; AGT: Distance from acromion to the tip of the greater tuberosity; AHD: Acromiohumeral distance; Values for age, weight and height are mean values (± standard deviation or range).

3.2.6.2 *Acromiohumeral distance in pathologic populations*

Table 5 summarises the USI studies that obtained AHD values in populations with shoulder disorders (RC degeneration and SIS), and in athletes with or without shoulder symptoms (basketball, tennis, and baseball athletes). Azzoni et al (2004) found that the AHD decreased significantly with increasing severity of RC pathology ($p < 0.05$). Similarly, Cholewinski et al (2008) described that the distance between the acromion and the greater tuberosity (AGT) and RC thickness were significantly smaller in the affected shoulders of SIS patients compared to the unaffected shoulders (median difference of 2.2 cm) and compared to a healthy control group (median difference of 2.27 cm) ($p < 0.0001$). In addition, Cholewinski et al (2008) calculated a norm - difference for the AGT based on the average difference between the right and left shoulder of healthy individuals. They concluded that differences in the AGT exceeding 2.1 mm between the right and left shoulder might indicate RC dysfunction.

For evaluation of the AHD in overhead athletes, Girometti et al (2006) used a cut-off point for the AHD of smaller than 7 mm, thereby identifying a decreased AHD in six out of ten professional basketball players. Four players had mild SIS symptoms, or a history of non-traumatic GH instability. Interestingly, in all four symptomatic athletes the AHD was reduced on the affected side. Moreover, no other pathologic changes were diagnosed in the athletes' shoulders regarding tendon echotexture, dynamic anterior impingement testing, and thickness of RC tendons or bursa. The AHD was reduced in only two out of twelve asymptomatic shoulders, whereas a reduced AHD was found in both shoulders of the two athletes with non-traumatic GH instability. Consequently, Girometti et al (2006) suggested that a reduction of the AHD beyond the cut-off point of 7 mm might be an early detectable sign of secondary SIS.

Similarly, Silva et al (2008) found in elite junior tennis players significantly smaller AHD values in a neutral shoulder position compared to a non-athlete control group ($p < 0.001$). This finding is particularly interesting, because none of the tennis players had shoulder pain or a history of injury, yet 43% demonstrated scapular dyskinesia, with the majority being affected bilaterally. Moreover, athletes with scapular dyskinesia, showed a significantly greater AHD reduction when the shoulder was abducted to 60º compared to athletes who did not demonstrate scapular dyskinesia (0.19 cm compared to 0.14 cm; 21.4% versus 16.1% narrowing).

With respect to AHD changes during active abduction, SIS patients demonstrated more pronounced AHD narrowing in early ranges of abduction (from 0° to 45°) compared to a healthy group (21% versus 15%), and displayed more stable AHD values between 45° and 60° abduction (Desmeules, et al., 2004). Furthermore, in this study, a strong relationship was found between functional improvement following neuromuscular SIS rehabilitation and the occurrence of AHD reduction during abduction. In other words, after rehabilitation, AHD did not decrease as strongly as before the intervention. Thus, SIS rehabilitation seems to have had a normalising effect on faulty kinematics of the GH joint. Interestingly, AHD values tended to be higher in the SIS group than in the healthy group. The researchers thought that insufficient activation of the RC muscles in SIS patients was responsible for both the excessive superior translation of the humeral head during early ranges abduction and the larger AHD values at rest (Desmeules, et al., 2004). However, the study's results must be interpreted with caution, due to a small sample size of only seven subjects with SIS.

Another study found a mean AHD decrease of 2.5 mm in patients with SIS, when their affected shoulders were moved from neutral into 60º abduction (Pijls, et al., 2010). Although this change was significant, the results were not compared to a healthy control group. In contrast to those results, Wang et al (2005) reported significantly greater AHD values at 0º and 90º abduction in elite baseball athletes with and without shoulder injuries compared to a control group. The researchers suggested that joint hyperlaxity in the athletes' shoulders might have caused this difference. In addition, injured athletes demonstrated a significant increase of the AHD when the arm was abducted passively, whereas the AHD in uninjured athletes and the control group did not increase. The researchers suggested that this AHD increase with abduction either occurred to avoid further injury, or might be a result of shoulder injury (Wang, et al., 2005).

Jerosch at al (1991) examined the amount of inferior humeral head translation occurring with an inferiorly directed force in patients with multidirectional GH instability. They found that in multidirectional unstable shoulders, the increase of inferior translation of the humeral head was significantly larger compared to the unaffected side and compared to a control group ($p \leq 0.05$). The mean inferior translation in unstable shoulders was 0.37 cm larger than in healthy shoulders, and could reach up to 1.0 - 1.5 cm (Jerosch, et al., 1991).

Table 5. ***Acromiohumeral distance in pathologic populations.***

Author	Characteristics of studied population; Patient position	AHD Mean ± SD / range	Main Findings/ Difference to control groups
Azzoni et al (2004)	- Shoulder pain group with different stages of RC degeneration, n = 200. Group 1: Painful normal RC: n = 70, age: 48.6 years, (right: 38; left: 32; dominant 40) Group 2: RC tendinopathy: n = 54; age: 57.5 years; (right: 34; left: 20; dominant 40) Group 3: Partial RC tear: n = 20; age: 64 years; (right: 10; left: 10; dominant 15) Group 4: Complete RC tear: n = 26, age: 60.4 years, (right: 16; left: 10; dominant 18). - Patient position: Sitting, arm in extension, internal rotation.	Group 1: *0.69 - 1.66 cm* Group 2: *0.96 - 1.74 cm* Group 3: *0.65 - 1.31 cm* Group 4: *0.61 - 1.29 cm*	- AHD decreases with increasing severity of RC pathologies. - AHD decreased significantly between the four groups ($p < 0.05$). - AHD significantly reduced in females versus males ($p < 0.05$) - Prevalence of RC pathologies higher on dominant side - No correlation of AHD with age for each group.
Cholewinski et al (2008)	- Patients with SIS, Degenerative RC: 61% Partial RC tear: 16% Complete RC tear: 11%. Mean duration of SIS: 7 (6-48) months (32 right, 25 left, 36 dominant side). n = 57 (♀:34, ♂: 23), age: 56 (34 - 83) years - Asymptomatic control group, n = 72 (♀: 22, ♂: 14), age: 57 (38-79) years. - Patient position: Sitting, arm in neutral rotation	Median AGT distance in SIS affected side: *1.94 (1.12 - 3.12) cm* Difference in AGT distance between both shoulders: Range - 0.39 cm to + 0.86 cm (difference between median values: 0.27cm)	Study group: - AGT distance and RC thickness smaller in SIS affected versus non-affected side (p < 0.000001) ((Non-affected side median value: 2.22 (1.64 - 3.42) cm) - AGT distance smaller in SIS shoulders versus control (p < 0.000001) (Control median: 2.27 (1.83 – 2.94) cm) - no difference in AGT of non-affected side in SIS group versus control (p= 0.13) - Mean difference in AGT distance between both shoulders of the same subject in SIS group greater than in control group (p < 0.00001) (In control group, difference in AGT distance between both shoulders range 0.0 to + 0.36 cm (difference between median values: 0.06 cm)) Control group: - No difference in AGT distance between dominant and non-dominant side - Significant correlation between AGT distance and body height ($p < 0.03$) - Difference of AGT distance of more than 2.1mm between affected and unaffected shoulder may indicate RC dysfunction.

Desmeules et al (2004)	- Patients with SIS, n = 7, age: 44 ± 3.8 years. - Patient position: Sitting, arm at side, active abduction at 45º and 60º shoulder abduction.	*0º: 1.20 ± 0.19 cm* *45º: 0.95 ± 0.27 cm* *60º: 0.96 ± 0.23 cm* Differences between positions: 0º and 45º: significant (*p* ≤ 0.001) 21%; 0º and 60º: significant (*p* ≤ 0.001); 45º and 60º: non-significant (*p* = 0.99).	- Mean maximal AHD decrease with abduction: SIS group: 0.28 ± 0.11 cm Healthy group: 0.25 ± 0.11 cm - No significant difference between SIS group and healthy group in AHD values in the three shoulder positions (*p* = 0.06), and in mean maximal AHD decrease with abduction (*p* = 0.77). - SIS group showed more pronounced AHD decrease from 0º - 45º in SIS group than in healthy group (21% versus 15%). - SIS group showed less AHD decrease between 45º and 60º than healthy group. - Strong relationship between larger AHD values with abduction and functional improvement following SIS rehabilitation. -Excessive superior translation of humeral head in first portion of abduction may be associated with insufficient RC activity.
Girometti et al (2006)	- Professional basketball players, n = 10, age: 20.4 (19-22) years. Symptomatic, n = 4 (non-traumatic instability n = 2, anterior shoulder pain / crepitus: n = 2), asymptomatic n = 6. weight: 86.7 (62-115) kg, height: 1.94 (1.73-2.08) m. All subjects right hand dominant - Non-athlete control group, n = 10 - Patient position: Sitting, arm behind back position (shoulder internal rotation, extension)	*Right: 0.719 ± 0.159 cm* *Left: 0.770 ± 0.146 cm* Cut-off point of AHD < 7 mm applied to 6 out of 10 subjects (4 symptomatic and 2 non-symptomatic subjects) (5 / 10 right shoulders and 8 / 20 shoulders in total).	- AHD reduction (< 7 mm) was the only parameter with significant difference between the groups (p < 0.05). - USI parameters (RC tendon echotexture, RC tendon and bursal thickness) and dynamic anterior impingement testing were not pathologic in both groups and not different between study and control group (p > 0.05). - There was no AHD reduction (< 7 mm) in the control group. - AHD reduction (< 7 mm) occurred in subjects with non-traumatic GH instability (n = 2), painful shoulder (n = 2) and asymptomatic players (n = 2). Six shoulders in 4 symptomatic subjects displayed reduced AHD. -AHD reduced beyond cut-off point was observed even in absence of clinical or sonographic evidence of SIS. -AHD reduction might be early detectable sign of secondary shoulder impingement, independent from clinical onset.

Jerosch et al (1991)	- Patients with multidirectional instability, n = 34 - Patient position: Sitting, arm in neutral, manual caudal force.	Inferior translation of humeral head with caudally directed force: *0.61 ± 0.33 cm* (affected side) *0.44 cm* (non affected side)	- Inferior translation with caudally directed force significantly larger in shoulders with multidirectional instability compared to control group (0.61 versus 0.24 cm; *p* = 0.05), and unaffected side compared to control group (0.61 cm versus 0.44 cm) (p < 0.05). - Inferior subluxation of humeral head in multidirectional instability can reach up to 1.0 – 1.5 cm.
Pijls et al (2010)	- Patients with SIS, n = 43, 50 shoulders, 2 groups: Group 1 (neutral): n = 21 (♀: 12, ♂: 9), 24 shoulders (9 right, 16 left), age: 51 (34 – 74) years, height: 174 (162 – 193) cm. Group 2 (60º abduction): n = 22 (♀: 12, ♂: 10), 25 shoulders (9 right, 16 left), age: 52 (34 – 68) years, height: 172 (160 – 186) cm. - Patient position: Sitting, arm in 0º, neutral and in 60º abduction.	*0º: 0.92 ± 0.14 cm* *60º: 0.67± 0.14 cm* - Experienced examiner: 0.93 ± 0.17 cm (0.61 -1.27) (0º neutral) 0.67 ± 0.17 cm (0.40 – 1.06)(60º) -Novice examiner: 0.90 ± 0.14 cm (0.64 – 1.20) (0º neutral) 0.67 ± 0.14 cm (0.51- 1.10) (60º)	- Mean AHD in neutral 2.5 mm greater than mean AHD in 60º abduction (*p*< 0.0001). - Accuracy for consecutive AHD measurements on same individual by same examiner: 0.11 mm (95% CI 0.07-0.15 cm) (0º neutral), 0.14 cm (95% CI 0.08-0.2 cm) (60º abduction)
Silva et al (2008)	- Elite junior tennis athletes, non-symptomatic, non-injured, n = 53, 106 shoulders, (♀: 22, ♂: 31), age: 14.6 (11 – 18) years, height: 166.6 cm, weight: 57.2 kg. - 43.4% of athletes had scapular dyskinesia (20% of subjects with scapular dyskinesia in control group). Training volume: 11.4 hours/week, participation in competitions: 6 (2 – 12) years.	- All athletes : *0º : 0.88 ± 0.15 cm* (0.55-1.32) *60º : 0.72 ± 0.15 cm* (0.45- 1.19) - AHD reduction from 0º - 60º in all athletes: : 0.16 ± 0.09 cm (-0.03 – 0.41) - AHD reduction from 0º - 60º in athletes with scapular dyskinesia: 0.19 ± 0.08 (- 0.03 –0.41); 21.4% - AHD reduction from 0º - 60º in athletes without scapular dyskinesia: 0.14 ± 0.09 cm (-0.01- 0.39); 16.1%.	- In 0º, AHD in athletes is significantly smaller compared to non-athlete control group (*p* < 0.001). - In 60º abduction, AHD is smaller in athletes versus control group, but not significant (*p* = 0.136). - Decrease of AHD with abduction is significantly greater in athletes with scapular dyskinesia compared to athletes without scapular dyskinesia (0.19 cm versus 0.14 cm versus; 21.4% versus 16.1%; p=0.002). - Decrease of AHD with abduction significantly greater in non-athlete controls versus athletes (0.21± 0.11 cm versus 0.16 ± 0.09) (*p* < 0.001).

Wang et al (2005)	- Elite baseball athletes with shoulder injuries, n = 42, (43 injuries, n = 40 dominant side, n = 27 with RC lesion) n =31 throwing related pain (VAS pain 4.7 ± 1.6), Pathologic physical examination results: n = 27. Age: 20.6 ± 1.8 years, height 177.5 ± 5.2 cm, weight: 78.5 ± 8.1 kg, training history: 9.3 ± 2.2 years. - Patient position: Frontal and scapular plane in 0º and 90º of passive abduction.	0º, frontal plane : *0.78 ± 0.28 cm* (dominant) *0.81 ± 0.27 cm* (non-dominant) 90º, frontal plane : *0.96 ± 0.31 cm* (dominant) *0.96 ± 0.33 cm* (non-dominant) 0º, scapular plane : *0.77 ± 0.33 cm* (dominant) *0.68 ± 0.22 cm* (non-dominant) 90º, scapular plane : *0.83 ± 0.23 cm* (dominant) *0.77 ± 0.25 cm* (non-dominant)	- AHD in frontal plane in 0º and 90º abduction is significantly greater in athletes (injured and uninjured) compared to control ($p < 0.05$), but no significant difference between groups in scapular plane. - Significant increase of AHD with abduction from 0º to 90º in frontal plane in injured group ($p = 0.003$). - No significant change in AHD between 0º and 90º abduction in uninjured athletes and control group in frontal and scapular plane. - Increased tendon thickness of supraspinatus and biceps in athletes (injured and uninjured) compared to control group, but no significant correlation between hypertrophic supraspinatus tendon and AHD ($p > 0.05$, $r = 0.3$). - Plane of scanning (frontal compared to scapular plane) did not significantly influence AHD in shoulder abduction. - GH joint laxity possible reason for increased AHD.

Note.♀: Female; ♂: Male; 0º, 45º, 60º, 90º: Refers to degrees of shoulder abduction; AHD: Acromiohumeral distance; Values for age, weight and height are mean values (± standard deviation or range).

3.2.6.3 Anterior-posterior humeral head translations in asymptomatic populations

Table 6 summaries the distance measurements between the humeral head and scapular landmarks in the anterior-posterior direction that were obtained with anterior or posterior transverse USI scans in healthy individuals. In one study, the distance between the posterior edge of the humeral head and the dorsal glenoid rim ranged between 0.8 cm - 1.0 cm (Jerosch, et al., 1991). No study has reported on the distance between the anterior edge of the humeral head and the anterior glenoid. However, several studies examined the distance changes in anterior humeral head translation that occurred with the application of anteriorly directed glides (Court-Payen, et al., 1995; Jerosch, et al., 1991; Krarup, et al., 1999; Yeap, et al., 2003). Mean anterior humeral head translation ranged between 0.11 cm and 0.18 cm and did not exceed 0.41 cm when the arm was positioned along the side of the body in internal rotation and a force of 60 - 90 N was applied (Court-Payen, et al., 1995; Krarup, et al., 1999; Yeap, et al., 2003). In a neutral arm position, the net amount of humeral head translation between the application of an anterior and posterior drawer force resulted in 0.66 cm and 0.41 cm for the dominant and non-dominant side respectively (Jerosch, et al., 1991).

When an anterior glide was applied in shoulder abduction and external rotation, Borsa et al (2005a; 2005b) found mean anterior humeral head translation between 0.27cm and 0.30 cm (100 - 150 N), whereas Yeap et al (2003) reported considerably smaller values, some of which even were negative (- 0.07 cm - 0.001 cm; 60 – 90 N). This finding could not be logically explained by the authors, because negative values would indicate a posterior humeral glide, despite the use of an anterior force. However, it is likely that the study's poor measurement reliability has contributed to these conflicting results.

Examining the dorsal projection of the humeral head over the posterior glenoid, mean values of 0.99 cm for the dominant side and 1.09 cm for the non-dominant side in neutral were reported, when a manual posterior drawer was applied (Jerosch, et al., 1991). Borsa et al (2005a; 2005b) found posterior humeral head translation ranging between 0.49 - 0.55 cm in shoulder abduction and external rotation with the application of 100 -150 N posteriorly directed force compared to the non-stressed position.

3.2.6.4 Anterior-posterior humeral head translations in pathologic populations

Four studies reported results of anterior and posterior USI view measurements in pathologic or athletic populations (Table 7). In a study with elite swimmers, anterior-posterior humeral head translation with anterior and posterior force application in abduction and external rotation was measured (Borsa, et al., 2005b). There was no significant difference in swimmers compared to a control group ($p = 0.49$), and between swimmers with history and without history of shoulder pain ($p = 0.68$). This might be due to increased capsuloligamentous tension in shoulder abduction and external rotation inhibiting humeral head translation compared to the neutral shoulder position (Abboud & Soslowsky, 2002; Lugo, et al., 2008; Veeger & van der Helm, 2007).

In contrast, Jerosch et al (1991) found significantly larger anterior-posterior humeral head translation in patients with anterior GH instability between the affected and unaffected shoulders and compared to a control group with the application of an anterior and posterior drawer in a neutral shoulder position ($p < 0.0001$). Similarly, Krarup et al (1999) reported significantly more anterior humeral head translation in patients with unilateral GH instability compared to a healthy control group (4.9 mm versus 1.9 mm, $p < 0.01$) and compared to the contralateral shoulders ($p < 0.01$) when an anteriorly directed force was applied. Another study measured the distance between the posterior glenoid and the posterior edge of the humeral head in patients with a history of shoulder trauma (Bianchi, et al., 1994). The main finding of this study was that the difference between the affected and unaffected side was larger than 2 cm in patients with posterior shoulder dislocation, and lay between 1.2 cm and 1.8 cm in patients with posterior subluxation.

Table 6. ***Anterior-posterior translation of humeral head in asymptomatic populations.***

Author	**Participants' characteristics**	**Mean value of anterior-posterior humeral head translation ± SD (range)**	**Shoulder position**	**Action**
Borsa et al (2005a)	- n = 13, (♀: 3; ♂: 10); (right dominant n = 9, left dominant n = 4); age: 22.9 ± 3.4 years; height: 175.5 ± 14.2 cm; weight: 75.2 ± 15.5 kg	Change from non-stressed position to stressed position: - Anterior: Session 1: *0.28* ± *0.14 cm* Session 2: *0.30* ± *0.18 cm* - Posterior: Session 1: *0.55* ± *0.25 cm* Session 2: *0.50* ± *0.18 cm*	Sitting, - 90º abduction and 60º external rotation.	Posterior and anterior directed linear force (100 N) to proximal humerus.
Borsa et al (2005b)	- n = 44 - ♂: n = 26, age: 21.5 ± 3.3 years; height : 179 ± 9.7 cm; weight : 79.2 ± 16.6 kg - ♀: n = 18, age: 18.7 ± 0.6 years; height : 165.3 ± 5.5 cm; weight : 62.3 ± 8.5 kg	Change from non-stressed position to stressed position Anterior: *0.27* ± *0.17 cm* Posterior: *0.49* ± *0.27 cm*	Sitting, - 90º abduction, 60º external rotation, scapular plane.	Posterior and anterior directed linear force on proximal humerus (150 N).
Jerosch et al (1991)	- n = 150 (bilateral scans in all participants), age range: 17-58 years.	- Difference between anterior and posterior drawer: *0.66 cm (dominant)* *0.41 cm (non-dominant)* Significantly more anterior translation in dominant versus non-dominant side (*p* = 0.0045) - Resting position of humeral head in normal shoulders: Posterior humerus projects 0.8 – 1.0 cm posterior to dorsal glenoid rim. (Trend of difference between dominant and non-dominant arm and between male and female at rest). - Posterior projection of humeral head over posterior glenoid with anterior drawer: *0.33* ± *0.27 cm (dominant)*; *0.68* ± *0.26 cm (non-dominant,* With posterior drawer: *0.99* ± *0.34 cm (dominant); 1.09* ± *0.23 cm (non-dominant)*	Sitting, - arm in neutral	Rest; anterior and posterior drawer (manually applied).

Krarup et al (1999)	- n = 20 (♀: 10; ♂: 10); age: 34 ± (22 – 35) years.	Mean anterior: *0.18 ± 0.01 cm* (SEM) Mean difference *0.07 ± 0.04 cm* (SEM) - No differences in anterior translation among different rotational positions of the shoulder. - No difference in anterior translation for gender or side.	sitting, - arm in internal rotation with elbow at body.	90 N anterior linear force.
Court-Payen et al (1995)	- n = 20, (♀: 10; ♂: 19); age: 35 (26 – 53) years.	Mean anterior: *0.18 ± 0.01 cm* (SEM) (range 0.04 – 0.41) Mean difference between right and left shoulder: *0.07 ± 0.01 cm* (SEM) (range 0.01 – 0.19). - No significant differences regarding sex, age or side - In all subjects, anterior translation of normal shoulders ≤ 0.41 cm - In all subjects, difference of anterior translation between right and left shoulders ≤ 0.2 cm.	sitting, - arm in internal rotation with elbow at body.	90 N anterior linear force.
Yeap et al (2003)	- n = 22 (♀: 4; ♂: 19); age: 30 (22 – 46) years, right dominant n = 19, left dominant n = 4.	1. Mean anterior in neutral: Rater 1: *0.21 ± 0.31 cm* (- 0.26 – 1.29), Rater 2: *0.11 ± 0.22 cm* (- 0.41 – 0.47). 2. Mean anterior in 90º abduction: Rater 1: *- 0.03 ± 0.19 cm* (- 0.33– 0.37), Rater 2: *- 0.07 ± 0.26 cm* (- 0.83 – 0.45). 3. Mean anterior in 90º abduction using thumb pressure: Rater 1: *0.01 ± 0.17 cm* (- 0.37– 0.37), Rater 2: *0.05 ± 0.27 cm* (- 0.36 – 0.83).	1. Sitting, - arm in internal rotation, arm at side. 2. Sitting, - arm in 90º abduction, external rotation.	1. 90 N anterior force perpendicular to scapular plane 2. 60 N anterior force perpendicular to scapular plane 3. anterior displacement of humeral head using thumb pressure

Note. ♀: Female; ♂: Male; SEM: Standard error of measurement; SD: Standard deviation; Values for age, weight and height are mean values (± standard deviation or range).

Table 7. ***Anterior-posterior humeral head translation in pathologic populations.***

Author	Characteristics of studied population; Patient position	Mean anterior-posterior humeral head translation ± SD (range)	Main Findings/ Difference to control groups
Bianchi et al (1994)	- Patients with history of shoulder trauma, n = 10 (Fall: n = 1, minor sport injuries: n = 3, occupational minor trauma: n = 5, seizure: n = 1).	n/a	- Difference between affected and non-affected side: 1. In posterior shoulder dislocation (n = 2): ≥ 0.2 cm. 2. In posterior subluxation (n = 3): 0.12 - 0.18 cm.
Borsa et al (2005b)	- Elite swimmers, competitive swimming for 11.8 ± 2.3 years. n = 42 (n = 27 with history of unilateral or bilateral shoulder pain). Women: n = 16; age: 19.7 ± 1.0 years; height: 170 ± 7.2 cm; weight: 65.5 ± 4.5 kg. Men: n = 26; age: 19.4 ± 1.6 years; height: 187.9 ± 6.6 cm; weight: 82.3 ± 6.2 kg. Patient position: Sitting, 90º abduction, 60º external rotation, scapular plane.	- Swimmers: Anterior: *0.28 ± 0.17cm* Posterior: *0.53 ± 0.24 cm.* - History of shoulder pain: Anterior: *0.29 ± 0.16 cm* Posterior: *0.54 ± 0.23 cm* - No history of shoulder pain: Anterior: *0.27 ± 0.18 cm* Posterior: *0.51 ± 0.26 cm*	- Matched control group, n = 44: Anterior: 0.27 ± 0.17cm; Posterior: 0.49 ± 0.27. - Difference between swimmers and control group: Anterior: 0.008 ± 0.17 cm; Posterior: 0.04 ± 0.25 cm. - No significant difference in anterior-posterior humeral translation between swimmers and control group (p = 0.49). - Difference between humeral head translation in swimmers with history and without history of shoulder pain: Anterior: 0.02 ± 0.17 cm; posterior: 0.03 ± 0.24 cm. - No significant differences between groups (p = 0.68). - Mean side-to-side difference: 0.1 cm. - Posterior translation significantly greater than anterior translation for swimmers and control group (p < 0.01), and in swimmers with and without history of shoulder pain (p = 0.001) - Clinically significant between-group mean difference: 0.15 ± 0.20 cm.
Jerosch et al (1991)	- Patients with anterior instability, n = 23; patient characteristics not specified. - Patient position: Sitting, arm in neutral. - Translation with manually applied anterior and posterior drawer.	- Dorsal projection of humeral head with anterior translation: *- 0.36 cm* (affected), *0.25 cm* (non affected) - Dorsal projection of humeral head with posterior translation: *1.09 cm* (affected), *0.75 cm* (non affected). - Anterior-posterior translation: *1.43 cm* (affected), *0.75 cm* (non-affected).	- Anterior-posterior translation: Significant difference between affected and unaffected shoulder (1.43 versus 0.75 cm); and compared to healthy control group (1.43 versus 0.66 cm) (p < 0.0001).

Krarup et al (1999)	- Patients with unilateral traumatic anterior shoulder instability, n=20; Women: n = 7; men n = 13; age: 28 (18 – 57) years; Patient position: Sitting, arm in internal rotation with elbow at body.	- Anterior translation: Affected side: *0.49 ± 0.06 cm* (SEM) Unaffected side: *0.21 ± 0.02 cm* - Mean difference between sides: *0.28 ± 0.06 cm*	- Mean and maximum anterior translation was significantly higher in unidirectional instability (4.9 mm) versus healthy control group (1.9 mm) (p<0.01). - Mean difference of anterior translation between shoulders was significantly higher in unidirectional instability (2.8 mm) versus control group (0.7 mm) (p < 0.01). - Significantly more anterior translation in unidirectional instability shoulders compared to contralateral shoulders (p < 0.01). - No difference in anterior translation for gender or side in healthy control group.

Note. Values for age, weight and height are mean values (± standard deviation or range); SEM: Standard error of measurement.

3.2.7 Reliability of superior and posterior imaging views

Reliability of USI measurements were reported by seven studies using the superior USI view and three studies using the anterior or posterior USI view (Table 8).

For AHD measurements taken with a superior USI view in a neutral shoulder position, high to excellent reliability is reported. Intraclass correlation coefficient (ICC) values for measurements taken by one or several examiners range between 0.70 and 0.97 (Azzoni, et al., 2004; Cheng, et al., 2008; Desmeules, et al., 2004; Fremont, et al., 2000; Pijls, et al., 2010; Schmidt, et al., 2004; Wang, et al., 2005). This also includes the results of Cheng et al (2008) who measured the distance between the coracoid and the humeral head in the superior-inferior direction. Several of these studies report reduced reliability for measurements taken by several examiners (inter-rater reliability) compared to one examiner (intra-rater reliability) (Cheng, et al., 2008; Fremont, et al., 2000; Pijls, et al., 2010).

Four of these studies examined the reliability for AHD measurements in shoulder abduction (Desmeules, et al., 2004; Fremont, et al., 2000; Pijls, et al., 2010; Wang, et al., 2005). Within the studies, the results vary between moderate and excellent inter-rater reliability, with ICC values ranging between 0.64 and 0.92. Intra-rater reliability is reported as high to excellent, with ICC values ranging between 0.81 and 0.92. Desmeules et al (2004) and Fremont et al (2000) describe slightly higher reliability for AHD measurements taken in active shoulder abduction (45º and 60º) compared to the neutral shoulder position. In contrast, Wang et al (2005) and Pijls et al (2010) report that the reliability for AHD measurements in 60º and 90º shoulder abduction is slightly reduced compared to the neutral shoulder position. Pijls et al (2010) provided the most detailed description of reliability with the shoulder in neutral and in 60º abduction in patients with SIS. These researchers describe considerable lower inter-rater reliability compared to intra-rater reliability. The greater measurement variation between two raters was also expressed through large confidence intervals for the inter-rater ICC values.

Interestingly, Fremont et al (2000) report reliability levels for two Physiotherapists taking USI measurements that are comparable to the reliability of two experienced radiologists in the study of Desmeules et al (2004). Similarly, Cheng et al (2008) and Pijls et al (2010) describe comparably high reliability between novice and experienced US examiners.

With respect to the posterior imaging view, Borsa et al (2005a) report excellent inter-rater reliability for the measurement of anterior-posterior humeral head translation with ICC values of 0.96 and 0.99, and moderate to high intra-rater reliability with ICC values of 0.72 and 0.85. However, the values for inter-rater reliability refer to two raters measuring a distance on the same printed US image and reliability analysis was based on just thirteen individuals. For distance measurements using the anterior USI view, relatively poor reliability is reported (Krarup, et al., 1999; Yeap, et al., 2003). This becomes evident in the high coefficient of variation values (CV) for both for intra-rater reliability (50% and 49.9%) and inter-rater reliability in the study of Krarup et al (1999). Although Yeap et al (2003) report lower variation between measurements for one rater (3.9% and 5.1%), poor agreement between two raters is expressed by the CV of 9.3% and the ICC values between -0.058 and 0.562.

Within the studies, there were considerable differences regarding the methodology of reliability analysis, the number of scans, sample size and participants' characteristics (Table 8). The following limitations of the studies were identified. Only four out of ten studies provide further data of accuracy of their measurement, such as confidence intervals for the ICC values or SEM values, which allow for further interpretation of the accuracy of the measurement (Borsa, et al., 2005a; Cheng, et al., 2008; Pijls, et al., 2010; Schmidt, et al., 2004). However, Schmidt et al (2004) reports ICC values not specifically for the measurement of the AHD, but as part of a more extensive US shoulder examination. Wang et al (2005) derived the reliability data from a pilot study, but the researchers did not provide any information about the pilot study's method (e.g. sample size, blinding). Moreover, it remains unclear whether the data refer to intra- or inter-rater reliability.

Two studies report on the reliability of repeatedly measuring the distance on the same US image (Pijls, et al., 2010; Schmidt, et al., 2004). Schmidt et al (2004) used this method to derive inter-rater reliability for two raters, and Pijls et al (2010) report intra-rater reliability between two sessions that were 6 months apart. Although the repeatability of distance measurement on the same image constitutes an interesting aspect of the measurement, this practice does not indicate the reliability of the actual repetition of the USI measurement.

Another limitation is that no study described whether the transducer was removed from the participant's skin between consecutive measurements in one session. Keeping the transducer in the same position between measurements would probably result in higher reliability values, because the error of repeatedly defining the correct transducer placement on the participant would not play a role. Furthermore, most studies failed to describe if and how blinding of examiners to their own data and to other examiners data was achieved. The results of Desmeules et al (2004), Borsa et al (2005a) Fremont et al (2000) should be interpreted with caution due to small sample sizes (13, 13 and 10 participants respectively). Intra-rater reliability values supplied by Schmidt et al (2004) also lack strength, because they were based on just two individuals.

In summary, the literature review revealed methodological weaknesses of the reliability studies for the superior, posterior and anterior USI views. This highlights the need for a methodologically robust investigation of reliability in these USI views under consideration of functionally relevant shoulder positions, such as passive and active shoulder abduction.

Table 8. ***Reliability of ultrasound imaging studies.***

Author	Number of examiners / Type of population	Number of USI scans/ measurement sessions	ICC Intra-rater (one rater)	ICC Inter-rater (between raters)	Appraisal of reliability and critique
Superior view					
Azzoni et al (2004)	- 2 examiners, - Pathologic population	- 3 scans; scan with greatest distance was used	n/a	0.8	- High inter-rater reliability
Cheng et al (2008)	- 2 (rater 1: senior radiology technician, rater 2: non radiologist); - Healthy population	- 2 scans - 2 sessions	Within session: - Rater 1: 0.94 (SEM 0.06 cm) - Rater 2: 0.89 (SEM 0.066 cm) Between sessions: - Rater 1: 0.97 (SEM 0.041 cm)	0.85 (SEM 0.085 cm)	- High reliability between raters (accuracy lower than for Rater 1 between sessions). - Excellent reliability data between sessions for experienced examiner - Reliability dependent on examiner's experience - Similar accuracy between examiners (similar SEM within sessions) (+) - Examiners blinded to their results
Desmeules et al (2004)	- 2 radiologists; - Healthy population (13 subjects).	- 2 scans	n/a	Between raters 0.86 (0º) 0.91 (active 45º) 0.92 (active 60º)	- High to excellent reliability between 2 raters in neutral at rest, and in active abduction. (-) - Underpowered results (13 subjects)
Fremont et al (2000)	- 2 non radiologists (1 Physiotherapist, 1 physician) - Healthy population, (20 shoulders)	- 2 scans - 2 session (5-7 days apart)	Test-retest: - Rater 1: 0.69 (0º); 0.81 (active 45º) - Rater 2: 0.81 (0º); 0.92 (active 45º)	Between raters: - Session 1: 0.78 (0º) 0.90 (active 45º) - Session 2: 0.79 (0º) 0.86 (active 45º)	- High intra-rater reliability between sessions. - High inter-rater reliability. - Reliability for measurements in active abduction higher than in neutral at rest. - Non- radiologists achieved high reliability. - Small subject number

Pijls et al (2010)	- 2 raters (Rater 1: Experienced operator; Rater 2: Novice operator), - Pathologic population (50 shoulders; 25 shoulders in neutral group, 25 shoulders in 60º abduction group.	- 3 measurements in 1 session - Re-measurement with callipers on 25 blank US images after 6 months.	- Rater 1: 0.94 (0.89-0.97) (0º) 0.90 (0.82-0.95) (60º) - Rater 2: 0.92 (0.85-0.96) (0º) 0.87 (0.77-0.94) (60º) - Calliper placement on US images : - Rater 1: 0.56 (0.22-0.77) (0º) 0.82 (0.61-0.91) (60º) - Rater 2: 0.57 (0.24-0.78) (0º) 0.85 (0.69-0.93 (60º)	- 0.70 (0.43 – 0.86) (0º), - Accuracy: 1.1 mm. - 0.64 (0.33 – 0.82) (60º), - Accuracy: 1.4 mm.	- High to excellent intra-rater reliability (higher for experienced examiner) - High inter-rater reliability for measurement in neutral - Moderate reliability for measurement in abduction. - Large confidence intervals for inter-rater reliability. - Accuracy was defined as the difference of 2 measurements from the same observer in the same shoulder. - Only within session intra-rater reliability results provided, no information, whether transducer was removed from skin between measurements. - Small subject number per group (n = 25).
Schmidt et al (2004)	- 2 sonographers (1 sonographer took scans and measurements, 1 sonographer measured distances on the saved images) - Healthy population	- 1 scan; - 2 sessions (for 2 subjects only (1 and 9 months apart).	- Between sessions after 1 and 9 months (for 2 subjects) Rater 1: 0.86 (0.70-0.97)	0.92 (0.83-0.99) for measurement of the same images in 20 cases	- Excellent inter-rater reliability; good intra-rater reliability between sessions. - Inter-rater ICC applies only for repeatability of distance measurements of two raters on the same image. - Intra-rater ICC reported only for two subjects - ICC for AHD measurement not reported separately.
Wang et al (2005)	- Number of examiners not reported - Sport population (healthy and injured)	Not reported	n/a	0.91 (0º frontal plane) 0.81 (90º abduction, frontal plane) 0.88 (0º scapular plane) 0.75 (90º abduction, scapular plane)	- High to excellent reliability - ICC derived from pilot data, no detail of subject numbers, numbers of scans and sessions. - No report if ICC refer to intra- or inter-rater reliability.

Table 8 continued

Author	Number of examiners / Type of population	Number of USI scans/ measurement sessions	ICC Intra-rater (one rater)	ICC Inter-rater (between raters)	Appraisal of reliability and critique
Posterior view					
Borsa et al (2005a)	- 1 radiologist for scan and calliper placement - 2 clinicians for distance measurement - Healthy population	- 1 scan, - 2 sessions (24 hours apart)	Test – retest reliability: - Anterior translation: 0.72 (SEM 0.15 cm) - Posterior translation: 0.85 (SEM 0.083 cm)	Between raters: - Anterior translation: 0.96 (SEM 0.040 cm) - Posterior translation: 0.99 (SEM 0.034)	- Excellent inter-rater reliability. - Moderate to good intra-rater reliability. - SEM between sessions for anterior translation nearly twice as high than for posterior translation. Critique: - Low subject number (n=13), - Only right shoulders scanned, - Blinding procedure of examiners for test-retest distance measurement not described. - Inter-rater ICC relates to distance measurement from the same printed image.

Anterior view

Krarup et al (1999)	- 2 examiners - Healthy population	- 5 scans	Mean CV: - Rater 1: 50.0% (13.9% to 98.0%). - Rater 2: 49.9% (10.6% - 114.0%).	Overall mean CV between raters: - 32.7% (0.5 – 95.3%)	- Very high variation (CV) between measurements. - Measurements of rater 2 higher than rater 1 ($p < 0.01$). - Low subject number (n = 20). - Blinding of examiners to their own and to each other's measurements not reported.
Yeap et al (2003)	- 2 examiners - Healthy population	- 3 scans	Overall mean intra-rater CV (%): - Rater 1: 3.8 ± 2.5% (range: 0 – 13.0%) - Rater 2: 5.1 ± 3.9 % (range 0.5 – 20.9 %)	Overall mean inter-rater CV: - 9.3 ± 7.3% (range 0 – 29.8%). - ICC between raters: 0.029 (at 0º, internal rotation); - 0.058 (at 90º, external rotation) - 0.562 (with anterior thumb pressure).	- Good intra-rater reliability (CV) - High variation (CV) of measurements and poor reliability between raters. - Mean intra-rater (CVs) at rest were lower than the mean intra-rater CVs after application of translatory force. - Mean intra-observer CV for the abducted and externally rotated position was lower than neutral position (not statistically significant). - Blinding procedures not evident

Note. 0º, 45º, 60º, 90º: Refers to degrees of shoulder abduction; 95% CI: 95% confidence interval; CV: Coefficient of variation, ICC: Intraclass correlation coefficient; n: Number; n/a: Not applicable; SEM: Standard error of measurement; US: Ultrasound; USI: Ultrasound imaging.

3.2.8 Relationships between distance measurements and participants' characteristics

With respect to healthy individuals, no relationships were found between the amount of anterior-posterior humeral head translation and gender, age, body side or hand-dominance with the shoulder either in adduction and internal rotation or in abduction and external rotation (Borsa, et al., 2005b ; Court-Payen, et al., 1995; Krarup, et al., 1999). Regarding the posterior projection of the humerus over the dorsal edge of the glenoid at rest, Jerosch et al (1991) found a trend (non-significant) for differences between dominant and non-dominant shoulders and between men and women. However, when an anterior drawer force was applied, the dominant shoulder displayed significantly larger anterior-posterior translation compared to the non-dominant side (p = 0.0045). The researchers interpreted this as indicative of more laxity in the dominant than the non-dominant shoulder (Jerosch, et al., 1991).

Regarding the AHD, one study did not find a significant difference between the dominant and non-dominant arm in an asymptomatic population (Cholewinski, et al., 2008). In the same study, the median distance between both shoulders was 0.6 mm (range between 0.0 and 3.6 mm). Based on this, the authors concluded that a normal value for the difference of the AHD between the dominant and non-dominant limb would be smaller than 2.1 mm (interval between 5^{th} and 95^{th} percentile).

No particular influence on the AHD has been found for weight, body mass index (BMI) and hand dominance in normal shoulders; age in both normal and pathological shoulders; and the position of the scapula regarding the frontal or the scapular plane in athletes (Azzoni, et al., 2004; Cholewinski, et al., 2008; Wang, et al., 2005). However, smaller AHD values were strongly correlated with decreasing height in normal shoulders (p < 0.03) and with female gender in patients with various stages of RC pathology (p < 0.05) (Azzoni, et al., 2004; Cholewinski, et al., 2008).

3.2.9 Scapular plane position

The literature review revealed that some studies took US images with the shoulder positioned in the frontal plane, while others adopted the scapular plane. The normal resting position of the scapula on the posterior thorax lies at an angle of 30º - 40º anterior to the frontal plane, which constitutes the scapular plane (Greenfield, Catlin, Coats, Green, McDonald, & North, 1995; Ludewig & Borstead, 2005; Poppen & Walker, 1976). For practical reasons in measuring GH movements, previous studies researching shoulder kinematics assumed a mean position for the scapular plane between 30º and 40º anterior to the frontal plane (Freedman & Munro, 1966; Lukasiewicz, et al., 1999). However, this can only approximate the scapular plane and does not consider individual variation of the resting position of the scapula.

Wang et al (2005) measured the AHD in both the scapular and the frontal plane. For the scapular plane, the researchers positioned the scapula in protraction and the arm in 30º horizontal adduction. To measure the AHD in the frontal plane, the researchers asked the participants to retract the scapula. However, retraction of the scapula constitutes a position of the shoulder, which does not necessarily match up with a normal upright posture. Borsa et al (2005a; 2005b) took measurements in the scapular plane, but failed to describe how the scapular plane was defined and reproduced.

The influence of the position of the scapula on the AHD is debatable. Previous research using MRI has suggested that the AHD decreases with scapular movement from retraction into protraction (Solem-Bertoft, Thuomas, & Westerberg, 1993). However, Wang et al (2005) did not detect a significant difference in AHD in neutral and 90º shoulder abduction when the scapula was moved from retraction into protraction with the humerus in 30º of abduction. For reasons of reproducibility of participants’ positions and comparability of results, the importance of a consistent way of defining and recording the scapular plane during arm movements becomes evident. Furthermore, because physiological arm movements usually occur in the scapular plane, it is important to consider this in participants’ positioning for USI measurements.

3.3 *Objectives of the experimental study*

The literature review identified three USI views most commonly used for distance measurements and translation of the humeral head in the superior-inferior and anterior-posterior direction. These were a superior, anterior and posterior USI view. However, the articles using these USI views, displayed large variations in the USI methodology as well as some methodological limitations. Key questions resulting from this review mainly focus on the reliability of the USI methods. This involved selection of reproducible landmarks, use of transducers, participant position and methods of distance measurement on the US image.

Therefore, the objectives of the experimental part of this research are:

- To develop an USI method and test its intra-rater reliability and accuracy in a healthy population.
- To determine distances between the humeral head and scapular landmarks in the superior-inferior and anterior-posterior direction using USI and to measure the influence of passive and active shoulder abduction on these measurements.
- To investigate the relationship between distance measurements and participants' characteristics.

It is hypothesised that the USI method is a reliable and accurate tool to determine distance measurements between the humeral head and scapular landmarks in the superior-inferior and anterior-posterior direction. Furthermore, it is hypothesised that these distances are influenced by passive and active shoulder abduction and that there are correlations between measured distances and participants' characteristics.

4 Research Design

4.1 Pilot study

4.1.1 Introduction

The pilot section of this research aimed at replicating and refining the USI methodology, which has been described and discussed in the preceding literature review. In line with the research objectives, piloting was necessary to establish the USI views used in the main study. Three USI views were investigated in the pilot study: 1) the anterior, 2) superior, and 3) posterior USI view.

4.1.2 Material and methods

Participants

A sample of thirteen healthy participants was recruited for the pilot study. Individuals were eligible if they had no history of shoulder pain or injury requiring medical attention in the year prior to the study. Exclusion criteria included a history of dislocation or subluxation of the GH joint, bone fractures involving the clavicle, scapula, or humerus, or injury to the AC joint. Additional exclusion criteria were the presence of inflammatory conditions and a history of pain in the cervical spine six months prior to the participation in the study (Appendix B: Demographic data collection sheet). All participants read the information sheet before giving written consent to participate in the study (Appendix C: Participant Information Sheet; Appendix D: Participant Consent Sheet). Ethical approval for this study was obtained from the Auckland University of Technology Ethics Committee (AUTEC) (Appendix A: Ethics Approval).

Apparatus

All images were taken with an US scanner (Philips HD / 11 SE). A 12-5 MHz (L 12-5) linear-array transducer and a 9-4 MHz (C 9-4) curved-array transducer were used. Preset USI parameters for musculoskeletal imaging were selected on the US scanner. These USI parameters, including depth, focus point, gain and fusion were adjusted depending on the USI view and the individual being scanned in order to receive the best image of the landmarks.

Participant position

The participants were sitting upright on a chair during the USI procedure. US images were taken in a neutral and an abducted shoulder position (Figure 4).

Neutral shoulder position

The first set of measurements was collected in a neutral shoulder position, with the humerus hanging vertically along the side of the participant's body, 90º elbow flexion and forearm pronation (Figure 4 a). A pillow underneath the participant's hand and distal forearm ensured a relaxed resting position of arm and shoulder.

Abducted shoulder position

The second set of measurements was taken in 60º shoulder abduction in the scapular plane with the arm placed on a height-adjustable table (Figure 4 b). The height of the table was adjusted for each participant to yield 60º shoulder abduction. The angle of shoulder abduction was confirmed with a digital goniometer, which was placed along the distal humerus with one end located over the lateral epicondyle of the humerus.

The scapular plane was identified by placing a ruler along the participant's spine of the scapula. Subsequently, the plane was projected onto a sheet of paper that was aligned with the participant's frontal plane (Figure 5). For the second measurement session, the participant's arm was aligned according to the same plane, thus replicating the arm's position of the first session. The angle of the scapular plane was measured with a goniometer and recorded.

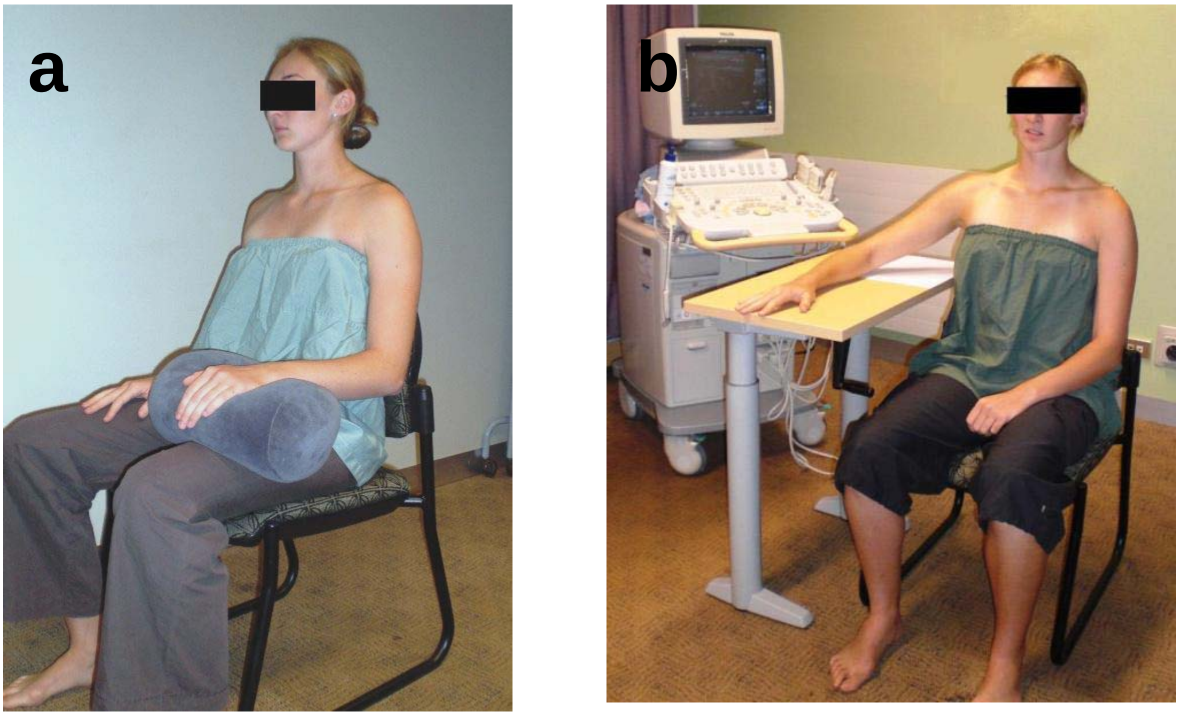

Figure 4. **Ultrasound imaging setup in (a) neutral and (b) 60º abduction in the scapular plane.**

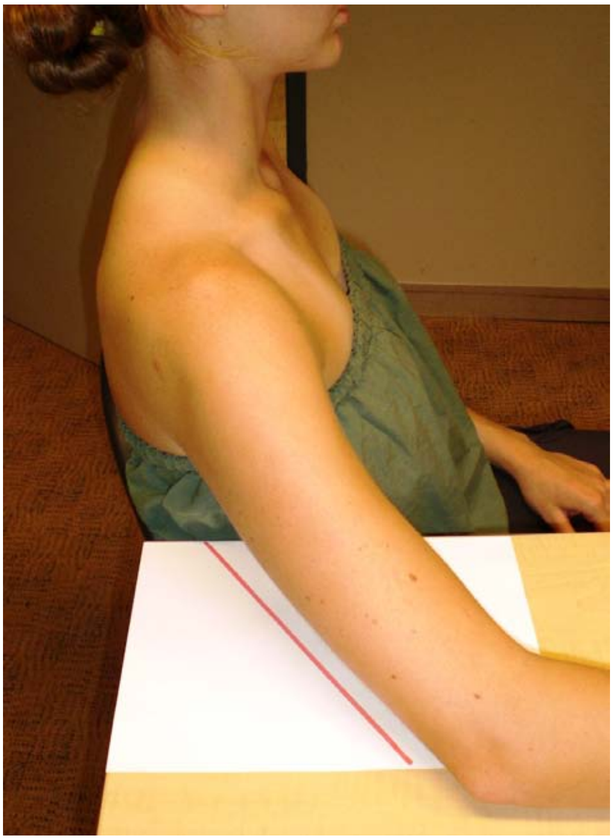

Figure 5. **Setup and recording of scapular plane**

Measurement protocol

All measurements were taken by the same examiner (M.D). There were two measurement sessions (Session 1 and Session 2), which were between four and seven days apart. Both shoulders of each participant were examined. Shoulders were scanned with the anterior, superior and posterior USI view in neutral and 60º of passive and active shoulder abduction. For measurements in active shoulder abduction, participants were asked to lift the forearm gently without losing skin contact with the surface of the table. This ensured that the angle of abduction remained steady. In order to calculate the reliability of two consecutive measurements, and to obtain mean values of measurements, two consecutive measurements were recorded for each view and arm position. This resulted in 36 images for each participant.

Image analysis

Images were stored on the US machine for analysis. All distance measurements were conducted using the US machine's inbuilt electronic callipers (PHILIPS HD 11 SE; Software Version: 1.0.10). For each image, landmarks were identified, marked, and linked with electronic line callipers. Distances were recorded in centimetres. On-screen measurements could not be seen by the examiner during distance measurement, as the measurement display of the US machine was hidden, ensuring blinding to all measurements. In addition, the measurement values were not transcribed on spreadsheets until all measurements of the session were completed.

4.1.3 Ultrasound imaging views

Anterior imaging view

For visualising the distance between the humeral head and the glenoid from anterior, we modified an USI method that was first described by Court-Payen et al (1995) and replicated in other studies (Krarup, et al., 1999; Yeap, et al., 2003). The transducer was placed horizontally on the anterior part of the shoulder at the level of the coracoid process (Figures 6 c and 6 d). In this position, three hyperechoic bony landmarks were identified: The coracoid process, the anterior part of the glenoid and the humeral head (Figures 6 b and 7). Five participants were scanned with a 12-5 MHz linear array transducer, and eight participants were scanned with a 9-4 MHz curved array transducer. The distance between the anterior part of the glenoid and the anterior edge of the humeral head was measured by a perpendicular line drawn from the top of the humerus meeting a horizontal line along the landmark of the glenoid (Figure 7).

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a b

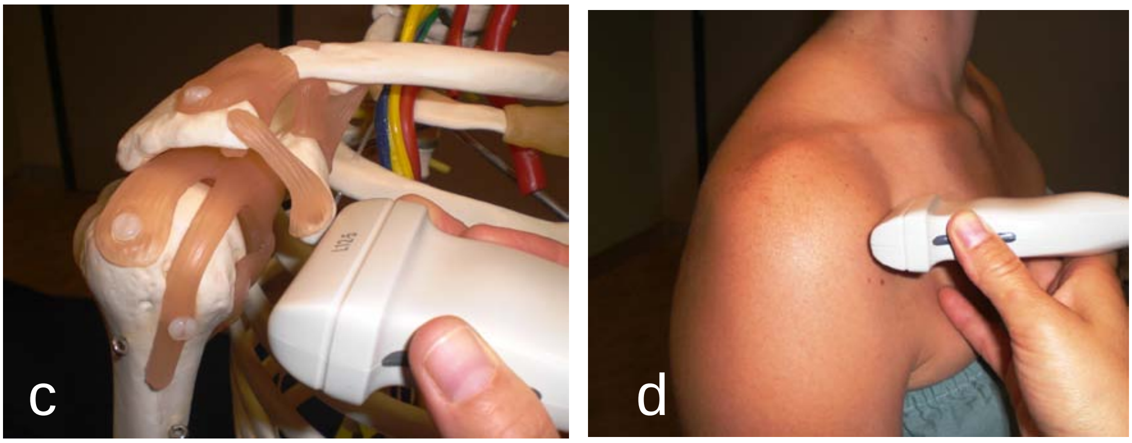

Figure 6. **Transducer placement for anterior imaging view.**
(a) Landmark identification on right shoulder, view from top. Ant: anterior; Post: posterior; Ant. sup. portion of scapular neck: anterior glenoid. (b) Transducer placement on right shoulder, view from top. Transducer is placed anteriorly. Shaded area shows ultrasound image obtained. (c) Transducer placement on skeleton model and (d) participant on right shoulder.
Figure 6a and 6b adapted from “Ultrasonic measurement of the anterior translation in the shoulder joint,” by A. L. Krarup, M. Court-Payen, B.Skjoldbye and G. S. Lausten, 1999, *Journal of Shoulder and Elbow Surgery, 8*, p. 137.

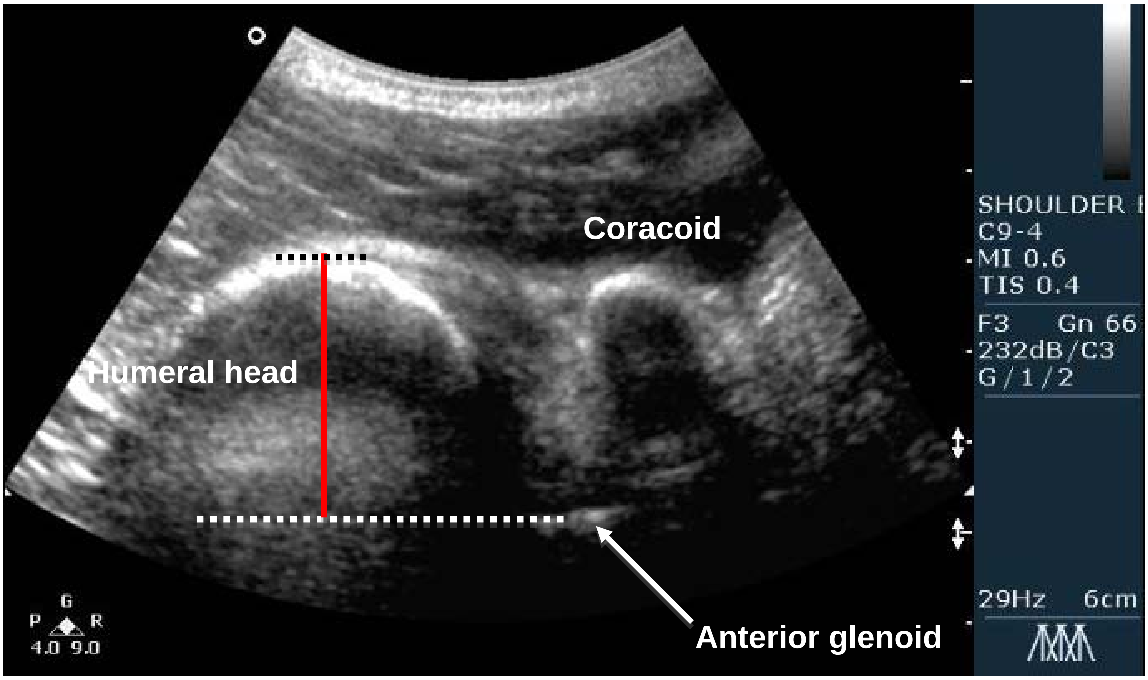

Figure 7. **Ultrasound image obtained with anterior imaging view and measured distance.**
Note. Red line*:* Distance measured between anterior glenoid and most anterior part of humeral head.

Superior imaging view

The superior USI view was used to measure the distance between the acromion and the humeral head at the anterior edge of the acromion. For this research, a USI method described by Jerosch et al (1991) was modified. The exact localisation of scanning at the anterior edge of the acromion was determined by visualising the attachment site of the CAL and involved the following procedure. The transducer was positioned horizontally on the anterior shoulder, visualising the landmarks of the coracoid process and the humerus. Maintaining the landmark of the coracoid process, the lateral part of the transducer was moved in a cranial direction until the anterior edge of the acromion was visualised. The CAL was identified between the bony landmarks of the coracoid process and the anterior edge of the acromion. Subsequently the transducer was placed perpendicular to the axis of the CAL (Figures 8 a and 8 b), producing an image of the subacromial space with the landmarks of the anterior edge of the acromion, the humeral head, and the greater tuberosity (Figure 9).

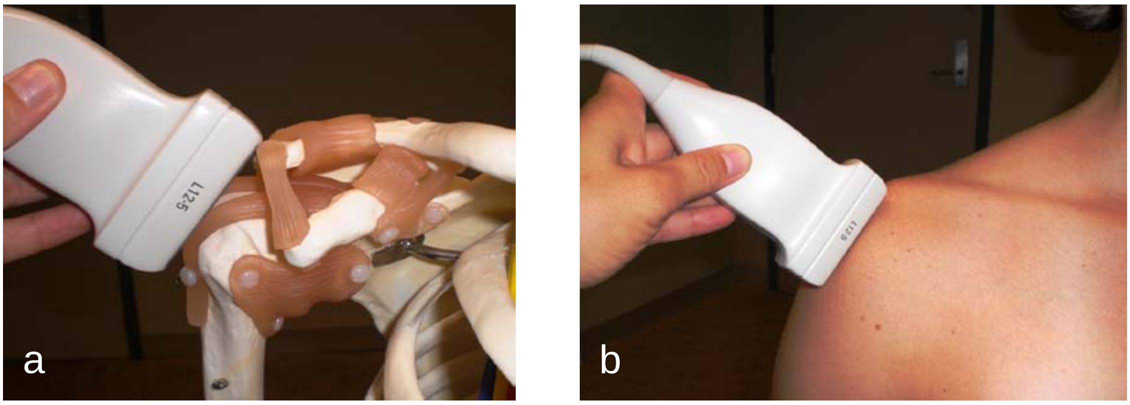

Figure 8. **Transducer placement for superior imaging view.**
(a) On skeleton model; (b) on participant.

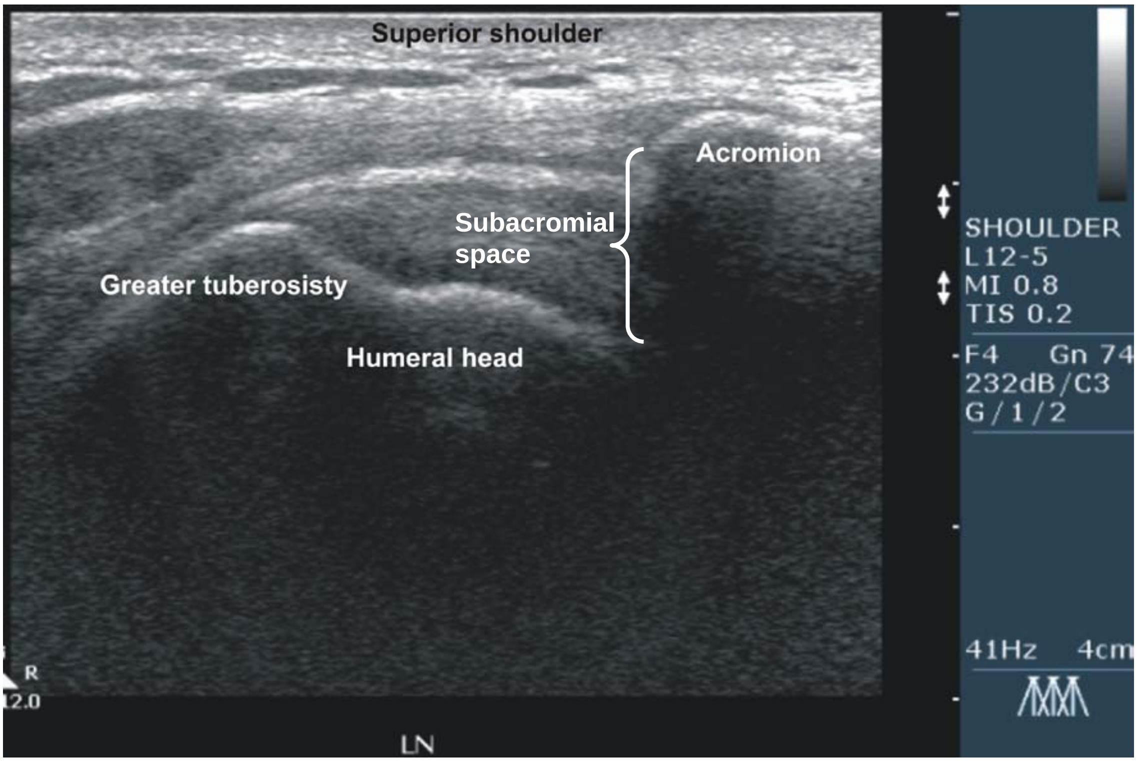

Figure 9. **Ultrasound image obtained with superior imaging view.**

Two distances were measured between the acromion and the humeral head. One measurement quantified the AHD by placing markers at the external inferior edge of the acromion and at the most superior aspect of the surface of the humeral head, which yielded the smallest distance (Figure 10) (Azzoni, et al., 2004; Pijls, et al., 2010). The second measurement contained the distance between the acromion and the edge of the greater tuberosity (AGTD). The AGTD was measured from the external inferior edge of the acromion to the edge of the greater tuberosity (Figure 10).

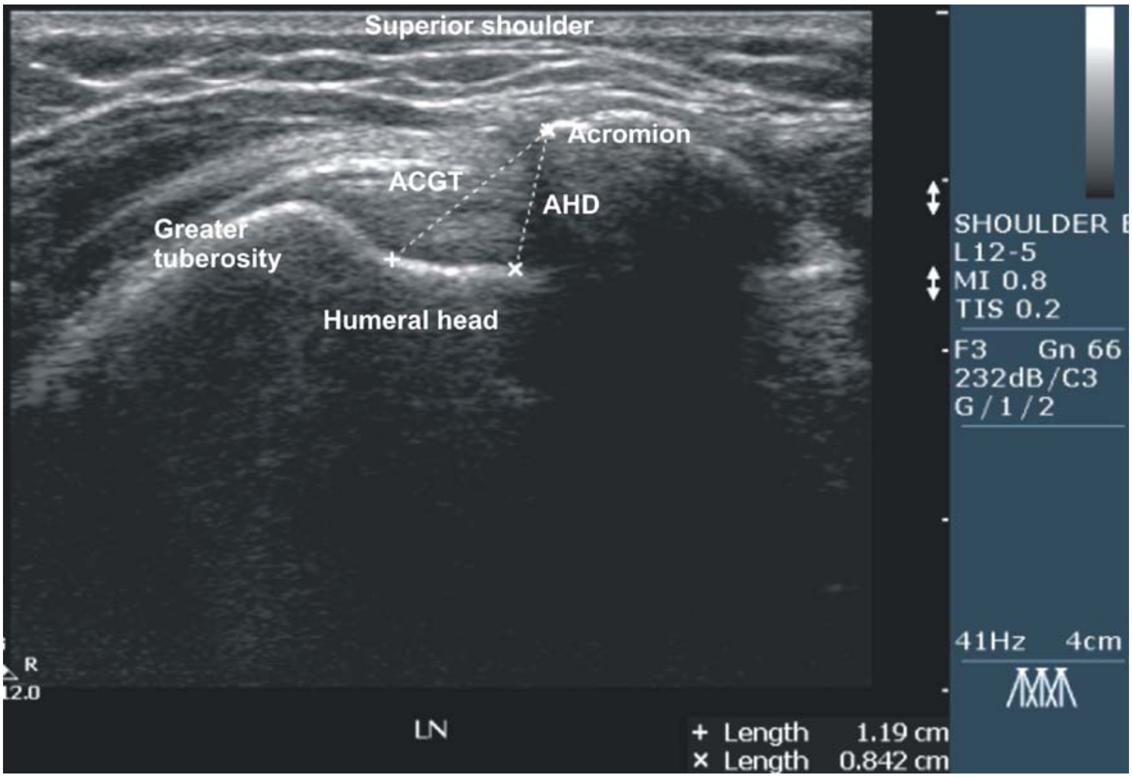

Figure 10. **Distance measurement in superior imaging view.**
Measurement of acromiohumeral distance (AHD) and acromion - greater tuberosity distance (AGTD), which is labelled as ACGT in this picture.

Posterior imaging view

The posterior USI view was utilised to measure the distance between the humeral head and the glenoid from the posterior shoulder. The transducer was placed horizontally at the dorsal contour of the participants' shoulder below the spine of the scapula (Figures 11 a and 11 b). The central tendon of the infraspinatus muscle, and the posterior part of the glenoid, the scapula, and the posterior humeral head were identified as landmarks (Figure 12). The distance between the posterior humeral head and the posterior glenoid has been described previously as a measure for the position of the humeral head relative to the glenoid or the scapula in an anterior-posterior direction (Borsa, et al., 2005a; Jerosch, et al., 1991). For this research, the distance between the humeral head and the glenoid was termed humeroglenoid distance (HGD), and was measured from the posterior edge of the glenoid to the posterior edge of the humeral head (Figure 13). To measure the HGD on the posterior US image, a horizontal line was drawn along the posterior glenoid. Then, a vertical line was drawn from the highest point of the posterior edge of the humeral head to meet the horizontal line along the posterior glenoid. This vertical line represented the HGD (Figure 13).

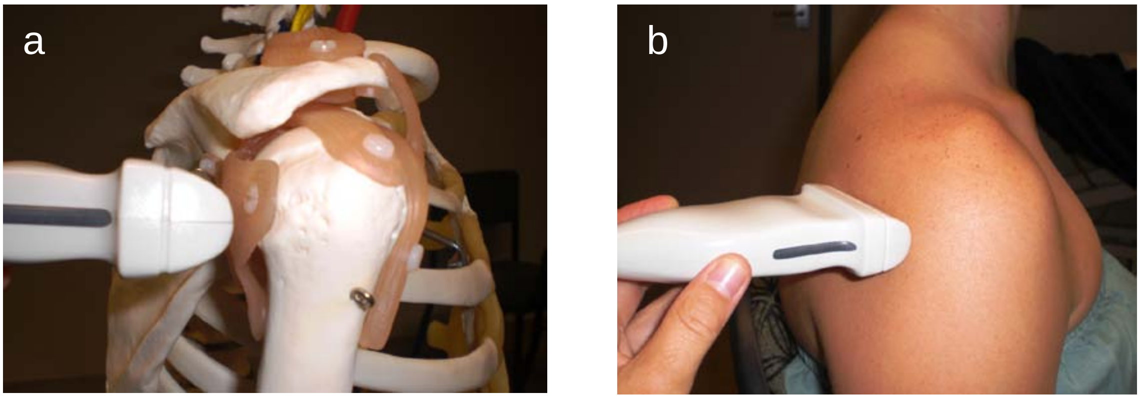

Figure 11. **Transducer placement for posterior imaging view.**
(a) On skeleton model; (b) on participant.

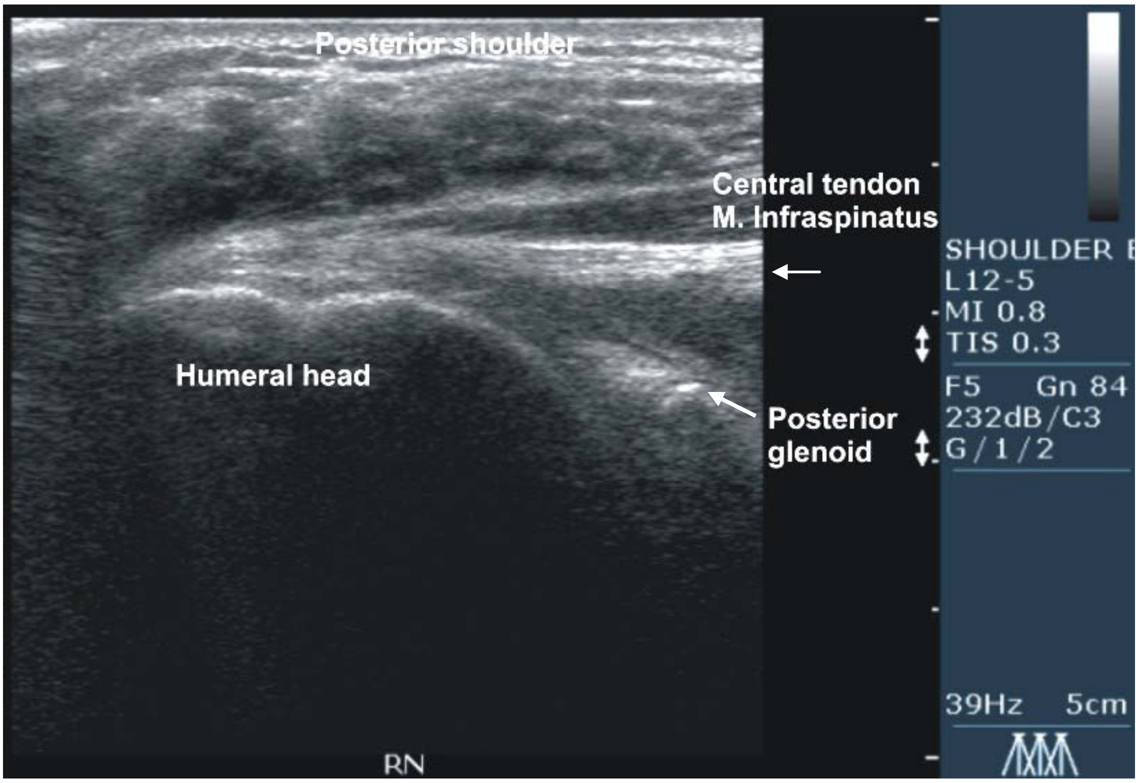

Figure 12. **Ultrasound image obtained with posterior imaging view.**

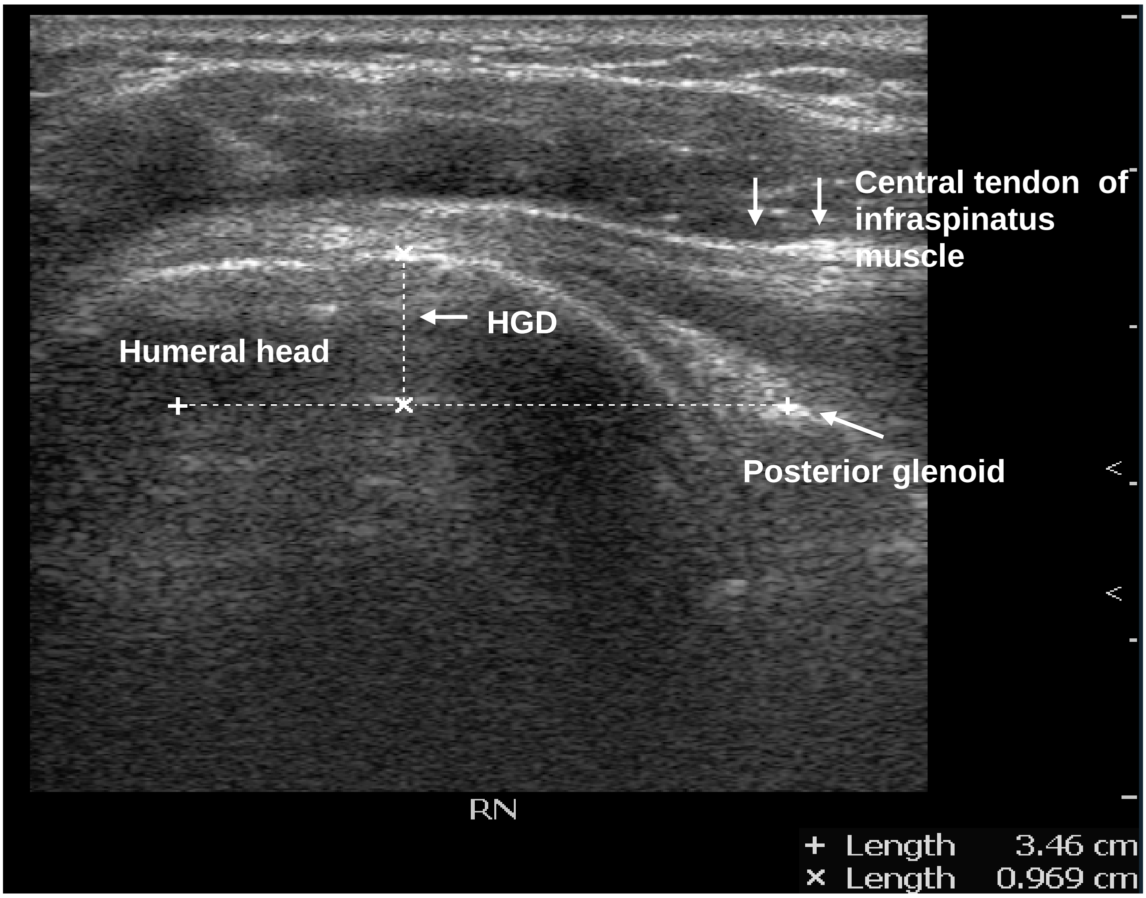

Figure 13: **Measurement of humeroglenoid distance (HGD) in posterior imaging view.**

4.1.4 Results

In the pilot study, the anterior, superior and posterior USI views were trialled and modified. The anterior USI view did not result in satisfactory images. Scanning with the 12-5 MHz linear-array transducer failed to produce a clear image of the anterior glenoid landmark in many participants. Moreover, in some participants, the correct scanning position at the horizontal level of the coracoid and the anterior glenoid could not be determined, because visualisation of both landmarks at the same time was difficult to realise. This resulted in inconsistent distance measurements between the two landmarks. Figure 14 illustrates an example of an anterior USI view image, in which the hyperechoic landmark of the humeral head and the coracoid process are well visualised, but the anterior glenoid is not visible. Using a 9-4 MHz curved-array transducer rendered better delineation of the glenoid, but resulted in distortion and curving of images, which caused difficulties in measuring distances between landmarks correctly. In particular, images of the landmarks of the anterior circumference of the humerus and the coracoid process were bent and distorted, thereby precluding accurate distances measurement (Figure 15).

The superior USI method produced clear images of the anterior acromion, the humeral head and the edge of the greater tuberosity, allowing measurements of the AHD and AGTD. Figure 16 illustrates an example of the superior USI view obtained in 60º abduction at rest (16 a) and with active muscle contraction (16 b). The AHD reduces from 0.515 cm to 0.445 cm, indicating a superior translation of the humeral head towards the acromion.

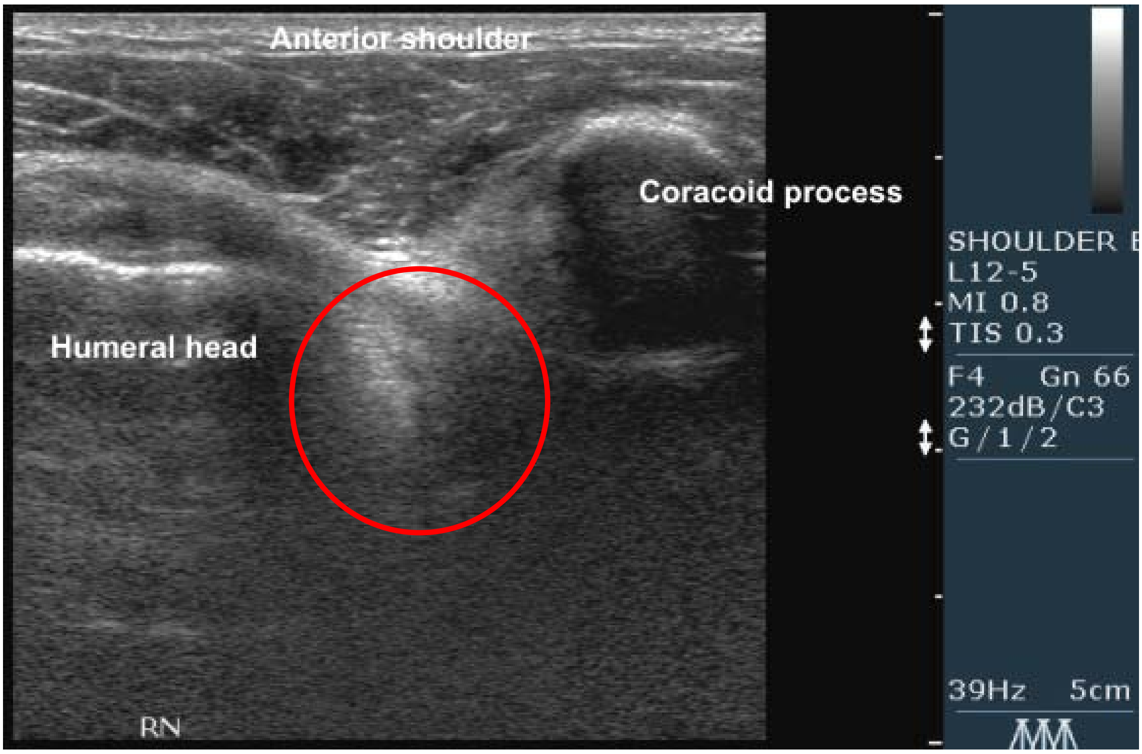

Figure 14. **Anterior imaging view obtained with 12-5 MHz linear transducer.**
Landmark of anterior glenoid is not visible in circled area.
Note. Anterior shoulder: Anterior part of shoulder where transducer was placed for measurement.

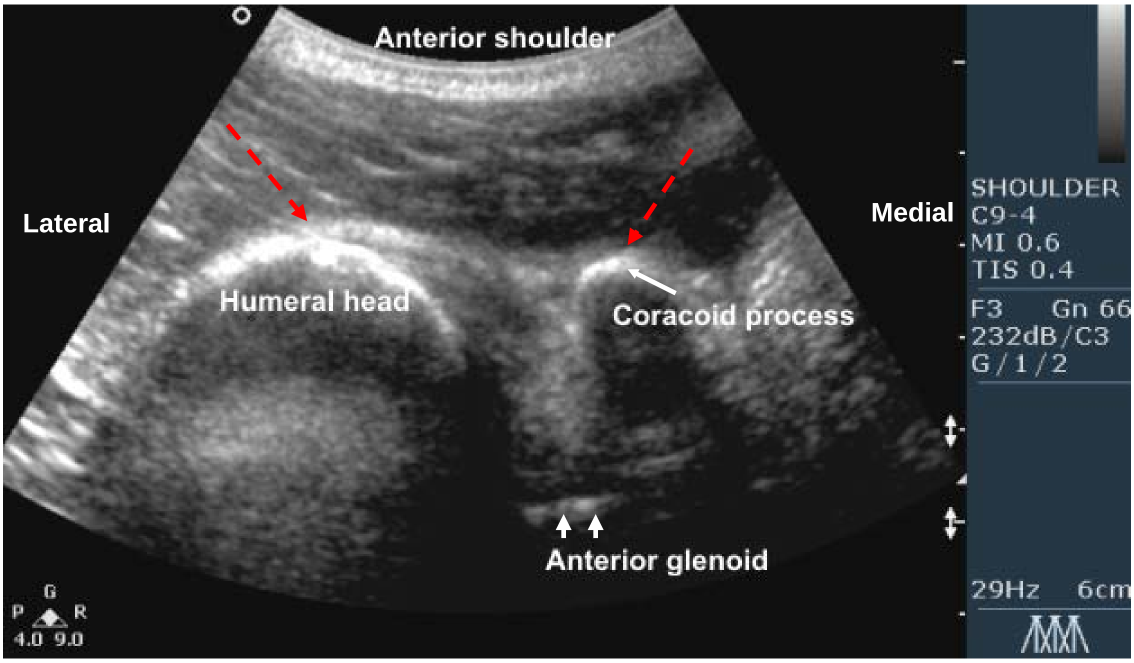

Figure 15. **Anterior imaging view obtained with 9-4 MHz curved array transducer.**
Red dashed arrows indicate the distortion of landmarks associated with the use of this transducer.
Note. Anterior shoulder: Anterior part of shoulder where transducer was placed for measurement.

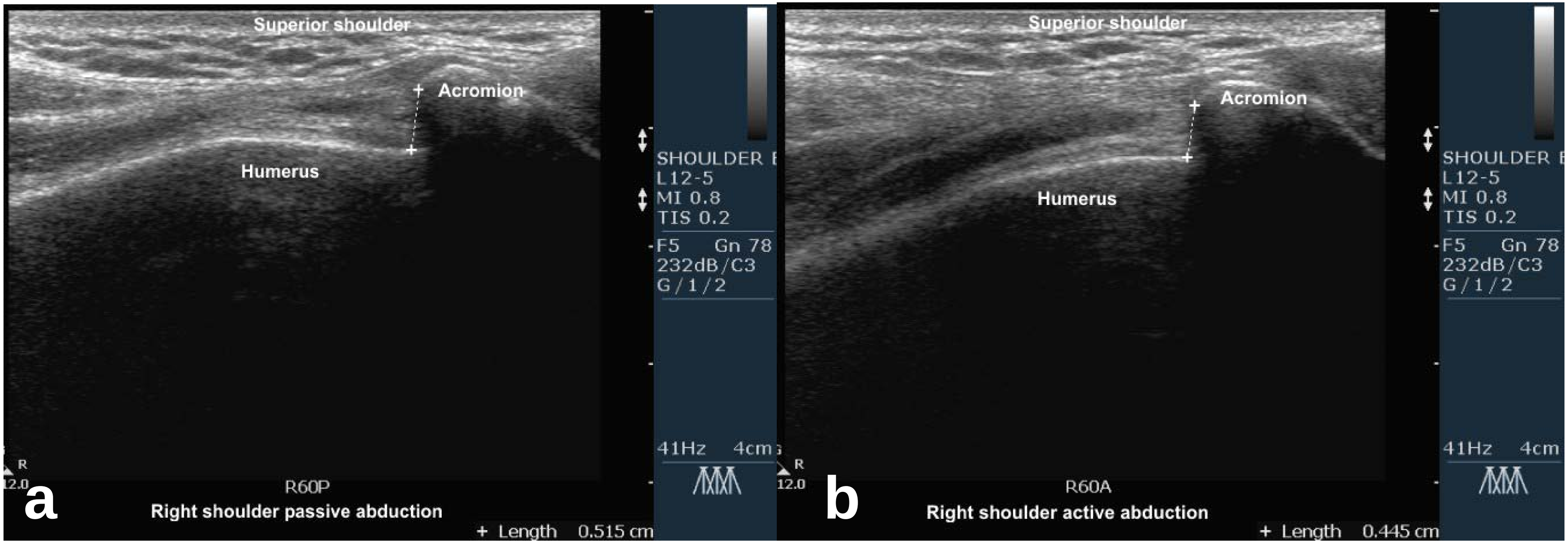

***Figure 16.* Acromiohumeral distance change with abduction.**
Acromiohumeral distance change from (a) 60º passive (0.515 cm) to (b) 60º active abduction (0.445 cm) indicates superior translation of humeral head.
Note. Superior shoulder: Superior part of shoulder where transducer was placed for measurement.

The posterior USI method described by Jerosch et al (1991), which involved visualising a flat part of the scapula on the US image, could not be replicated in the pilot study. This was due to insufficient space on the US screen to determine the posterior edge of the humeral head when a flat part of the scapula was visualised at the same time (Figure 17). Therefore, the posterior USI method was modified for this research, which involved the visualisation of the central tendon of the infraspinatus muscle, the posterior glenoid and the posterior humeral head. This enabled reproducible transducer alignment and clear visualisation of the landmarks. Figure 18 shows an example of HGD change with shoulder abduction. The measurement shows a reduction of the HGD from the passive to the active position, which indicates an anterior translation of the humeral head occurring with active shoulder abduction.

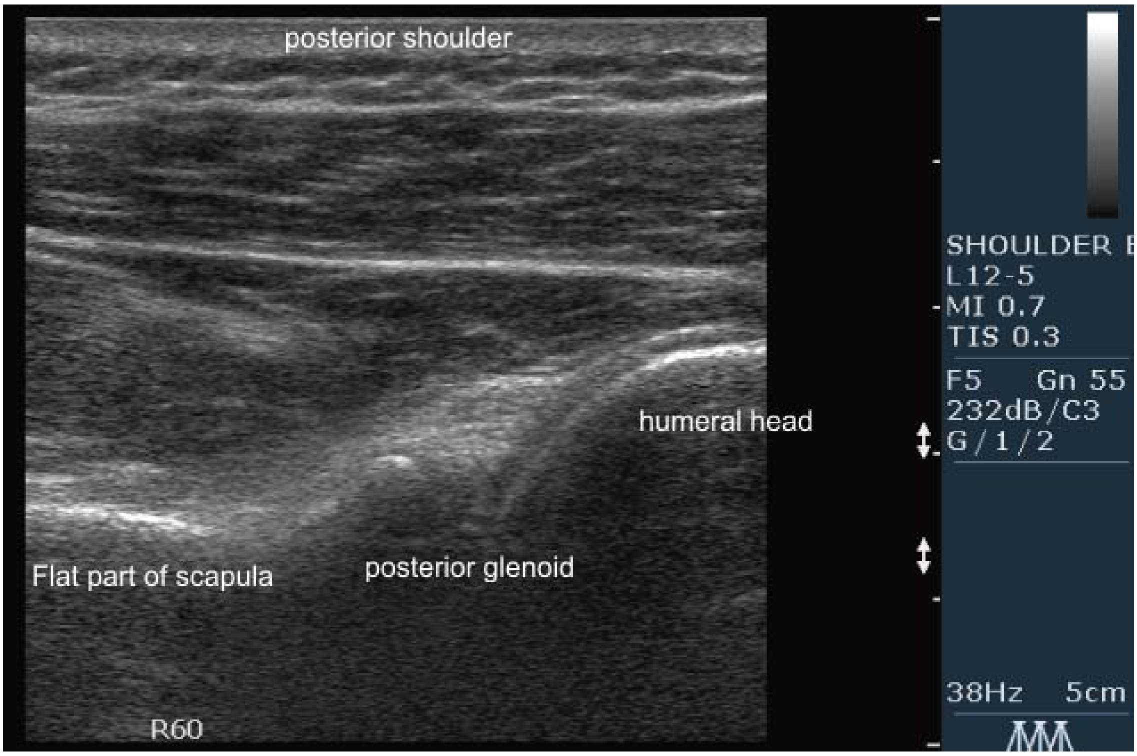

Figure 17. **Posterior imaging view right shoulder (pilot method).**
Note that the posterior circumference of humeral head is not completely visible due to the space that is required to image the flat part of scapula.
Note. Posterior shoulder: Posterior part of shoulder where transducer was placed for measurement.

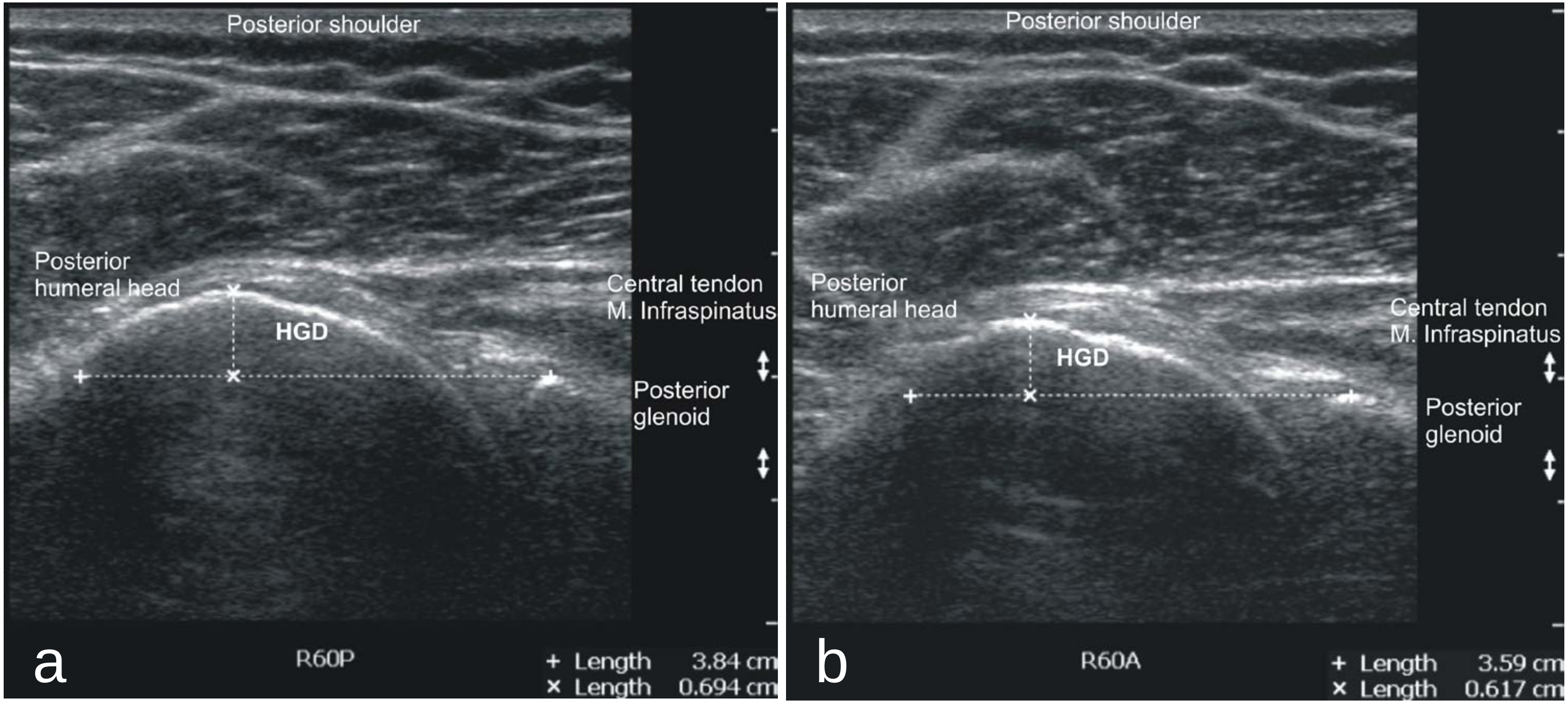

Figure 18. **Reduction of humeroglenoid distance (HGD) from passive to active shoulder abduction.**
Reduction of HGD from (a) 60º passive shoulder abduction (0.694 cm) to (b) 60º active shoulder abduction (0.617 cm) indicates anterior translation of humeral head.
Note. Posterior shoulder: Posterior part of shoulder where transducer was placed for measurement.

4.1.5 Discussion of pilot study

In the pilot study, the anterior USI view resulted in poor image quality leading to inconsistent measurements. Replication of the anterior USI method described by Court-Payen et al (1995) exposed several problems. Both US transducers we used posed various difficulties regarding image acquisition and analysis resulting in variations of distance measurements between the anterior humeral head and the anterior glenoid. The 12-5 MHz linear-array transducer failed to provide sufficient penetration to define adequately the anterior glenoid. This may have lead to incorrect determination of the landmarks, particularly the anterior glenoid. The 9-4 MHz curved-array transducer allowed deeper penetration and improved visualisation of the anterior glenoid. However, scanning with the curved-array transducer resulted in distortion and curving of images, making correct distance measurement between landmarks difficult. Court-Payen et al (1995) and Krarup et al (1999) used a 3.5 MHz linear-array transducer, which presumably allowed sufficient penetration without distorting the US image.

The position of the arm might have been another reason for inconsistent data. Unlike the previously described method by Court-Payen et al (1995) and Krarup et al (1999), who placed the arm in internal rotation with a sling, our study placed the arm in neutral rotation with the forearm pointing straight forward, and in 60º abduction in the scapular plane. Court-Payen et al (1995) described that the bony landmarks are best recognised when the shoulder is internally rotated. According to these authors, with internal rotation of the shoulder, the greater tuberosity is easily located as a landmark because it moves in an anterior position, thus defining an almost horizontal scanning plane with the extremity of the coracoid process and the anterior glenoid. Interestingly, Krarup et al (1999) who examined various ranges of internal and external rotation, did not document deviations in visualisation of the anterior structures regarding the rotational position of the arm. However, the neutral shoulder position we utilised might have impaired the visualisation of the glenoid in particular, and spoilt the horizontal alignment of the greater tuberosity, the coracoid process and the anterior glenoid.

Other researchers reported similar problems with the anterior USI view. Borsa et al (2005a) intended to assess anterior and posterior translation of the humeral head in asymptomatic shoulders using the anterior USI view. With the shoulder positioned at 90º abduction and 60º external rotation, they could not visualise the landmarks through overlying soft tissue, and consequently, utilised a posterior USI method for their measurements. Another study used a 10 MHz linear transducer for the anterior USI view, and found landmark visualisation considerably easier in an abducted and externally rotated position compared to a position that involved the arm in internal rotation at the side of the body (Yeap, et al., 2003). Illogically, this study reported negative values, which would indicate posterior translation of the humeral head, despite the application of anteriorly directed forces of 60 and 90 Newton. With a biomechanical explanation lacking for this observation, the researchers suggested measurement errors or muscle contractions of the participants as possible responsible factors and concluded that the anterior USI method requires refinement before a recommendation for routine use in clinical practice could be given.

Reports on reliability of the anterior USI view are scarce. Studies that assessed reliability report poor agreement for intra-, and inter-rater reliability (Krarup, et al., 1999; Yeap, et al., 2003) (Table 8). While intra-rater coefficients of variation (CV) were acceptable in a study of Yeap et al (2003) (3.8% and 5.1% for two examiners), corresponding values of Krarup et al (1999) were 49% and 50%. Yeap et al (2003) reported a mean inter-rater CV of 9.4%, whereas Krarup et al (1999) found considerably higher inter-rater CVs (32.7%). Reasons for this poor reliability could be due to the methods. Yeap et al (2003) used surface palpation of the coracoid process to define the level of scanning. The researchers thought that the high inter-rater CV potentially might have been due to the examiners not scanning at the same level, because the coracoid process may extend up to 1.5 cm. Similarly, with the method described by Krarup et al (1999), the transducer placement is not clearly defined by three bony landmarks. There is still variability in the vertical direction even if all three landmarks are visualised. Furthermore, in both studies the shoulders were not fixed in an apparatus during force application, but were manually stabilised, which might have led to variation in measurements.

Previous studies using the superior USI view displayed weaknesses regarding clear description of landmarks and AHD measurement (Azzoni, et al., 2004; Cheng, et al., 2008; Cholewinski, et al., 2008; Desmeules, et al., 2004; Girometti, et al., 2006; Jerosch, et al., 1991; Pijls, et al., 2010; Schmidt, et al., 2004; Wang, et al., 2005). Therefore, the superior USI view was modified for this research. A method of landmark detection was chosen that did not rely on surface landmarks or palpation. The attachment site of the CAL as a reference point was easily identified in each participant. The region of the insertion of the CAL at the anterior edge of the acromion is commonly associated with shoulder impingement (Neer, 1972; Wang, Wang, Chen, & Wang, 2009). Therefore, measuring the AHD at this area, compared to the middle of the acromion, might be more appropriate to detect relevant changes or abnormalities of the AHD, which might be associated to pathology. Methods for measurement of the AHD as the smallest distance between the acromion and the humeral head have been described previously by other authors (Azzoni, et al., 2004; Desmeules, et al., 2004; Fremont, et al., 2000; Girometti, et al., 2006; Pijls, et al., 2010; Silva, et al., 2008). Cholewinski et al (2008) described a method of measuring the distance between the acromion and the tip of the greater tuberosity. Similarly, in this research, the AGTD was determined as the distance between the acromion and the edge of the greater tuberosity, in the attempt to utilise two bony landmarks instead of a shortest distance to the humeral head. A drawback of the AGTD measurement was that it could only be determined in the neutral shoulder position, owing to the greater tuberosity disappearing from the visible scanning field as the arm was abducted.

The posterior USI method described by Jerosch et al (1991) and Borsa et al (2005a; 2005b) was modified, in order to establish a more consistent method of transducer placement. Jerosch et al (1991) visualised the corpus scapulae as a reference landmark and measured the distance between the posterior glenoid and the posterior humeral head. The transducer position was described as midway between the upper and lower edge of the glenoid. However, the researchers failed to explain how the middle of the glenoid was actually ascertained. Borsa et al (2005a; 2005b) adapted the posterior USI method described by Jerosch et al (1991) by employing the ‘flat segment’ of the posterior scapula as x-axis and measuring the distance to the posterior humeral head by drawing a perpendicular line to that x-axis. However, the researchers did not describe how the same ‘flat part’ on the posterior scapula was repeatedly identified. Furthermore, they used a curved probe, generating curved images, which distorted the alignment of the reference line along the scapular landmark and calliper placement on the humeral head.

Several problems with the posterior USI method described by Jerosch et al (1991) were encountered. Visualising a part of the corpus scapulae of sufficient length often resulted in an incomplete image of the dorsal circumference of the humeral head. This made the definition of the posterior edge of the humeral head impossible. Furthermore, visualising a hyperechoic part on the corpus scapulae did not distinctly determine the transducer placement in the superior-inferior direction. Therefore, the posterior USI view was modified by visualising the central tendon of the infraspinatus muscle as a reference landmark for the transducer position, which yielded a consistent USI level with every participant. Correct alignment of the transducer with visualising the central tendon of the infraspinatus muscle in continuity was crucial, because an incorrect transducer position might lead to variation between measurements, mimicking a distance change.

4.1.6 Summary of pilot study

The purpose of the pilot study was to trial and modify the USI methods that were described in the literature for measuring the distances between the humeral head and the acromion in a superior-inferior direction, and the distances between the humeral head and the glenoid in an anterior-posterior direction. Regarding the anterior USI view, unsatisfactory and skewed images were obtained, which hampered accurate and true distance measurement. Thus, the anterior USI method was not utilised in the main data collection. A superior and posterior USI method that was modified from previously published methods resulted in clear and reproducible landmark visualisation and transducer placement. The main data collection included the superior USI view with the measurement of the AHD and AGTD and the posterior USI view with the measurement of the HGD.

4.2 Main study

4.2.1 Introduction

The main data collection had two major purposes: Firstly, to establish the reliability of the superior and posterior USI views in neutral and shoulder abduction with and without muscle activation. Secondly, to collect data from a healthy population in order to define normal distances, and to analyse relationships between distances and participants' characteristics.

4.2.2 Material and methods

Participants

Forty healthy participants (80 shoulders) were recruited from the AUT University population by local advertising. Eligibility criteria and procedure of gaining informed consent were identical to the pilot study (Section 4.1.2; Appendices A - D: Ethics Approval; Demographic data collection sheet; Participant information sheet; Participant Consent Sheet).

Apparatus

All images were recorded with an US scanner (PHILIPS HD / 11 SE) with a 12-5 MHz linear-array transducer. Preset musculoskeletal USI parameters, as described in the pilot study, were utilised and adjusted according to the USI view and the individual being scanned (Section 4.1.2).

Participant position

The participants were positioned sitting in neutral and 60º shoulder abducted as described in the pilot study (Section 4.1.2).

Measurement protocol

Two measurement sessions (Session 1 and Session 2), which were between four and seven days apart, were undertaken by the same examiner (M.D.). On both measurement sessions, bilateral scans of each participant were performed. Shoulders were scanned from the superior and posterior USI view in neutral and 60º passive and active abduction. According to the pilot study, two consecutive measurements were acquired in each USI view and arm position, resulting in 24 images per participant.

Image analysis

The same methods were applied as described previously in the pilot study (Section 4.1.2).

Superior and posterior imaging views

The superior and posterior USI views were employed as described in the pilot study (Section 4.1.3). Figure 19 illustrates imaging in neutral and 60º shoulder abduction using the superior USI view (Figures 19 a and 19 b) and the posterior USI view (Figures 19 c and 19 d).

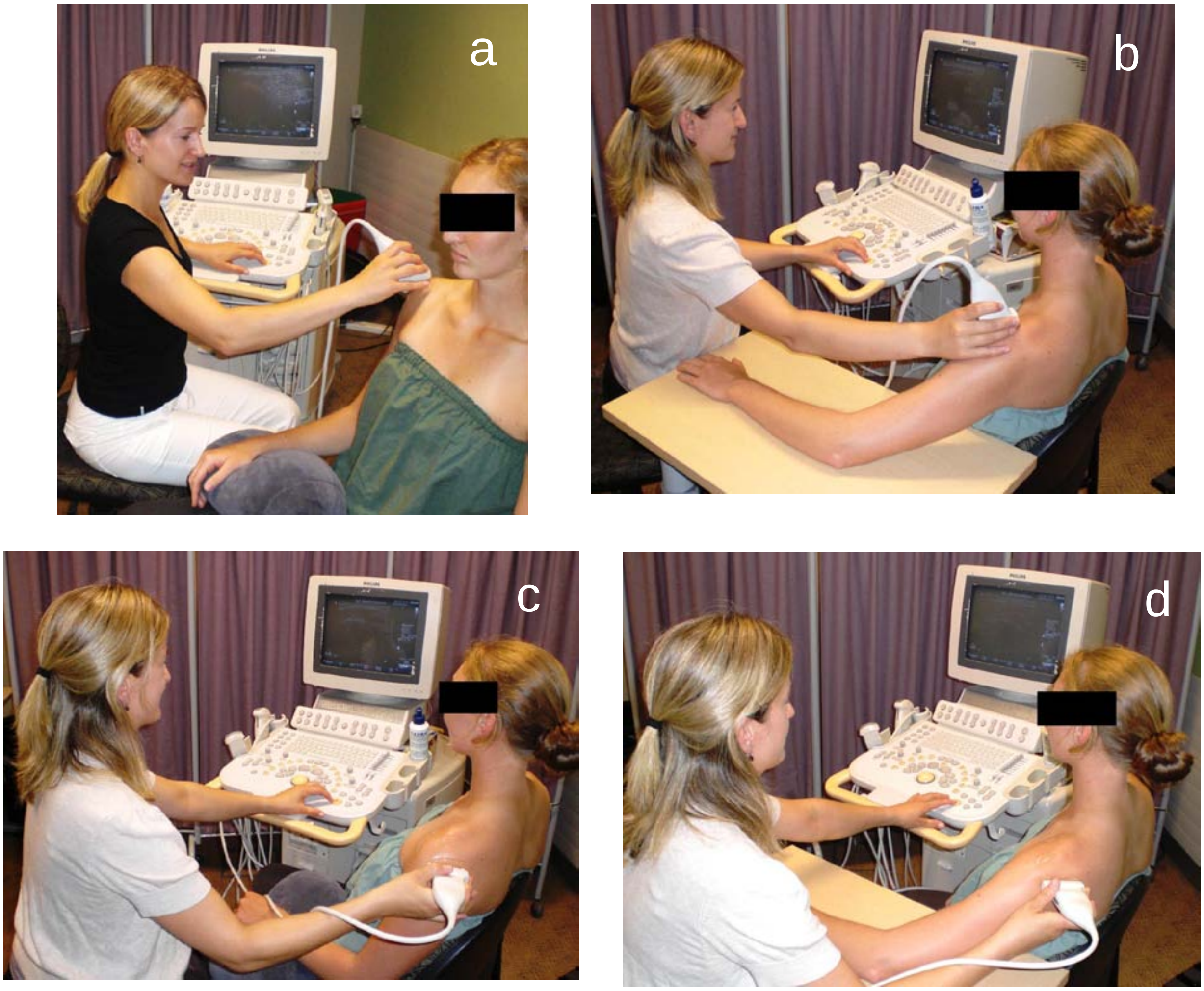

Figure 19. **Ultrasound imaging setup and participant position.**
Superior imaging view in (a) neutral and (b) 60º shoulder abduction; posterior imaging view in (c) neutral and (d) 60º shoulder abduction

4.2.3 Statistical analysis

Statistical analyses were performed with SPSS® version 15.0 statistical program for Windows (SPSS, Chicago, IL, USA). Descriptive data including mean distances with standard deviations (SD), minimum, maximum and range were calculated for the superior and posterior USI views in each shoulder position.

Reliability of distance measurements within and between measurement sessions by a single rater was determined using the intraclass correlation coefficient (ICC) (Rankin & Stokes, 1998; Shrout & Fleiss, 1979). The ICC is calculated as the ratio of the variance between subjects (i.e. the variance of interest) and the total variance (Beckerman, Roebroeck, Lankhorst, Becher, Bezemer, & Verbeek, 2001). Reliability analysis produces an ICC that represents consistency in the rank order of scores and an F statistic, which represents systematic change in size of scores (Wallwork, et al., 2007). Thus, the ICC indicates the degree of variability in the study that is due to true variation among the subject themselves and the degree of variability that is due to measurement error (Greenfield, Kuhn, & Wojtys, 1998). Intra-rater reliability refers to the consistency with which one examiner is able to reproduce the same measurements (Greenfield, et al., 1998).

A two-way mixed effects $ICC_{2,1}$ model using single measures with 95% confidence interval was applied (Weir, 2005). An ICC of 1.0 indicates that there is perfect agreement between tests, whilst an ICC ratio of 0.0 indicates no agreement at all (Domholdt, 2005). All ICC were interpreted as follows: 0.00 - 0.25: little if any correlation; 0.26 - 0.49: low; 0.50 - 0.69: moderate; 0.70 - 0.89: high; and 0.90 - 1.00: excellent correlation (Domholdt, 2005). Separate ICC analyses were conducted for the following data: View (superior and posterior); angle of the arm (neutral and 60º shoulder abduction) and muscle activity (passive or active muscle contraction in 60º abduction).

Bland and Altman plots were calculated using the software Prism® version 4.0 (Graphpad Software, Inc. San Diego, CA) to provide a visual illustration and 95% limits of agreement (LOA) between the mean differences across the test and the mean values across the range of data (Bland & Altman, 1986).

Using independent samples *t-test*, mean differences between shoulder positions, significance (2-tailed), upper and lower confidence intervals of the difference (95%), and standard error of the difference were also calculated. Independent samples *t-tests* were also used to calculate differences between female and male participants. Bivariate correlation analyses using *Pearson* correlation were employed to detect relationships between measured distances and participants' characteristics of height, age, body weight and participation in sports activities. Significance level for correlations was set at $p < 0.05$.

In addition, consistency of measurement was examined across trials by calculation of the standard error of the measurement (SEM), which represents the standard deviation of the measurement errors (Domholdt, 2005). The SEM is calculated by the square root of the within subject variance (i.e. the square root of the total variance, excluding the variance between subjects) and is expressed in the same dimension as the measurement (Beckerman, et al., 2001; Hopkins, 2000). The SEM represents the difference between the actual measured score across trials and an estimated "true" score, and was calculated as *SEM = pooled SD x* $\sqrt{1-ICC}$ (Beckerman, et al., 2001; Wallwork, et al., 2007; Weir, 2005).

In order to gauge the sensitivity of the US measurement in assessing the position of the humeral head, the smallest real difference (SRD) was calculated to estimate the magnitude of change that would exceed the expected session-to-session variability. The SRD has been defined as the smallest measurement change that can be interpreted as a real difference, i.e. beyond zero (Beckerman, et al., 2001). The SRD was calculated based on the average SEM for the intra-rater reliability analysis, using the following formula:
SRD = SEM x $\sqrt{2}$ x 2.0 (1.994 respectively). The number 2.0 (1.994 respectively) represents the value of the *t* distribution for a 95 % confidence level (*df* = n-1). This value indicates that there would be a 95 % certainty, that any differences within an individual (i.e. a treatment effect) would reflect a true difference of change (Beckerman, et al., 2001; Ota, Ward, Chen, Tsai, & Powers, 2006; Wallwork, et al., 2007).

5 Results

5.1 Demographics

Table 9 summarises the characteristics of the participants. Forty participants, 21 (52.5%) female and 19 (47.5%) male were included in the study. The sample had a mean age of 28.6 (± 9.03) years, mean height of 1.72 (± 0.08) m, and mean body weight of 70.7 (± 14.42) kg. Thirty-three participants (82.5%) were right hand dominant, while seven participants (17.5%) were left hand dominant. Angles for the right and left scapular plane were 36.83º (± 3.99) and 35.80º (± 5.40) respectively. Seven women and twelve men were participating in overhead sport activities on a weekly basis of at least one-hour duration. Overhead sport activities included netball, basketball or volleyball (5), paddling / surfing (3), golf (3), swimming (2), cricket (2), pump aerobics (2), rugby (2), weightlifting (1), yoga (1), softball (1). Numbers in brackets signify the number of participants involved in the sport (multiple answers were possible).

Table 9. ***Demographic data of participants***

	All participants	**Women**	**Men**
Number	40	21 (52.5%)	19 (47.5%)
Right dominant (%)	33 (82.5%)	18 (85.7%)	15 (78.9%)
Left dominant (%)	7 (17.5%)	3 (14.3%)	4 (21.1%)
Height (m)*	1.72 ± 0.08 (1.55 – 1.88)	1.67 ± 0.05 (1.55 – 1.76)	1.76 ± 0.07 (1.66 - 1.88)
Age (years)*	28.6 ± 9.03 (18 – 54)	27.7 ± 9.44 (18 – 52)	29.6 ± 8.71 (20 – 54)
Body weight (kg)*	70.7 ± 14.42 (49 –102.1)	61.1 ± 7.92 (49 – 77)	81.2 ± 12.50 (66.2 – 102.1)
Right scapular plane in degrees (º)*	36.83 ± 3.99º (28º - 44º)	n/a	n/a
Left scapular plane in degrees (º)*	35.80 ± 5.40º (24º - 48º)	n/a	n/a
Overhead sport	19 (47.5 %)	7 (33.3%)	12 (63.2%)

Note. *: Mean value ± standard deviation; n/a: Not applicable; Numbers in brackets: Range of values.

5.2 Exclusion of images

US images were excluded from statistical analyses when accurate measurements of distances were prevented purely due to poor image quality or unsuccessful visualisation of landmarks. The decision to exclude an image was made by the examiner during image analysis. Poor image quality, in which distances could not be measured, mainly occurred in images taken in the posterior USI view. Images of the first measurement session were lost for two participants due to a data storage fault. The number of images / missing data is indicated in Table 12 and Table 13 under valid number (n).

5.3 Intra-rater reliability

Distance measurements were taken in two measurement sessions. Distances that were measured included the AHD and AGTD using the superior USI view and the HGD in the posterior USI view. Table 10 summarises the ICC values followed by confidence intervals for distance measurements taken in the three arm positions of neutral, 60º passive and 60º active shoulder abduction.

Table 10. ***Intra-rater reliability for distance measurements using ultrasound imaging.***

Type of measurement	ICC single measures (95% CI)		
	Session 1	**Session 2**	**Between sessions**
Superior view			
Neutral AGTD	0.92 (0.87 - 0.95)	0.88 (0.82 – 0.92)	0.80 (0.70 – 0.87)
AHD overall	0.95 (0.94 – 0.96)	0.97 (0.96 – 0.98)	0.89 (0.86 – 0.91)
Neutral AHD	0.87 (0.81 – 0.92)	0.97 (0.95 – 0.98)	0.89 (0.83 – 0.93)
60º passive AHD	0.96 (0.94 – 0.98)	0.98 (0.96 – 0.99)	0.83 (0.75 – 0.89)
60º active AHD	0.94 (0.91 – 0.96)	0.94 (0.90 – 0.96)	0.82 (0.73 – 0.88)
Posterior view			
HGD overall	0.95 (0.93 – 0.96)	0.95 (0.94 – 0.96)	0.74 (0.67 – 0.80)
Neutral HGD	0.93 (0.88 – 0.96)	0.97 (0.95 – 0.98)	0.74 (0.59 – 0.83)
60º passive HGD	0.97 (0.94 – 0.98)	0.96 (0.93 – 0.97)	0.73 (0.59 – 0.83)
60º active HGD	0.94 (0.91 – 0.96)	0.92 (0.87 – 0.95)	0.70 (0.54 – 0.80)

Note. AHD: Acromiohumeral distance; AGTD: Acromion-greater tuberosity distance;
CI: Confidence interval, HGD: Humeroglenoid distance; ICC: Intraclass correlation coefficient.

There was no significant difference detected between ICC values of the first versus the second session (F-tests < 0.001 for all measurements). ICC values were excellent to high for all measurements. Generally, the ICC values tended to be higher within the measurement sessions compared to between the two measurement sessions. There was also a trend for ICC values being lower for measurements obtained in active shoulder abduction.

Table 11 summarises the values for SEM and SRD, along with the standard deviations of the difference between two measurements for Session 1 and Session 2. SEM and SRD values were low in both measurement sessions.

Table 11. Measurement error: ***Standard error of the measurement - Smallest real difference in cm.***

Type of measurement	Difference of Session 1 (SD)	SEM	SRD	Difference of Session 2 (SD)	SEM	SRD
Superior						
AGTD neutral	0.11	0.03	0.09	0.13	0.04	0.12
AHD neutral	0.09	0.03	0.09	0.05	0.01	0.03
AHD 60º passive	0.06	0.01	0.03	0.04	0.01	0.02
60º AHD active	0.07	0.02	0.04	0.07	0.02	0.05
Posterior						
HGD neutral	0.14	0.04	0.11	0.10	0.02	0.05
HGD 60º passive	0.11	0.02	0.06	0.13	0.03	0.08
HGD 60º active	0.14	0.03	0.09	0.17	0.05	0.14

Note. AGTD: Acromion-greater tuberosity distance; AHD: Acromiohumeral distance; HGD: Humeroglenoid distance; SD: Standard deviation, SEM: Standard error of the measurement, SRD: Smallest real difference.

Figures 20 to 23 provide the Bland Altman Plots and 95% limits of agreement (LOA) of the mean differences plotted against the mean values for the AHD and HGD data in one single session (Session 1), and between two sessions (Session 1 and Session 2). Regarding the AHD measurements, the LOA for distances measured in Session 1 lay between – 0.17 and 0.16 cm, and for distances measured between Session 1 and Session 2, the LOA lay between – 0.19 and 0.20 cm. The LOA for the HGD measurements in Session 1 ranged between – 0.32 and 0.24 cm, and lay between – 0.59 and 0.54 cm between the two sessions.

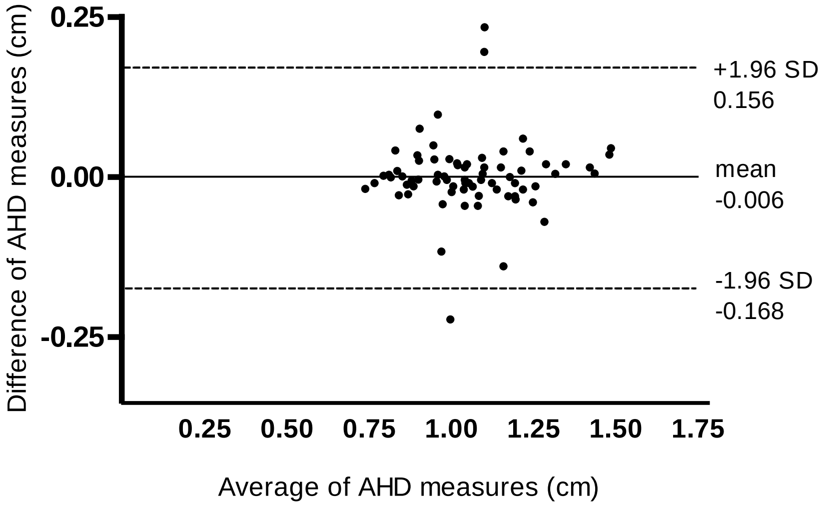

***Figure 20.* Plot of the difference between two acromiohumeral distance measurements in neutral shoulder position in Session 1 against their mean value.**
Bias: -0.00567124; SD of bias: 0.0826479; 95% Limit of agreement: From -0.168 to 0.156 cm.
Note. AHD: Acromiohumeral distance; SD: Standard deviation.

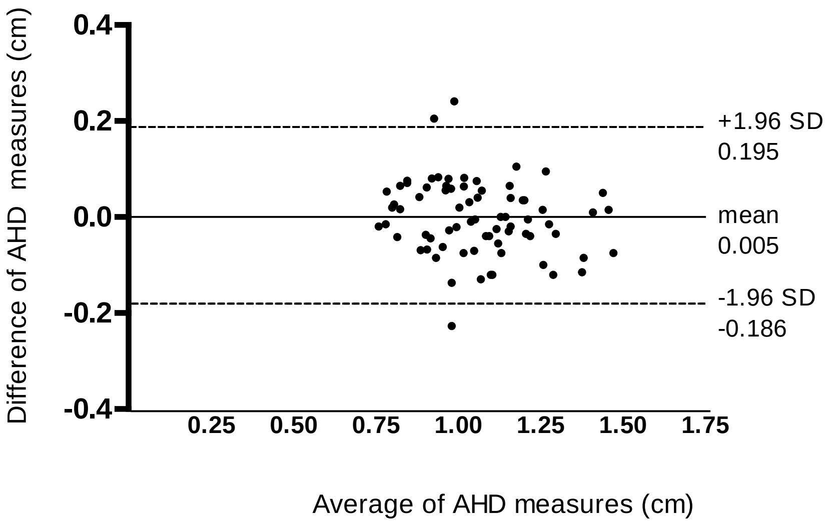

***Figure 21*. Plot of the difference between acromiohumeral distance measurements in neutral shoulder position in Session 1 and Session 2 against their mean value.**
Bias:0.00468920; SD of bias:0.0972413; 95% Limit of agreement from -0.186 to 0.195 cm.
Note. AHD: Acromiohumeral distance; SD: Standard deviation.

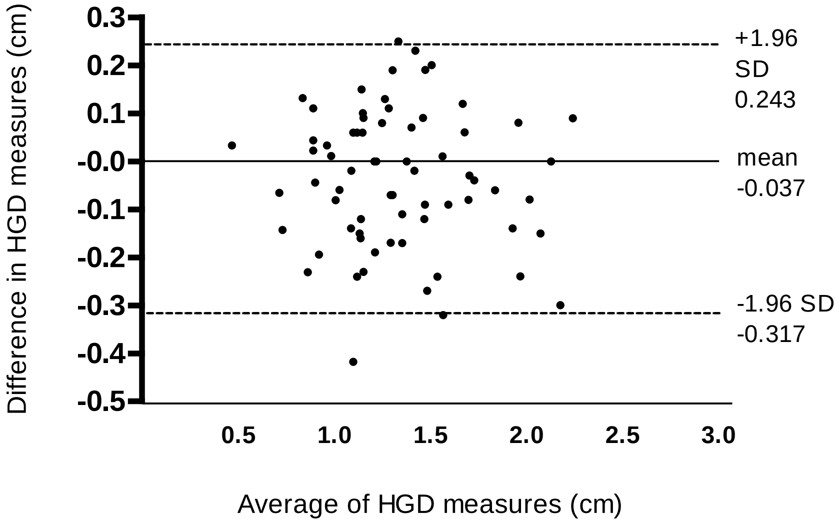

***Figure 22.* Plot of the difference between two humeroglenoid distance measurements in neutral shoulder position in Session 1 against their mean value.**
Bias:-0.0368406; SD of bias: 0.142690; 95% Limit of agreement from -0.317 to 0.243 cm.
Note. HGD: Humeroglenoid distance; SD: Standard deviation.

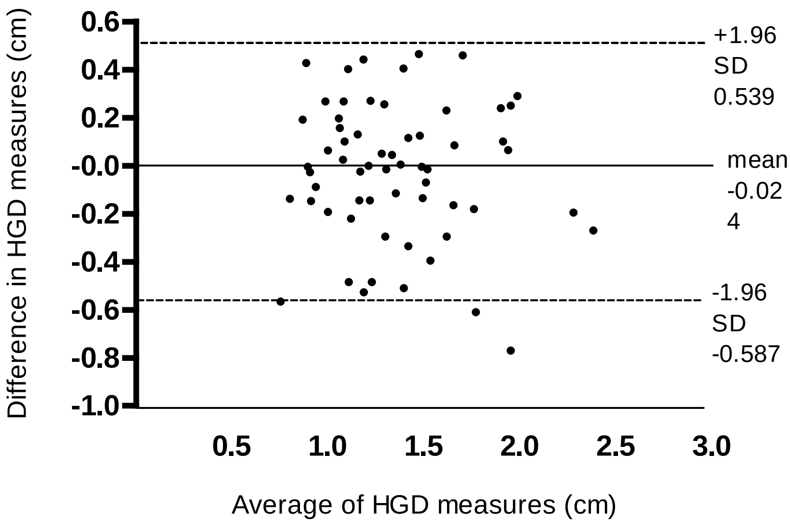

***Figure 23.* Plot of the difference between humeroglenoid distance measurements in neutral shoulder position in Session 1 and Session 2 against their mean value.**
Bias: -0.0236885, SD of bias: 0.287037; 95% Limit of agreement from -0.587 to 0.539 cm.
Note. HGD: Humeroglenoid distance; SD: Standard deviation.

5.4 Distances

The mean distance values of the AGTD, AHD and HGD that were obtained in Session 1 and Session 2 are presented in Table 12 and Table 13 respectively.

Table 12. ***Distances in cm for superior and posterior imaging view - Session 1***

Type of measurement	Valid (n) out of 80	Mean (± SD)	Minimum-Maximum	Range
Superior view	(80)			
AGTD Neutral	74	1.45 (± 0.28)	0.95 – 2.11	1.16
AHD Neutral	75	1.07 (± 0.18)	0.75 – 1.56	0.81
AHD 60º passive	75	0.81 (± 0.21)	0.38 – 1.24	0.86
AHD 60º active	75	0.78 (± 0.19)	0.42 – 1.32	0.91
Posterior view	(80)			
HGD Neutral	69	1.34 (± 0.38)	0.47 – 2.25	1.78
HGD 60º passive	67	1.20 (± 0.41)	0.45 – 2.35	1.89
HGD 60º active	68	1.08 (± 0.40)	0.11 – 2.24	2.13

Note. AGTD: Acromion-greater tuberosity distance; AHD: Acromiohumeral distance; HGD: Humeroglenoid distance; SD: Standard deviation.

Table 13. ***Distances in cm for superior and posterior imaging view - Session 2***

Type of measurement	Valid (n) out of 80	Mean (± SD)	Minimum-Maximum	Range
Superior view	(80)			
AGTD Neutral	80	1.41 (± 0.25)	0.92 – 2.04	1.11
AHD Neutral	80	1.06 (± 0.18)	0.75 – 1.56	0.76
AHD 60º passive	79	0.84 (± 0.22)	0.41 – 1.36	0.94
AHD 60º active	79	0.79 (± 0.20)	0.40 – 1.33	0.92
Posterior view	(80)			
HGD Neutral	70	1.32 (± 0.41)	0.60 – 2.52	1.92
HGD 60º passive	68	1.19 (± 0.43)	0.40 – 2.31	1.91
HGD 60º active	69	1.07 (± 0.42)	0.00 – 2.27	2.27

Note. AGTD: Acromion-greater tuberosity distance; AHD: Acromiohumeral distance; HGD: Humeroglenoid distance; SD: Standard deviation.

Further calculations were performed with the data distance measurements of Session 1. The differences between the neutral and the abducted shoulder positions are presented in Table 14. In 60º passive abduction, the mean AHD was 0.25 cm smaller than the mean AHD in the neutral position, representing a statistically significant decrease by 23.7% (p < 0.000). Similarly, the mean AHD in 60º active abduction was 0.29 cm smaller than the mean AHD in the neutral position, representing a statistically significant decrease by 26.9% (p < 0.000). The mean difference of the AHD between passive and active abduction was 0.03 cm, representing a statistically insignificant change of 4.2% (p = 0.30) (Table 14; Figure 24). Similarly, the mean HGD in 60º passive abduction was 0.14 cm smaller than the mean HGD in the neutral position, which was a statistically significant change by 10.5% (p = 0.04). The mean HGD in 60º active abduction was 0.25 cm smaller than the mean HGD in the neutral position, which equalled a 19.0% decrease and was statistically significant (p < 0.000). The mean difference of HGD between passive and active abduction resulted in 0.11 cm and was not statistically significant (p = 0.11; 9.5 %) (Table 14; Figure 25).

Table 14. ***Differences between distances in neutral and abduction in Session 1 in cm***

Type of measurement	Mean difference (cm)	Significance (2-tailed)	95% CI of the difference (cm)	Standard error of difference (cm)
Superior view				
AHD neutral vs 60º passive	0.25	0.000**	0.19 – 0.32	0.03
AHD neutral vs 60º active	0.29	0.000**	0.23 – 0.35	0.03
AHD 60º passive vs 60º active	0.03	0.30	- 0.03 – 0.10	0.03
Posterior view				
HGD neutral vs 60º passive	0.14	0.04*	0.01 – 0.27	0.07
HGD neutral vs 60º active	0.25	0.000**	0.12 – 0.39	0.07
HGD 60º passive vs 60º passive	0.11	0.11	- 0.03 – 0.30	0.07

Note. AGTD: Acromion-greater tuberosity distance; AHD: Acromiohumeral distance; HGD: Humeroglenoid distance; vs: versus; *: Difference is significant at the 0.05 level (2 -tailed); **: Difference is significant at the 0.001 level (2-tailed).

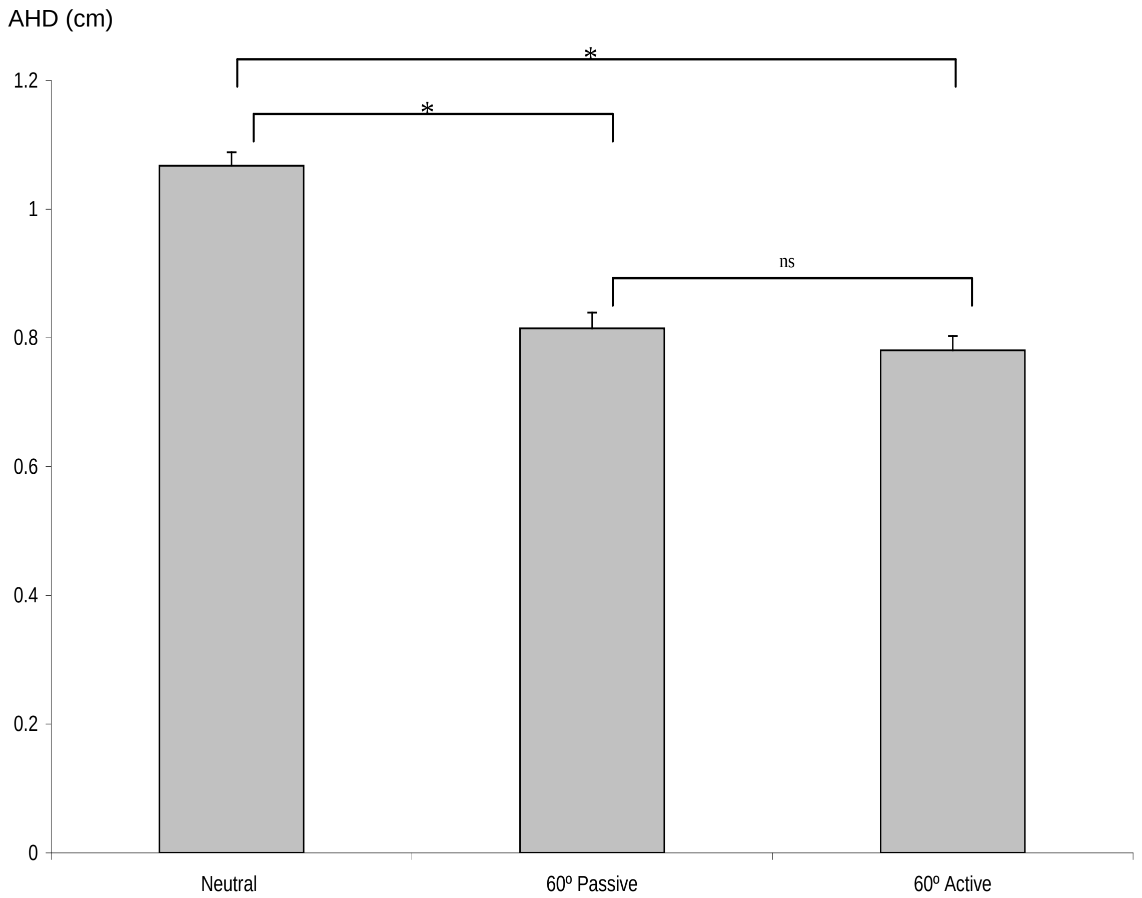

Figure 24. **Change of acromiohumeral distance with abduction (Session 1).**
Note. AHD: Acromiohumeral distance; ns: Non-significant change; *: Statistical significant change (*p* < 0.05).

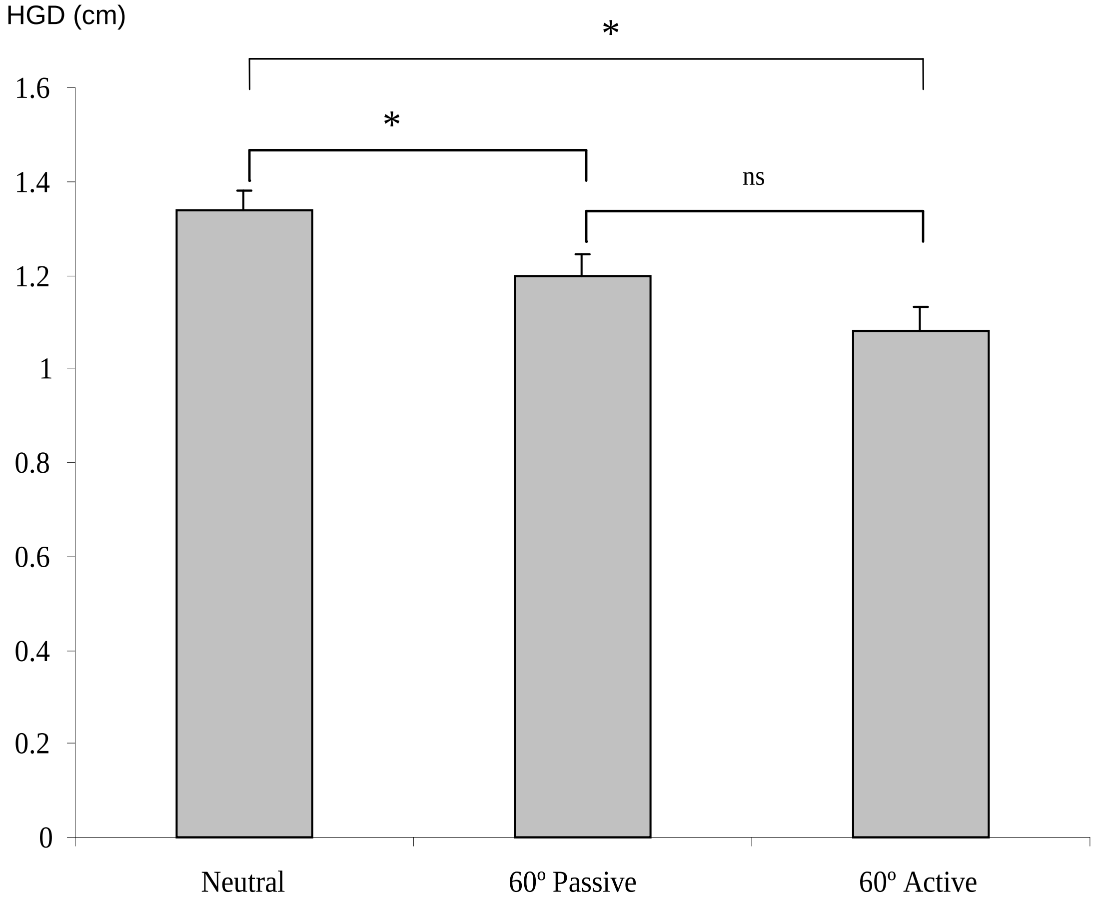

Figure 25. **Change of humeroglenoid distance with abduction (Session 1).**
Note. HGD: Humeroglenoid distance; ns: Non-significant change; *: Statistical significant change ($p < 0.05$).

5.5 *Influence of participants' characteristics on measured distances*

The relationship of participants' characteristics and values of AHD and HGD were tested. The analysis of the effect of gender revealed statistically significant lower values in females compared to male participants for all measurements, except for the HGD in 60º active abduction (Table 15). No significant differences were found between the participants' dominant and non-dominant shoulders (Table 16).

Table 15. ***Differences between genders (Mean values Session 1 in cm)***

Type of measurement	Female	Male	Mean difference	Independent *t*-test (2-tailed)
AHD neutral	1.01 ± 0.17	1.13 ± 0.17	0.12	0.003*
AHD 60º passive	0.73 ± 0.20	0.90 ± 0.19	0.16	0.001*
AHD 60º active	0.70 ± 0.16	0.86 ± 0.19	0.16	0.000**
HGD neutral	1.18 ± 0.33	1.50 ± 0.36	0.32	0.000**
HGD 60º passive	1.06 ± 0.35	1.32 ± 0.42	0.27	0.006*
HGD 60º active	1.00 ± 0.39	1.16 ± 0.40	0.16	0.106

Note. AGTD: Acromion-greater tuberosity distance; AHD: Acromiohumeral distance; HGD: Humeroglenoid distance;*: Difference is significant at the 0.05 level (2 -tailed); **: Difference is significant at the 0.001 level (2 – tailed).

Table 16. ***Differences between dominant and non-dominant side. (Mean values Session 1 in cm)***

Type of measurement	Dominant	Non-dominant	Mean difference	Independent *t*-test (2-tailed)
AGTD neutral	1.41 ± 0.28	1.50 ± 0.27	0.09	0.182
AHD neutral	1.05 ± 0.16	1.09 ± 0.19	0.04	0.373
HGD neutral	1.37 ± 0.36	1.30 ± 0.40	0.07	0.438

Note. AGTD: Acromion-greater tuberosity distance; AHD: Acromiohumeral distance; HGD: Humeroglenoid distance. Significance level is set at $p < 0.05$.

Table 17 presents the relationship between distance measurements and age, height, body weight and overhead sports participation. Correlations were found for body weight, age and height with the measured AHD and HGD values. No relationship was found between participation in overhead sports and measured distances.

Table 17. ***Correlations between mean distances (Session 1) and participants' characteristics***

Measurement	Body height	Body weight	Age	Overhead sport
AHD neutral	*r* = 0.116	*r* =0.401**	*r* = - 0.094	*r* =0.011
AHD 60º passive	*r* = 0.157	*r* = 0.445**	*r* = 0.094	*r* = 0.08
AHD 60º active	*r* = 0.226	*r* = 0.415**	*r* = - 0.025	*r* = 0.072
HGD neutral	*r* = 0.256*	*r* = 0.444**	*r* = - 0.293*	*r* =0.177
HGD 60º passive	*r* = 0.281*	*r*= 0.369*	*r* = - 0.248*	*r* = 0.168
HGD 60º active	*r* = 0.200	*r* = 0.195	*r* = - 0.252*	*r* = 0.186

Note. AGTD: Acromion-greater tuberosity distance; AHD: Acromiohumeral distance; HGD: Humeroglenoid distance; *r*: Pearson correlation;*: Correlation is significant at the 0.05 level (2-tailed);**: Correlation is significant at the 0.001 level (2-tailed).

There was a strong relationship between body weight and AHD in neutral and abduction ($p < 0.001$). Similarly, a strong relationship was found between body weight and HGD in neutral ($p < 0.001$). However, this relationship was less significant in passive shoulder abduction ($p = 0.02$) and not significant in active shoulder abduction ($p = 0.111$). Figure 26 illustrates the correlation between bodyweight, and AHD and HGD in neutral. There was a significant relationship between body height and HGD in neutral and passive shoulder abduction ($p < 0.05$), but no correlation was found with AHD measurements. Participants' age was inversely correlated with the HGD ($p < 0.05$), but not with the AHD. In other words, the HGD was getting smaller as the participants' age increased.

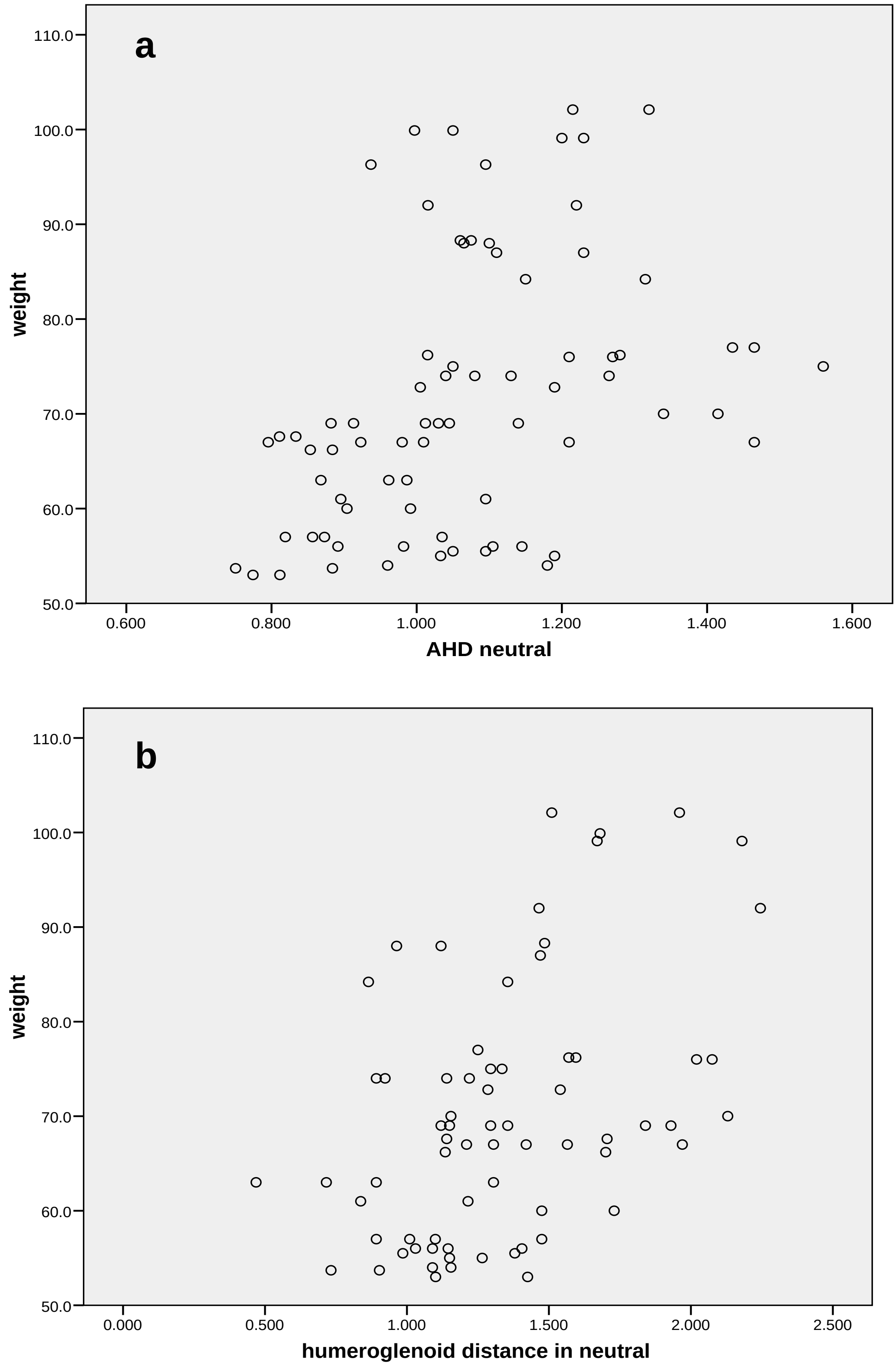

Figure 26. **Correlation of body weight and acromiohumeral and humeroglenoid distances – Session 1.**
a) Acromiohumeral distance and b) humeroglenoid distance in a neutral shoulder position. Body weight in kg, distances in cm.
Note. AHD: Acromiohumeral distance.

6 Discussion

6.1 Outline

This study shows that the superior and posterior USI methods are reliable for the repeated application by a single examiner. The main objectives of this research were to establish the reliability and accuracy of the USI method; to quantify acromio-humeral and gleno-humeral distances in neutral and abducted shoulder positions; and to investigate any correlations between distance measurements and participants' characteristics. The individual results for these objectives are discussed in detail in the following section with reference to existing literature.

6.2 Reliability

The reliability analysis demonstrated high to excellent intra-rater reliability for all measurements. This indicates that the USI method that was developed in this research is reliable when utilised by one examiner. The between-session ICC values were lower than the within-session ICC values and displayed larger confidence intervals, particularly in the posterior USI view. This suggests that the reliability of the USI method is lower between two measurement sessions than when two consecutive measurements are taken in one single session. This is also illustrated in the Bland Altman plots, which show that the data is more widely distributed for the between-session analyses compared to the within-session analyses (Figures 20 to 23).

6.2.1 Intra-rater reliability of superior imaging view

The AHD measurement in the neutral shoulder position displayed excellent within-session reliability (ICC: 0.95 for Session 1 and 0.97 for Session 2) and high between-session reliability (ICC: 0.89). Cheng et al (2008) and Pijls et al (2010) report comparable within-session intra-rater reliability in healthy and SIS populations for experienced raters. Both authors report ICC values of 0.94. However, it is worth noting that Cheng et al (2008) measured the amount of inferior translation between the coracoid and the humeral head instead of the AHD (Table 2). Interestingly, Pijls et al (2010) took the mean value of three consecutive measurements in one session, but did not yield higher reliability than this research. This indicates that with the methods described in this research, taking the mean value of two consecutive measurements might be sufficient to obtain high to excellent intra-rater reliability.

Schmidt et al (2004) and Cheng et al (2008) found high between-session reliability (ICC: 0.86 and 0.97 respectively). These findings are consistent with this research. However, Schmidt et al (2004) measured only two individuals, which limits the strength of the results. In addition, both authors report the reliability for experienced examiners only, and Cheng et al (2008) did not provide the reliability of their second, less experienced examiner.

This research also established high intra-rater reliability for the measurement of the AGTD, which was used as alternative distance to measure the subacromial space. Yet, the definition of a specific landmark on the humeral head for the measurement of the AGTD (i.e. the edge of the greater tuberosity) did not improve the reliability compared to the AHD measurement. Cholewinski et al (2008) who employed a similar landmark on the humeral head (the tip of the greater tuberosity) did not describe the reliability of the method. Furthermore, the edge of the greater tuberosity could only be seen on the US images of the neutral shoulder position, thus limiting its applicability for abducted shoulder positions. Therefore, the method of landmark definition for the AHD measurement seems to be appropriate to determine the AHD in both neutral and abducted shoulder positions.

Regarding the AHD measurement in 60° shoulder abduction, this research established excellent within-session reliability for both passive abduction (ICC: 0.96 for Session 1 and 0.98 for Session 2) and active abduction (ICC: 0.94 for Session 1 and 0.94 for Session 2). Further, between-session reliability was high in both passive and active abduction (ICC: 0.83 and 0.82 respectively). These results are comparable to a study reporting excellent within-session intra-rater reliability (ICC: 0.90) in a population with SIS in 60º shoulder abduction for an experienced examiner (Pijls, et al., 2010). However, compared to the experienced examiner, a novice examiner reached slightly lower reliability (ICC: 0.87) (Pijls, et al., 2010). Another study found similar intra-rater within-session reliability for two inexperienced examiners measuring the AHD at 45º active abduction in healthy individuals (ICC: 0.81 and 0.92) (Fremont, et al., 2000).

6.2.2 Intra-rater reliability of posterior imaging view

This study established excellent within-session intra-rater reliability for the HGD measurement in the neutral and abducted shoulder positions with ICC values between 0.93 and 0.97. Borsa et al (2005a) report a slightly higher within-session intra-rater reliability of the posterior USI view (ICC: 0.99). However, methodological differences between the studies limit comparability of the results. Borsa et al (2005a) fixed the shoulder in a specific apparatus in abduction and external rotation and applied anteriorly and posteriorly directed forces when measuring the translation of the humeral head, while in this study no apparatus was used, and the arm position was different. In addition, Borsa et al (2005a) performed the two measurement sessions only 24 hours apart, while in this study, the measurement sessions were up to one week apart. A shorter gap between measurement sessions might contribute to accuracy of the examiner and therefore increase reliability.

This study found that between-session reliability is reduced, but is still high for the neutral and the passively abducted shoulder position (ICC: 0.74; 95% CI: 0.59 – 0.83 for neutral; ICC: 0.73; 95% CI: 0.59 – 0.83 for 60° passive abduction). However, reliability decreased for the HGD measurement in 60° active abduction (ICC: 0.70; 95% CI: 0.54 – 0.80), which indicates a trend to moderate reliability. The confidence intervals of the between-session ICC values were considerably larger compared to the within-session ICC values. This indicates greater variability in the HGD measurements between two measurement sessions. Several reasons for the decrease in reliability have been identified. For the HGD measurement in active abduction, the participants were required to lift their arm and hold it steady while the US image was taken. Although participants were asked to keep skin contact with the table, it is possible that a variable amount of movement occurred while the participant performed this active abduction task on two separate measurement sessions. Additionally, the participant's arm might have moved unintentionally during the active abduction task, which might have affected the quality of landmark visualisation, thus impairing calliper placement. This might be why a larger number of posterior than superior USI view images were unreadable and had to be excluded.

The lower reliability and larger confidence intervals suggest that the posterior USI view tends to be more fault prone than the superior USI view. As pointed out previously in the discussion of the pilot study (Section 4.1.5), correct transducer alignment was crucial to imaging the posterior landmarks. In the future, the reliability of the posterior USI view might be improved by tracking the posterior landmarks (i.e. posterior glenoid and central tendon of infraspinatus muscle) when the arm is moved from the neutral into the abducted position by keeping the US transducer on the participant's skin.

With respect to both the superior and posterior USI views, variability of distance measurements might have been influenced by the placement of the transducer on the skin and the visualisation of the landmarks when the US image was captured. Additionally, the positioning of the participant might have been slightly different between two measurement sessions. In particular, the position of the arm in the scapular plane and in 60° abduction might have differed slightly from one measurement to the next, thereby causing variation. Moreover, the calliper placement on the US images might have caused some variability. For example, cortical irregularity (e.g. of the greater tuberosity) has been described as a source of measurement error in musculoskeletal US (Jacobson, et al., 2004).

Musculoskeletal USI has been stated to be operator dependant, thus requiring training and experience (Kane, et al., 2004a). However, even inexperienced examiners can achieve a high level of inter- and intra-rater reliability (Balint & Sturrock, 2001; Cheng, et al., 2008; Fremont, et al., 2000; Pijls, et al., 2010; Wallwork, et al., 2007). The examiner in this study was a physiotherapist and a novice to musculoskeletal USI, with a relatively short training period. It has been shown that well-defined anatomic landmarks contribute to high intra-, and inter-rater reliability (Balint & Sturrock, 2001). The high reliability found in this study may be in part due to the anatomical landmarks used. However, despite the high intra-rater reliability that was established in this research, the reliability of this USI method for multiple examiners is yet to be investigated.

6.3 Humeral head translation

6.3.1 Acromiohumeral distance

In the neutral shoulder position, the mean AHD equalled 1.07 (± 0.18) cm. This corresponds well with AHD data that has been published for healthy populations Overall, the mean AHD has been described as approximately 1 cm wide (Table 4). Schmidt et al (2004) described AHD values of 1.09 (± 0.42) cm. Desmeules at al (2004), Fremont et al (2000) and Silva et al (2008) reported very similar mean AHD values of 0.99 (± 0.15) cm, 0.98 (± 0.15) cm and 0.98 ± (0.14) respectively. Jerosch et al (1991) found larger mean AHD values of 1.34 (± 0.21) cm for 150 healthy individuals, which were more similar to the size of our AGTD measurements (1.45 ± 0.28) cm. Two further studies described shorter AHD distances (Girometti, et al., 2006; Wang, et al., 2005). Girometti et al (2006) reported slightly smaller AHD values of 0.86 cm. Wang et al (2005) found markedly smaller AHD values between 0.56 cm and 0.74 cm. These deviations are likely to be due to the differences in USI methods between the studies, including landmark selection, calliper placement, assessment of dominant or non-dominant shoulder and the positioning of the participant's shoulder.

The minimum AHD that has been measured in the neutral position was 0.75 cm. This value lies beyond the cut-off points of 0.5 cm to 0.7 cm that have been suggested for normal AHD using other imaging methods (Petersson & Redlund-Johnell, 1984; Saupe, et al., 2006; Weiner & Macnab, 1970). Using USI, Girometti et al (2006) found that an AHD value of smaller than 0.7 cm was the only parameter that was significantly different between basketball players, some of which had shoulder pathology, and a healthy control group. It is interesting to note that all symptomatic shoulders and several non-symptomatic shoulders of the basketball players displayed an AHD of smaller than 0.7 cm, while none of the control subjects showed a reduced AHD. Girometti et al (2006) interpreted a reduced AHD of smaller than 0.7 cm as a potential early sign for secondary impingement, which could be detected independent from clinical onset. Although the definition of a cut-off point for a normal AHD value sounds interesting, more research is needed to support this data.

In this research, the mean AHD in 60º passive and active shoulder abduction equalled 0.81 (± 0.21) cm and 0.78 (± 0.19) cm respectively. Desmeules et al (2004) described almost identical values for 60º active abduction (0.76 ± 0.17 cm). Silva et al (2008) also reported very similar AHD values for 60º abduction (0.762 ± 0.15 cm), but did not specify whether the measurements were taken in active or passive abduction. Wang et al (2005) found slightly smaller AHD values of 0.67 cm - 0.74 cm for passive abduction in the scapular plane. However, those measurements were taken in 90º shoulder abduction, which might explain the smaller distance.

The AHD decreased significantly from neutral to 60º passive abduction by 0.25 cm and from neutral to 60º active abduction by 0.29 cm ($p < 0.001$). This data corresponds well with the findings of Desmeules et al (2004) who described a statistically significant AHD reduction of 0.23 cm between neutral and 60º active abduction, and Silva et al (2008) who reported an AHD reduction of 0.22 (± 0.11) cm for 60º shoulder abduction. However, Silva et al (2008) did not specify whether the measurement was taken in active or passive abduction. Desmeules et al (2004) and Fremont et al (2000) described a significant decrease of the AHD of 0.15 cm with active abduction from neutral to 45º, which constitutes approximately half of the distance we measured for 60º abduction. The findings also correspond closely with radiographic findings of Poppen and Walker (1976), who determined the superior-inferior translation of the humeral head on the glenoid surface in increments of 30º abduction. For healthy subjects, the average superior translation of the humeral head during abduction from 0º to 60º in the scapular plane was approximately 0.3 cm. For abduction beyond 60º, only marginal superior or inferior translation of the humeral head (0.1 – 0.2 cm) was detected. This might suggest that translation of the humeral head occurs relatively evenly through the range up to 60º. In contrast, Wang et al (2005) reported a non significant AHD reduction of 0.02 cm between neutral and 90º passive abduction. This disagreement could be due to differences in the measurement method. Wang et al (2005) used different landmarks on the humeral head for measurements in neutral and in the abducted shoulder position.

According to results of this study, an AHD decrease during abduction between 0.25 – 0.29 cm occurs in healthy individuals, which can be attributed to a superior translation of the humeral head. The superior translation can be explained by an initial sag of the humeral head in the neutral relaxed position, when the arm is at the side of the body (Poppen & Walker, 1976). Furthermore, the deltoid muscle might have a stronger superiorly translating influence in the early ranges of abduction, before the RC muscles provide more centralising forces and limit further superior translation (Graichen, Bonel, Stammberger, Eeglmeier, Reiser, & Eckstein, 1999a; Graichen, et al., 2000; Poppen & Walker, 1976).

6.3.2 Humeroglenoid distance

In this research, the anterior-posterior translation of the humeral head on the glenoid was measured through the HGD, which is the dorsal projection of the humeral head over the dorsal edge of the glenoid. A mean HGD of 1.34 (± 0.38) cm in the neutral shoulder position was found. Jerosch et al (1991) reported smaller HGD values between 0.8 - 1.0 cm. This disagreement might be due to differences in the determination of transducer placement on the posterior shoulder.

Furthermore, a significant decrease in the mean HGD was found when the arm was moved from the neutral position into passive and active abduction. This indicates that the humeral head glides anteriorly during abduction. Active shoulder abduction induced more anterior translation of the humeral head than passive abduction (active: 0.25 cm, $p \leq 0.001$; passive: 0.14 cm, $p = 0.04$). Thus, activation of surrounding shoulder muscles seems to influence humeral head translation to a stronger degree than passive structures such as the joint surfaces and capsuloligamentous structures. Because healthy individuals were examined, it is plausible that the humeral head was well centred in the glenoid during the movements. However, the position of the humeral head in relation to the centre of the glenoid cannot be visualised with USI. Therefore, USI cannot determine whether the humeral head is centred in the glenoid in a resting position or during translation. No previous USI studies have reported values for HGD changes with shoulder abduction. However, studies using other imaging methods reported similar findings for normal shoulders (Graichen, et al., 2000;

Harryman, et al., 1990). Graichen at al (2000) described anterior translation of the humeral head in relation to the centre of the glenoid with passive shoulder abduction in the range of 30º and 90º, as well as at 120º active abduction. Harrymann et al (1990) found anterior humeral head translation beginning beyond 55º shoulder flexion.

The relevance of assessing anterior humeral head translation lies in its potential association with the development of shoulder disorders. With anterior translation, the humeral head moves closer towards the anterior part of the coracoacromial arch. Thus, the space for clearance between the humeral head and the anterior compartment of the subacromial space is reduced. Increased anterior translation of the humeral head has been described in the presence of shoulder disorders, such as SIS, posterior capsule tightness and GH instability (Harryman, et al., 1990; Howell, et al., 1988; McKenna, et al., 2009).

Stieler (2002) identified an interesting association between the decrease of the distance between the coracoid process and the humeral head and patients with SIS, using an anterior USI view. Stieler (2002) considered this to indicate an altered geometry of the subacromial space, such as alterations in the length of the root of the coracoid process and its angle of ascent from the glenoid, leading to a closer proximity between the coracoid process and the humeral head than between the coracoid process and the acromion. This seems to be a plausible cause for a reduction of the anterior compartment of the subacromial space and its association with SIS and underlines the importance of the assessment of the anterior compartment of the subacromial space. This measurement could not be replicated due to the difficulties that were associated with the USI anterior view that have been discussed previously in the pilot study.

6.4 Correlations between distances and participants' characteristics

This research identified correlations between body weight and AHD and HGD measurements. Age and height were correlated with HGD measurements only. There was no relationship between participation in overhead sports activities and distances. In addition, distances between men and women differed significantly, whereas no difference was found between the dominant and non-dominant side.

Women displayed smaller AHD values compared to men. The mean differences of the AHD between men and women were relatively small with 0.12 cm in neutral and 0.16 cm in passive and active abduction, but statistically significant (neutral: $p = 0.003$; 60º passive and 60º active: $p \leq 0.001$). Significantly smaller AHD in women has also been described in radiographic and CT studies (Gumina, et al., 2008; Petersson & Redlund-Johnell, 1984). In an MRI study, Graichen et al (2001) described significantly smaller AHD values in women compared to men at 30º passive shoulder abduction but not at 90º passive and active abduction and attributed this to an increasing variability in neuromuscular control patterns between individuals when they actively abducted the arm. The findings in this study did not support this idea. In this research, the actual AHD changes from neutral to abduction were very similar between men and women and the mean differences between genders remained stable in each shoulder position, indicating that the humeral head translated superiorly in a similar pattern in men and women.

Women also displayed smaller HGD values than men (except in active abduction). The mean differences of the HGD values between genders were large (0.32 cm in neutral and 0.27 cm in passive abduction) and statistically significant (neutral: $p \leq 0.001$; 60º passive: $p = 0.006$). However, in active abduction no significant difference between genders was observed (0.16 cm, $p = 0.106$). This means that significant differences between males and females in the HGD were largest in neutral and decreased with abduction and muscle activity. Greater anterior translation in the neutral shoulder position in women may have been influenced by differences in joint laxity. Borsa, Sauers and Herling (2000) found that women displayed greater GH joint laxity than men in a neutral shoulder position, which may help explain this finding. Interestingly, women showed the largest amount of HGD reduction between the neutral and passively abducted position (0.12 cm). Muscle activity in abduction led to a small further reduction of 0.06 cm. In contrast, men featured a similar HGD reduction between neutral and passive abduction (0.18 cm), but showed a considerable further reduction of 0.16 cm with muscle activity in abduction. This suggests that muscle activity in abduction had a stronger effect on anterior humeral head translation in men than in women, which might indicate that neuromuscular control patterns differ within genders. However, there is a lack of evidence for this explanation.

The values for HGD in neutral and passive abduction were correlated with body height. Men in this study were on average 9 cm taller than women, which might result in larger distances between anatomic landmarks. In addition, AHD and HGD values in neutral and passive abduction were correlated with body weight. Comparable correlations have been rarely reported in the literature. One study described significant correlations between the AHD and body height (r = 0.67) and body weight (r = 0.72) at 30º passive abduction (Graichen, et al., 2001). In this research, a correlation of the AHD with body height would have been reasonable based on the assumption that larger distances between landmarks would concur with increasing body height. The correlation with body weight, however, cannot be readily explained.

In the previous literature, a correlation between a reduction of the AHD and increasing age has been described for men and women over the age of 60 (Gumina, et al., 2008), and in men only (Petersson & Redlund-Johnell, 1984). This research could not verify any relationship between AHD reduction and age. This may have been due to the relatively small range of ages that were included. However, based on the inverse correlation of HGD measurements with age, it is suggested that the humeral head adopts a more anteriorly located position with increasing age of the participant. This could be mediated through postural changes, such as increasing thoracic kyphosis that occur with increasing age (Schwab, Lafage, Boyce, Skalli, & Farcy, 2006). In summary, the relationships between participants' characteristics and measured distances suggest that the position and translation of the humeral head in the superior-inferior and the anterior-posterior direction are influenced by gender, body weight and, in the case of anterior translation, age and height.

6.5 Measurement error

The reported SEM and SRD values were small when compared to the distance values for AGTD, AHD and HGD. The relatively low SEM and SRD values suggest that the method is able to detect a real difference between measurements. This is important because the most likely application of the USI method is to assess differences in distances (e.g. side to side differences, before and after an intervention etc).

To our knowledge, no other USI study measuring humeral head translations has calculated SRD values. In our opinion, the SRD is an important measure to interpret the reproducibility, utility and applicability of an USI method in retrieving clinically important results. If a differences between two distance measurements falls within the SRD, this should be interpreted as measurement error, because it cannot be confidently assumed that a true change in the position of the humeral head has occurred (Beckerman, et al., 2001). The SRD values did not exceed the differences between two distance measurements in both Session 1 and Session 2. This indicates that the USI method exhibits high reproducibility and enables the detection of changes in humeral head position of larger than 0.12 cm for AGTD, 0.09 cm for AHD and 0.05 cm for HGD in the neutral shoulder position, and of larger than 0.05 cm for AHD and 0.14 cm for HGD in abducted shoulder positions. In patients with SIS, Pijls et al (2010) report comparable values for accuracy for the AHD measurement in neutral and 60º abduction of 0.11 cm and 0.14 cm respectively. However, the authors defined accuracy as the difference of two measurements of the same observer in the same shoulder, which is not directly comparable to the SRD.

This research found that SEM values for distance measurements did not exceed 0.05 cm. McKenna et al (2009) report considerably larger SEM values of 0.22 cm in the neutral shoulder position and 0.3 cm in shoulder abduction for the manual palpation of the anterior position of the humeral head and anterior translation in 90º GH abduction. Despite the fact that McKenna et al (2009) report high intra-rater reliability for their manual palpation method, the comparatively high SEM values underline the accuracy of the USI method in comparison to manual assessment of the position of the humeral head in an anterior-posterior direction. This study shows that USI can provide a more reliable method to assess anterior-posterior humeral head position and translation, which may be useful in a clinical environment.

7 Conclusions

The findings show that the superior and posterior USI methods used are reliable for the repeated application by a single examiner. This USI method enables the assessment of the GH joint in functionally important arm positions and provides insight into neuromuscular control mechanisms through examining during active muscle contraction. The use of the AHD measurement method proved superior to the AGTD measurement, because the latter was unmanageable in the abducted shoulder positions, due to the greater tuberosity disappearing under the edge of the acromion. Differences between genders and correlations between measured distances and participants' characteristics that have been established in this research underline the variability of AHD and HGD distance measurements. Therefore, the assessment of distance changes in one individual is likely to be of more use in clinical practice than the determination of 'normal distances' based on the mean value of many individuals.

Moreover, this study has contributed to a database of AGTD, AHD and HGD distances in a healthy population in a neutral shoulder position, and 60° passive and active shoulder abduction. These values are useful in describing 'normal' distance values. In the future, deviations from these normal distance values might be associated with kinematic changes of the GH joint and/or shoulder disorders.

The accuracy, as expressed by the small SRD, indicates that the USI method described displays high reproducibility and is capable of detecting small distance changes of AGTD, AHD and HGD between measurements. With this level of accuracy, the USI method may well allow kinematic abnormalities of the GH joint to be detected. Other research has shown a relationship between altered humeral head position and shoulder disorders using various imaging methods, including ultrasound. The methods outlined in this study use reproducible anatomical landmarks visible on the ultrasound image for the location of the transducer, functionally relevant arm positions, active arm movement in the scapular plane, and measurements in both superior-inferior and anterior-posterior directions. This has resulted in a method that is well described, reliable, accurate, easy to administer, and achievable for novice examiners. The use of USI is safe, low cost, and transportable compared to other imaging techniques capable of performing the same measurements. The application of this method to understanding the kinematics of the GH joint has several advantages over other existing methods, and exciting potential for further understanding abnormal GH kinematics.

Several areas for further research have been identified. Firstly, the investigation of the inter-rater reliability of the USI method is important to determine the use of the USI method among several examiners. Secondly, the USI method needs to be applied in different populations (e.g. elderly, athletic etc) to establish reliability and normal values for AHD and HGD. Thirdly, the role of these measurements in those with shoulder disorders needs to be clarified further. The accuracy and reliability of the methods described in this study may well provide the tool necessary to detect signs of abnormal humeral head translation. The ability to detect such signs may well lead to more effective management of shoulder problems.

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9 Appendices

Appendix A Ethics Approval

MEMORANDUM

To: WayneHing
From: **Madeline Banda** Executive Secretary, AUTEC
Date: 2 March 2006
Subject: Ethics Application Number 05/237**Musculoskeletal Imaging Unit within the Physical Rehabilitation Research Centre, AUT, Akoranga Campus, School of Physiotherapy.**

Dear Wayne

Thank you for providing written evidence as requested. I am pleased to advise that it satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC) at their meeting on 12 December 2005. Your ethics application is now approved for a period of three years until 2 March 2009.

I advise that as part of the ethics approval process, you are required to submit to AUTEC the following:

- A brief annual progress report indicating compliance with the ethical approval given using form EA2, which is available online through *http://www.aut.ac.nz/research/ethics*, including a request for extension of the approval if the project will not be completed by the above expiry date;
- A brief report on the status of the project using form EA3, which is available online through *http://www.aut.ac.nz/research/ethics*. This report is to be submitted either when the approval expires on 2 March 2009 or on completion of the project, whichever comes sooner;

You are remindedthat, as applicant, you are responsible for ensuring that any research undertaken under this approval is carried out within the parameters approved for your application. Any change to the research outside the parameters of this approval must be submitted to AUTEC for approval before that change is implemented.

Please note that AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to make the arrangements necessary to obtain this.

To enable us to provide you with efficient service, we ask that youuse the application number and study title in allwritten and verbal correspondence with us. Should you have any further enquiries regarding this matter, you are welcome to contact Charles Grinter, Ethics Coordinator, by email at charles.grinter@aut.ac.nz or by telephone on 921 9999 at extension 8860.

On behalf of the Committee and myself, I wish you success with your research and look forward to reading about it in your reports.

Yours sincerely

Madeline Banda
Executive Secretary
Auckland University of Technology Ethics Committee

Appendix B   Demographic data collection sheet

Date:

MRN number:

Please tick boxes

Gender	female	male
Age		years
Height		m
Weight		kg
Hand dominance (preferred writing and throwing arm)	right	left

Do you currently have or did you experience in the past year:

Shoulder pain requiring medical attention?	yes	no
Pain in the cervical spine?	yes	no

Did you ever have:

Dislocation or subluxation of the shoulder joint?	yes	no
Fracture involving the clavicle, scapula, or humerus, injury to the acromioclavicular joint (ligamentous injury)?	yes	no

Do you suffer from:

Systemic joint disease or other inflammatory conditions?	yes	no
Are you involved in sports, involving racquet sports, rowing, swimming or throwing?	yes	no
If yes, which?		
How many hours per week?		hrs/week

Appendix C Participant Information Sheet

Date Information Sheet Produced:**13th August, 2009**

Project Title

Glenohumeral joint translation in two planes in neutral and in shoulder elevation. Normative data from a healthy population – A diagnostic ultrasound study

Invitation

You are invited to take part in a research study. Information from this research will be published as a research paper and may also be presented within academic publications or verbal presentations.

Participation is completely voluntary and you may withdraw from the study at anytime without giving a reason or being disadvantaged.

What is the purpose of this research?

The purpose of this research is to utilize real-time diagnostic ultrasound to measure and compare the distances measured from several specific bony landmarks of the shoulder at two different arm positions; and to evaluate the variation of these distancesbetween the right and left side and during relaxation and active muscle contraction.

How are people chosen to be asked to be part of this research?

People with normal shoulders will be asked to volunteer to take part in the study. Note that subjects with the following criteria will be excluded with reference to ACC shoulder injury guidelines: Fractures, inflammatory and degenerative arthritic conditions, endocrinological and neurological conditions, shoulder instability, adhesive capsulitis and previous surgery involving the neck and the shoulder.

What happens in this research?

You will be asked to sit on the chair and the images of your shoulder joint will be taken with the arm at two different positions. Ultrasound images will be taken from the top and the back of the shoulder. In the elevated position, you will be asked to lift your arm slightly off the supporting table. The probe of the machine will be applied to the skin surface with transmission gel and moved around until a clear image is achieved. The image will show on a monitor from which recordings and calculations can be made.
This procedure will be repeated at another day within 1 week.

What are the discomforts and risks?

There are no risks or discomfort from the ultrasound scanning. The transmission gel is water-based thus precluding an allergic reaction. The measurements will be taken in a neutral and midrange shoulder position, which will not be uncomfortable.

What are the benefits?

The benefit of performing this research is to identify the accuracy of real-time ultrasound and the normative values in a healthy population. Ultimately, this study's results would provide unique and important information regarding normal shoulder movement, shoulder pathology and the management thereof.

What compensation is available for injury or negligence?

Compensation is available through the Accident Compensation Corporation within its normal limitations.

How will my privacy be protected?

Your privacy will be protected by identifying you only by a number. Access to the data is restricted to the researchers.

What are the costs of participating in this research?

There is no monetary cost. It will however cost approximately 45 minutes at two different days. Thus, requiring 1.5 hours of your time in total.

What opportunity do I have to consider this invitation?

Before volunteering, please consider carefully whether you are prepared to be part of the study. Any students with whom the researchers have or have had a supervisory relationship will be excluded from this study. There will be some flexibility around the appointment times for the data collection. Please communicate clearly with us so convenience is optimised for all concerned, and appointments run smoothly and are on time.

How do I agree to participate in this research?

You will need to read the Consent Form and to sign this in order to consent to and participate in this study. A consent form can be obtained from the researcher (see contact details below).

Please contact the researcher if you wish to join this study. You will be contacted prior to the start of data collection, which is scheduled for August 2009.

Will I receive feedback on the results of this research?

Results will be made available to you at the completion of the study, and will be in the form of a written summary. If you wish to receive this, please indicate on the relevant section of the consent form. Any papers that may be published arising from the research can be accessed on request.

What do I do if I have concerns about this research?

If you have any concerns regarding the nature of this project then you should contact the supervising researcher, Dr Wayne Hing, 921-9999 ext 7800.

Any concerns regarding the conduct of the research should be made to the Executive Secretary, AUTEC, Madeline Banda, madeline.banda@aut.ac.nz , 921 9999 ext 8044.

Who do I contact for further information about this research?

Researcher Contact Details:

Marion Duerr, mobile 021 1006994

Dr Wayne Hing, work phone: 921-9999 ext 7800

Approved by the Auckland University of Technology Ethics Committee on *2 March 2006*, AUTEC Reference number *05/ 237*

Appendix D Consent to Participation in Research

Title of Project: **Glenohumeral joint translation in two planes in neutral and shoulder elevation. Normative data from a healthy population – A diagnostic ultrasound study.**

Researcher: **Marion Duerr,Dr. Wayne Hing**

- I have read and understood the information provided about this research project (Information Sheet dated 13th August, 2009.)
- I have had an opportunity to ask questions and to have them answered.
- I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.
- If I withdraw, I understand that all relevant data, or parts thereof, will be destroyed.
- I agree to take part in this research.
- I wish to receive a copy of the report from the research: tick one: Yes O No O

Participant signature: ....

Participant name: ....

Participant Contact Details (if appropriate):

....

....

....

....

Date:

Approved by the Auckland University of Technology Ethics Committee on 2 March 2006
AUTEC Reference number:05/237

Note: The Participant should retain a copy of this form.