Quantifying the Shoulder Rhythm and Comparing Non-Invasive Methods of Scapular Tracking for Overhead and Axially Rotated Humeral Postures

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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ABSTRACT

Shoulder rhythm is the three-dimensional relation between the humerus, clavicle and the scapula relative to the thorax. *A priori* estimates of orientations of these bones is required for biomechanical models to predict structural loads which are used as indicators of risk factors in workplaces to reduce prevalence of shoulder discomfort and disorders. The scapula and clavicle orientations are difficult to measure, but by mathematically quantifying the shoulder rhythm and developing regression models, the orientations of the clavicle and scapula can be estimated using externally measured humeral orientation. The aims of this study were to quantify the shoulder rhythm for arm postures that represent the right-handed reachable workspace and to compare three different methods of *in vivo* scapular tracking: acromion marker cluster (AMC), stylus and scapular locator.

Fourteen male and fourteen female participants performed static arm postures spread over five arm elevation angles: 0^o, 45^o, 90^o, 135^o, 180^o, three elevation planes: 0^o, 45^o, 90^o and, three axial rotations: maximum internal, neutral, and maximum external rotation. Kinematic data was collected using a Vicon MX20+ motion-tracking system. Bone rotations were calculated using Euler angles and continuous prediction models were generated to estimate scapular and clavicular orientations based primarily on thoracohumeral relative orientations. Methods of scapular tracking were compared using repeated measures analysis of variance.

Linear models were obtained for all scapular angles and for retraction/protraction and axial rotation of the clavicle and a quadratic model was obtained for clavicular elevation. Participant characteristics did not influence any of the scapular or the clavicular angles ($p>.05$). All three thoracohumeral angles significantly contributed to scapular lateral/medial rotation and anterior/posterior tilt and clavicular retraction/protraction and forward/backward rotation ($p<.0001$). Axial rotation did not influence scapular retraction/protraction and elevation plane did not influence clavicular elevation. Elevation angle was the largest contributor to lateral rotation and posterior tilt of the scapula and all clavicular angles. Plane of elevation was the largest contributor to scapular protraction. Using the stylus as the gold standard, the locator and the AMC underestimated lateral rotation, with a maximum difference of 11^{o} and 9^{o} between the locator and the stylus and AMC and the stylus measurements, respectively. The AMC and the locator overestimated posterior tilt at overhead elevation angles and underestimated it at low elevation angles. The maximum difference between the AMC- and the locator- and the stylus-measured tilt was 10^{o}. The scapular locator consistently overestimated protraction by approximately 5^{o}. The AMC underestimated protraction in the frontal plane at low elevation angle but overestimated it at all other postures and the overestimation increased with plane of elevation, internal rotation and elevation angle. Overall, it is recommended to use AMC rather than the scapular locator to measure scapular position, but careful consideration should be taken when interpreting the retraction/protraction results, especially during humeral postures in the sagittal plane.

The shoulder rhythm models can be incorporated into existing and future shoulder biomechanical models to determine shoulder geometry when simulating postures experienced in workplaces and thus have ergonomic implications for correctly identifying risk factors. The results of normal kinematics obtained also have clinical implications for detecting altered shoulder kinematics. This research will also provide guidance for future studies involving scapular tracking.

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1. INTRODUCTION

1.1 Shoulder Rhythm

The musculoskeletal system of the shoulder consists of the humerus and the closed chain mechanism of the thorax, clavicle and scapula. The shoulder bones form three synovial articulations: the glenohumeral, acromioclavicular and the sternoclavicular joints. The simultaneous motion at the acromioclavicular and the sternoclavicular joints allows the scapula to move relative to the thorax at the scapulothoracic articulation. The shoulder motion required to position the hand in space requires synchronous movement of the three shoulder bones at all four articulations and it is this distribution of motion that allows the shoulder to have a larger range of motion than any other joint in the body. Due to this functional relationship, the orientations of the shoulder skeletal elements are not arbitrary and this three-dimensional relationship is called the "shoulder rhythm".

1.2 Applications of Shoulder Rhythm

Shoulder discomfort and injury are common in work settings (Bernard, 1997). According to the Workplace Safety and Insurance Board report, 6.9% of all lost time claims were due to shoulder complications (2008). Shoulder musculoskeletal disorders are not only harmful to workers' health, they also pose a financial burden through lost productivity and rehabilitation costs.

Structural loads placed on the shoulder during tasks can be used as proactive and reactive indicators of risk factors in workplaces to reduce the prevalence of such discomfort and disorders. The structural loads are estimated using predictive shoulder biomechanical models (Hogfors, Sigholm and Heberts, 1987; Hogfors, Peterson, Sigholm and Heberts, 1991; van der Helm, 1994; Dickerson et al., 2007) that simulate the scenarios experienced in workplaces. Bone orientations in these scenarios determine lines-of-actions of muscles and change the moment equilibrium equations used to estimate structural loads (Hogfors et al., 1991). To ensure that the shoulder strengths are estimated with accuracy, an accurate geometric representation of the shoulder complex must be incorporated into the models (Karlsson and Peterson, 1992). In addition to this, it is desirable to calculate structural loads using only externally measurable variables (Hogfors et al., 1991). Externally determining the orientations of the scapula and the clavicle, however, is difficult. Fortunately, the shoulder rhythm allows estimations of scapular and clavicular orientations based on the externally measured orientation of the humerus relative to the thorax. The integrated movement of the three bones can be quantified by recording shoulder kinematics under static arm postures and fitting regression equations to the results (Hogfors et al., 1991; de Groot and Brand, 2001). Since there are no reported effects of movement velocity on the shoulder rhythm (de Groot, Valstar and Arwert, 1998), the static measurements can be extrapolated to dynamic situations. These regression models can be incorporated into existing shoulder biomechanical models to determine shoulder geometry so that more accurate predictions of structural loads can be acquired when simulating postures experienced in workplaces. A useful biomechanical model needs information about the shoulder kinematics in the whole humerus reachable workspace (Klopcar and Lenarcic, 2006). This warrants the quantification of shoulder rhythm for arm postures that cover the large range of motion of the arm.

A complete quantification of normal shoulder kinematics at all joints of the shoulder complex can also help identify the underlying cause(s) of shoulder discomfort and pathology. Shoulder bones' rotations are required to achieve hand position in space, to maintain optimal muscle length-tension relations and for glenohumeral joint alignment during arm elevation, and any abnormal motion can lead to joint pathology (Warner, Michelli, Arslanian, Kennedy J. and Kennedy R., 1992). Altered scapulothoracic motions during arm elevation have been observed in patients with shoulder impingement syndrome (Neer, 1983; Paletta, Warner, Warren, Deutsch and Altchek, 1997), glenohumeral instability (Ozaki, 1990) and shoulder winging (Leffert and Gumley, 1987). Many studies limit their investigation of shoulder kinematics to planar elevation, and fail to account for the high range of thoracohumeral motion by excluding either multiple planes of elevation (Ludewig and Cook, 2000; Karduna, McClure, Michener and Sennett, 2001), humeral rotation (Hogfors et al., 1991; de Groot and Brand, 2001), or both (Bourne, Choo, Regan, MacIntyre and Oxland, 2009). Biomechanical analyses of clinical problems along with a record of normal shoulder kinematics for a full range of humeral movement will allow clinical treatments to be geared towards correcting the abnormal shoulder kinematics that occur during arm movement.

1.3 Existing Models of Shoulder Rhythm

First identified by Codman (1934), the two-dimensional shoulder rhythm has long been quantified (Inman, Saunders and Abbott, 1944; Freedman and Munro, 1966) but in order to obtain a complete geometry of the shoulder, quantification of three-dimensional (3-D) shoulder rhythm is required. Hogfors et al. (1991) first quantified the 3-D shoulder rhythm for 0^o to 90^o of arm elevation, well below the maximal humeral elevation. Karlsson and Peterson (1992) extrapolated the rhythm to 120^o of arm elevation in a range of different planes; however, the extrapolations were based on an “educated guess” supported by anatomical judgment (Makhsous, 1999). Graphic visualizations and experimental trials were used, but these trials were done on cadaver specimens and they were only done to infer what changes needed to be made to extrapolate the shoulder rhythm, not to directly quantify overhead shoulder rhythm (Makhsous, 1999). The methodology used, such as the arm postures that were examined and the instrumentation that was used, is also not reported in literature. Since evidence suggests that the shoulder rhythm changes non-linearly with arm elevation (McQuade and Smidt, 1998; Barnett, Duncan and Johnson, 1999; McClure, Michener, Sennett and Karduna 2001; Ludewig, Cook and Shields, 2009), extrapolation of shoulder rhythm at low arm elevation angles to high elevation angles may lead to inaccurate estimates of bone orientations. Furthermore, the axial rotations of the humerus were not investigated. Despite these limitations, Makhsous (1999) further modified the Hogfors et al. (1991) rhythm to retain ligament strains within physiological limits and included this rhythm in a revision of the Gothenburg shoulder model (Hogfors et al., 1987; Karlsson and Peterson, 1992). Dickerson, Chaffin and Hughes (2007) modified the rhythm used by Makhsous (1999) to account for the different anatomical landmarks and Euler rotation sequences used before incorporating it into the Dickerson shoulder model (Dickerson et al., 2007). This sub-model shows inconsistent results for overhead arm postures most likely due to extrapolations performed by Karlsson and Peterson (1992) and thus warrants a complete and accurate model of the shoulder rhythm at arm postures that represent the wide range of motion of the shoulder complex.

1.4 Scapular Tracking

It is difficult to measure scapular orientation and movement because the scapula is a broad, flat-shaped bone, with no fixed center of rotation and substantial amount of soft-tissue covering it (Hebert, Moffet, McFadyen and St-Vincent, 2000; Klopcar and Lenarcic, 2006; van Andel, van Hutten, Eversdijk, Veeger and Harlaar, 2009). Due to the skin motion that occurs over the scapula, surface or skin sensors placed on the anatomical landmarks of the scapula do not accurately measure 3-D scapular motion (Karduna et al., 2001). Invasive methods such as subcutaneous bone pins have been assumed as the "gold-standard" but they require surgical implantation (Karduna et al., 2001; Bourne et al., 2009), and the bone pins may bend due to skin tension (Bourne et al., 2009) leading to inaccurate measures of bone orientations. As a result, only a limited number of models of the shoulder rhythm are available (de Groot and Brand, 2001 and Hogfors et al., 1991). Non-invasive methods used to study scapular kinematics include acromial skin-based methods, such as electromagnetic surface sensors (Karduna et al. 2001; Ludewig, Cook and Shields, 2002) and acromion marker clusters(van Andel et al., 2009; Picco, Fischer and Dickerson, 2010), scapular locators or trackers (Johnson, Stuart and Mitchell, 1993; Karduna et al., 2001; van Andel et al., 2009) and styli or palpators (Pronk and van der Helm, 1991; de Groot and Brand, 2001). Each method has its limitations and the comparisons of their results are precluded by the lack of comparative studies resulting from each methodology. The comparison is further inhibited because of different methodological approaches, such as plane of arm elevation or whether static or dynamic positions were studied.

The reliability of the non-invasive methods is widely addressed but the accuracy of these methods is rarely determined. While the invasive methods are assumed to be “gold standards” (Karduna et al., 2001; McClure et al., 2001), the scapular locator is sometimes used as a non-invasive “silver standard” (van Andel et al., 2009) to concurrently validate the acromial skin based methods (Meskers, van de Sande and de Groot, 2007; van Andel et al., 2009). But the results of the scapular locator may be affected by the inability to align it with all scapular landmarks simultaneously due to soft-tissue over the scapula. The stylus on the other hand is used to digitize each landmark individually. Therefore, it was assumed to be the “gold-standard” of non-invasive methods in the current study to compare the other methods.

1.5 Purposes

The purposes of this research were:

1. To describe shoulder kinematics by measuring rotations occurring at the sternoclavicular and scapulothoracic joints during various arm postures that include maximum elevation and maximum internal and external rotations in various planes of elevation
2. To use these kinematic data to quantify multi-dimensional shoulder rhythm using regression equations

3. To contrast the performance of alternative methods of determining scapular orientation by comparing the stylus measurements with the scapular locator and acromion marker cluster measurements

The results should provide shoulder rhythm models that can be incorporated into biomechanical shoulder models to attain a more physiological geometric representation of the shoulder complex. Determining how the different methods of measuring scapular orientation compare helps provide guidance for future scapular tracking studies.

1.6 Hypotheses

Specific hypotheses were:

1. Shoulder rhythm would be influenced by relative orientations of the humerus and thorax, specifically by the plane of elevation, the amount of elevation and the degree of internal and external rotation
2. Differences between the scapular tracking methods would increase with arm elevation angle
3. Differences between the scapular tracking methods would increase with axial rotation of the arm
4. The scapular locator measurements would deviate less from stylus measurements than the acromion marker cluster measurements.

II. LITERATURE REVIEW

2.1 Functional Anatomy of the Shoulder

The shoulder complex has the greatest mobility of any joint in the body. Its three distal bones, the clavicle, scapula and humerus, move in an integrated fashion, allowing the arm to have a large range of thoracohumeral motion in its elementary movements of flexion, extension, abduction, adduction, external rotation and internal rotation.

2.1.1 Shoulder Complex Bones

The scapula is a broad, flat, thin sheet of bone that has substantial amount of soft-tissue over it (van Andel et al., 2009). It plays a role in providing stability for the glenohumeral joint, in retraction and protraction of the shoulder girdle around the thoracic wall and in elevating the shoulder (Kibler, 1998). The clavicle in an “s-shaped” bone that provides a strut for the acromion that the thoracoscapular muscles can use as a lever (van der Helm and Pronk, 1995). But the primary function of both the scapula and the clavicle is to provide muscle attachment sites. Approximately 18 muscles attach on the scapula, and 6 on the clavicle (Rockwood et al., 2009). The bone rotations allow shoulder muscles to maintain optimal length-tension ratios during humeral movements (Lucas, 1973). Changing the position and orientation of these bones changes the muscle moment arms and the contribution of the muscles to counterbalance external moments (van der Helm, 1994) while providing joint stabilization.

The humerus articulates with the scapula at the glenohumeral joint. Functionally, along with the scapula and the clavicle, the humerus forms a linked chain of bones that allows humeral abduction of about 180^o, internal to external rotation of about 150^o and flexion to extension of approximately 170^o (Rockwood et al., 2009). If this fully function relationship between the bones did not exist and the shoulder complex was rigid with just an articulation at the glenohumeral joint, the humerus could not be abducted higher than 90^o (Veeger, van der Helm and Rozendal, 1993).

2.1.2 Articulations at the Shoulder Complex

Positioning the hand in space requires integrated motion at four different joints of the shoulder complex. The three bones form three synovial joints, the sternoclavicular (SC) joint, acromioclavicular (AC) joint and the glenohumeral (GH) joint. The clavicle articulates with the thorax at its medial articulation at the sternoclavicular joint and it articulates with the scapula at the lateral acromioclavicular joint. While the phase and amount of movement at the two clavicular joints are unequally distributed, the combined, simultaneous motion at these joints enables the scapula to move across the thorax at the scapulothoracic (ST) articulation (Ludewig et al., 2009). The scapulothoracic joint is not a true synovial joint and its movements are completely dependent on the two clavicular joints (Thompson and Floyd, 2004). The scapulothoracic joint is a large contributor to shoulder function and to axial body function (Rockwood et al., 2009). The distribution of motion over the four articulations allows the muscles crossing each of these articulations to operate in the optimal portion of their length-tension curve (McClure et al., 2001). It also increases the articular version between the glenoid and the humeral head during arm suspension by allowing the glenoid to be brought underneath the humerus to bear some of the weight of the upper limb, which decreases the demand on the shoulder muscles (Sagano, Magee and Katayose, 2006).

2.1.3 Defining the Shoulder Rhythm

Due to their functional relation, the humerus, clavicle and scapular orientations are not arbitrary. This concerted relationship between the positions of the shoulder bones is called the “shoulder rhythm” (Codman, 1934) or “scapulohumeral (SH) rhythm” (Klopcar and Lenarcic, 2006; Pascoal, van der Helm, Correia and Carita, 2000; Hogfors et al., 1991). Originally, the definition of shoulder rhythm was confined to the planar scapular upward rotation and thoracohumeral elevation in scapular plane arm abduction (Inman et al., 1944), but the term has been extended to refer to the fully functional relationship between the 3-D positions of all shoulder complex bones under any arm motion (Hogfors et al., 1991). Since the position of the humerus can be externally determined with relative ease, the shoulder rhythm enables the orientations of the scapula and the clavicle to be estimated using only externally accessible variables (Hogfors et al., 1991).

2.2 Three-Dimensional Motion of the Shoulder Complex

The bone and joint rotations can be expressed as different combinations of Euler angles and the values depend on the order of decomposition of the orientation matrices (Karduna, McClure and Michener, 2000; Veeger et al., 2003). The Standardization and Terminology Committee of the International Society of Biomechanics (ISB) proposed a set of bony landmarks and local and joint coordinate system for the shoulder, elbow, wrist and hand to facilitate generalization, application and comparison of results across studies and allow communication among research parties (Wu et al, 2005). The rotation sequences are selected to ensure that rotation angles can be clinically interpreted and visualized with clarity, while minimizing the cumulative error due to multiplication of rotation matrices (Hebert et al., 2000). In addition to this, the rotation sequences are selected to avoid Gimbal Lock, although, this is not always possible (Meskers, Vermeulen, de Groot, van der Helm and Rozing, 1998) due to the high range of motion of the shoulder joint.

2.2.1 Shoulder Bone Rotations

Bone rotations are typically used to define the orientations of the scapula, humerus and clavicle with respect to the thorax (van der Helm, 1994; Veeger et al., 2003; Wu et al., 2003). Scapular orientation is determined by the rotations at the scapulothoracic articulation and these rotations are described as internal/external rotation or protraction/retraction (Figure 1A), upward/downward or lateral/medial rotation (Figure 1B) and anterior/posterior tilt (Figure 1C). Scapular motion affects glenohumeral joint stability (Kibler and McMullen, 2003), size of subacromial space (Matias and Pascoal, 2006) and transfers forces from the lower extremities and the thorax to the upper extremity (Solem-Bertoft, Thuomas and Westerberg, 2003). The rotations at the scapulothoracic joint describe the scapular contribution to the overall shoulder motion.

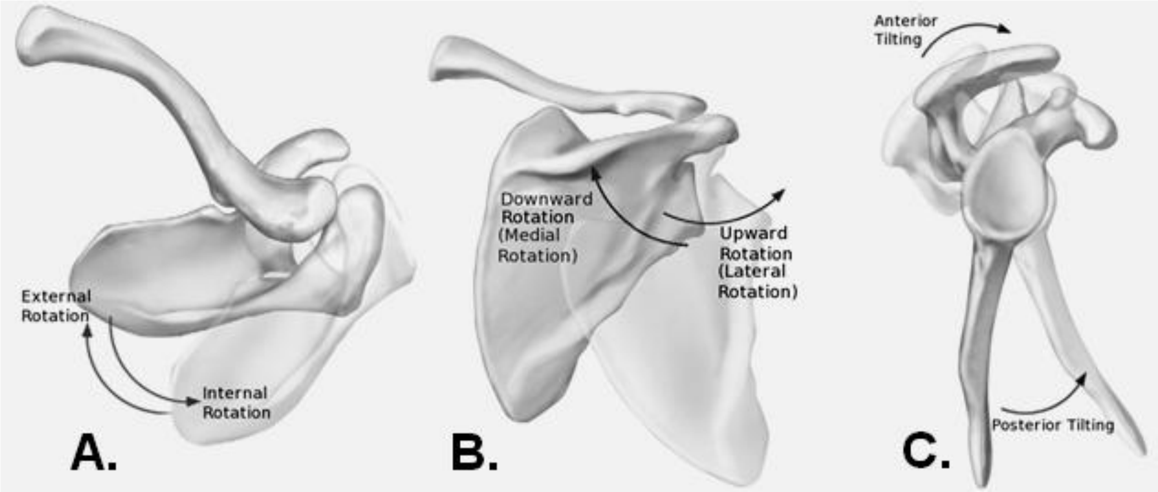


Figure 1: From Ludewig et al. (2009), the scapular rotations at the scapulothoracic articulation to describe the orientation of the scapula.

Clavicular orientation is described by protraction/retraction (Figure 2A), elevation/depression (Figure 2B) and anterior/posterior or forward/backward rotation (Figure 2C) angles at the sternoclavicular joint. The rotations at the sternoclavicular joint describe the clavicular contribution to the overall shoulder motion. Several studies (Ludewig, Cook and Nawoczenski, 1996; McQuade and Smidt, 1998; McClure et al., 2001) that quantify the scapular kinematics and orientation with respect to the thorax do not simultaneously measure clavicular orientation. However, the composite movement of the shoulder bones changes the orientation of the clavicle as well.

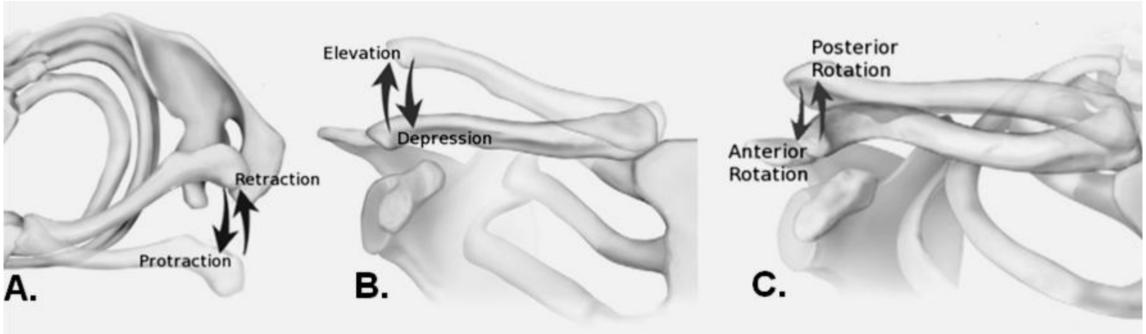


Figure 2: From Ludewig et al. (2009), the clavicular rotations at the sternoclavicular articulation to describe the orientation of the clavicle.

The bone orientation of the humerus relative to the thorax is described by the rotations at the “non-existent” thoracohumeral joint as the plane of elevation (Figure 3A), elevation angle (Figure 3B), and axial or more specifically, external/internal rotation (Figure 3C).

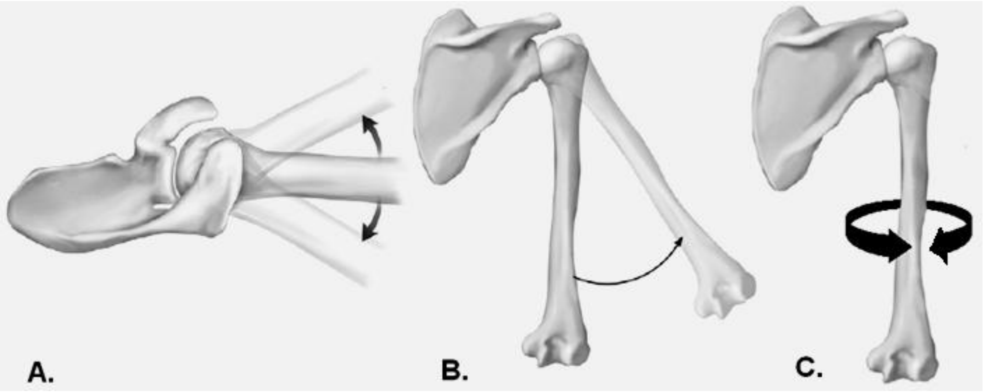


Figure 3: From Ludewig et al. (2009), the plane of humeral elevation (A), amount of elevation (B) and humeral axial rotation (C) to describe the orientation of the humerus.

The position of the scapula is determined by the orientation of the clavicle (de Groot , 1999; Karduna et al., 2001; McClure et al., 2001; Ebaugh and Spinelli, 2010). The sternoclavicular and the acromioclavicular joints connect the scapula to the thorax. The orientation of the scapula with respect to the thorax has three degrees of freedom. No translation occurs at the clavicular joints and since the clavicle is rigid, the distance between the two clavicular joints is constant (Karduna et al., 2001). Therefore, the position of the scapula relative to the thorax is restricted to only two degrees of freedom (McClure et al., 2001). If clavicular axial rotation is not considered to influence the scapular position (van der Helm, 1997), scapular position can be represented by elevation/depression and protraction/retraction of the clavicle (Karduna et al., 2001; McClure et al., 2001; Ebaugh and Spinelli, 2010).

2.2.2 Shoulder Joint Rotations

Joint rotations describe the orientation of a bone's local coordinate system with respect to the local coordinate system of the proximal bone (van der Helm, 1994). Rotations at the sternoclavicular joint, acromioclavicular joint and glenohumeral joint are joint rotations. The sternoclavicular joint rotations are the same as the bone rotations of the clavicle because the thorax is the proximal bone to the clavicle (van der Helm, 1994). The acromioclavicular joint rotations describe the orientation of the scapula with respect to the clavicle and the scapular rotations are described as internal/external rotation, upward/downward rotation, and anterior/posterior tilt relative to the clavicle. The glenohumeral joint motion describes humeral orientation with respect to the scapula, as plane of elevation, amount of elevation and internal/external rotation, similar to the humeral bone rotations at the thoracohumeral joint (Figure 3).

2.2.3 Virtual Reference Position

Bone rotations during arm movement can be described with respect to anatomical positions of the bones. In these cases, the calculated bone rotations would initially be 0^o at the start of arm elevation (de Groot and Brand, 2001). But no anatomical position for the shoulder exists and information about the global movement is lost (Johnson et al., 1993). Therefore, a virtual position is often used, at which the local coordinate system of the bones are aligned (Meskers et al., 1998; de Groot, 1999). When using a virtual coordinate system, the calculated rotations will be absolute bone orientations with offset values at the start of arm movement (Johnson et al., 2009).

2.3 Two-Dimensional Shoulder Rhythm

The shoulder rhythm was originally defined as the ratio of glenohumeral elevation to the scapular upward rotation during arm elevation (Inman et al., 1944) since, in the 2-D viewing techniques, such as goniometric methods or roentgenograms, the only accessible scapular rotation is the scapular upward rotation (Meskers et al., 1998). During the first 30^o of arm elevation or the setting phase, the scapula seeks stability and scapular motion is characteristic of the habitual position of the scapula at rest for each individual (Inman et al., 1944). This setting phase and the high inter-individual variability in scapular motion associated with this phase of arm movement has been confirmed by 3-D studies as well (Klopcar and Lenarcic, 2006; Braman, Engel, LaPrade and Ludewig, 2009). Past the setting phase, the commonly accepted ratio of GH:ST movement is 2:1 (Inman et al, 1944). That is, for every degree of arm elevation, the scapula rotates upward $.33^o$ and $.66^o$ of elevation occurs at the glenohumeral joint. Assuming that the arm can be elevated up to 180°, the ratio implies that the maximum glenohumeral motion is 120° and the maximum scapular rotation is 60° (Inman et al, 1944). But the methods used to determine shoulder rhythm in this widely cited landmark study are unclear (Braman et al., 2009).

Subsequent research studies also confirmed the existence of a shoulder rhythm, but dispute the amount of glenohumeral and scapulothoracic contribution to arm movement. The average reported ratios over the entire arm abduction movement tested range from 1.25:1 to 1.94:1 (Poppen and Walker, 1976; Bagg and Forrest, 1988; Freedman and Munro, 1966; Michiels and Grevenstein, 1995). The differences in reported values may be attributed to the reported non-linear change in ratio with change in arm elevation angles. Saha (1961) reported that the ratio varies between 2:1 and 3:1 with arm elevation. Scapular contribution has been shown to increase past 90° of arm elevation (Freedman and Munro, 1966; Doody, Freedman and Waterland, 1970), causing a decrease in the ratio. Non-linearity was less pronounced in Freemdan and Munro (1966) compared to Doody et al. (1970), who found that the ratio ranged from 7.290:1 during the first 30° of arm abduction to .787:1 during the arm abduction range of 90° and 145° when the scapular contribution was actually greater than the glenohumeral contribution. Past 145 ° of arm elevation, the scapular contribution decreased and the ratio increased (Doody et al., 1970). Similarly, Bagg and Forrest (1988) found a pattern of shoulder rhythm that was split into three phases, excluding the setting phase; 20.8°-81.8°, 81.8°-139.1° and 139.1°-170° of arm elevation, and the ratios of GH:ST movement were 3.29:1, .710:1 and 3.49:1, respectively for each phase. When the phases of arm elevation were not examined individually, the overall GH:ST ratio was 1.25:1. Therefore, the shoulder rhythm is more complex than the 2:1 ratio of scapulothoracic to glenohumeral contribution. Due to the lack of linearity, the shoulder rhythm at low elevation angles cannot likely be reliably extrapolated to the upper range of the humeral motion (Makhsous, 1999).

The variability in reported shoulder rhythm may be attributed to the methodology used to collect the data. Inman et al. (1944) and Saha (1961) examined the arm elevation in the frontal plane, while subsequent studies (Freedman and Munro, 1966; Doody et al., 1970; Poppen and Walker, 1976; Bagg and Forrest, 1988) examined arm elevation in the scapular plane. Since static measurement tools were used, the differences may also be ascribed to the increments between the measurement positions. Smaller increments of measurement may result in greater variability of shoulder rhythm at arm positions than larger increments of measurement (Bagg and Forrest, 1998).

2.4 Extrapolating 2-D Rhythms to 3-D Scapular Motion

Extrapolating 2-D rhythm to determine 3-D scapular orientation may lead to errors. Scapular motion is not planar due to the curvature of the clavicle (de Groot, 1999) and the complex motion constraints of the shoulder girdle (Veeger, 2003). If 2-D rhythm is extrapolated to determine 3-D scapular motion, projection errors will result (van der Helm and Pronk, 1995; de Groot, 1996; Hebert 2000). de Groot (1999) quantified the effect of 2-D projection to determine 3-D scapular motion and concluded that 2-D projection is affected by the choice of skeletal landmarks that define the scapular angle as well as the position of the participant in the data collection setting. Therefore, 2-D rhythm is an inaccurate parameter to define scapular motion (de Groot, 1999). Three-dimensional scapular motion must be measured directly to quantify shoulder rhythm.

2.5 Three-Dimensional Shoulder Rhythm

Three-dimensional shoulder rhythm is more complex than a single ratio of glenohumeral movement to scapulothoracic movement. Contrary to 2-D shoulder rhythm, 3-D shoulder rhythm refers to contribution of scapular motion at the scapulothoracic joint in all three axis (upward/downward rotation, protraction/retraction and anterior/posterior tilt) to the overall shoulder motion (Braman et al., 2009). Some studies (McQuade and Smidt, 1998; de Groot, 1999; Braman et al., 2009) infer the 2-D rhythm definition to 3-D rhythm. In these cases, the rhythm is still quantified as the ratio of glenohumeral elevation to scapular upward rotation, but the scapular upward rotation is measured independently of the simultaneous motion of the scapula about the other axes. Therefore, using 3-D measurement tools, the effect of the movement about the other two axes is adjusted for (McQuade and Smidt, 1998). The 3-D rhythm corresponding to this definition ranges from 2.3:1 to 2.7:1 from 30^o to 120^o of humeral elevation (Braman et al., 2009) to 3.1:1 to 4.3:1 (McQuade and Smidt, 1998).

Quantifying only one of the three scapular rotations has important implications when it comes to adopting shoulder rhythm into biomechanical models. The 3-D scapular orientation and position cannot be determined from one scapular rotation with respect to the thorax because the scapula rotates about three independent axes. Therefore, a full kinematic description and quantitative data of the 3-D orientations of all shoulder complex bones for a wide range of humeral postures is necessary. This “complete” shoulder rhythm has been confirmed to exist since the 3-D orientation of the scapula is significantly related with humerus elevation angles (Pascoal et al., 2000).

2.6 Normal Scapular and Clavicular Kinematics

2.6.1 Rest

At the resting position of the scapula when the arm elevation angle is 0^o, the scapula is internally rotated or protracted about 30^o with respect to the frontal plane, anteriorly tilted by approximately 20^o with respect to the frontal plane, and it is rotated upward by approximately 3^o with respect to the sagittal plane (Laumann, 1987; Rockwood et al., 2009). The resting scapular protraction and upward rotation angles relative to the thorax are consistent across studies (Culham and Peat, 1993; Laumann, 1984; McQuade, 1994; Ludewig et al., 1996; Gomes, Sesselmann, Faria, Araujo and Teixeira-Salmela, 2010), however, the magnitudes of anterior tilt differ. Ludewig et al. (1996) reported a value of 8^o, and Gomes et al. (2010) reported 5^o. These differences may be due to the different origins of the scapular local coordinate system used in their respective data analyses or the different measurement tools used. Ludewig et al., (1996) embedded the anatomical coordinate system at the root of the scapular spine and used palpation while Gomes et al. (2010) embedded the coordinate system at the acromial angle, based on the ISB recommendation (Wu et al., 2005) and used the moiré fringe projection technique. Despite this variability, all studies report protraction, anterior tilt and upward rotation of the scapula at rest. During relaxed standing, the clavicle is slightly elevated by approximately $1.6^o(\pm 3.3^o)$, retracted by approximately $18.2^o(\pm 5.8^o)$ and has a near neutral axial rotation of $0.5^o(+2.5^o)$ based on measurements taken from 30 participants (Ludewig, Behrens, Meyer, Spoden, and Wilson, 2004).

2.6.2 Setting Phase

During the initial 30^o of arm elevation, the scapula and the humerus seek a position of maximum congruence and maximum stability. This phase is characteristic of irregular motion and the setting action of muscles (Inman et al., 1944). The highest variability of shoulder rhythm between individuals (Braman et al., 2009) occurs during the setting phase and a constant relationship between the shoulder complex bones does not exist until the arm is out of this setting phase (Bagg and Forrest, 1988).

2.6.3 Kinematic Changes during Humeral Elevation

The glenohumeral contribution of the arm movement is greater from rest (non-abducted) to 30^o of arm elevation, but it decreases non-linearly as thoracohumeral elevation increases (Inman et al., 1944; Braman et al., 2009). At the glenohumeral joint, the humerus externally rotates with respect to the scapula as the arm is elevated and the peak of this external rotation occurs at approximately 110^o of arm elevation (Poppen and Walker, 1976; Koh, Grabiner and Brems, 1998; McClure et al., 2001; Braman et al., 2009; Ludewig et al., 2009). The magnitude of external rotation ranges from 10^o to 51^o depending on the plane of elevation (Ludewig et al., 2009). However, irrespective of the plane of elevation, the humerus moves towards a final position of external rotation, slightly anterior to the plane of the scapula (Ludewig et al., 2009).

The joint rotations at the acromioclavicular joint are small (Meskers et al., 1998) and posterior tilt is the predominant rotation of the scapula relative to the clavicle (Ludewig et al., 2009). Ludwig et al. (2009) reported internal rotation of 9^o, upward rotation of 11^o and posterior tilt of 19^o as the arm is elevated from 15^o to 140^o. Scapulothoracic joint motion is only possible because of the motion at the sternoclavicular and acromioclavicular joints. While a greater percentage of scapulothoracic movement is achieved through the sternoclavicular joint, scapular posterior tilting at the scapulothoracic joint was essentially found to be an acromioclavicular joint motion, since the clavicle, with the rotation of the scapula relative to clavicle constituted 19^o of the total 21^o of overall motion (Ludewig et al., 2009; van der Helm and Pronk, 1995).

Consistent scapular movement patterns during humeral elevation have been observed in both static (Ludewig et al., 1996; Lukasiewics, McClure, Michener, Pratt and Sennett, 1999) and dynamic conditions (Karduna et al., 2001; Ludewig et al., 2004). Scapular motion is important in attaining end-range positions of humeral rotation and a lack of scapular motion may lead to overstretching and laxity by producing greater stress on the glenohumeral joint capsule (McClure et al., 2001).When the humerus is elevated, the most commonly observed trend of scapular movement is retraction, upward rotation and posterior tilt (Ludewig et al., 1996; McClure et al., 2001; Meskers et al., 1998; Fung et al., 2001; Bourne et al., 2007). The magnitude of upward rotation and posterior tilt ranges from 27^o to 50^o and 0^o to 40^o, respectively, depending on the degree of arm elevation, plane of elevation and the methods of data collection (Klopcar and Lenarcic, 2006; Sagano et al., 2006; Bourne et al., 2007; Meskers et al., 2007). Braman et al.

(2007) has attributed the difference in scapular angles between their results and the results reported in McClure et al. (2001) to the different coordinate systems used. The posterior tilting reported by Braman et al. (2009) was two times higher than the average posterior tilting reported by McClure et al. (2001). This emphasizes the need to use the standardized methods for recording and presenting human joint motion (Wu et al., 2005).

Whether the scapula actually retracts during humeral elevation has been disputed and some studies (Kondo, Tazoe and Yamada, 1984; van der Helm and Pronk, 1995; Johnson et al., 1993) report protraction of the scapula instead of retraction. This discrepancy may be because in these studies, the humerus was elevated in the frontal plane (abducted), whereas, in the studies that report retraction (Ludewig et al., 1996, McClure et al., 2001; Bourne et a l., 2007) arm elevation occurred in other planes. Ebaugh, McClure and Karduna (2005) reported retraction with humeral elevation up to 90^o only, at which point the motion reached a plateau, whereas, Ludewig et al. (2009) reported minimal (2^o) protraction for the entire range of humeral elevation.

The clavicle elevates and retracts with arm elevation (Meskers et al., 1998; McClure et al., 2001; Ludewig et al., 2004; Ebaugh et al., 2005; Ludewig et al., 2009), but majority of the clavicular bone rotations are reported to occur after 90^o of elevation (Fung et al., 2001; McClure et al., 2001; Karduna et al., 2001). Clavicular retraction indicates posterior movement of the scapula and clavicular elevation indicates superior movement of the clavicle (McClure et al., 2001). The reported magnitude of clavicular retraction ranges from 5^o to 30^o with arm elevation (van der Helm and Pronk, 1995; de Groot, 1997; Fung et al., 2001; Karduna et al., 2001; McClure et al., 2001; Ludewig et al., 2004) and this rotation is offset by protraction of the scapula at the acromioclavicular joint (Ludewig et al., 2009). Ludewig et al. (2009) reported 6^{o} of clavicular elevation with arm elevation, while other studies have reported clavicular elevation of up to 25^{o} (van der Helm and Pronk, 1995; Fung et al., 2001; McClure et al., 2001; Ludewig et al., 2004; Ebaugh et al., 2005; Ludewig et al., 2009; Ebaugh and Spinelli, 2010). Due to methodological constraints, only a few studies have measured clavicular axial rotation (Inman et al., 1944; de Groot, 1997; Fung et al., 2001; Ludewig et al., 2004; Ludewig et al., 2009). This is because a third landmark and a third plane definition is absent (Meskers et al., 1998). In order to measure axial rotation, invasive bone-fixed methods have been used (Inman et al., 1944). Surface electromagnetic sensors have also been used; however, the error in measurement of axial rotation can be as high as 27% of the total clavicular axial rotation (Ludewig et al., 2002; Ludewig et al., 2009). van der Helm and Pronk (1995) assumed that axial rotation of the clavicle mainly takes place in the sternoclavicular joint and they estimated axial rotation of the clavicle by minimizing rotation of the acromioclavicular joint. Wide ranges of axial posterior rotation magnitudes have been reported. Inman et al. (1944) used bone pins and reported 40^{o} of axial rotation, while magnitudes in other studies range from 25^{o} to 31^{o} (Fung et al., 2001; Ludewig et al., 2004; Ludewig et al., 2009).

2.6.4 Overhead Shoulder Rhythm

High abduction angles and humeral elevation angles are of great importance because overhead work is often a factor contributing to shoulder pathology (Grieve and Dickerson et al., 2007; Bourne et al., 2009). This emphasizes the need for measuring the overhead shoulder rhythm with accuracy and reliability. The humerus and scapula followed a predictable pattern of motion relative to each other during overhead reaching (Braman et al., 2009). But the non-linear bone and joint rotations (McQuade and Smidt, 1998; McClure, 2001; Braman et al., 2009) implies that the overhead rhythm may not be the same as the rhythm during low arm elevation. Majority of scapular rotations have been reported to occur after 90° of arm elevation (Fung et al., 2001; Ebaugh et al, 2005). In addition to this, a dramatic change in scapular and clavicular angles is often seen during extreme thoracohumeral angles (Karduna et al., 2001; McClure et al., 2001; Braman et al., 2009). The substantial increase in scapular tilt and retraction during overhead movement is likely because the glenohumeral joint has reached its limit and the capsular tension generated as a result pulls the scapula along as the arm elevates (McClure et al., 2001). Therefore, scapular and clavicle position during overhead movement cannot be extrapolated from the shoulder rhythm at lower thoracohumeral angles.

2.6.5 Effect of Plane of Elevation on Shoulder Kinematics

A parameter that has not reached a consensus when studying shoulder kinematics is the plane of arm elevation. It has been noted that functional activities occur mainly in the scapular plane (Saha, 1961; Ludewig et al., 1996; McQuade and Smidt, 1998; Hebert et al., 2000) and scapular plane arm motion is preferred because it is less complex and more natural (Freedman and Munro, 1966). This may be because the humeroscapular muscles have a more direct line of action since they lie in a single plane and minimal humeral rotation is necessary for full abduction when the arm is elevated in the scapular plane (Johnston, 1937; Doody et al., 1970; Freedman and Munro, 1966). In this plane, the deltoid and the supraspinatus are optimally aligned for elevation of the arm (Poppen and Walker, 1976). Contrarily, when thoracohumeral external rotation was measured during humeral elevation, McClure et al. (2001) found that during scapular plane arm elevation, the humerus actually rotated sooner and to a greater extent than when the arm was elevated in other planes. The scapular plane orientation is variable between subjects but averages close to 30^o relative to the frontal plane (Ludewig et al., 1996). Although this value has been used by several studies (Doody et al., 1970; Ludewig et al., 1996; Graichen, Stammberger, Bonel, Haubner, Englmeier, Eiser and Eckstein, 2000), in recent studies (Ludewig and Cook, 2000; Karduna et al., 2001), 40^o anterior to the frontal plane has been identified as the scapular plane. When participants were given the freedom to choose their plane of elevation, the average preferred plane of elevation was $63.3^o \underline{+} 9^o$ when maximally elevating their arm (Braman et al., 2009). Given the relatively high standard deviation, individual preference of elevation plane is present, thus the shoulder kinematics and shoulder rhythm must be studied during arm movement in various planes. When plane of elevation was introduced as a covariate in multiple regression models, it influenced shoulder rhythm (McQuade and Smidt, 1998; de Groot and Brand, 2001). de Groot and Brand (2001) created regression equations of shoulder rhythm during arm elevation in 4 different planes (30^o, 60^o, 90^o, and 120^o) anterior to the frontal plane) and clavicular protraction, clavicular elevation and all three scapular rotations were influenced by the plane of elevation. The absolute effect ranged from -3^o for scapular tilt to 17^o for scapular protraction within the arm elevation range of 120^o.

The scapula has the tendency to “follow” the humerus elevation plane, and as a result, it retracts during elevation in the frontal plane, but protracts during sagittal plane elevation (Koh et al., 1998; Meskers et al., 1998). The degree of scapular protraction/retraction has also been measured to be less in frontal plane elevation (Meskers et al., 1998). Fung et al. (2001) supported this by reporting less scapular rotation during frontal plane elevation than scapular plane and sagittal plane elevation. However greater humeral elevation occurs during frontal plane elevation (Koh et al., 1998; Fung et al., 2001). The clavicle bone rotations were found to be greatest in the frontal plane arm elevation at low elevation angles, but the least at high elevation angles (Fung et al., 2001). Ludewig et al. (2004) found that clavicle retraction angle remained essentially unchanged during flexion, but became retracted during scapular and coronal plane abductions. The amount of elevation and posterior rotation of the clavicle and the scapular protraction and upward rotation at the acromioclavicular joint also depended on the plane of elevation, but these differences depended on the arm elevation angle (Ludewig et al., 2004; Ludewig et al., 2009). That is, the differences in shoulder rhythm between planes of elevation depended on the thoracohumeral angle for both scapulothoracic and sternoclavicular joint rotations (Ludewig et al., 2009).

2.6.6 Effect of Axial Rotation on Shoulder Kinematics

Only four studies (McQuade and Smidt, 1998; McClure et al., 1998; Sagano et al., 2006; van Andel et al., 2009) investigating the effect of internal and external thoracohumeral rotation on shoulder rhythm have been published. McQuade and Smidt (1998) only measured the humeral internal and external rotation that occurred during arm elevation and thus the internal and external rotation was minimal. In addition to this, the effect of internal/external rotation on scapular retraction/protraction and tilt was not considered (McQuade and Smidt, 1998). McClure et al. (2001) and van Andel et al. (2009) described 3-D motion of the scapula during humeral internal and external rotation but this was done at 90^o arm elevation angles only in one plane of elevation. Since shoulder rhythm depends on the amount of elevation, the effect of internal/external humeral rotation on shoulder rhythm may also depend on arm elevation angle. Despite this limitation, substantial scapular motion, with abrupt posterior tilting, upward rotation and external rotation at the end range of rotation occurred (McClure et al. 2001). Sagano et al. (2006) examined the effect of maximum internal and external arm rotation on scapular upward rotation at arm elevation angles of 0^o, 30^o, 60^o, 90^o in the scapular plane. The average maximal right arm internal and external rotations were $65.8^o \pm 8.2^o$and $108.6^o \pm 12.5^o$respectively (Sagano et al., 2006). There was no significant difference between scapular upward rotation at 0^o abduction, but internal rotation, neutral rotation and maximum external rotation resulted in significantly different scapular upward rotations at other angles of elevation (Sagano et al., 2006). Scapular upward rotation tended to increase when internal and external arm rotations were applied (Sagano et al., 2006). Limitations of this study were that, only upward scapular rotation was examined, shoulder rhythm during overhead arm elevation was not studied and only two planes of arm elevation were examined.

2.7 Incorporating Shoulder rhythm into Shoulder Models

In order to obtain a realistic morphological representation of the shoulder, a well-represented geometry of the shoulder must be integrated into the model (van der Helm, 1994). This should include accurate representation of the muscle attachment sites, lines-of-action as well as bone orientations (Dickerson et al., 2007). Since the shoulder bones act as muscle attachment sites, altering bone orientations also changes the global positions of muscle attachment sites. This alters the muscle moment arms and thus the ability of the muscles to counterbalance other moments (van der Helm, 1994). Therefore, accurate shoulder rhythm is critical to accurately represent bone orientations and changing geometry of the shoulder when performing different tasks.

The largest uncertainty in shoulder modeling is thought to be associated with the shoulder rhythm (Makhsous, 1999). Although the shoulder rhythm was first identified in 1934 by Codman (Bagg and Forrest, 1988), a 3-D models of the shoulder rhythm that could be incorporated into biomechanical models as sub-models were not developed until 1991 (Hogfors et al., 1991). These sub-models were incorporated into the Gothenburg shoulder model (Karlsson and Peterson, 1992). But since the shoulder rhythm models were only developed for arm elevation angles of up to 90^o, Karlsson and Peterson (1992) extrapolated the shoulder rhythm based on heuristic anatomical judgment to arm elevation angles of 120^o. Makhsous (1999) further modified the Karlsson and Peterson (1992) rhythm to retain ligament strains and bone rotations within physiological limits. The modification affected the rhythm mainly at the extreme range of arm motion, that is, the extrapolated portion of the original Hogfors et al. (1991) rhythm. The local coordinate systems of the bones and the rotation sequences used by Makhsous (1999) are presented in Figure 4 and Figure 5, respectively. The same rotation sequence was used to determine the rotations of the clavicle and the scapula.

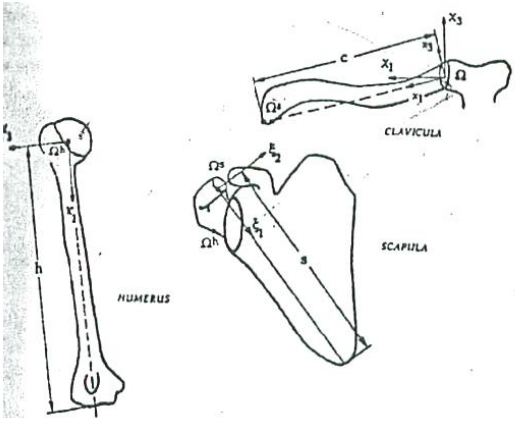


Figure 4: The local coordinate systems of the humerus, scapula and the clavicle used in the Gothenburg shoulder model.

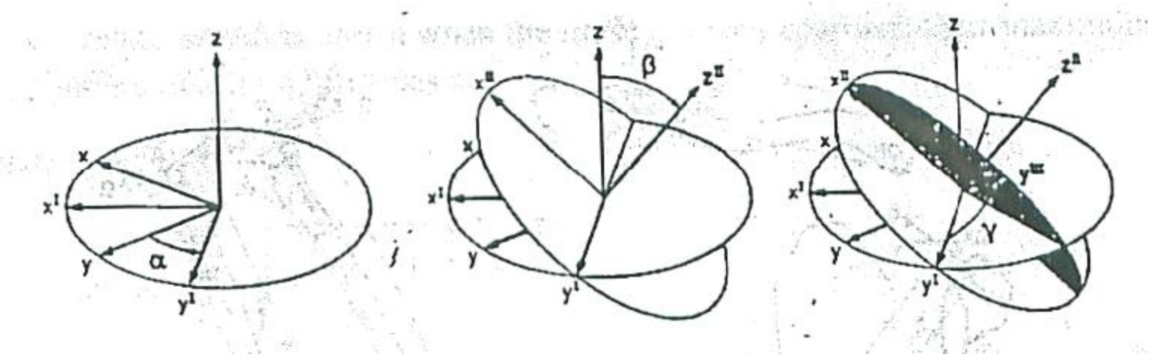


Figure 5: The Euler angle sequence used by Makhsous (1999) in the Gothenburg shoulder model.

The resulting models of the shoulder rhythm estimated the Euler angles to describe the orientation of the clavicle (equations 1 to 3) and the scapula (equations 4 to 6) in the local coordinate system of the thorax based on the humeral orientation. The α, β, γ are the Euler angles of the orientation of the humerus (h), clavicle (c) and the scapula (s).

$$\alpha_c = -35.15 + 11.15\cos[0.75(\beta_h + 90)]\,(0.08\alpha_h) \tag{1}$$
$$\beta_c = 18\{1 - \cos[0.8(\beta_h + 90)]\} + 9 \tag{2}$$
$$\gamma_c = 30\{1 - cos[0.75(\beta_h + 90)]\} + 3 \tag{3}$$

$$\alpha_s = 200 + 20\,cos[0.75(\beta_h + 90)] \tag{4}$$
$$\beta_s = -87 + 42\,cos[-0.75\beta_h - 70](0.1\,\gamma_h/90 + 1) \tag{5}$$
$$\gamma_s = 82 + 8\,cos\{\,(\alpha_h + 10)\sin\,[0.75(\beta_h + 90)]\} \tag{6}$$

de Groot and Brand (2001) also developed 3-D regression models of the shoulder rhythm. The inputs for the models were humerus orientation, direction of external force applied on the humerus as well as the initial orientation of the clavicle and scapula at a pre-defined body posture. While different plane of arm elevation were investigated, this study did not examine the shoulder rhythm during internal and external rotation of the humerus. Also, the model was not validated for high arm motions (over 120^{o}), and thus extreme tasks would need to be extrapolated (de Groot and Brand, 2001). The regression models have been adopted into an upper extremity model for simulating musculoskeletal surgery (Holzbaur, Murray and Delp, 2005) to calculate moments at the shoulder. The regression models of the shoulder rhythm were not validated separately from the model, but the whole simulation model was validated for shoulder flexion and abduction of up to 90^{o} (Holzbaur, Murray and Delp, 2005).

2.7.1 Dickerson Shoulder Model

The conceptual foundation for the orthopedic geometry of the Dickerson shoulder model (2007) is based on the Gothenburg shoulder model (Hogfors 1987; Karlsson and Peterson, 1992; Makhsous, 1999) and the shoulder rhythm sub-models are also based on the rhythm used by Makhsous (1999). Dickerson et al. (2007) mathematically modified the rhythm to account for the different landmarks, local coordinate systems and the rotations sequences used as per the recommendations outlined by ISB (Wu et al., 2005). A constraint was also added to keep the inferior angle of the scapula outside of the rib cage (Dickerson et al., 2007). Since the overhead shoulder rhythm was never determined using *in vivo* measurements, the sub-model adopted by Dickerson et al. (2007) demonstrates some inconsistent results for overhead postures. This encourages the integration of a more accurate quantification of overhead rhythm. The model itself is formatted in components, which allows incorporation of future alternative sub-models of shoulder rhythm or shoulder bones position prediction models.

2.8 Methods of Scapular Tracking

Scapular orientation cannot be measured directly by traditional surface marker-based motion tracking systems due to the shape of the scapula and the large overlying skin displacement. The need to measure scapular orientation with accuracy is emphasized by the fact that differences as small as 4-5^o from normal scapular orientation are associated with shoulder impingement syndrome (Lukasiewics, 1999; Ludewig and Cook, 2000) and decreased subacromial clearance (Karduna et al., 2002). Accuracy of measurements may be the most critical test of a method or a tool’s utility (Lundberg, 1996). Reliability of methods is often reported as interclass correlation coefficients (ICCs) or root meat square (RMS) errors over repeated measures. While reliability is vital to test the repeatability of a method, it does not give any information about the accuracy of the tool or how the measures from one tool compare with values from another method.

2.8.1 Invasive Methods

The two invasive methods to record scapular kinematics used are inserting tantalum balls and bone pins into the scapula. The earlier studies investigating shoulder rhythm using non-invasive methods (Freedman and Munro, 1966, Poppen and Walker, 1976, Michiels and Grevenstein, 1995) were restricted to 2-D shoulder rhythm because only one plane is discernable in the x-ray images. Projecting 2-D measurements in 3-D space leads to projection errors (de Groot, 1999; Karduna et al., 2001). To eliminate these projection errors, Hogfors et al. (1991) surgically implanted tantalum balls into the shoulder bones. The coordinates of the tantalum balls and bony landmarks were obtained using X-ray photometry. Researchers have also used tracking devices based on electromagnetic (Inman et al., 1944; McClure et al., 2001) or optical tracking methods (Koh et al., 1998; Bourne et al., 2007) to attain 3-D shoulder kinematics. Subcutaneous bone pins or tantalum beads are surgically implanted into the shoulder bones, and the bone orientations are subsequently measured via electromagnetic receivers or optical markers attached to the pins. Since the instrumentation is in direct contact with the shoulder complex bones, these methods are assumed to be “gold standards” to concurrently validate other methods (Karduna et al., 2001; McClure et al., 2001; Bourne et al., 2009).

There are several limitations of using invasive methods. The accuracy of these invasive methods has never been tested. The bone pins might bend due to skin tension (Bourne et al., 2009), causing movement artifact. In addition to this, metallic objects (such as bone pins) close to electromagnetic sensors may adversely affect the output of the receivers (McGill, Cholewicki and Peach, 1997). Due to the impracticality of invasive methods, these studies are often conducted on a limited number of participants, limiting their ability to be useful when results are extrapolated to the larger population.

2.8.2 Non-Invasive Methods

Non-invasive methods to record scapular kinematics include acromial methods such as electromagnetic skin sensors and acromion marker clusters, scapular locators and palpation techniques. The scapular locators and palpation techniques are used in combination with electromagnetic sensors or optoelectronic motion tracking system.

Palpation techniques involve palpating the landmarks of the scapula: acromion angle, root of the scapular spine, and inferior angle (Figure 6); and subsequently digitizing these landmarks using a stylus. The stylus, or sometimes called a palpator, (Pronk and van der Helm, 1991) was originally an open chain of four links connected by four hinges and the position of the end-point was calculated by recording the rotations of the hinges using potentiometers. But since then, the stylus design has progressed to a simple hand-held tool (Figure 7). Landmarks are digitized by determining the position of the tip of the stylus in space using electromagnetic receivers (van der Helm and Pronk, 1995) or optical motion tracking systems (Bourne et al., 2009).

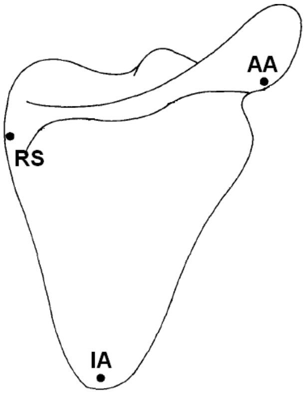


Figure 6: The anatomical landmarks of the scapula: root of the scapular spine (RS), acromion angle (AA) and the inferior angle (IA).

The major limitation of the stylus method is that it can only be used for static measurements. Isometric muscle contraction required to sustain a static posture may alter the scapular kinematics (Sagano et al., 2006). Additionally, muscle thickness influences the feel of the palpation point (Bourne et al., 2009).

Figure 7: A stylus used to digitize the anatomical landmarks of the scapula (Bourne et al., 2009).

van der Helm and Pronk (1995) examined the reliability of the stylus and reported measurement error of about 2^o for the calculated Euler angles in 10 subjects. While most of this error was attributed to palpation, the stylus measurements were deemed repeatable. Ludewig et al. (1996) also reported that surface palpation is reliable within 2-3^o.

Alternative to this probing method, Johnson et al. (1993) developed the scapular locator to reduce collection time by reducing the number of anatomical points that need to be digitized. Scapular locator (Figure 8) is a two-arm fixture that is adjusted over an individual's scapula so its ends are aligned with the three anatomical landmarks of the scapula (Figure 6). Once the scapular locator is adjusted, the two arms are locked into place to create a stiff and rigid construction. The scapular locator is positioned on the scapula at each arm posture and an electromagnetic sensor (Meskers et al., 1998) or a marker cluster (van Andel et al., 2009) records its position and orientation in space. The reliability values of scapular locator recordings are similar to the values reported for the stylus. Meskers et al. (1998) used a scapular locator with an electromagnetic sensor and determined its inter-trial variability to range from 2^o to 2.5^o. The inter-day variability however, was higher and ranged from 3^o to 4.2^o. Hebert et al. (2000) tested reliability over three testing sessions and the coefficient of variance was found to be less than 10% of scapular motion corresponding to 1.6^o to 5.9^o.

Much like the stylus, the scapular locator cannot be used for dynamic movement. The soft-tissue over the scapula may also prevent the scapular locator from being simultaneously aligned with all three scapular landmarks. T'Johnck (1996) and Gibson, Goebel, Jordan, Kegerreis and Worrell (1995) mentioned that the root of the scapular spine does not offer a reliable bony landmark, even at rest. Also, the inferior angle is an arc, rather than a point, and this may lead to large inter-observer variability (Gibson et al., 1995). Because all three landmarks are digitized simultaneously, error in the digitization of one landmark will result in error in obtaining accurate locations of the other two landmarks.

Figure 8: The scapular locator used in combinations with an active motion recording system (van Andel et al., 2009).

Barnett et al. (1996) improved the design of the scapular locator developed by Johnson et al. (1993) by attaching pins at the ends, perpendicular to the arms of the scapular locator. When this refined scapular locator was aligned with the anatomical landmarks, it allowed for a better contact of the scapular locator with the bony landmarks. Johnson et al. (1993) and Barnett et al. (1999) assessed reliability of scapular locators by quantifying inter-observer and inter-subject variability as well as the measurement errors and determining 95% confidence intervals (CIs). The CIs determined by Barnett et al. (1999) with the refined design of the scapular locator were considerably smaller than the CIs obtained by Johnson et al. (1993). The differences in the CIs reported in these two studies were 7.55^o, 2,47^o and 5.16^o for upward rotation, retraction and backward tilt, respectively. The CI obtained by Barnett et al. (1999) was 2.85^o for upward rotation. This indicates that the scapular locator method showed good reliability, with the largest confidence interval of 3.85^o for upward rotation (Barnett et al., 1999).

Acromial skin based methods, such as electromagnetic sensors or acromion marker clusters are also commonly used due to their ease of use and low cost. An electromagnetic sensor is attached to the flat posterior-lateral acromion (McQuade, and Smidt, 1998; Ludwig et al., 2002; Karduna et al., 2001). The 3-D positions of the anatomical landmarks of the scapula are assessed in the local coordinate system of the scapula by digitizing using a stylus during initial measurements. The orientation of the receiver is measured at various arm postures and the orientations of the anatomical landmarks are subsequently derived and the scapular rotations are calculated. The drawback of using electromagnetic sensors directly on the skin is the skin motion artifact. Meskers et al. (2007) reported inter-trial RMS errors of 2^{o}, indicating that the skin based sensors had high reproducibility.

van Andel et al. (2009) recently developed an acromion marker cluster (AMC) to obtain dynamic measures of scapular kinematics (Figure 9). It consisted of three active light emitting diode markers in a triangular cluster with a base that was placed on the posterior-flat portion of the acromion (van Andel et al., 2009). The position of the AMC was recorded using an Optotrak motion tracking system and the scapular rotations were derived (van Andel et al., 2009). Picco et al. (2010) used a similar cluster, but instead of LED markers, reflective markers were used and a Vicon passive motion tracking system was used. At high elevation angles, the deltoid contracts and the resulting deformation causes alteration in the shape of soft-tissue and it leads to a loss of contact between AMC and the acromion, underestimating the scapular movement (van Andel et al., 2009). The reliability measures of AMC resulted in high ICC values except when measuring the scapular tilt and the standard deviation of the scapular rotations tended to increase with arm elevation (van Andel et al., 2009).

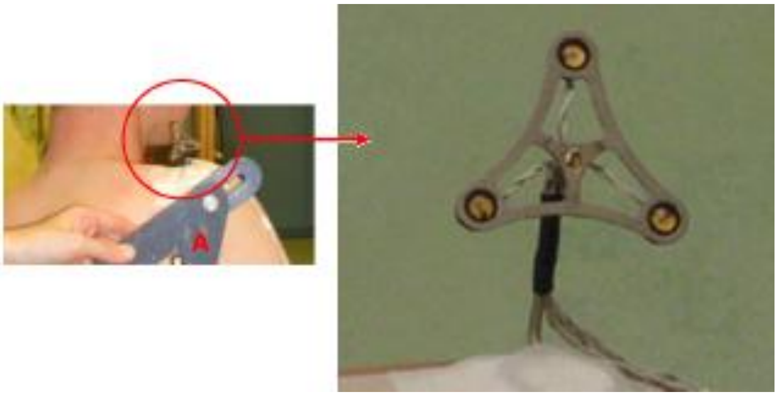


Figure 9: The AMC adhered to the posterior flat portion of the acromion (van Andel et al., 2009).

2.8.3 Validation of Non-Invasive Methods

While all methods are reliable (at low elevation angles), they are not necessarily valid. Validity or accuracy of methods is more difficult and only a handful of studies have tackled it. Hebert et al. (2000) was the first study to address the accuracy of palpation by testing the accuracy of a probing accessory (stylus) of the Optotrak motion capture system. A unique method was used, where angular displacements were imposed on an anatomical model, and anatomical landmarks' positions were recorded using the probe accessory and compared to measurements from fixed markers. The mean differences between the two methods ranged from 1.5^o to 4.2^o for the scapular angles, and the Optotrak probing method was deemed accurate, but it did not address the issue of palpating when there is significant amount of tissue overlying the anatomical landmarks. Bourne et al. (2009) tested concurrent validity of digitization using bone pins as the gold standard. Four active movements were tested and RMS errors between the two methods were calculated. RMS error ranged from 2^o to 12.5^o for individual positions and the greatest RMS error was observed at full abduction (Bourne et al., 2009).

The accuracy of acromial methods has also been addressed by some previous studies. Karduna et al. (2001) calculated the RMS errors between 3Space Fastrak skin sensor and bone pins with electromagnetic receiver measurements and the RMS errors were assumed to be errors due to skin displacement. Upward rotation of the scapula was overestimated (RMS error = 6.3^o), while posterior tilting and external rotation had relatively low RMS error. However, a sharp increase in RMS error was seen after 120^o of arm elevation. Meskers et al. (2007) found that acromion electromagnetic skin sensors underestimated scapular rotations compared to the scapular locators. A 7^o and 13^o difference was found between the recordings from the two methods during sagittal and frontal plane elevations of up to 130^o, respectively. The differences between the two methods increased with elevation angle, indicating that accuracy problems exist when acromial methods are used at high elevation angles. Karduna et al. (2001) attained a maximum RMS error of 11.4^o when comparing the acromion electromagnetic sensor measurements to bone pin measures. The acromion sensor overestimated scapular angles (Karduna et al., 2001). Therefore, the skin sensors are affected by the errors introduced by soft-tissue movement.

Van Andel et al. (2009) also used the scapular locator as a reference to validate the acromion marker cluster (AMC) for up to 90^o of arm elevation in the sagittal and the frontal plane. In contrast to Karduna et al. (2001), the AMC underestimated the scapular angles in frontal and sagittal plane arm elevation except for protraction and upward rotation during arm elevation in the sagittal plane (van Andel et al., 2009). However no significant differences were present when comparing scapular rotations derived from AMC to the results from the scapular locator, except for the external rotation of the scapula, where a mean difference of 8.4^{o} in protraction was found between the two methods. Recently, Warner, Chappell and Stokes (2010) compared acromion marker cluster and scapular locator techniques during arm elevation in the sagittal plane, and found a significant difference between the two methods for scapular tilt only.

A major limitation of the studies that examine the validity of scapular tracking methods is that only arm elevation in a single plane has been examined by most studies. Also, it is unknown what method overestimates or underestimates scapular rotations during internal and external rotation of the arm. Therefore, further research is needed to determine how shoulder rhythms attained using different non-invasive methods compare. This directly influences the implication of the results of future studies that involve quantifying scapular kinematics, especially since the non-invasive methods are becoming more common in clinical settings. No previous research has used the stylus as the "gold-standard" and no previous studies directly compared more than two methods of determining scapular orientation during arm elevation and rotation in different planes.

III. METHODS

3.1 Participants

Twenty-eight (14 males and 14 females) right-hand dominant participants from the university population took part in this study. The mean characteristics of the participants are summarized in Table 1. Participants who experienced any injury or chronic pain in the last year to their right shoulder and neck were excluded from the study. The study was approved by the Office of Research Ethics, University of Waterloo. The participants gave informed consent prior to participating in the study.

Table 1: Mean participant data and the standard deviations.

Gender	**Age (years)**	**Stature (cm)**	**Mass (Kg)**
Male	22.6 (±1.3)	181.1(±6.7)	79.7(±10.0)
Female	22.8(±3.0)	167.0(±7.6)	61.4(±12.7)

3.2 Instrumentation

3.2.1 Motion Capture

A Vicon MX20+ (Vicon Motion Systems, Oxford, UK) optoelectronic passive motion tracking system was used to record body kinematics. Eight cameras were positioned around the collection space to capture the collection volume. The cameras recorded the global positions of spherical reflective markers adhered unilaterally to the skin overlying the anatomical landmarks of the thorax, clavicle and the arm (Table 2), as well as a 3-marker clusters adhered to the acromion (Figure 10) and a 4-marker cluster adhered to the upper arm. The cameras also recorded the global positions of the marker clusters on the stylus and the scapular locator.

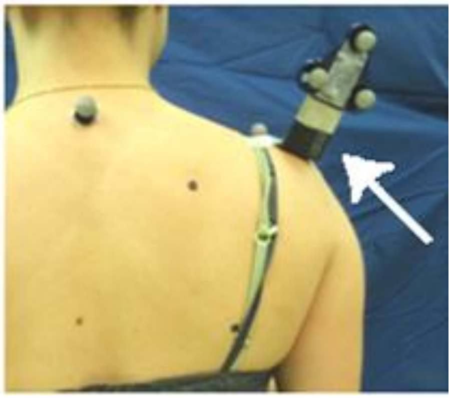


Figure 10: Location of the acromion marker cluster.

Table 2: The anatomical landmarks for each segment (Wu et al., 2005).

Segment	Marker	Anatomical Landmark
Thorax	C7	Spinous process of the 7th cervical vertebra
	T8	Spinous process of the 8th thoracic vertebra
	SS	Suprasternal notch
	XP	Xyphoid process
Clavicle	SC	Sternoclavicular joint
	AC	Acromioclavicular joint
Arm	LE	Lateral epicondyle
	ME	Medial epicondyle

Motion data was sampled at 50Hz. The cameras and the collection space were calibrated, and the origin and the axes of the global coordinate system were set by placing the calibration wand in the center of the collection space (Table 3). During data collection, the participants were seated upright facing the positive global X-axis. The global positive Z-axis pointed to the participants left, orthogonal to the global X-axis. A calibration trial was recorded with the participant in the collection space to associate all the markers to a Vicon template made for this study (prior to data collection) to describe the bone structures and to calculate marker positions in real time. The segments were constructed digitally using Vicon Nexus 1.2 software.

Table 3: The axes directions of the global coordinate system.

Axes	Direction
X	Forward/backward
Y	Vertical
Z	Medial/lateral

3.2.2 Stylus

The stylus (Figure 11) was a 5mm thick sheet of metal with four reflective markers. The tip of the stylus was the top of a screw that was secured tightly into the metal base to create a blunt point 4mm in diameter. This was used to digitize anatomical landmarks.

Figure 11: Stylus with four reflective markers.

3.2.3 Scapular Locator

The scapular locator consisted of two transparent arms connected by a hinge (Figure 12). The length of the arms and the angle between the arms were adjusted to ensure that the three ends of the scapular locator aligned with three anatomical landmarks of the scapula: acromion angle, root of the scapular spine and the inferior angle (Figure 6). There was a four-marker cluster on the top arm that aligned with the root of the scapular spine and the acromion angle. Prior to data collection, the scapular locator was adjusted to custom fit to each participant and locked to create a rigid construction representing the scapula. During each trial, the hinge-fixed locator was held over the scapula, while the global location of its marker cluster was captured. In cases where all ends of the scapular locator could not be contacted with all three anatomical landmarks of the scapula due to soft tissue impedance, the scapular locator was aligned as closely as possible to the scapular spine.

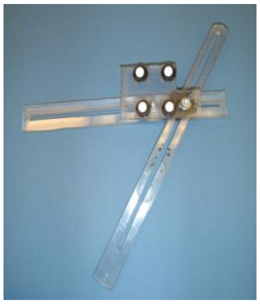


Figure 12: The scapular locator.

3.3 Experimental Procedures

Once the reflective markers, the acromion marker cluster (AMC) and the clavicular cluster were attached to their respective anatomical landmarks, the participants sat comfortably on a wooden stool in the center of the collection space. The seat position was marked to standardize the seated position across all trials. The participants sat upright and they were continually reminded to maintain an upright posture throughout the trials. A pole was placed against the participants' backs to help them maintain an upright posture. The initial arm posture was dictated by arm elevation of 0^o and elbow flexed at 90^o and thumb pointing up, parallel to the arm.

3.3.1 Initial Calibration Trials

With the arm in the initial posture, initial 3-second calibration trials were captured to associate the AMC with the anatomical landmarks of the scapula. During these trials the stylus was used to digitize the acromion angle, root of the scapular spine and the inferior angle. The scapular locator was held over the scapula and 3-second trials were captured to digitize the anatomical landmarks of the scapula. This associated the position of the cluster on the scapular locator with the anatomical landmarks of the scapula. Therefore, a total of 6 initial calibration trials were captured. These trials also determined the initial orientations of the scapula.

3.3.2 Arm Posture Trials

The arm postures were spread over 5 arm elevation angles: 0^o, 45^o, 90^o, 135^o, 180^o, 3 arm elevation planes: 0^o, 45^o, 90^o (frontal, 45^o to frontal and sagittal plane, respectively) and 3 arm axial rotations: maximum external rotation, 0^o or neutral and maximum internal rotation. At 0^o arm elevation, only one plane of elevation could be discerned, therefore a total of 39 arm postures were examined. The elevation angles were measured using a goniometer and marked on a pole. The planes of elevation were marked on the floor. This pole was placed in the desired plane of elevation on the markings, and it served as a guide for arm postures.

A complete randomized block design was used to determine the order of the arm postures, with the planes of elevations as blocks. This decreased the chances of arm fatigue by decreasing the collection time since the pole was not adjusted in between each trial to indicate the plane of elevation, while still controlling for and possibly reducing experimental error variance. At each arm posture, the anatomical landmarks of the scapula were palpated and the scapular locator was held in place while a trial was captured. Subsequently, the stylus was held with the tip on each of the anatomical landmarks of the scapula, while 1-second trials were captured. The stylus tip was first placed on the root of the scapular spine, then the inferior angle and finally on the acromion angle. The AMC remained attached to the acromion during all trials. Participants were allowed to rest at any time during the protocol.

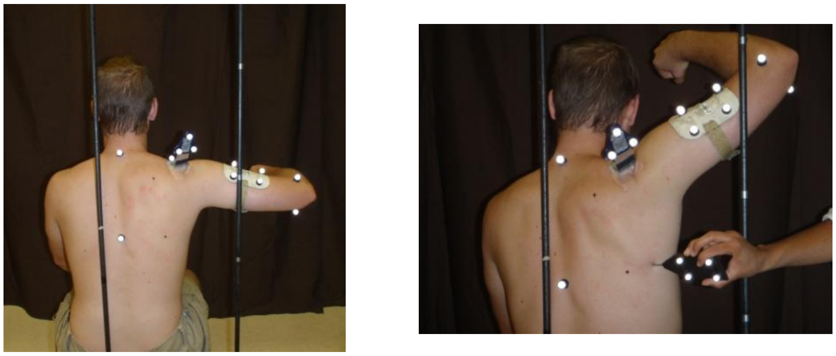


Figure 13: Examples of the arm postures in the protocol: the figure on the left shows the participant in arm posture with 90^o arm elevation and neutral axial rotation in the frontal plane. The figure on the right illustrates 135^o arm elevation with neutral rotation in the frontal plane.

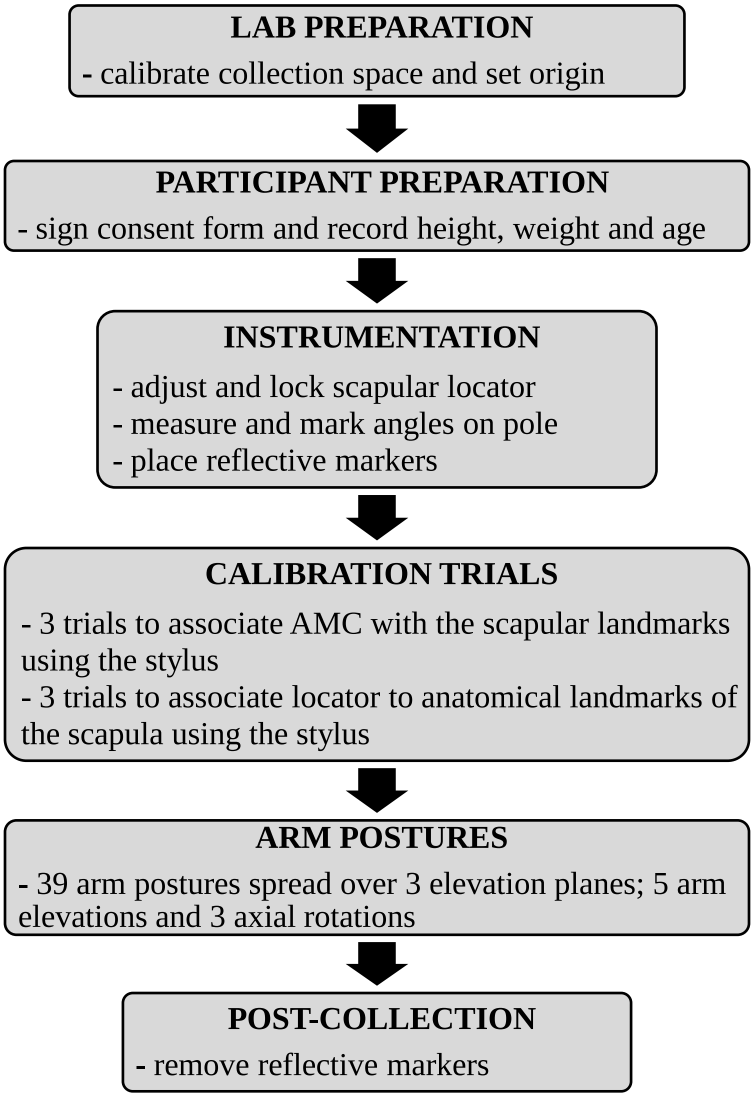


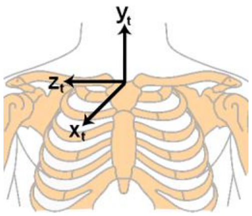
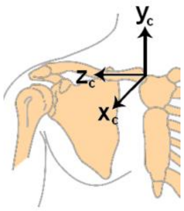
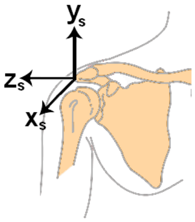
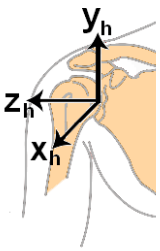
Figure 14: Overview of the methodology of the experiment.

3.4 Data Analysis

Using Vicon Nexus 1.2 software, any mislabeled or unlabeled markers were labeled correctly. All motion capture data was dual-pass butterworth filtered with a cut-off frequency of 6Hz (Winter, 2009). All recorded kinematic data represented the positions of the markers and their respective anatomical landmarks in the global coordinate system.

A custom software developed using MATLAB 7.9.0 R2009B (Mathworks, Natick, MA) was used for data reduction. Using the global positions of the reflective markers, local coordinate system of each segment was determined (Table 4). The local coordinate systems were based on the recommendations made by the International Society of Biomechanics (ISB) for recording human joint motion (Wu et al., 2005). Three non-collinear anatomical landmarks were required on a segment to construct each local coordinate system. The glenohumeral joint center was used as the third landmark on the arm and it was calculated as 50mm below the acromion (Nussbaum and Zhang, 2000) + 10mm distance between the center of the acromion reflective marker and the skin.

Table 4: The local coordinate systems of each segment and their respective origins as recommended by the ISB standards (Wu et al., 2005).

Body Segment	Origin	Local Coordinate System
Thorax - $x_ty_tz_t$ 	IJ	y_t: line connecting the mid-point between XP and T8 and the mid-point between IJ and C7, pointing upward z_t: line perpendicular to the plane formed by IJ, C7, and midpoint between IJ, C7 and the midpoint between XP and T8 pointing upward x_t: The common line perpendicular to y_t-axis, pointing forwards
Clavicle – $x_cy_cz_c$ 	SC	z_c: The line connecting SC and AC, pointing to AC x_c: The line perpendicular to z_c and y_t, pointing forward y_c: The line perpendicular to the x_c- and z_c-axis, pointing upward
Scapula – $x_sy_sz_s$ 	AA	z_s: line connecting TS and AA, pointing to AA x_s: line perpendicular to the plane formed by AI, AA, and TS, pointing forward y_s: common line perpendicular to the x_s- and z_s-axis pointing upward
Humerus – $x_hy_hz_h$ 	GH	y_h: line connecting GH and the midpoint of the EL and EM, pointing to GH x_h: line perpendicular to the plane formed by EL, EM, and GH, pointing forward z_h: common line perpendicular to the y_h- and z_h-axis, pointing to the right

3.4.1 Scapular Local Coordinate System

Three sets of Euler angles (for 3 methods) described the scapular orientation at each arm posture. To construct the scapular local coordinate system using the stylus, the global orientation of the tip of the stylus was attained using equation 7. The superscripts G and L indicate that the coordinates or vectors are in the global or local coordinate system, respectively. The components of the vector (V^L) describe the translation from the origin of the stylus local coordinate system to its tip. This vector was converted in the global coordinate system using the rotation transformation matrix $[R_G^L]$. The global position vector of the tip [Tip] of the stylus was then determined by transforming the origin of the stylus local coordinate system [O^G]. Each landmark of the scapula was digitized the same way, at each arm posture. Using the global positions of the scapular anatomical landmarks, the local coordinate system of the scapula was then determined at each arm posture.

$$[Tip] = [R_G^L][V^L] + [O^G] \tag{7}$$

Reconstructing the anatomical landmarks of the scapula using the AMC required the initial calibration trials. The transformation vector (V^G) between each anatomical landmark $[L^G]$ and the origin of the AMC local coordinate system $[O^G]$ was determined using the simultaneous measurement of the global positions of the scapular landmarks and the AMC during the calibration trial (equation 8). The transformation vector was then expressed in the AMC local coordinate system using the rotation transformation matrix $[R_L^G]$ (equation 9).

$$[V^G] = [L^G] - [O^G] \tag{8}$$

$$[V^L] = [R_L^G][V^G] \tag{9}$$

For all arm posture trials, this vector was transformed back into global coordinate system using the rotation transformation matrix $[R_G^L]$ and the components of the position vector of the origin (O^G) of the AMC were translated by this vector to determine the global position vector of the anatomical landmark $[L^G]$ (equation 10).

$$[L^G] = [R_G^L][V^L] + [O^G] \tag{10}$$

For each arm posture, once the global positions of the three scapular landmarks were attained, the local coordinate system of the scapula was constructed.

The local coordinate system of the scapula using the scapular locator was attained in a similar manner. In the calibration trial, the transformation vectors from the cluster to the anatomical landmarks of the scapula (tip of the stylus) were determined and these vectors were converted into the local coordinate system of the scapular locator. For all arm posture trials, the transformation vectors were converted to global coordinate system and the origins of the scapular locator local coordinate system were transformed by these vectors to attain the global positions of the scapular landmarks.

3.4.2 Bone Orientations

The scapular, clavicular and humeral local coordinate systems were described with respect to the thorax local coordinate system as the shoulder complex bone rotations. The scapular rotations were described as protraction/retraction, lateral/medial rotation or upward/downward rotation and anterior/posterior tilt (Figure 1). The clavicular rotations were described as protraction/retraction, elevation/depression and forward/backward rotation (Figure 2). The humeral rotations were described as the plane of elevation, magnitude of elevation and internal/external rotation (Figure 3). The rotation sequences that were used (Table 5) were based on the ISB recommendations in Wu et al. (2005). A detailed description of the rotation sequences is stated Table 42 in the Appendix A.

Table 5: Euler decomposition orders and their interpretations based on ISB standards (Wu et al., 2005).

Bone Rotations	Order	Interpretation
Thorax (with respect to global coordinate system)	Z X’ Y’’	Flexion/extension Lateral flexion Axial rotation
Clavicle	Y X’ Z’’	Retraction/protraction Elevation/depression Forward/backward rotation
Scapula	Y X’ Z’’	Retraction/protraction Lateral/medial rotation Anterior/posterior tilt
Humerus	Y X’ Y’’	Plane of elevation Elevation Axial rotation

For all bones, the rotation about the local x-axis was indicated by β, the rotation about the local y-axis was indicated by γ and the rotation about the local z-axis was α, irrespective of the order of rotation. The interpretation of these angles depended on the local coordinate systems (Table 5). The orientation of the humerus relative to the thorax was determined by extracting the Euler angles from equation 11, where the x_{h}, y_{h} and z_{h} represent the axes of the humeral local coordinate system. The transformation matrix was derived using the Y-X’-Y’’ Euler sequence (Table 5).

$$\begin{Bmatrix} \mathrm{x_h} \\ \mathrm{y_h} \\ \mathrm{z_h} \end{Bmatrix} = \begin{bmatrix} (\cos\gamma_2\cos\gamma - \sin\gamma_2\cos\beta\sin\gamma) & \sin\beta\sin\gamma_2 & (-\cos\gamma_2\sin\gamma\sin\gamma_2 - \sin\gamma_2\cos\beta\cos\gamma) \\ \sin\beta\sin\gamma & \cos\beta & \sin\beta\cos\gamma \\ (-\sin\gamma_2\cos\gamma + \cos\gamma_2\cos\beta\sin\gamma) & -\cos\gamma_2\sin\beta & (-\sin\gamma_2\sin\gamma + \cos\gamma_2\cos\beta\cos\gamma) \end{bmatrix} \begin{Bmatrix} x_t \\ y_t \\ z_t \end{Bmatrix} \quad (11)$$

To describe the scapula and the clavicle with respect to the thorax, a Y-X’-Z’’ rotation sequence (Table 5) was used to derive the transformation matrix and the Euler angles were extracted from equation 12.

$$\begin{Bmatrix} x \\ y \\ z \end{Bmatrix} = \begin{bmatrix} (\cos\alpha\cos\gamma + \sin\gamma\sin\alpha\sin\beta) & \sin\alpha\cos\beta & (-\cos\alpha\sin\gamma + \sin\alpha\sin\beta\cos\gamma) \\ (-\sin\alpha\cos\gamma + \cos\alpha\sin\beta\sin\gamma) & \cos\alpha\cos\beta & (\sin\alpha\sin\gamma + \cos\alpha\sin\beta\cos\gamma) \\ \cos\beta\sin\gamma & -\sin\beta & \cos\beta\cos\gamma \end{bmatrix} \begin{Bmatrix} x_t \\ y_t \\ z_t \end{Bmatrix} \tag{12}$$

In Equation 12, the x, y and z represent the axes of the scapular or clavicular local coordinate system while x_t, y_t and z_t are the axes of the thorax coordinate system.

3.5 Statistical Analysis

3.5.1 Quantification of Shoulder Rhythm

JMP software v. 9.0 (SAS, NC, USA) was used for the statistical analysis. The shoulder rhythm was quantified using the data extracted from the stylus method. The participant characteristics (height, age, weight and gender) and the humeral angles (plane of elevation, elevation angle and axial rotation) were the independent variables and the scapular rotations (protraction/retraction, lateral/medial rotation and anterior/posterior tilt) and clavicular rotations (protraction/retraction, elevation/depression and axial rotation) were the dependent variables. In the first step, the height, weight and age were treated as ordinal variables while participant gender and humeral angles were treated as nominal or categorical variables. A repeated-measures analysis of variance (ANOVA) was used to assess the influence of all the independent variables on the dependent variables. If a significant effect on scapular kinematics existed ($p < 0.05$), a post-hoc Tukey HSD test was performed to confirm the differences.

The significant independent factors from the previous step were then treated as continuous variables or regressors in a second-order full-factorial model. A linear regression procedure generated continuous prediction models (for each scapular and clavicular dependent variable) for significant predictors determined in the previous step (equation 13). This fitting technique produced estimates for each significant predictor and linearly combined them to fit the dependent variables (equation 13). In equation 13, the $\hat{y}$ value is the predicted value of the dependent variable, b values are the coefficients for the linear combinations, x values are the significant predictors or independent factors, and e is the residual between the actual value and the predicted value using the model. Each of the six dependent variables (three scapular and three clavicular rotations) was fitted with a separate model. To create the most parsimonious models, the interactions between the significant factors that provided additional variance explanation of less than 2% were excluded from the models.

$$\hat{y} = b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_n x_n + e \tag{13}$$

If the linear models were significant, quadratic relations were determined to see if they contributed to the predictions of the scapular and the clavicular angles. If the quadratic relations were statistically significant but did not provide any further variance explanation of greater than 2%, linear models were used. The obtained predictions models can be utilized to estimate the scapular and clavicular orientations at any arm elevation and axial rotation in the planes between frontal and sagittal plane.

3.5.2 Comparison of Methods of Scapular Tracking

A repeated measures ANOVA for each scapular rotation was used with the method of scapular tracking (AMC, stylus and scapular locator), and humeral posture parameters (plane of elevation, elevation angle and axial rotation) as the independent variables to test whether significant differences existed between the methods of scapular tracking. If significant differences between the methods existed ($p < 0.05$), a post-hoc Tukey's HSD test was used to make all possible pair-wise comparisons to determine which methods result in significantly different scapular rotations. Significant two-way interactions ($p<0.05$) between the method of scapular tracking and the plane of elevation, elevation angle and axial rotations were also determined.

IV. RESULTS

The results are presented in three parts. The thoracohumeral angles calculated using Euler angles are presented first. The second section examines the regression models generated to predict the scapular and clavicular angles. The stylus was used as the criterion measurement for building prediction equations for all derived angles. The significant independent factors ($p<.05$) included in the models were thoracohumeral angles. Gender and anthropometrical factors did not significantly influence any of the dependent variables and thus were excluded from these models. The final section compares the scapular angles obtained using the three different measurement techniques: stylus, AMC and the scapular locator. Data on the main effect of the method used on each scapular angle and the interaction effects between the method used and the thoracohumeral angles are presented.

4.1 Thoracohumeral Angles

The thoracohumeral angles calculated using the Euler method (Wu et al., 2005) were not identical to the thoracohumeral angles measured using a goniometer when the participants placed their arm in a given position. Table 6 summarizes the planes of elevation that were achieved at all arm postures obtained by calculating the humeral orientation with respect to the trunk. Although the arm postures were spread over three planes of elevation, 0^o, 45^o, and 90^o to the frontal plane, the calculated planes of elevation achieved across postures ranged from -45.7^o to 69.3^o to the frontal plane. The calculated thoracohumeral elevation angles are summarized in Table 7. Except for 0^o elevation angle postures, the thoracohumeral elevation angles were underestimated. The participants did not achieve 180^o of thoracohumeral elevation at any of the humeral postures. At each elevation angle in the three planes of elevation, the participants were required to maximally rotate their arm externally, internally or maintain a neutral humeral rotation. Table 8 summarizes the thoracohumeral axial rotations achieved at each arm posture and highlights the differences in active axial rotation range of motion across different arm postures.

Table 6: The calculated mean thoracohumeral planes of elevation at 0^o, 45^o, 90^o, 135^o and 180^o humeral elevation angles in frontal (0^o), 45^o to frontal and sagittal (90^o) planes of elevation with humerus maximally externally rotated (ER), neutral and maximally internally rotated (IR).

Elevation	**Plane 0^o**			**Plane 45^o**			**Plane 90^o**		
	ER	**Neutral**	**IR**	**ER**	**Neutral**	**IR**	**ER**	**Neutral**	**IR**
0^o	-43.0^o	-45.7^o	-12.1 ^{o}						
45^o	-4.3^o	-15.2^o	-22.6^o	32.7^o	32.0^o	20.8^o	68.7^o	69.3^o	63.8^o
90^o	4.2^o	-0.2^o	-11.8^o	34.2^o	36.3^o	23.7^o	63.4^o	66.1^o	61.4^o
135^o	18.5^o	11.7^o	8.4^o	38.9^o	35.4^o	30.8^o	56.6^o	55.7^o	51.8^o
180^o	21.1^o	15.1^o	14.3^o	36.8^o	38.7^o	33.6^o	54.5^o	52.5^o	47.8^o

Table 7: The calculated mean thoracohumeral elevation angles at 0^o, 45^o, 90^o, 135^o and 180^o humeral elevation angles in frontal (0^o), 45^o to frontal and sagittal (90^o) planes of elevation with humerus maximally externally rotated (ER), neutral and maximally internally rotated (IR). Positive angles denote arm elevation.

Elevation	**Plane 0^o**			**Plane 45^o**			**Plane 90^o**		
	ER	**Neutral**	**IR**	**ER**	**Neutral**	**IR**	**ER**	**Neutral**	**IR**
0^o	13.7^o	15.7^o	13.7^o						
45^o	40.2^o	44.4^o	41.1^o	36.4^o	39.4^o	37.5^o	34.0^o	39.2^o	36.2^o
90^o	71.9^o	77.9^o	65.4^o	71.5^o	79.78^o	67.7^o	69.7^o	77.7^o	72.0^o
135^o	110.6^o	111.8^o	99.8^o	109.6^o	115.8^o	105.4^o	107.9^o	116.4^o	111.1^o
180^o	119.2^o	121.8^o	110.4^o	119.0^o	128.4^o	116.1^o	116.3^o	126.5^o	122.4^o

Table 8: Average thoracohumeral axial rotation angles calculated during maximum externally rotated arm postures (ER), neutral arm axial rotation and maximum internally rotated (IR) humeral rotation postures. Negative thoracohumeral axial rotation values indicate external axial rotation, while a positive thoracohumeral axial rotation values indicate internal rotation of the humerus.

Elevation	**Plane 0°**			**Plane 45°**			**Plane 90°**		
	ER	**Neutral**	**IR**	**ER**	**Neutral**	**IR**	**ER**	**Neutral**	**IR**
0°	16.5°	59.4°	63.9°						
45°	-39.4°	15.4°	69.7°	-62.2°	-31.1°	43.7°	-69.6°	-59.0°	20.2°
90°	-58.1°	-4.1°	48.6°	-67.2°	-42.4°	25.2°	-67.8°	-62.1°	16.8°
135°	-63.1°	-18.6°	0.1°	-59.8°	-42.4°	0.9°	-60.7°	-55.8°	-2.8°
180°	-60.1°	-21.9°	-6.0°	-59.9°	-48.3°	-10.7°	-59.7°	-62.3°	-23.4°

4.2 Regression Models

4.2.1 Nominal Model

In the first step of linear regression, the thoracohumeral angles and gender were treated as nominal factors while the other participant characteristics were treated as continuous factors to determine what independent factors significantly influenced the scapular and clavicular angles. The results are summarized in Table 9. Gender, age and the anthropometric factors (height and weight) did not have a significant effect on any of the dependent variables and thus were excluded from the final models. The plane of elevation, elevation angle and the internal/external rotation of the humerus, however, significantly contributed to at least one of the scapular or clavicular angles and thus were included in the final models.

Table 9: The p-values of factors determining the clavicular and the scapular outcome angles. Gender and the thoracohumeral angles were treated as nominal variables.

Dependent Variable	**Independent Variable**						
	Gender	**Age**	**Height**	**Weight**	**Thoracohumeral Angles**		
					Plane	**Elevation**	**Axial Rotation**
Scapular lateral/medial rotation	0.573	0.457	0.748	0.842	0.0002*	<0.0001*	<0.0001*
Scapular anterior/posterior tilt	0.574	0.473	0.919	0.265	<0.0001*	<0.0001*	<0.0001*
Scapular retraction/protraction	0.944	0.621	0.244	0.408	<0.0001*	<0.0001*	0.113
Clavicular elevation/depression	0.079	0.462	0.733	0.204	0.156	<0.0001*	<0.0001*
Clavicular retraction/protraction	0.158	0.290	0.434	0.623	<0.0001*	<0.0001*	<0.0001*
Clavicular forward/backward rotation	0.609	0.144	0.533	0.191	<0.0001*	<0.0001*	<0.0001*

*indicates statistical significance ($p<.05$)

4.2.2 Continuous Prediction Models

Using repeated measurements models, the significant independent factors from the nominal models were used to create prediction models for the dependent variables. Linear prediction models were obtained for each of the scapular angles and clavicular retraction/protraction and forward/backward rotation. A quadratic relationship contributed significantly to the variance explained in the prediction of the clavicular elevation/depression.

Significant two-way interactions were included in the models and these interactions were centered at the means of the independent factors, summarized in Table 10. In order to obtain the most parsimonious models, the significant interactions that increased the r^2 value by less than 0.02 were excluded. The r^2 values and the RMS error values of the full-factorial models if all the two-way interactions between the significantly independent factors were kept in the models are summarized in Table 44 in Appendix B.

Table 10: The mean values of the thoracohumeral angles across all participants and postures.

Independent Factor	Mean
Plane of elevation	26.9°
Elevation angle	-77.7°
Axial rotation	-24.4°

The resulting prediction models of scapular orientation are listed in equations 14 to 16, where the β_s, α_s and γ_s represent scapular lateral/medial rotation, anterior/posterior tilt and retraction/protraction respectively. Equations 17 to 19 are the prediction models of clavicular orientation where β_c, γ_c and α_c represent clavicular elevation/depression, retraction/protraction and forward/backward rotation. In the prediction models, γ_{TH1}, β_{TH} and γ_{TH2} represent humeral plane of elevation, elevation angle and external/internal rotation relative to the trunk, respectively.

$$\beta_S = -1.68 + (0.034\gamma_{TH1}) + (0.238\beta_{TH}) + (-0.017\gamma_{TH2}) + (\gamma_{TH1} - 26.9)(\gamma_{TH2} + 24.4(-0.001) \tag{14}$$

$$\propto_S = -11.2 + (0.050\gamma_{TH1}) + (-0.298\beta_{TH}) + (-0.021\gamma_{TH2}) \tag{15}$$

$$\gamma_S = 0.1 + (0.170\gamma_{TH1}) + (-0.032\beta_{TH}) + (\gamma_{TH1} - 26.9)(\beta_{TH} + 77.7)(-0.001) \tag{16}$$

$$\beta_C = -14.6 + (0.057\beta_{TH}) + \left(0.002\beta_{TH}{}^{2}\right) + (-0.031\gamma_{TH2}) \tag{17}$$

$$\gamma_C = -13.3 + (0.073\gamma_{TH1}) + (0.358\beta_{TH}) + (00.035\gamma_{TH2}) \tag{18}$$

$$\propto_C = 0.411 + (-0.016\gamma_{TH1}) + (-0.201\beta_{TH}) + (0.030\gamma_{TH2}) + (\beta_{TH} + 77.7)(\gamma_{TH2} + 24.4(-0.0007) \tag{19}$$

Scapular Lateral/medial Rotation

The correlation between actual and the predicted lateral/medial rotation of the scapula (Figure 15) resulted in r^2 value of .80 and RMS error of 5.26° (Table 11). This indicated that 80% of the variance in the observations was explained by the resulting model.

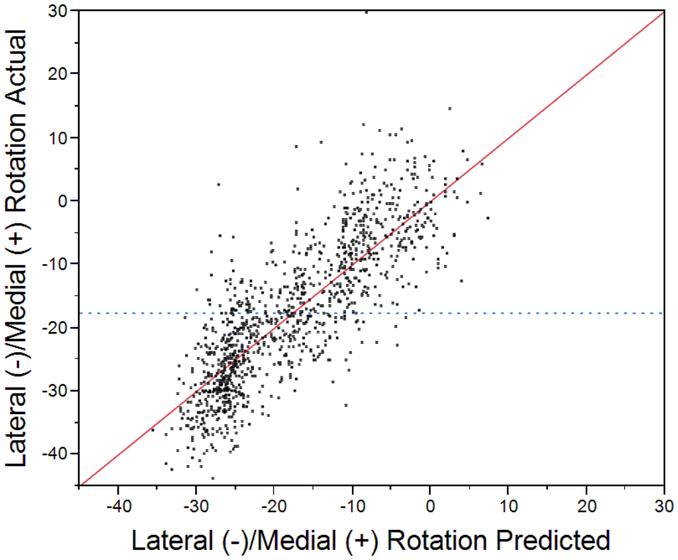


Figure 15: Actual versus predicted values of lateral/medial rotation. The red line is the line of best fit between the actual and the predicted values and the blue dotted line is the mean lateral rotation recorded across all postures.

Table 11: Summary of fit of the lateral (-)/medial (+) rotation.

r^2	0.80
RMS error	5.26°
Number of observations	1083
Mean lateral rotation	-17.67°

The coefficients of the prediction model for lateral/medial rotation of the scapula are summarized in Table 12. The initial lateral/medial rotation of the scapula, when there was no humeral elevation or axial rotation, was not a significant predictor of the lateral/medial rotation of the scapula. The plane of elevation, elevation angle and axial rotation of the humerus were all significant predictors of scapular lateral/medial rotation. The scapula laterally rotated with increasing elevation angle and the F-ratios (Table 13) indicated that humeral elevation was the greatest contributor to the lateral rotation of the scapula, since its F-value (2184.8) was considerably larger than the F-values of other significant predictors. The plane of elevation and axial rotation and an interaction between these two factors were also significant predictors of lateral/medial rotation. The F-values in Table 13 show that the interaction effect (F-value = 173.1) contributed more to scapular lateral/medial rotation than the main effects of the plane of elevation (F-value = 27.1) and the axial rotation of the humerus (F-value = 16.2).

Table 12: Regression parameters, their corresponding standard errors and p-values for the significant independent factors and two-way interactions determining lateral/medial rotation of the scapula.

Term	Coefficient	Standard Error	p-value
Intercept (initial posture)	-1.680	0.882	0.063
Plane of elevation	0.034	0.007	<0.0001*
Elevation angle	0.238	0.005	<0.0001*
External/internal rotation	-0.017	0.004	<0.0001*
Plane of elevation* External/internal rotation	-0.001	0.0001	<0.0001*

*indicates statistical significance (p<.05)

Table 13: The F-ratios and the corresponding p-values of the significant independent factors and two-way interactions determining the lateral/medial rotation of the scapula.

Source	DF	F-ratio	p-value
Plane of elevation	1055	27.1	<0.0001*
Elevation angle	1053	2184.8	<0.0001*
External/internal rotation	1056	16.2	<0.0001*
Plane of elevation*External/internal rotation	1053	173.1	<0.0001*

*indicates statistical significance (p<.05)

The interaction effect between the plane of elevation and axial rotation on lateral/medial rotation of the scapula is illustrated in Figure 16. As the humerus rotated externally in the abduction plane, slight lateral rotation of the scapula occurred, and as the humerus rotated internally, the scapula rotated medially. However, as the plane of elevation moved towards the sagittal plane, the trend reversed and the magnitude of scapular lateral/medial rotation increased. In the sagittal plane (plane 90^o), the scapula rotated medially with external rotation of the humerus, and laterally with internal rotation of the humerus.

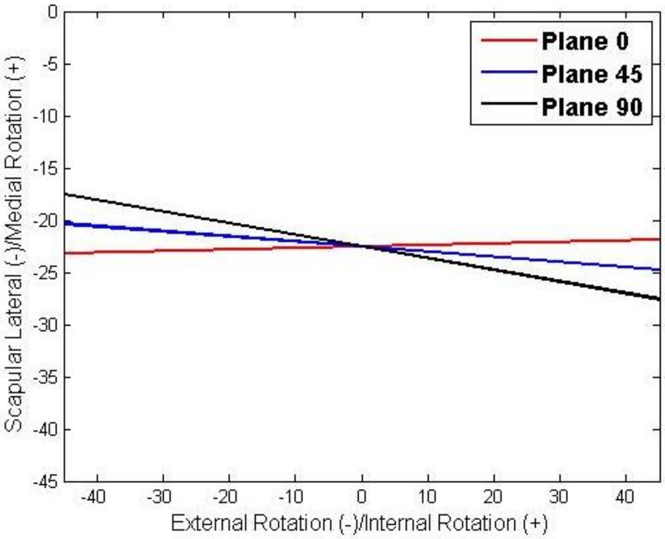


Figure 16: Two-way interaction between the humeral plane of elevation and axial rotation of the humerus in determining the lateral/medial rotation of the scapula.

Scapular Anterior/posterior Tilt

The linear trend between the actual and the predicted anterior/posterior tilt values (Figure 17) indicated that the obtained linear model was sufficient to determine the anterior/posterior tilt of the scapula and 82% of the variance in the data was explained by the factors included in the prediction model (Table 14).

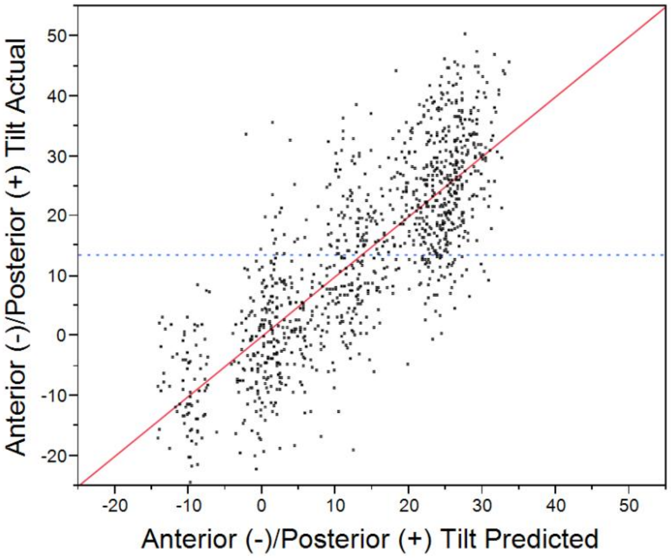


Figure 17: The actual versus predicted values of the anterior/posterior tilt of the scapula. The red line is the line of best fit between the actual and the predicted values and the blue dotted line is the mean posterior tilt recorded across all postures.

Table 14: Summary of the fit of anterior (-)/posterior (+) tilt of the scapula.

r^2	0.82
RMS error	6.54^o
Number of observations	1083
Mean posterior tilt	13.54^o

The results of the linear model to estimate anterior/posterior tilt are summarized in Table 15. When the humerus was not elevated, nor axially rotated, the scapula was anteriorly tilted by approximately 11.2^o, and this initial position was a significant predictor of the anterior/posterior tilt. The plane of elevation, elevation angle and axial rotation were all significant predictors of the scapular tilt. According to the relatively larger F-value of elevation angle (Table 16), the elevation angle (F-value = 2412.8) was a major contributor to the scapular tilt. The scapula tilted posteriorly as the humerus elevated, as the plane of elevation changed from frontal plane to sagittal plane and with external humeral rotation. Anterior scapular tilt occurred when the humerus rotated internally.

Table 15: Regression parameters, their corresponding standard error values and p-values for the significant independent factors determining anterior/posterior tilt of the scapula.

Term	Coefficient	Standard Error	p-value
Intercept (initial posture)	-11.154	1.340	<0.0001*
Plane of elevation	0.050	0.008	<0.0001*
Elevation angle	-0.298	0.006	<0.0001*
External/internal rotation	-0.021	0.005	<0.0001*

*indicates statistical significance (p<.05)

Table 16: The F-ratios and the corresponding p-values of the significant independent factors determining the anterior/posterior tilt of the scapula.

Source	DF	F-ratio	p-value
Plane of elevation	1054	40.9	<0.0001*
Elevation angle	1053	2412.8	<0.0001*
External/internal rotation	1055	15.3	<0.0001*

*indicates statistical significance (p<.05)

Scapular Retraction/protraction

The r^2 value of 0.60 of the actual versus predicted values plot of scapular/retraction indicated that the correlation between the actual and predicted data was weaker for scapular retraction/protraction than scapular lateral/medial rotation and anterior/posterior tilt (Figure 18 and Table 17). Linear model was the most parsimonious model for scapular retraction/protraction. Quadratic relations of the significant independent variables did not provide any additional variance explanation.

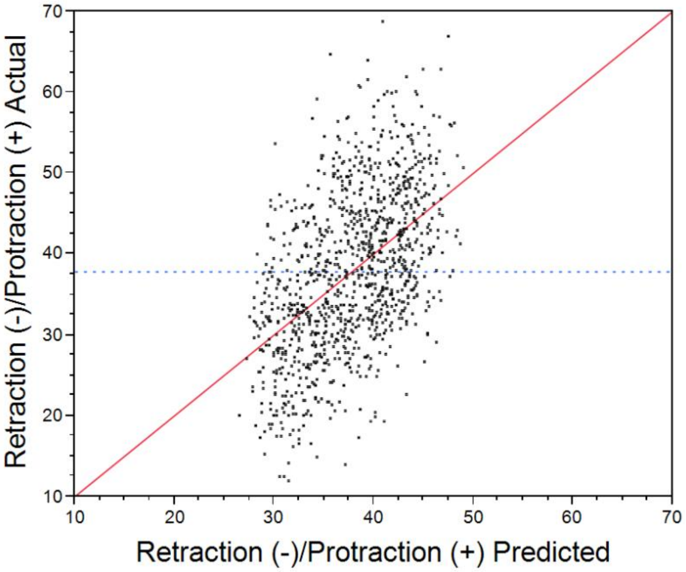


Figure 18: The actual versus predicted values of the retraction/protraction of the scapula. The red line is the line of best fit between the actual and the predicted values and the blue dotted is the mean protraction recorded across all postures

Table 17: Summary of the fit of retraction (-)/protraction (+) of the scapula.

r^2	0.60
RMS error	6.31°
Number of observations	1083
Mean protraction	37.81°

The regression parameters to estimate scapular retraction/protraction are summarized in Table 18. The initial protracted position of the scapula was a significant predictor of scapular retraction/protraction. Only the plane of elevation and elevation angle contributed significantly to the prediction of the retraction/protraction of the scapula. There was also a significant interaction between these two factors that provided additional variance explanation to the prediction model. Based on the F-ratios (Table 19), the main effect of the plane of elevation (F-value = 408.5) contributed more to protraction of the scapula than its interaction effect with elevation angle (F-value = 65.2).

Table 18: Regression parameters, their corresponding standard error values and p-values for the significant independent factors and two-way interactions determining the retraction/protraction of the scapula.

Term	Coefficient	Standard Error	p-value
Intercept (initial posture)	30.110	1.188	<0.0001*
Plane of elevation	0.170	0.008	<0.0001*
Elevation angle	-0.032	0.006	<0.0001*
Plane of elevation*Elevation angle	-0.001	0.0001	<0.0001*

*indicates statistical significance (p<.05)

Table 19: The F-ratios and the corresponding p-values of the significant independent factors and two-way interactions determining the retraction/protraction of the clavicle.

Source	DF	F-ratio	p-value
Plane of elevation	1056	408.5	<0.0001*
Elevation angle	1053	31.1	<0.0001*
Plane of elevation*Elevation angle	1055	65.2	<0.0001*

*indicates statistical significance (p<.05)

The interaction effect of the elevation angle and the plane of elevation (Figure 19) on retraction/protraction showed that in the frontal plane (plane 0^{o}), the scapula retracted slightly as the elevation angle increased. However, as the plane of elevation moved towards the sagittal plane, the scapula protracted with elevation angle. The rate of protraction with respect to elevation angle also increased as the plane of elevation moved towards the sagittal plane. The main effect of the plane of elevation showed that as the plane of elevation increased from abduction plane to the flexion plane, the scapula protracted.

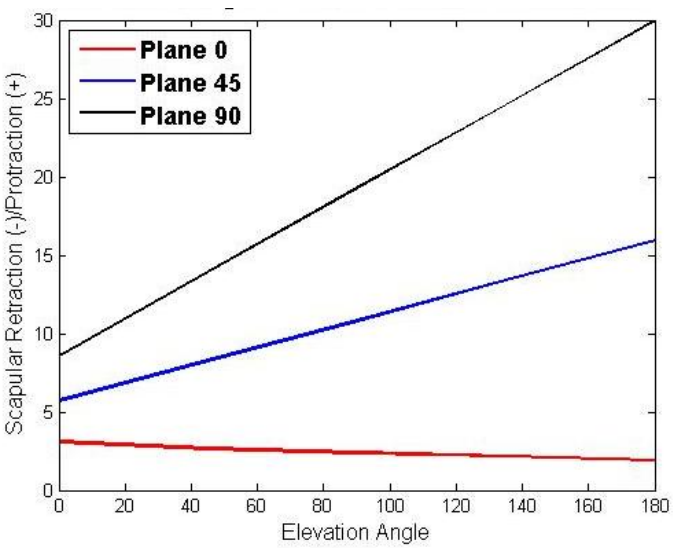


Figure 19: Interaction effect between the humeral elevation angle and the plane of elevation on retraction/protraction of the scapula.

Clavicle Elevation/depression

In the clavicle elevation/depression prediction model, elevation was included as a second-order or quadratic variable because this provided additional variance explanation. The r^2 of the actual versus predicted plot of the elevation/depression increased from 0.62 to 0.74 when elevation angle was included as a quadratic variable instead of a linear variable (Figure 20 and Table 20).

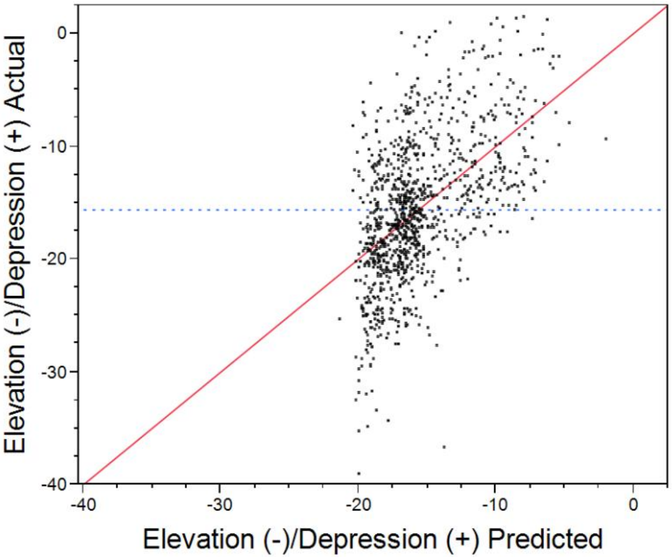


Figure 20: Actual versus predicted values of elevation/depression of the clavicle. The red line is the line of best fit between the actual and the predicted values and the blue dotted line is the mean elevation recorded across all postures.

Table 20: Summary of the fit of elevation (-)/depression (+) of the clavicle.

r^2	0.740
RMS error	3.24^o
Number of observations	1083
Mean elevation	-15.63^o

The regression parameters to estimate clavicular elevation/depression are summarized in Table 21. The initial elevated position of the clavicle of 14.6^o was a significant predictor of the clavicular elevation/depression. Elevation angle and axial rotation of the humerus were significant predictors of clavicular elevation/depression. The clavicle elevated with arm elevation and with internal rotation of the humerus. The F-value in Table 22 indicated that the squared elevation term (F-value = 466.5) contributed more to clavicular elevation/depression than the linear elevation term (F-value = 345.9).

Table 21: Regression parameters, their corresponding standard error values and p-values for the significant independent factors determining the elevation/depression of the clavicle.

Term	Coefficient	Standard Error	p-value
Intercept (initial posture)	-14.643	0.845	<0.0001*
Elevation angle	0.057	0.003	<0.0001*
External/internal rotation	-0.031	0.002	<0.0001*
Elevation angle*Elevation angle	0.002	0.00009	<0.0001*

*indicates statistical significance ($p<.05$)

Table 22: The F-ratios and the corresponding p-values of the significant independent factors determining the elevation/depression of the clavicle.

Source	DF	F-ratio	p-value
Elevation angle	1053	345.9	<0.0001*
External/Internal rotation	1053	178.5	<0.0001*
Elevation angle*Elevation angle	1053	466.5	<0.0001*

*indicates statistical significance ($p<.05$)

Clavicular Retraction/protraction

An r^2 value of 0.89 of the predicted and actual retraction/protraction plot (Figure 21 and Table 23) indicated a good correlation between the actual and predicted values of clavicular retraction/protraction.

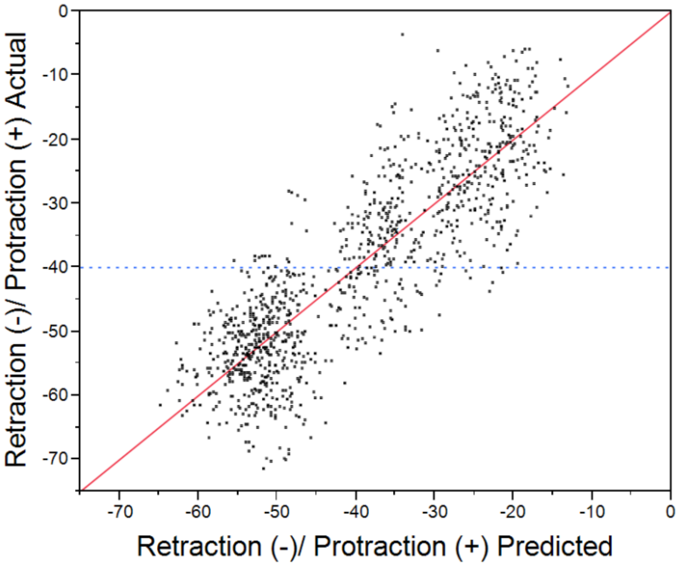


Figure 21: Actual versus predicted values of retraction/protraction of the clavicle. The red line is the line of best fit between the actual and the predicted values and the blue dotted line is the mean retraction recorded across all postures.

Table 23: Summary of the fit of retraction (-)/protraction (+) of the clavicle.

r^2	0.89
RMS error	5.11°
Number of observations	1083
Mean protraction	-39.99°

The linear model parameters to estimate clavicular retraction/protraction are summarized in Table 24. The initial retraction of the clavicle was a significant predictor of the clavicle retraction/protraction. The plane of elevation, elevation angle and axial rotation all significantly influenced the clavicle retraction/protraction. The interactions between these factors did not provide any additional variance explanation and were not included in the model. The clavicle retracted as the humeral elevation angle increased, and as the humerus rotated internally. Protraction of the clavicle occurred as the plane of elevation changed from frontal plane to the sagittal plane of elevation, as well as with internal rotation of the humerus.

The F-ratios of this model are summarized in Table 25.The elevation angle had the largest F-ratio of all three factors (F-ratio = 5672.6), and it was considerably larger than the F-ratio of plane of elevation (F-ratio = 145.1) and axial rotation (F-ratio = 71.4). This indicates that of the three significant independent factors, elevation angle contributed considerably more to the clavicle retraction/protraction than the other factors. Axial rotation contributes the least to retraction/protraction of the clavicle.

Table 24: Regression parameters, their corresponding standard error values and p-values for the significant independent factors determining the retraction/protraction of the clavicle.

Term	Coefficient	Standard Error	p-value
Intercept (initial posture)	-13.298	1.191	<0.0001*
Plane of elevation	0.073	0.006	<0.0001*
Elevation angle	0.358	0.005	<0.0001*
External/internal rotation	0.035	0.004	<0.0001*

*indicates statistical significance (p<.05)

Table 25: The F-ratios and the corresponding p-values of the significant independent factors determining the retraction/protraction of the clavicle.

Source	DF	F-ratio	p-value
Plane of elevation	1054	145.1	<0.0001*
Elevation angle	1053	5672.6	<0.0001*
External/internal rotation	1054	71.4	<0.0001*

*indicates statistical significance (p<.05)

Clavicular Axial Rotation

Figure 22 shows the correlation of the measured or actual and the predicted values of axial rotation of the clavicle. The r^2 value of 0.84 (Table 26) indicated good correlation between actual and predicted values. An RMS error of 3.50^o was obtained.

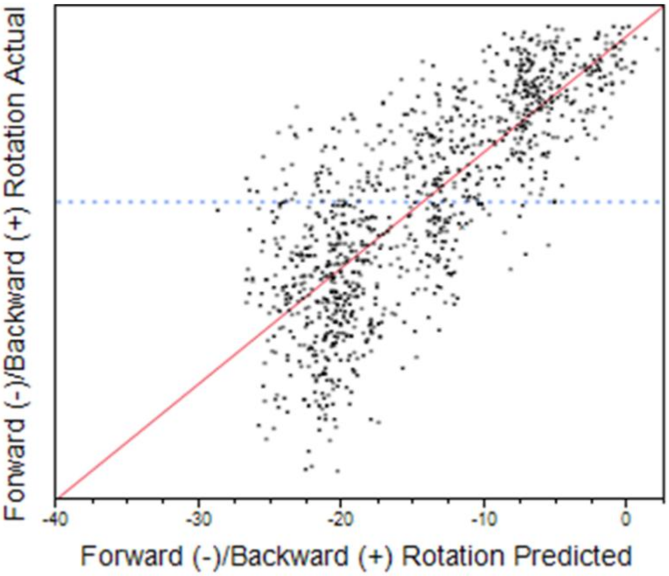


Figure 22: Actual versus predicted values of forward/backward rotation of the clavicle. The red line is the line of best fit between the actual and the predicted values and the blue dotted line is the mean backward rotation recorded across all postures.

Table 26: Summary of the fit of forward (-)/backward (+) rotation of the clavicle.

r^2	0.84
RMS error	3.50°
Number of observations	1083
Mean backward rotation	-14.40°

The parameters of the linear regression model to predict clavicular axial rotation are summarized in Table 27. The initial backward rotation of the clavicle was not a significant predictor of the axial rotation of the clavicle. All three humeral rotation angles significantly contributed to the axial rotation of the clavicle. There was also a significant interaction effect between the elevation angle and axial rotation of the humerus. The clavicle rotated backwards with elevation angle. The clavicle rotated forward slightly as the plane of elevation increased. However, the F-values (Table 28) of the significant independent factors indicated that the contribution of the plane of elevation (F-ratio = 12.6) to axial rotation of the clavicle was considerably less than the other significant independent factors. As the arm elevation increased, the clavicle rotated backwards. While the humeral elevation angle also significantly interacted with the axial rotation of the humerus, the main effect of elevation angle (F-ratio = 3819.9) contributed more to axial rotation of the clavicle than the interaction effect (F-ratio = 108.1).

Table 27: Regression parameters, their corresponding standard errors and p-values for the significant independent factors and two-way interactions determining forward/backward rotation of the clavicle.

Term	**Coefficient**	**Standard Error**	**p-value**
Intercept (initial posture)	0.411	0.830	0.624
Plane of elevation	-0.016	0.004	0.0004*
Elevation angle	-0.201	0.003	<0.0001*
External/internal rotation	0.030	0.003	<0.0001*
Elevation angle*external/internal rotation	-0.0007	0.00007	<0.0001*

*indicates statistical significance (p<.05)

Table 28: The F-ratios and the corresponding p-values of the significant independent factors and two-way interactions determining the forward/backward rotation of the clavicle.

Source	**DF**	**F-ratio**	**p-value**
Plane of elevation	1053	12.8	0.0004*
Elevation angle	1052	3819.9	<0.0001*
External/internal rotation	1053	102.4	<0.0001*
Elevation angle*external/internal rotation	1052	108.1	<0.0001*

*indicates statistical significance (p<.05)

The interaction effect between the elevation angle and the axial rotation of the humerus on axial rotation of the clavicle is illustrated in Figure 23. The interaction effect shows that the effect of axial rotation of the humerus on axial rotation of the clavicle depended on the arm elevation angle. At elevation angles less than 120^o, the clavicle rotated backwards with external rotation of the humerus, forwards with internal rotation of the humerus. But at elevation angles greater than 120^o, the clavicle rotated forwards with external rotation and backwards with internal rotation. Therefore, the change in backward rotation with elevation angle was the greatest when the arm was internally rotated and the smallest when the humerus was externally rotated.

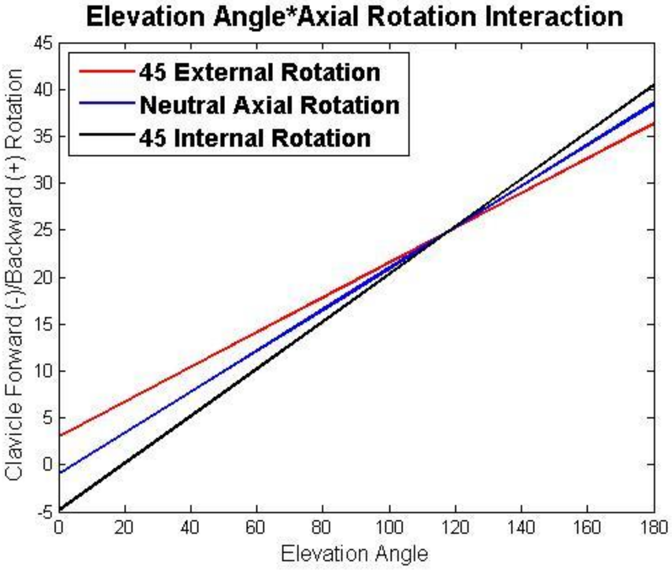


Figure 23: Two-way interaction between the humeral elevation angle and axial rotation of the humerus in determining the forward/backward rotation of the clavicle.

4.3 Comparison of Methods of Measuring Scapular Rotations

The scapular angles were determined using three different methods of measuring scapular position. The method used significantly interacted with thoracohumeral elevation angle and plane of elevation for lateral/medial rotation of the scapula. All three thoracohumeral elevation angles significantly interacted with the method for both scapular tilt and scapular retraction/protraction.

4.3.1 Lateral/medial Rotation of the Scapula

The results of the ANOVA for scapular lateral/medial rotation are summarized in

Table 29. The results indicated that at least one of the methods was significantly different from another method. There was also a significant interaction between the method of measurement and elevation angle and between the method of measurement and the plane of elevation.

Table 29: Results of ANOVA for the lateral/medial rotation of the scapula.

Source	**DF**	**F-Ratio**	**p-value**
Plane of elevation	1	196.8	<.0001*
Elevation angle	1	4712.3	<.0001*
External/internal rotation	1	31.5	<.0001*
Method	2	104.1	<.0001*
Plane of elevation*Elevation angle	1	65.4	<.0001*
Plane of elevation*External/internal Rotation	1	160.3	<.0001*
Method*Plane of elevation	2	15.9	<.0001*
Method*Elevation angle	2	12.5	<.0001*

*indicates statistical significance (p<.05)

Main Effect of Method of Measuring Scapular Position

Post-hoc Tukey's HSD test was performed to determine which method of measurement produced significantly different results. The results are summarized in

Table **30**. Across all postures, all three methods of measuring scapular position were significantly different from each other. Since a negative number denoted lateral scapular rotation, the stylus predicted the greatest amount of lateral rotation across all postures, and the locator estimated the least. The ordered differences between the measurement methods are summarized in Table 31**.** Across all postures, both AMC and the locator significantly underestimated scapular lateral rotation compared to the stylus.

Table 30: Results of post-hoc Tukey's HSD test for lateral/medial rotation of the scapula. The methods not connected by the same letter are significantly different.

Level (Method)		Least Squares Mean	Standard Error
Locator	A	-16.3	1.1
AMC	B	-19.4	1.1
Stylus	C	-20.3	1.1

Table 31: The ordered differences between the lateral/medial rotation measured using the different methods (CL = confidence limit).

Level – Level	Difference	Standard Error Difference	Lower CL	Upper CL	p-value
Stylus – Locator	-4.0	0.3	-4.7	-3.3	<.0001*
AMC –Locator	-3.2	0.4	-3.8	-2.5	<.0001*
Stylus – AMC	-0.9	0.3	-1.6	-0.2	0.0073*

*indicates statistical significance (p<.05)

Interaction Effects: Stylus versus Locator Measurements

There was an ordered interaction between the stylus and the locator measurements and elevation angle (Figure 29). At low elevation angles, there was a relatively large difference between the lateral/medial rotations measured using these two methods but the difference decreased with arm elevation. At 0^o elevation, the locator predicted scapular medial rotation of 6.5^o, whereas the stylus estimated negligible lateral/medial rotation. With arm elevation, both methods estimated lateral rotation of the scapula, but the measurements from the locator were underestimated. This underestimation decreased as overhead elevation occurred. At 180^o elevation, both methods estimated similar amounts of lateral rotation. As the plane of elevation increased the locator predicted less laterally rotated position of the scapula than the stylus at all elevation angles (Figure 30). The underestimation of lateral rotation by the scapular locator increased with an increase in plane of elevation.

Interaction Effects: Stylus versus AMC Measurements

The AMC slightly underestimated scapular lateral rotation at low elevation angles and this difference decreased with an increase in elevation (Figure 29). Across plane of elevation there was no interaction between the two methods (Figure 30).

Interaction Effects: AMC versus Locator Measurements

Since the AMC measurements were similar to the stylus measurements, the interaction between AMC and the locator were similar to the interactions between the stylus and the locator (Figure 29 and Figure 30). The locator underestimated lateral rotation compared to the AMC and the difference decreased with elevation angle and increased with plane of elevation. The differences between the locator and AMC at low elevation angles were slightly less than the differences between stylus and the locator measurements.

4.3.2 Anterior/posterior Tilt of the Scapula

Table 32 summarizes the results of the ANOVA for the effects of humeral posture and method of scapular tracking on anterior/posterior tilt of the scapula. At least one of the methods was significantly different from another method in determining anterior/posterior tilt of the scapula. The method of measuring scapular position significantly interacted with the plane of elevation, elevation and the axial rotation of the humerus.

Table 32: Results of ANOVA for the anterior/posterior tilt of the scapula.

Source	DF	F-Ratio	p-value
Method	2	64.4	<.0001*
Plane of elevation	1	68.3	<.0001*
Elevation angle	1	5364.0	<.0001*
External/internal rotation	1	224.2	<.0001*
Method*Plane of elevation	2	3.6	0.0279*
Method*Elevation angle	2	19.6	<.0001*
Method*External/internal rotation	2	16.6	<.0001*
Plane of elevation*Elevation angle	1	39.1	<.0001*
Plane of elevation*External/internal rotation	1	158.7	<.0001*
Elevation angle*External/internal rotation	1	105.9	<.0001*

*indicates statistical significance (p<.05)

Main Effect of Method of Measurement

Tukey's HSD test (Table 33) revealed that all three methods produced significantly different results from each other. The ordered differences (Table 34) indicated that across all postures, the AMC and the locator overestimated the anterior/posterior tilt of the scapula compared to the stylus. The AMC method also resulted in significantly greater anterior/posterior tilt values than the locator.

Table 33: Results of post-hoc Tukey's HSD test for anterior/posterior tilt of the scapula. The methods not connected by the same letter are significantly different.

Level (Method)		Least Squares Mean	Standard Error
Locator	A	18.9	1.1
AMC	B	17.2	1.1
Stylus	C	15.0	1.1

*indicates statistical significance (p<.05)

Table 34: The ordered differences between the anterior/posterior tilt measured using the different methods (CL = confidence limit).

Level – Level	Difference	Standard Error Difference	Lower CL	Upper CL	p-value
AMC – stylus	3.9	0.3	3.1	4.7	<.0001*
Locator – stylus	2.2	0.3	1.4	3.0	<.0001*
AMC – locator	1.7	0.4	0.9	2.5	<.0001*

*indicates statistical significance (p<.05)

Interaction Effects: Stylus versus Locator Measurements

At low elevation angles, the locator underestimated posterior tilt but overestimated it at greater elevation angles. The overestimation of posterior tilt by the scapular locator increased with humeral elevation (Figure 31). Therefore, the change in scapular posterior tilt was greater when the locator was used than when the stylus was used to measure scapular position. For example, when the humerus was 45^o externally rotated in the frontal plane, the locator estimated 60.5^o posterior tilt of the scapula, while the stylus detected only 49.7^o of posterior tilt over 180^o of humeral elevation. The change in scapular tilt was 10.8^o more when the scapular locator was used. A slight decrease in differences between stylus and locator measurements occurred with internal rotation (Figure 32). The difference between the measurements changed with the plane of elevation (Figure 33). The difference between the two methods ranged from 0.5^o, which occurred at 90^o elevation in 90^o plane of elevation, to 8.9^o, which occurred at 180^o of elevation in frontal plane. At low elevation angles, below 45^o of humeral elevation, the difference between the locator and the stylus increased as the plane of elevation changed from frontal plane to sagittal plane. For overhead postures however, the difference between the two methods decreased as the plane of elevation changed from the frontal plane to the sagittal plane. The locator was less sensitive to the change in plane of elevation. Over all planes of elevation, the change in scapular tilt measured using the locator was 3.1^o less than the scapular tilt measured using the stylus.

Interaction Effects: Stylus versus AMC Measurements

There was an ordinal interaction between the AMC and the stylus and arm elevation (Figure 31). The AMC underestimated posterior tilt at low elevation angles and overestimated it higher elevation angles. The deviation of the AMC results from the stylus results increased with arm elevation. At neutral axial rotation, the difference between the measurements between the two methods ranged from 0.2^o at 45^o elevation in the sagittal plane to 7.6^o at 180^o arm elevation in 45^o plane. The overestimation of posterior tilt by the AMC decreased with internal rotation and increased with external rotation of the humerus (Figure 32). The AMC was more sensitive to axial rotation than the stylus in measuring anterior/posterior tilt of the scapula. The interaction between the two methods with change in plane was relatively weak (Figure 33). The overestimation of posterior tilt by the AMC decreased slightly with the change in the plane of elevation.

Interaction Effects: Locator versus AMC Measurements

When the humerus was externally rotated, the locator slightly underestimated posterior tilt but when the humerus was internally rotated, the locator slightly overestimated posterior tilt (Figure 31 and Figure 32). Both methods measured similar values during neutral axial rotation of the humerus. Only slight changes between the measurements between these two methods occurred with elevation angle (Figure 31) and with change in plane of elevation (Figure 33).

4.3.3 Retraction/protraction of the Scapula

The ANOVA results for retraction/protraction are summarized in Table 35. Across all arm postures, at least one of the methods was significantly different from another method. The method used to determine retraction/protraction of the scapula also significantly interacted with the plane of elevation, elevation angle and the axial rotation of the humerus.

Table 35: Results of ANOVA for the retraction/protraction of the scapula.

Source	**DF**	**F-Ratio**	**p-value**
Method	2	236.0	<.0001*
Plane of elevation	1	1798.6	<.0001*
Elevation angle	1	287.1	<.0001*
External/internal rotation	1	108.4	<.0001*
Method*Plane of elevation	2	48.0	<.0001*
Method*Elevation angle	2	6.5	0.0016*
Method*External/internal rotation	2	92.7	<.0001*
Plane of elevation*Elevation angle	1	30.6	<.0001*
Plane of elevation*External/internal rotation	1	11.4	0.0007*
Elevation angle*External/internal rotation	1	145.2	<.0001*

*indicates statistical significance (p<.05)

Tukey’s HSD test revealed that across all postures, the AMC and the stylus were not significantly different from each other; however, both methods were significantly different from the locator (Table 36). Ordered differences (Table 37) showed that compared to both the AMC and the stylus, the locator over-estimated the scapular protraction.

Table 36: Results of post-hoc Tukey’s HSD test for retraction/protraction of the scapula. The methods not connected by the same letter are significantly different.

Level (Method)		**LSM**	**Standard Error**
Locator	A	42.4	1.1
AMC	B	37.1	1.1
Stylus	B	36.8	1.1

Table 37: The ordered differences between the retraction/protraction of the scapula measured using the different methods (CL = confidence limit).

Level – Level	Difference	Standard Error Difference	Lower CL	Upper CL	p-value
Locator – stylus	5.6	0.3	4.9	6.3	<.0001*
Locator – AMC	5.2	0.3	4.6	5.9	<.0001*
AMC – stylus	0.4	0.3	-0.3	1.1	0.400

*indicates statistical significance (p<.05)

Interaction Effects: Stylus versus Locator

The locator overestimated scapular protraction and retraction at all postures, that is, at all humeral elevation angles in all planes of elevation, regardless of the axial rotation of the humerus (Figure 34, Figure 35 and Figure 36). There was only a slight interaction with the change in elevation angle and with change in axial rotation of the humerus (Figure 34 and Figure 35) and these two methods did not interact over the change in plane of elevation (Figure 36). The locator consistently overestimated scapular protraction as the plane of elevation and axial rotation of the humerus changed. There was only a slight interaction between the two methods. At 180^o arm elevation, where the largest difference occurred between the two methods, the difference in measured protraction ranged from 5.3^o at 45^o internal rotation of the humerus to 7.3^o at 45^o external rotation.

Interaction Effects: Stylus versus AMC

The stylus and the AMC interacted with plane of elevation, humeral elevation and with the axial rotation of the humerus. In the frontal plane, when the humerus was externally rotated, at low elevation angles, the AMC underestimated scapular protraction and this underestimation decreased with elevation angle (Figure 34). However, when the humerus was neutral or internally rotated, the AMC overestimated scapular protraction and this overestimation increased with elevation angle. Likewise, in the 45^{o} to frontal plane and the sagittal plane, the overestimation of scapular protraction by the AMC increased with elevation angle. The maximum difference between the two methods occurred in the sagittal plane when the humerus was internally rotated.

In the frontal plane, at low elevation angles, the AMC underestimated protraction, and this underestimation decreased with internal rotation of the humerus (Figure 35). But for overhead postures, the AMC overestimated retraction and this overestimation increased with internal rotation. In the 45^{o} plane of elevation and the sagittal plane of elevation, the AMC overestimated protraction and this overestimation increased with internal rotation of the humerus.

Both methods estimated scapular protraction with an increase in the plane of elevation (Figure 36). The AMC estimated a greater change in protraction as the plane of elevation changed than the scapular locator. When the humerus was externally rotated, the AMC underestimated protraction in the frontal plane but overestimated it in the sagittal plane. When the humerus was neutral or internally rotated, the AMC overestimated protraction and the difference between the methods increased with plane of elevation.

Interaction Effects: Locator versus AMC

In the frontal plane, locator overestimated protraction but the difference between the two methods decreased with elevation angle (Figure 34). In the 45^{o} plane, the same trend occurred, except when the humerus was internally rotated, where protraction was overestimated by the AMC and the overestimation increased with elevation angle. The overestimation by the AMC also occurred in the sagittal plane.

In the frontal plane, the AMC underestimated protraction but this underestimation decreased with internal rotation (Figure 35). In the 45^o plane, the AMC underestimated when the humerus was externally rotated of the humerus and overestimated protraction when the humerus was internally rotated. The differences between the two methods increased with axial rotation of the humerus. In the sagittal plane, the AMC overestimated scapular protraction and this overestimation increased with internal rotation of the humerus.

When the humerus was externally rotated, the AMC underestimated protraction and this underestimation decreased with the plane of elevation (Figure 36). When the humerus was neutral, the AMC underestimated protraction at lower values of planes of elevation, but overestimated protraction as the plane of elevation moved towards the sagittal plane. When the humerus was internally rotation, the AMC overestimated protraction and this protraction increased with the plane of elevation.

V. DISCUSSION

This study had two major purposes:

1. To describe and quantify the shoulder rhythm by determining regression equations that predict the bone orientations of the scapula and the clavicle based on the externally measured positions of the humerus relative to the trunk.
2. To compare the scapular bone orientations obtained using three methods: the scapular locator, stylus and the AMC

The regression models were determined using a wide range of humeral postures, which spanned over full range of humeral elevation and axial rotation in planes of elevation from 0^o to 90^o. The current study is the first study to include the effect of axial rotation of the humerus as a determinant of scapular and clavicular positions. Overall, the scapular and clavicular movements estimated using the obtained models show good agreement with results of previous studies. The obtained models can be incorporated into shoulder models so that realistic representations of the shoulder complex can be achieved when simulating postures to estimate structural loads placed on the shoulder.

For the purpose of comparing the methods of scapular tracking, the stylus was considered the best possible non-invasive method and thus it was used as the gold standard to compare the locator and the AMC measurements. The stylus has been considered an accurate tool by de Groot (1997), who estimated a palpation and digitization error of less than 3^o using the stylus. Previously, the stylus has been used by de Groot and Brand (2001) to measure the orientation of the scapula and subsequently determine prediction models of shoulder rhythm. Although the stylus measurements of the scapular position have been shown to be different from bone-pins measurements at high elevation angles (Bourne et al., 2009), during data collection, this method appeared to be the least affected by the soft tissue deformation that occurred with humeral movement. The locator could not be aligned with all three landmarks of the scapula for many postures, and the acromion skin surface methods, such as electromagnetic sensors and AMCs, have been shown to be highly influenced by the soft-tissue for overhead arm postures (van Andel et al., 2009; Karduna et al., 2001). Recently, reliability of using a stylus in the sagittal plane was tested over humeral elevation of 0^o to 120^o and interclass coefficient values that ranged from 0.70 and 0.99 were obtained, indicating good to excellent reliability of the measurements (Lempereur, Brochard, Burdin andRemy-neris, 2010). Therefore, it was assumed that this method provided the most accurate measurements of scapular position.

5.1 Addressing the Hypotheses

Hypothesis 1

It was hypothesized that all dependent measures of the shoulder rhythm would be influenced by all components of the relative orientations of the humerus and the thorax, specifically by the plane of elevation, amount of elevation and the axial rotation of the humerus. All three throracohumeral angles significantly influenced scapular lateral/medial rotation and anterior/posterior tilt and clavicular retraction/protraction and axial rotation. Scapular retraction/protraction was significantly influenced by all factors except for the axial rotation of the humerus. The thoracohumeral plane of elevation was analogously not significantly influential for clavicular elevation/depression rotation, but the other factors were. As a whole, the results of this study supported hypothesis 1.

Hypothesis 2

It was hypothesized that the differences between the scapular tracking methods would increase with elevation angle. The change in lateral/medial rotation of the scapula with elevation angle did not help to support this hypothesis since the differences between the three methods decreased with elevation angle. However, this hypothesis proved to be true for anterior/posterior tilt of the scapula for overhead arm postures. For scapular retraction/protraction, this hypothesis was supported by the increasing differences between the locator and the stylus and between the AMC and the stylus except in abduction when the humerus was externally rotated. This hypothesis was not true for the differences in measurements of scapular anterior/posterior tilt using the locator and AMC for all planes of elevation and axial rotations. Hypothesis 2 was partially supported.

Hypothesis 3

It was hypothesized that the differences between the methods would increase with axial rotation of the humerus. The lateral/medial rotations detected by the three methods did not change with axial rotation of the humerus. For scapular anterior/posterior tilt, this hypothesis was partially supported for external rotation during overhead arm postures only, where the difference between the methods increased with external rotation of the humerus, but decreased with internal rotation. For retraction protraction, stylus and the locator differences stayed relatively consistent with axial rotation, but the other methods supported the hypothesis. Overall, hypothesis 3 was partially supported.

Hypothesis 4

The fourth hypothesis was that the scapular locator measurements would deviate less from the stylus measurements than the AMC measurements. Based on the main effects of method on the scapular angles, this hypothesis was only supported for anterior/posterior tilt. The main effect of method on lateral/medial rotation and the retraction/protraction of the scapula showed that the deviation between the stylus and the locator measurements were greater than the AMC and the stylus measurements. Therefore, the current study partially supported this hypothesis.

5.2 Thoracohumeral angles

5.2.1 Plane of Elevation

Differences were present between the plane of elevation measured using the goniometer during data collection and those mathematically calculated using Euler angles for all arm postures (Table 6). For arm postures at 0^o elevation, the participants were required to keep the upper arm aligned with the long axis of the trunk. A slight misalignment caused a relatively large deviation from frontal plane of elevation. Therefore, the plane of elevation at 0^o humeral elevation varied a lot from the frontal plane. At 90^o and greater elevation angles in the frontal plane, the plane of elevation was overestimated, and the overestimation increased with elevation angle. This may be because maximum elevation of the humerus takes place in planes anterior to the frontal and scapular plane (An, Korinek, Tanaka and Morrey, 1991). Therefore, as the elevation angle approached maximum elevation, the plane of elevation moved anteriorly. The 45^o to the frontal and the sagittal planes of elevation were both underestimated for all postures. The participants may have rotated their trunks axially to place their arm in these planes. This overestimation of frontal plane and the underestimation for 45^o plane and the sagittal plane may have occurred because motion in the scapular plane is less complex and more natural since the humeroscapular muscles have a more direct line of action during arm elevation in the scapular plane or 30^o anterior to the frontal plane (Doody et al., 1970; Freedman and Munro, 1966; Johnston, 1937). For arm postures at greater elevation angles, lack of flexibility caused by upper body muscle definition, such as large anterior deltoids or pectoralis muscles may have also prevented the participants from attaining arm elevation in the sagittal plane without rotating their trunks. This also helps to explain the increasing underestimation of the sagittal plane of elevation with increasing arm elevation. The frontal plane values and the 45^o plane values increased with elevation angle while the sagittal plane values decreased with elevation angle. This may be because the humerus tends to move towards the same final position at the end range of humeral elevation regardless of the plane of elevation (Meskers et al., 2007). This final position is an externally rotated position in the scapular plane (Meskers et al., 2007). The planes of elevation also interfere with each other because the maximum arm elevation positions approach a singular position in the Euler decomposition (Meskers et al., 1998).

5.2.2 Elevation Angle

The thoracohumeral elevation angles were generally underestimated for all postures except for the 0^o humeral elevation postures (Table 7). The 0^o arm elevation was never achieved due to the soft-tissue overlying the humerus and the trunk that prevented the local y-axis of the humerus from being parallel to the y-axis of the trunk. At greater elevation angles, thoracohumeral elevation was underestimated and the underestimation of thoracohumeral elevation angle increased with arm elevation. A pole was placed behind the participants' backs as a reminder to keep their trunk in an upright position, but the trunk position was not constrained and the participants tilted their trunks with respect to the global coordinate system as they elevated their arms, especially for the overhead postures. The deviation of the actual thoracohumeral elevation from the externally measured thoracohumeral elevation obtained using a goniometer is not uncommon. McClure et al. (2001) found that even though participants were required to maintain an arm elevation of 90^o during humeral axial rotation, the actual elevation during this task ranged from 75^o to 95^o.

None of the participants could elevate their arm 180^o relative to the trunk, so, they maximally elevated their arms for these postures. It has been reported that greater elevation angles than those obtained in this study can be attained (Braman et al., 2009), but in the current study the elbow was flexed at 90^o to visually monitor the pre-determined axial rotation of the humerus, whereas the elbow was fully extended and the participants were free to choose the plane of elevation and the axial rotation of the humerus in Braman et al. (2009). Since the humerus externally rotates and the plane of elevation moves anteriorly during humeral elevation, it is possible to attain greater arm elevation with the elbow extended and when the other thoracohumeral angles are not restricted (McClure et al., 2001, Ludewig et al., 2009). Regardless, the maximum arm elevation attained by participants in this study has been shown to be adequate to perform many overhead functional tasks, which included ADLs such as combing hair and an overhead reaching task (Magermans e t al., 2005; van Andel, Wolterbeek, Doorenbosch, Veeger and Harlaar., 2008; Ebaugh and Spinelli, 2010).

In all three planes of elevation, highest elevation was achieved during neutral axial rotation postures. In plane 0^o and plane 45^o, greater elevation angles were achieved with the arm externally rotated than when the arm was internally rotated. This was because it was difficult to internally rotate the humerus at higher elevation angles since external rotation clears the greater tuberosity from beneath the coracoacromial arch allowing for greater elevation (Browne, Hoffmeyer, Tanaka, An and Morrey, 1990). It also relaxes the capsular ligamentous constraints (Browne et al., 1990).

5.2.3 Axial Rotation

For neutral axial rotation postures, the axial rotation of the humerus was never calculated to be 0^o (Table 8). Although during the data collection, participants were required to keep their thumbs parallel to the upper arm for these postures, it was still possible to rotate the humerus and keep the thumb parallel to the upper arm. Therefore, it was extremely difficult to determine whether the humerus was mathematically neutral. During the neutral axial rotation postures, external rotation of the humerus occurred with elevation. This was not surprising since external rotation of the humerus is associated with arm elevation (Ludewig et al., 2009). McClure et al. (2001) also observed external rotation of the humerus with arm elevation in the scapular and sagittal plane of elevation despite instructing the participants not to axially rotate their arms (Figure 24A and Figure 24B). In the current study a sharp increase in external rotation occurred during first 50^o of arm elevation and it leveled off at greater elevation (Figure 25), but McClure et al. (2001) observed continued external rotation of the arm with elevation angle. Averaged across participants, approximately 20^o and 10^o of external rotation occurred from 50^o to 140^o of arm elevation in scapular and sagittal planes of elevation (Figure 25). Much like McClure et al. (2001), the current study also found that greater external rotation of the humerus occurred in the sagittal plane than the 45^o plane (Figure 24 and Figure 25). The increasing external rotation of humerus in all three planes further supports the premise stated by Meskers et al. (1997) that the humerus tends to move towards a similar final position of external rotation in the scapular plane at the end range of humeral elevation, regardless of the plane of elevation. (Meskers et al.,1997).

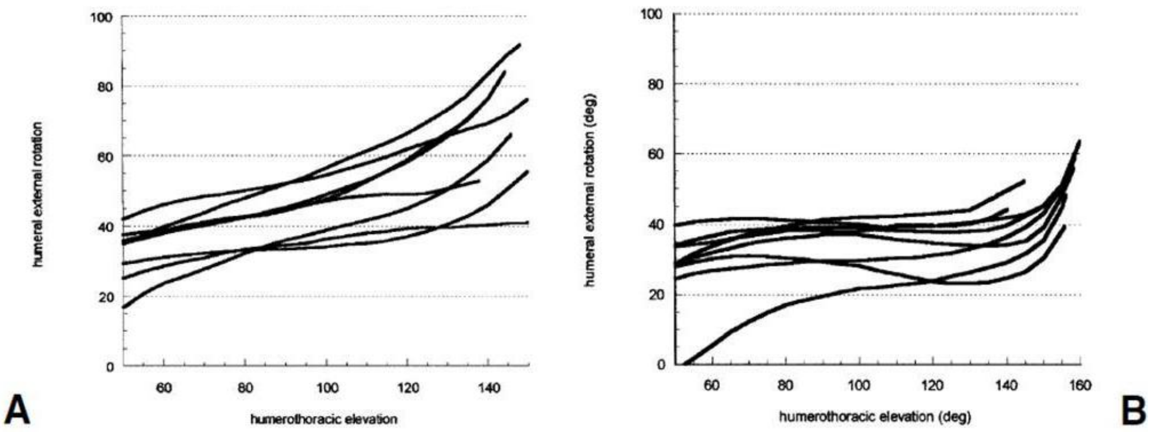


Figure 24: From McClure et al. (2001), the lines represent the humeral external rotation relative to the thorax during the arm elevation for each subject in the scapular plane (A) and the sagittal plane of elevation (B).

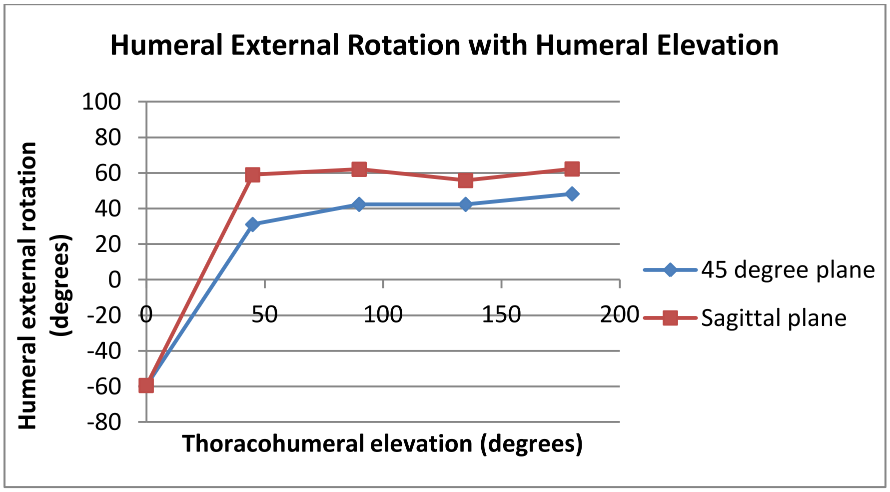


Figure 25: The average humeral external rotation that occurred during thoracohumeral elevation in the 45^{o} plane and the sagittal plane in the current study.

5.3 Regression Equations of the Shoulder Rhythm

Regression models obtained to estimate the positions of the scapula and the clavicle relative to the thorax in the current study have several strengths. Unlike the previous models obtained by Hogfors et al. (1991) and later modified by Karlsson and Peterson (1992) and Makhsous (1999), the models obtained in this study are simpler since they do not include trigonometric functions. The models are parsimonious and more practical for the purpose of adapting and including them into shoulder models used to simulate postures experienced in workplaces to estimate structural loads placed on the shoulder. Additionally, the models in the current study were obtained using arm postures that extended over a wider range of humeral postures, such as maximum elevation angle, 0^o to 90^o plane of elevation, and full range of axial rotation of the humerus. This is a significant improvement from the models obtained by Hogfors et al. (1991) since they did not quantify overhead shoulder rhythm using *in vivo* measurements, but instead it was extrapolated based on heuristic anatomical judgments. Therefore, the models obtained in this study provide a more realistic representation of the shoulder bones of overhead work postures. These postures are of particular importance since overhead work is associated with shoulder pathology (Grieve and Dickerson, 2007; Mani and Gerr, 2000).

While the method of attaining regression equations to estimate the scapular and clavicular positions was similar to de Groot and Brand (2001), the current study is the first study to include the effect of axial rotation of the humerus on the scapular and clavicular positions. Since external/internal rotation of the humerus had a statistically significant influence on all scapular angles and clavicular angles except scapular retraction/protraction ($p<0.0001$), it is a necessary independent factor to estimate scapular and clavicular positions. This study is also the first to include two way interactions between the significant independent factors in the models when they provided additional variance explanation of greater than 2%. Therefore, it is anticipated that these models can represent the geometry of the shoulder complex more accurately than the past models of shoulder rhythm.

5.3.1 Subject-Related Factors

Gender, age and anthropometric factors (height and weight) did not significantly influence any of the scapular or the clavicular angle predictions (Table 9). This agreed with the findings of de Groot and Brand (2001). The participants in this study were all university-aged healthy students. Thus the age range was only 6 years. If this range was larger, age may have influenced one or more of predicted angles. Likewise, if the participants had a higher diversity of body types, then perhaps height and weight effects would have existed.

5.3.2 Rest Position of the Scapula and Clavicle

The rest position of the scapula and clavicle were similar to the rest positions reported in previous research, with some differences in magnitudes of lateral rotation of the scapula and the elevation of the clavicle (Table 38). The differences in the rest position may be because rest position in previous research was defined as the arm by the side. In this position, due to the soft tissue overlying the humerus and the trunk, humeral elevation is not empirically 0^{o}. For example, at rest Fung et al. (2001) determined approximately 20^{o} of humeral elevation while McClure et al. (2001) estimated 15^{o} of humeral elevation at rest. But when determining the scapular and clavicular position at rest in this study, 0^{o} of humeral elevation was used as input in the models. The model for clavicular elevation appears to overestimate the elevation. Other factors may have also played a role, such as skin displacement, variability in marker placement or the methods used to measure the positions of the bones.

Table 38: The average rest positions of the scapula and the clavicle calculated in the current study and in previous research.

Scapula					
	Current Study	**McClure et al. (2001)**	**Fung et al. (2001)**	**Meskers et al. (2007)**	**Ludewig et al. (2009)**
Lateral Rotation	1.68^{o}	15^{o}	5^{o}	5.4^{o}	10^{o}
Anterior tilt	11.1^{o}	5^{o}	2^{o}	13.5^{o}	9^{o}
Protraction	30^{o}	35^{o}	37^{o}	41.1^{o}	33^{o}
Clavicle					
	Current Study	**Meskers et al. (1998)**	**Fung et al. (2001)**	**Ludewig et al. (2004)**	**Ludewig et al. (2009)**
Elevation	14.6^{o}	3^{o}	4^{o}	1.6	5.9
Retraction	13.3^{o}	-20^{o}	17^{o}	18.2	19.2
Forward Rotation	0.4^{o}	0^{o}	2.5^{o}	0.5	-0.1

5.3.3 Continuous Prediction Models

The r^2 values of the actual and predicted values plots were used to determine how well the obtained models represented the actual data. Although de Groot and Brand. (2001) did not report r^2 values, the plots of the estimated angles and the recorded angles showed similar patterns to those obtained in this study (Figure 26). In the current study, the smallest r^2 value was attained for retraction/protraction of the scapula ($r^2 = 0.60$). The visualization of the data indicated that de Groot and Brand (2001) also attained the least variance explanation for retraction/protraction.

For all the scapular angles and for clavicular retraction/protraction and axial rotation, linear models obtained were considered sufficient if quadratic models did not provide additional variance explanation of greater than 2%. Through visualization of the linearity of the recorded and the estimated clavicular protraction values, de Groot and Brand (2001) also reported that linear models were appropriate for these rotations (Figure 26). Other studies (Fung et al., 2001; Karduna et al, 2001; McQuade and Smidt, 2001; McClure et al, 2001) on the other hand indicate a non-linear trend of at least one of the scapular or clavicular angles with changes in thoracohumeral angles. To characterize a non-linear relationship of lateral/medial rotation of the scapula and humeral elevation, McClure et al. (2001) fit both a linear and a polynomial fit to upward rotation of the scapular and obtained an r^2 value of .957 for a linear relation and 0.999 for a cubic relation during dynamic elevation of the arm. Even though the r^2 value increased with the polynomial fit, it is assumed that this increase is not large enough to replace the simpler linear relation with a polynomial relation.

For elevation of the clavicle, a quadratic model was obtained. (Table 21). de Groot and Brand (2001) determined a linear relation for humeral elevation but noted that the linear relation between the recorded clavicular elevation and estimated clavicular values was not clear (Figure 26). It is unlikely that that a greater r^2 value would not have resulted if humeral elevation was included as non-linear factor.

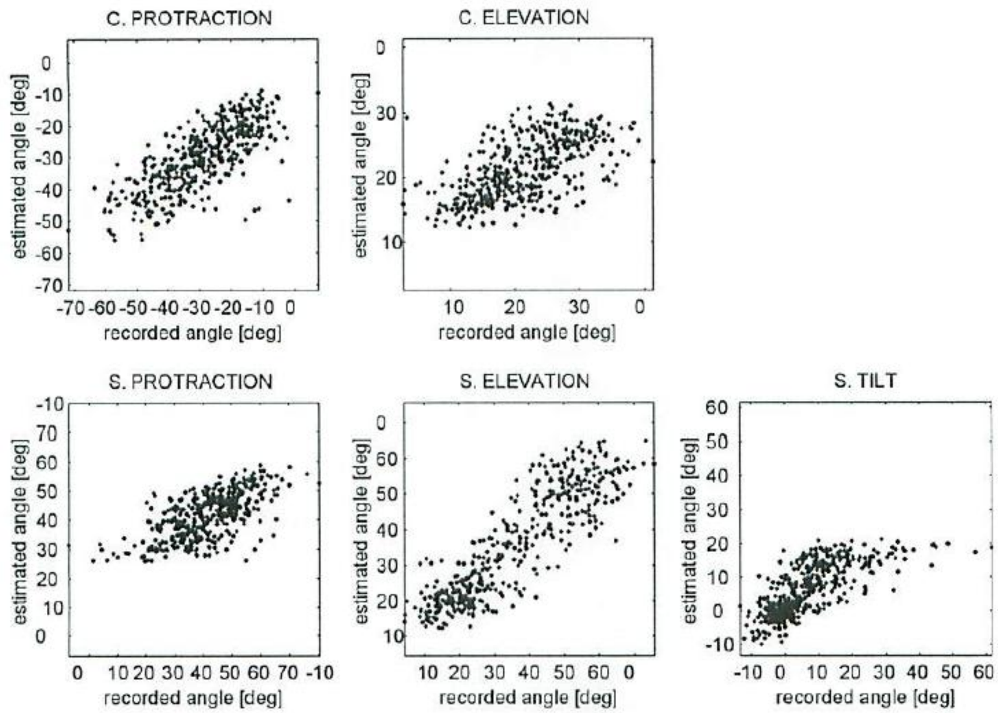


Figure 26: From de Groot and Brand (2001), the correlations between the recorded and the estimated data for the clavicular and the scapular angles. The top row represents the clavicle angles and the bottom row represents the scapular angles.

Lateral/medial Rotation of the Scapula

The scapula laterally rotated with humeral elevation and this is a common finding reported by previous studies. The regression coefficient obtained in the current study for the humeral elevation angle was 0.238 (Table 12) while de Groot and Brand (2001) obtained -0.396 (Table 39). After taking into account the different sign conventions, both studies estimate an increase in lateral rotation with humeral elevation. The difference in the regression parameters between the two studies can be attributed to part of the variance in the current study being explained by axial rotation of the humerus and the two-way interaction between the plane of elevation and axial rotation. McClure et al. (2001) and van Andel et al. (1999) also report lateral rotation of the scapula with humeral elevation. Lateral rotation is a necessary rotation to allow the greater tuberosity of the humerus to pass freely beneath the acromion (Ludewig and Cook, 2000). Lateral rotation also helps align the glenoid with the humeral head to maintain congruency with the humeral head during arm elevation (Ludewig et al., 2009). In the frontal plane, Ludewig et al. (2009) reported a lateral rotation increase from 10^o to 52^o over arm elevation from 15^o to 140^o. In the current study, the model estimated an increase in lateral rotation from 2^o to 35^o over 15^o to 140^o of arm elevation. van Andel et al. (2009) reported an increase from 12^o to 50^o in lateral rotation over 20^o to 100^o of humeral elevation. The differences in the magnitude of lateral rotation between the previous research and the current study can be attributed to either the different methodologies for measuring scapular lateral rotation or that the axial rotations of the humerus was not restricted in McClure et al. (2001) or van Andel et al. (1999).

Table 39: Summary of the linear regression parameters for the independent variables determining the clavicular and the scapular output parameters obtained by de Groot and Brand (2001).

Dependent Variable		**Plane of Elevation**	**Elevation**
Scapula	Lateral Rotation	-0.079	0.396
	Protraction	0.140	-0.049
	Posterior Tilt	-0.028	0.184
Clavicle	Elevation	-0.046	0.123
	Protraction	0.120	-0.242

While interaction effects have not been included in the prediction models of shoulder rhythm prior to this research, this is not the first study to find a significant effect of plane of elevation and axial rotation of the humerus on lateral/medial rotation. Ludewig et al. (2009) and McQuade and Smidt (1998) also reported a significant influence of the plane of elevation on lateral rotation of the scapula. In the current study, when the humerus was externally rotated, the lateral rotation of the scapula decreased with the plane of elevation. Ludewig et al. (2009) also reported significantly less lateral rotation in the frontal plane than the sagittal plane, but axial rotation was not measured. McQuade and Smidt (2001) did not find a significant effect of axial rotation on scapular upward rotation, but only the effect of passive axial rotation that occurred with humeral elevation was studied. Therefore, range of the axial rotation used by McQuade and Smidt (2001) was smaller than the range of axial rotation of the humerus examined in this study. Sagano et al. (2006) investigated the effect of maximum external and internal rotation on scapular upward rotation at humeral elevation from 0^o to 90^o in the scapular plane, defined as 30^o anterior to the frontal plane (Table 40). In the scapular plane, the upward rotation of the scapula increased with external rotation, while in this study, in the 45^o plane, the opposite trend was observed. The current study also estimated less lateral rotation at 90^o humeral elevation compared to Sagano et al. (2006). Since Sagano et al. (2006) used an electromagnetic sensor and the current study used a stylus to measure scapular angles, it is unknown whether Sagano et al. (2006) overestimated or this study underestimated the lateral rotation of the scapula. The maximum average external and internal rotations of the humerus obtained by Sagano et al. (2006) were 108.6^o ($\pm 12.5^o$) and 65.8^o ($\pm$ 8.2^o), respectively, while 45^o of external and internal rotation were used as input in the model obtained in the current study.

Table 40: Summary of the scapular upward rotation values obtained by Sagano et al. (2006) and the current study at four elevation postures with arm at maximum internal rotation, neutral and maximum external rotation, and their respective standard deviations.

Elevation Angle	**External Rotation**		**Neutral Rotation**		**Internal Rotation**	
	Sagano et al. (2006)	**Current study**	**Sagano et al. (2006)**	**Currents tudy**	**Sagano et al. (2006)**	**Current study**
0^o	0.3^o	1.0^o	2.3^o	1.2^o	1.9^o	3.4^o
30^o	5.3^o	6.1^o	4.9^o	8.3^o	8.3^o	10.5^o
60^o	18.7^o	13.2^o	14.1^o	15.4^o	21.9^o	17.6^o
90^o	36.2^o	20.3^o	27.5^o	22.5^o	40.2^o	24.7^o

Scapular Anterior/posterior Tilt

Posterior tilt of the scapula was observed with humeral elevation but the obtained models overestimate posterior tilt compared to previous research. Functionally, posterior tilt allows for clearance for the humeral head and the rotator cuff tendons under the anterior portion of the acromion during elevation to prevent impingement (McClure et al., 2001). de Groot and Brand (2001) determined the regression coefficient to be 0.184 (Table 39) for humeral elevation, while 0.298 was attained in this study (Table 15), meaning that the models obtained in the current study estimate greater posterior tilt of the scapula with humeral elevation than de Groot and Brand (2001). The posterior tilt in the current study was also overestimated compared to Ludewig et al. (2009), who reported an increase of 21^o in posterior tilt as the participants elevated their arms from 20^o to 140^o. Using the models obtained in the current study, 48^o of posterior tilt results over the same range. The overestimation may be because Ludewig et al. (2009) did not constrain axial rotation of the humerus, whereas 0^o axial rotation was used as input in the model obtained in this study.

Although posterior tilt occurred with increasing plane of elevation in this study, it did not agree with previous studies. Fung et al. (2001) reported that scapular tilt did not change with plane of elevation except between 30°-40° of humeral elevation, where the posterior tilt was larger for sagittal plane than the frontal and the scapular (40° to frontal) plane. Ludewig et al. (2009) also reported that there was no significant difference between the three planes of humeral elevation for scapular tilting. In the current study, based on the F-ratios (Table 16), the effect of plane of elevation was not as great as the effect of the humeral elevation angle. In contrast to the current study, de Groot and Brand (2001) reported anterior tilt with increasing plane of elevation. This means that the overestimation of posterior tilt by the current study compared to de Groot and Brand (2001) will be even greater with increasing plane of elevation.

The posterior tilt that occurred with humeral elevation was overestimated compared to previous research but posterior tilt that occurred with the axial rotation of the humerus was underestimated. The results of this study indicated posterior tilting of the scapula with external rotation of the humerus and the influence of external rotation on scapular tilt was less than the plane of elevation and elevation angle, albeit statistically significant. McClure et al. (2001) and van Andel et al. (2009) also examined the effect of axial rotation of the humerus on scapular tilting. Over the range of 80° external rotation to 45° internal rotation at 90° abduction, approximately 20° of posterior tilt was estimated by McClure et al. (2001). In van Andel et al. (2009), anterior tilt was estimated over axial rotation range of 90° external rotation to 60° internal rotation at 90° humeral abduction. Five degrees of posterior tilt was estimated using the locator and 11° was estimated using an AMC (van Andel et al., 2009). Over the same range of axial rotation at 90° abduction, the models in the current study estimate 3.2° of posterior tilt. This means that although the model overestimates posterior tilt during humeral elevation, it slightly underestimates scapular tilt that occurs with axial rotation of the humerus, but further comparisons at other elevation angles would be required to conclude whether this overestimation occurs at all elevation angles.

Scapular Retraction/protraction

Plane of elevation and elevation angle had a significant ordinal interaction effect on the retraction/protraction of the scapula (Table 12). In the frontal plane, the models in the current study estimated approximately 1.5^o of retraction with elevation from 0^o to 180^o. This is similar to Ludewig et al. (2009) who reported an average retraction of 2^o as the arm elevated from 0^o to 140^o, but Ludewig et al. (2009) averaged this across three planes of elevation. At more anterior planes of elevation, protraction of the humerus occurred with elevation and the rate of protraction increased with the plane of elevation. Protraction of the scapula is necessary along with lateral rotation of the scapula as the plane of elevation moves towards to sagittal plane to align the glenoid so that it is congruent with the humeral head (Ludewig et al., 2009).

Unlike scapular lateral rotation and anterior-posterior tilt, F-values (Table 19) indicated that plane of elevation had a greater influence on scapular retraction/protraction. Bourne et al. (2009) obtained the greatest influence of change in plane on transverse-joint angle of the scapulothoracic joint, which in this case is retraction/protraction. de Groot and Brand (2001) and Fung et al. (2001) also concluded that protraction changes more with change in plane of elevation than with change in elevation angle. Ludewig et al. (2009) reported that protraction in the sagittal plane was significantly greater than protraction in the frontal plane ($p<0.0001$). There was an average and statistically significant difference of 7.5° in the measured scapular protraction between frontal plane and the scapular plane and 7° difference between the scapular plane and the sagittal plane (Ludewig et al., 2009), suggesting that the plane of elevation had a linear effect on the protraction/retraction of the scapula.

Clavicular Elevation/depression

Unlike previous research, plane of elevation did not significantly influence clavicular elevation in the current study. Fung et al. (2001), Ludewig et al. (2004), Ludewig et al. (2009) and de Groot and Brand (2001) reported a significant influence of plane of elevation on clavicular elevation. Once again, this may be because some of the variance in determining clavicular elevation in this study was explained by the axial rotation of the humerus, which was not considered in previous efforts.

Regardless, similar to this study, both de Groot and Brand (2001) and Fung et al. (2001) reported that the clavicle elevated with humeral elevation in all planes of elevation. Clavicular elevation occurs with scapular lateral rotation by means of coracoclavicular and the acromioclavicular ligaments (Ludewig et al., 2009). A regression parameter of .002 was attained for quadratic relation of the elevation angle and 0.057 for the linear relation of humeral elevation in this study, compared to 0.123 attained by de Groot and Brand (2001). The difference in these coefficients can be explained by the inclusion of axial rotation and the humeral elevation as a quadratic factor in the regression model obtained in this study.

Clavicular Retraction/protraction

The clavicle retracted with humeral elevation (Table 24), but the clavicular retraction measured in the current study is overestimated compared to previous research. This may be because during data collection, acromioclavicular reflective marker appeared to move posteriorly with the skin overlying the acromion during humeral elevation. From 15^o to 150^o of humeral elevation, Fung et al. (2001) obtained approximately 30^o of clavicular retraction, whereas the model in the current study estimated 48^o of clavicular retraction for the same range of humeral elevation. Ludewig et al. (2009) on the other hand only estimated approximately 20^o of retraction from 15^o to 130^o of humeral elevation in the frontal plane.

The influence of humeral axial rotation and plane of elevation agreed with previous research. Past clinical studies (Kibler, 1998; McClure, Michener and Karduna, 2006; Oyama, Myers, Wassinger and Lephart, 2010) reported retraction of the clavicle with axial rotation of the humerus, much like the current study. In terms of change in plane, de Groot and Brand (2001) also reported protraction as the plane of elevation increased. Fung et al (2001) reported that the clavicle was significantly more retracted in the scapular plane than the sagittal plane between 30^o-90^o of humeral elevation. Ludewig et al. (2004) and Ludewig et al. (2009) reported less retraction of the clavicle in abduction than flexion. At 130^o thoracohumeral elevation, the maximum elevation studied by Ludewig et al. (2009), 44^o of retraction in the frontal plane was measured but $31^o$of retraction in the sagittal plane. In the current study, the model estimated 52.7^o in the frontal plane and 46.1^o in the sagittal plane. Ludewig et al. (2004) also measured significantly more retraction ($p<0.0001$) in the frontal plane than the sagittal plane.

Forward/Backward Rotation of the Clavicle

Posterior rotation of the clavicle with arm elevation is a common finding in studies investigating change in clavicle position (Fung et al., 2001, Ludewig et al., 2004, Ludewig et al., 2009). Previous research (Fung et al., 2001; Ludewig et al., 2004; Ludewig et al, 2009) also reported similar magnitudes of posterior rotation with humeral elevation. For example, Ludewig et al. (2009) reported approximately 30^o of posterior rotation in the frontal plane over 15^o to 140^o of humeral elevation, while the model in the current study estimates 27.3^o of posterior rotation over the same range.

The decrease in backward rotation of the clavicle with an increase in plane of elevation has also been reported previously. Fung et al. (2001) and Ludewig et al. (2009) both found that backward rotation of the clavicle decreased with the plane of elevation. Over arm elevation from 40^o to 100^o, backward clavicle rotation was significantly less in the sagittal plane than the coronal plane (Fung et al., 2001). The backward rotation was also significantly larger in the scapular plane than the sagittal plane over the elevation range of 20^o-90^o (Fung et al., 2001).

Shoulder Complex as a Closed Chain Mechanism

Since the shoulder joint is considered by many to be a closed chain mechanism, the rotations that occur at one shoulder joint result in rotations occurring at the other shoulder joints. For example, the clavicular rotations that occur with respect to the trunk at the sternoclavicular joint must either be offset by the rotations of the scapula against the thorax or offset by opposing movements at the acromioclavicular joint. Therefore any motion that occurred at the sternoclavicular and acromioclavicular joint in this study was linked to the scapular motion (Fung et al., 2001; Ludewig et al., 2004). The closed chain linkage of the shoulder complex was evident during humeral elevation when scapular lateral rotation was accompanied by clavicular elevation. During humeral elevation, posterior tilt of the scapula also caused posterior rotation of the clavicle at the sternoclavicular joint by means of the coracoclavicular and acromioclavicular ligaments. During protraction of the scapula, the clavicle would be expected to protract as well. However, in the current study, the clavicle retracted. Retraction of the clavicle with protraction of the scapula has previously been explained by simultaneous internal rotation of the acromioclavicular joint with overhead elevation of the arm (Ludewig et al., 2009). At rest position, the local axes of the clavicle are not parallel with the local axes of the scapula. Therefore, rotations about one of the local axes of the scapula would result in rotation about more than one axis of the clavicle and vice versa. This means that protraction of the scapula would not only cause protraction of the clavicle, but also elevation of the clavicle. It is possible that a larger component of the protraction of the scapula caused the clavicle to elevate, reducing the amount of protraction that would have to be counteracted at the acromioclavicular joint. This is plausible since the rotations at the acromioclavicular joint are usually less than the rotations at the sternoclavicular joint (Ludewig et al., 2009; van der Helm and Pronk, 2005). Similarly, because the local coordinate systems of the clavicle and scapula are not aligned, lateral rotation of the scapula also occurred with posterior rotation of the clavicle along with clavicular elevation.

Although the rotations at the acromioclavicular joint were not determined, due to the redundancy of the shoulder complex, these rotations combined with the rotations of the clavicle with respect to the thorax at the sternoclavicular joint should be equivalent to the scapulothoracic angles. The acromioclavicular orientations angles can be extracted from rotation matrix representing the scapula relative to the clavicle, $[R]_S^C$, in equation 20, where the C, S and T are the clavicle, scapula and trunk, respectively. The $[R]_S^T$ and $[R]_C^T$ are the rotation matrices representing scapula relative to the thorax and the clavicle relative to the thorax, respectively. Both $[R]_S^T$ and $[R]_C^T$ are obtained using the same rotation sequence, the resulting matrix is outlined in equation 12. Similarly, the glenohumeral rotations combined with scapulothoracic angles should be equivalent to thoracohumeral angles. The glenohumeral rotations can be extracted from $[R]_H^S$, the rotation matrix representing the humerus relative to the scapula in equation 21, where $[R]_H^T$ represents the humerus relative to the thorax and this matrix is outlined in equation 11.

$$[R]_S^C = \{[R]_S^T\}'[R]_C^T \tag{20}$$

$$[R]_H^S = \{[R]_S^T\}'[R]_H^T \tag{21}$$

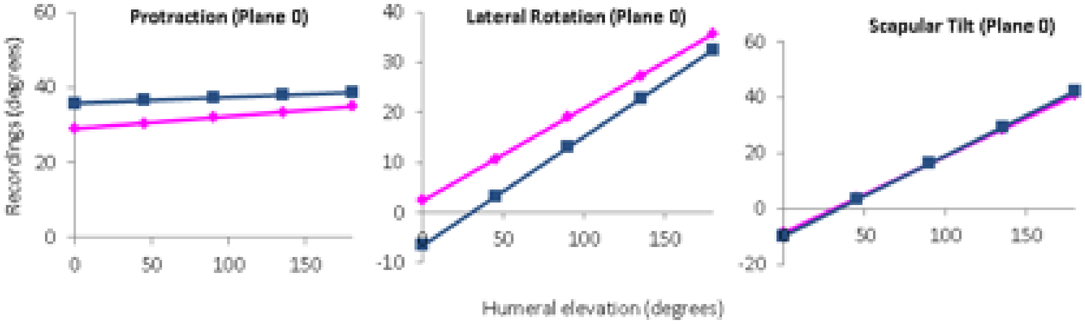
5.4 Comparison of Methods of Scapular Tracking

For the purpose of comparing scapular measurements obtained using different methods, the stylus was assumed to be the gold standard or the best possible non-invasive method of measuring scapular position. The significant interactions between method and thoracohumeral angles indicated that the magnitude of overestimation or underestimation of scapular angles using the scapular locator and the AMC depended on the plane of elevation, elevation and axial rotation of the humerus.

5.4.1 Lateral/medial Rotation of the Scapula

The underestimation of lateral rotation by the scapular locator during elevation (Figure 29) in the sagittal plane agrees with previous research, but the underestimation during humeral elevation in the frontal plane does not. van Andel et al. (2009) compared scapular angles obtained using an AMC with those obtained using a scapular locator or tracker during humeral elevation in the frontal plane and sagittal plane of elevation. Figure 27 and Figure 28 summarize the measurements of scapular angle obtained by van Andel et al. (2009) and the current study using the AMC and the locator in the frontal and sagittal plane, respectively. Meskers et al. (2007) used an electromagnetic skin surface sensor on the acromion as opposed to an AMC and measured scapular positions during humeral elevation up to 130^o in the frontal and sagittal plane. Much like the current study, van Andel et al. (2009) reported underestimation of lateral rotation of the scapula in the sagittal plane using the scapular locator. Meskers et al. (2001) also found the same, but only up to 90^o of humeral elevation, after which, the scapular locator overestimated lateral rotation compared to the skin sensor. In the frontal plane, both studies (Meskers et al., 2007 and van Andel et al., 2009) reported that the scapular locator overestimated lateral rotation compared to the acromial methods, in contrast to the current study. Karduna et al. (2001) compared measurements from an acromial method (electromagnetic sensor on the acromion) and the locator to bone pins measurements by determining the RMS errors between the measurements (Table 41). Like the current study, underestimation of lateral rotation using the locator compared to the gold standard was obtained (Karduna et al., 2001). An average RMS error of 4.2^o and 4.1^o between the locator method and bone pins measurements over the entire range of elevation in the scapular and the sagittal plane were obtained, respectively (Karduna et al., 2001). This study on the other hand found an average difference of approximately 5^{o} and 7^{o} over the entire range of humeral elevation in the 45^{o} plane and the sagittal plane, respectively.

A.



B.

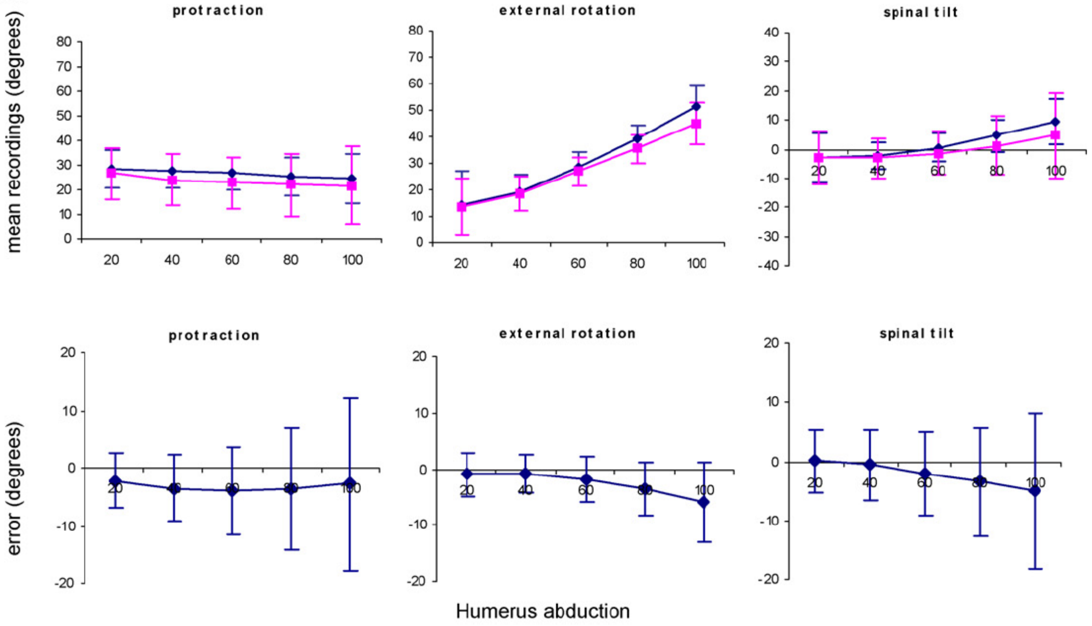


Figure 27: A illustrates the scapular rotations measured using the AMC (pink) and the scapular locator (blue) during frontal plane elevation in the current study. From van Andel et al. (2009), top row in B illustrates the scapular angles during frontal plane abduction measured using the two methods and B illustrates the error, calculated as the difference between the AMC and scapular locator measurements. In each row the left graph represents protraction, the middle represents lateral rotation and the right graph represents spinal tilt.

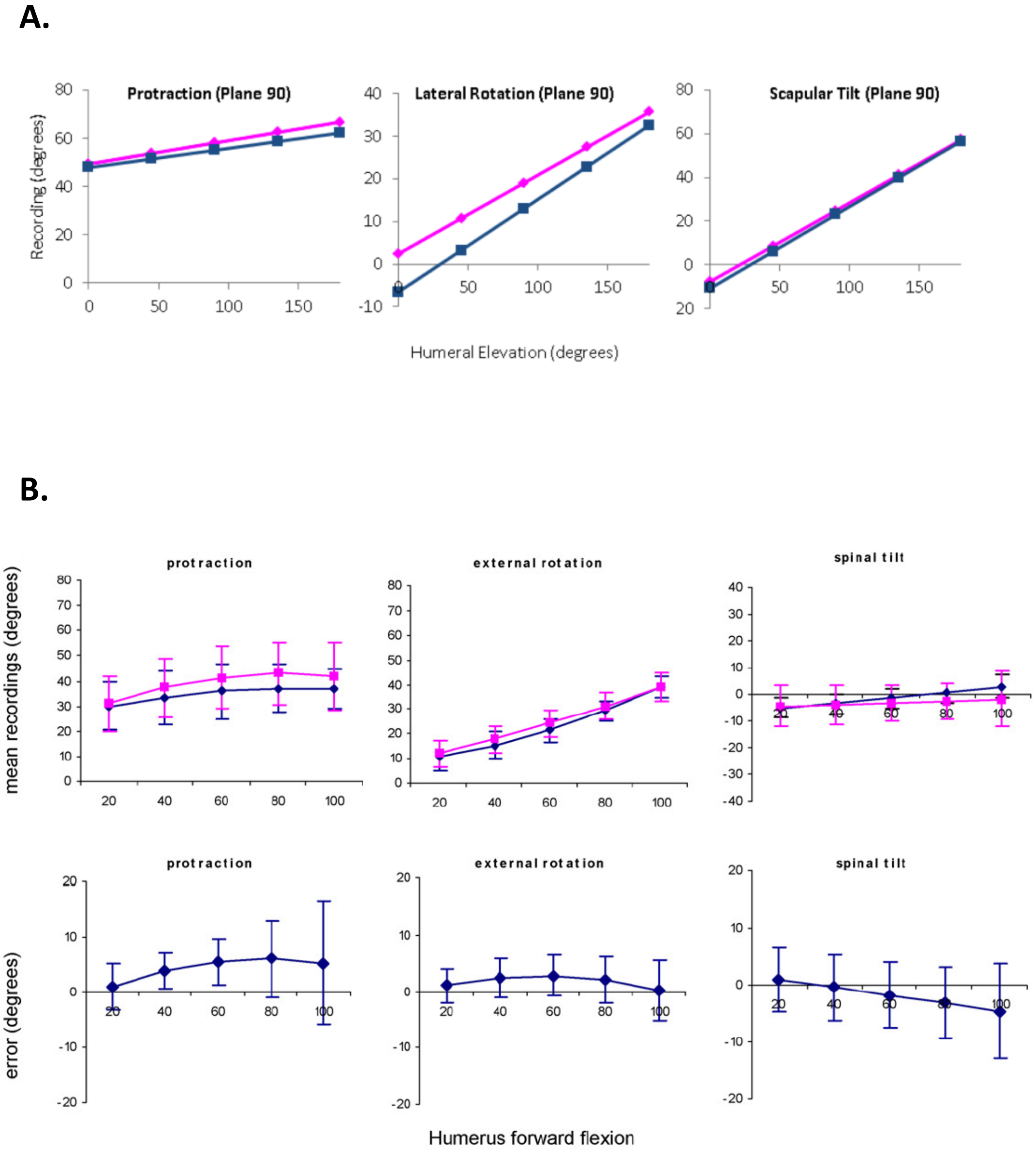


Figure 28: A illustrates the scapular rotations measured using the AMC (pink) and the scapular locator (blue) during sagittal plane elevation in the current study. From van Andel et al. (2009), top row in B illustrates the scapular angles during sagittal plane elevation measured using the two methods and B illustrates the error, calculated as the difference between the AMC and scapular locator measurements. In each row the left graph represents protraction, the middle represents lateral rotation and the right graph represents spinal tilt.

Compared to the gold-standard, the AMC underestimated lateral rotation as well (Figure 29), but previous studies obtained overestimation of lateral rotation with the AMC compared to their respective gold standards. In the current study, the largest difference between the stylus and AMC occurred at 0^{o} humeral elevation, where the AMC underestimated lateral rotation by approximately 2^{o}. Karduna et al. (2001) found a maximum RMS error of 4^{o} at 150^{o} of humeral elevation, where the AMC overestimated lateral rotation. Nevertheless, both Karduna et al. (2001) and the currently study found that the acromial method deviated less from the gold standard.

In the current study, the differences between the methods decreased with elevation angle, but previous research shows otherwise. Figure 27B illustrates increasing deviation between the measurements obtained using the locator and the AMC with elevation angle obtained by van Andel et al. (2009), while the trend in the current study illustrated in, Figure 27A shows a decreasing difference between the measurements with elevation angle in the frontal plane. Karduna et al. (2001) obtained an RMS error of 4.0^{o} at 150^{o} elevation, compared to approximately 1.5^{o} obtained at rest between the acromial skin sensor and the bone pins method in the scapular plane. On the other hand, the difference between the gold standard stylus and the AMC decreased in this study, from 2^{o} at rest to approximately 0^{o} at 150^{o} elevation, in the 45^{o} plane of elevation. The results of the current study did agree with van Andel et al. (2009) in the sagittal plane, where the differences between the AMC and the locator decreased with elevation angle in both studies (Figure 28).

Table 41: The RMS errors calculated between scapular locator (tracker) and bone pins measurements and between the electromagnetic acromion skin sensor method (acromial method) and bone pins method by Karduna et al. (2001) during arm elevation of up to 140^{o} in scapular and the sagittal plane and during external rotation of the humerus.

	Scapular plane (40^{o}) elevation		**90^{o} plane of elevation**		**External rotation**	
	Locator	**Skin sensor**	**Locator**	**Skin Sensor**	**Locator**	**Skin Sensor**
Upward Rotation	4.2^{o}	2.0^{o}	4.1^{o}	2.5^{o}	4.5^{o}	4.0^{o}
Posterior Tilt	4.7^{o}	6.6^{o}	6.2^{o}	8.6^{o}	4.6^{o}	3.7^{o}
Protraction	3.2^{o}	9.4^{o}	3.8^{o}	11.4^{o}	4.4^{o}	6.2^{o}

5.4.2 Anterior/posterior Tilt of the Scapula

The differences between the posterior tilt values derived from scapular locator and the AMC and the gold standard stylus increased with elevation (Figure 31). Karduna et al. (2001) also reported an increasing RMS error with elevation angle. At 15^{o} arm elevation, the RMS errors were 1.0^{o} and 4.0^{o} for the acromial method and locator method respectively, but at 150^{o} or arm elevation, the RMS errors were approximately 13^{o} and 21^{o}, respectively (Karduna et al., 2001). In the current study, the differences between the AMC and stylus gold standard and between the locator and the stylus measurements of posterior tilt were approximately 1.3^{o} and 3.4^{o} degrees, respectively, at 15^{o} arm elevation, and the differences increased to 7.4^{o} for both methods at 150^{o} arm elevation.

The overestimation of posterior tilt at higher elevation angles but slight underestimation at lower elevation angle by the locator compared to the gold standard (Figure 31) was likely due to the skin deformation over the acromion angle. This prevented the scapular locator from being confidently aligned with the three anatomical landmarks of the scapula. For most postures, the deltoid caused a bulge over or adjacent to the acromion angle leading to a loss of contact between the acromion angle bony landmark and the locator. As the plane of elevation increased, the deltoid may have moved anteriorly with the humerus since it inserts on the humerus. This would reduce the amount of soft tissue over the acromion angle, reducing the distance between the end of the scapular locator and the acromion angle landmark.

The AMC also overestimated posterior tilt compared to the stylus at higher elevation angles but underestimated it at lower elevation angles compared to the stylus (Figure 31). The overestimation of posterior tilt of the scapula may be because the base of the AMC adhered to the posterior portion of the acromion is larger than the posterior portion of the acromion. Therefore, its edges were adhered to the surrounding tissue. It is likely that this would cause the AMC to move with the soft tissue around the acromion. If this is the case, the deltoid would cause the AMC to tilt posteriorly with elevation causing the AMC to overestimate posterior tilt compared to the stylus. In the sagittal plane, the scapula is protracted, therefore, if the deltoid causes the AMC to tilt backwards, it would not measure the tilt as posterior tilt of the scapula, but instead it would quantify it as lateral rotation. This would cause the overestimation of posterior tilt by the AMC to decrease with plane of elevation.

Only a small difference between the measurements using the AMC and the scapular locator was found. In Meskers et al. (2007), in the frontal plane, the maximum error occurred at 130^{o} arm elevation, where the error between the two methods was approximately 3^{o}, and in the sagittal plane, the maximum error between the two methods occurred at 50^{o} arm elevation, where the error was approximately 2^{o} between the two methods. In the current study, in the frontal plane, the maximum error occurred at 180^{o} arm elevation with internal rotation and the error was approximately 3^{o} and the maximum error in the sagittal plane occurred at minimum elevation angle with the arm externally rotated, where the difference between the two methods was approximately 9°. It is also important to note that the scapular locator and the AMC overestimated scapular tilt in the current study, compared to the measurements obtained by van Andel et al. (2009) in both the frontal and the sagittal plane (Figure 27 and Figure 28, respectively). For example, at 100° elevation in the frontal plane, the locator estimated 10° of posterior tilt in van Andel et al. (2009), whereas, the current study estimated approximately 20° of posterior tilt.

The differences between the methods tended to decrease with internal rotation, especially between the AMC and the stylus. Van Andel et al. (2009) also reported a significant difference between the measurements obtained from scapular locator and AMC with axial rotation of the humerus. This may have occurred because the deltoid caused a more prominent bulge over the acromion angle during external rotation, causing the posterior tilt to be overestimated. But as the humerus rotated internally, the deltoid moved anteriorly allowing the scapular locator to be better aligned with the anatomical landmarks. This may have also prevented the deltoid from tilting the AMC posteriorly.

5.4.3 Retraction/protraction of the Scapula

The increasing overestimation of the protraction (Figure 34) by the AMC has been reported by previous research. Meskers et al. (2007) showed that at low elevation there was no difference between the skin sensor and the locator values, but at higher elevations, the acromion skin sensor overestimated protraction in the frontal plane compared to the scapular locator. The maximum difference between the two methods was 7.0° at 130° arm elevation, in the frontal plane (Meskers et al., 2007). The maximum difference between the locator and the AMC was 9° in the current study, which occurred in the sagittal plane at 180^o elevation. Karduna et al. (2001) also reported increasing deviation of values with elevation angle. The RMS error between the bone pins and the acromial method approached a maximum of 25^o at 150^o arm elevation (Karduna et al, 2001). In the current study, the maximum difference between the gold standard stylus and the AMC was approximately 15^o, which occurred in the sagittal plane when the arm was internally rotated at maximum elevation of 180^o.

The current study is not the first study to report overestimation of protraction by the AMC with increasing plane of elevation. In the sagittal plane, the AMC estimated the most protraction. Karduna et al. (2001) also attained greater average RMS errors in the sagittal plane than the scapular plane over the entire range of humeral elevation and the change in RMS errors was also greater for the acromial method than the locator method with an increase in plane of elevation (Table 41).

The underestimation of protraction by the AMC in the frontal plane agrees with previous research but the decreasing difference between the AMC and the locator measurements with internal rotation does not. van Andel et al. (2009) found that the AMC underestimated scapular protraction during axial rotation at 90^o arm elevation but the underestimation increased with internal rotation of the humerus compared to the locator. At neutral axial rotation, van Andel et al. (2009) underestimated protraction by approximately 3^o and in this study the AMC underestimated protraction by 5^o. In van Andel et al. (2009), at 45^o internal rotation, the AMC underestimated posterior tilt by approximately 8^o, but in the current study, the AMC estimated the same protraction as the locator at 45^o internal rotation during 90^o abduction in the frontal plane.

The AMC maybe more influenced by the soft-tissue than the scapular locator when determining scapular protraction. This is because, overall, the AMC either underestimated or overestimated protraction depending on the plane of elevation, elevation angle or axial rotation compared to stylus whereas the overestimation of protraction by scapular locator compared to the stylus was consistent across all postures. The greater change in protraction recorded by AMC can once again be attributed to the soft tissue surrounding the base of the AMC. Because the AMC moved anteriorly with the soft tissue, the protraction of the scapula was overestimated as the plane of elevation moved towards the sagittal plane and as the internal rotation of the humerus increased. The scapular locator on the other hand, can be better aligned with the scapula in the sagittal plane, thus the protraction angle measurements are closer to the stylus measurements than the AMC measurements. The RMS error between the AMC and bone pins method with elevation angle was also greater in Karduna et al. (2001) than the RMS error between the locator or tracker method and the bone pins method (Table 41). At maximum elevation, the RMS error for the acromion method approached 25^o, whereas the RMS error for the scapular locator was approximately 6^o.

The largest difference between the scapular angles measured using different methods occurred between the scapular protraction angles. For protraction/retraction, a maximum difference of 15^o was recorded between the methods for protraction/retraction which occurred in the sagittal plane between AMC and the stylus. For both lateral/medial rotation and anterior/posterior tilt, a maximum difference of 10^o was recorded between the methods. Because protraction occurs about the transverse plane, it is more influenced by the soft tissue over the scapula than the other scapular rotations, and thus, it is more difficult to measure than the other scapular rotations, particularly, the lateral rotation of the scapula. This is consistent with Karduna et al. (2001) who obtained larger average RMS errors between methods for scapular protraction than the other methods (Table 41). In terms of maximum RMS error between the methods, Karduna et al. (2001) also attained highest RMS error for protraction (25^o) compared to approximately 20^o and 15^o, obtained for posterior tilt and lateral rotation, respectively.

5.5 Limitations

5.5.1 Study Population

The participant characteristics in this study did not represent the larger working population. The study population in this study was limited to university-aged healthy population. It is assumed that the regression equations obtained are appropriate across the human population, even though the average age of the working population is 40.5 years (Statistics Canada, 2009), much higher than the average age of the participants in this study (22.7 years).The anthropometric measures of the working population may also differ from the anthropometric characteristics of the participants in the current study. A non-significant effect of age and anthropometric measures on the scapular and clavicular angles may be attributed to the relatively homogenous study population. A more diverse study population that includes a larger range of age and body types would more closely represent the general population and it may provide greater insight into the shoulder rhythm.

5.5.2 Standardization of Arm Postures

Although the planes of elevation were marked on the ground and the elevation angles were marked on the pole, the attained thoracohumeral angles deviated from the measured plane of elevation and elevation angles. For the most part, the elevation angle and the plane of elevation were underestimated and thus the models obtained in this study were based on elevation angle range of less than 180^o and plane of elevation range of less than 90^o. Also, for the postures with neutral humeral rotation, it was not possible to ensure that the participants were maintaining neutral axial rotation. This was particularly true at higher elevation angles. The participants were required to keep their elbow flexed at 90^o for all posture. While this made it easier to determine the axial rotation of the humerus, it may have limited the maximum elevation that could be achieved.

5.5.3 Soft-Tissue Artifact

A major limitation in determining scapular position was the soft-tissue overlying the bony landmarks, an inherent problem whenever motion capture is used. This is not a major issue for the landmarks that are relatively superficial such as the thorax landmarks, for which it is assumed that there is negligible skin movement under the markers. But soft-tissue posed a major limitation during palpation and digitization of the scapula. This was particularly true for the overhead arm postures in the frontal plane. It was increasingly difficult to palpate the acromion angle due to the skin deformation caused by the deltoid muscle. The skin deformation caused by the posterior deltoid also prevented the scapular locator from being aligned with the anatomical landmarks of the scapula and it increased the distance between the acromion and the base of AMC during overhead postures. Bourne et al. (2009) found that errors between stylus and bone pins measurements of scapulothoracic angles during abduction were influenced by participants' body mass indices. The errors increased with elevation angle and individual errors for each participant errors approached 20^o in participants with BMIs over 28 (Bourne et al., 2009). Since most participants in this study were healthy and physically active, with average BMIs of 24.3 for males and 22.0 for females, subcutaneous fat was not a particular problem, but soft tissue lead to errors in palpating and determining scapular position in participants with relatively higher muscle definition. This effected retraction/protraction and anterior/posterior tilt of the scapula more than scapular upward rotation because these rotations are more difficult to measure and upward rotation has been found to be less influenced by BMI that the other angles (Bourne et al., 2009). It is likely that BMI would also influence the measurements of scapular locator and the AMC.

The skin motion artifact occurring over the clavicle also effected the sternoclavicular measurements. The difficulty in recording clavicular motion in-vivo has been previously noted by Ludewig et al. (2004). Due to the limitation posed by the skin movement underneath the markers, indirect methods have been used to record position of the clavicle (Ebaugh et al., 2005), but axial rotation cannot be determined using these methods. There are only two discernible bony landmarks on the clavicle and this augments the difficulty in attaining accurate measurements of sternoclavicular angles. As per the recommendations of Wu et al. (2005) for reporting human joint motion, the y-axis of the thorax was used to calculate the x-axis of the clavicle. The x-axis was then used to determine the z-axis of the clavicle. Therefore, it is likely that there is error associated with the rotations that occur about the x-axis and the z-axis of the clavicle, that is, elevation/depression and retraction/protraction of the clavicle, respectively.

5.5.4 Stylus as the Gold Standard

The stylus was assumed to be the gold standard method, but its measurements are also affected by the obscurity of bony landmarks caused by soft-tissue deformation. No other study has used the stylus as the gold standard to compare other methods of scapular tracking. It remains unknown whether the stylus overestimates or underestimates scapular positions, particularly during humeral axial rotation. Bourne et al. (2009) compared the results obtained using a stylus to scapular rotations obtained using bone pins, but only in the frontal and scapular plane and the axial rotation of the humerus was not constrained. Participants were required to maximally elevate their arm and the scapular position was measured at 3 positions in this range of motion and a significant difference between posterior tipping ($p<.006$), upward rotation ($p<.001$) and protraction ($p<.003$) was found between the two methods (Bourne et al., 2009). The error between the measurements of the two methods also increased with humeral elevation and it ranged from 2^o to 12.5^o. In the current study at 0^o elevation, the locator and the AMC underestimated lateral rotation by 6.0^o and 1.4^o in the frontal plane respectively, and at 180^o elevation, the differences were reduced to 0^o for both methods. It is possible that the locator and the AMC continued to underestimate lateral rotation at higher elevation angles, but if the stylus also underestimated scapular lateral rotation, the differences between the methods decreased. Bone pins could not be used in the present study due to the invasive nature of the method. In addition to this, the stylus was used in the initial calibration trials to associate the scapular locator and the AMC with the scapular landmarks. The accuracy of this initial digitization is unknown and any errors during this initial calibration would lead to errors in all scapulothoracic angles for all three methods.

Regardless, in the current study, the stylus was chosen to be the best possible non-invasive method of measuring scapular orientation. For many postures, the locator could not be aligned with all three landmarks of the scapula, and the acromion skin sensors are highly influenced by the soft-tissue during overhead arm movement (Karduna et al., 2001). The stylus has been considered an accurate tool by de Groot (1997), who estimated a palpation and digitization error of less than 3^o using the stylus and it has been considered a reliable tool with ICC values ranging from 0.70 to 0.99 over 120^o of arm elevation (Lempereur et al., 2010). Also, it has been used by de Groot and Brand (2001) to determine scapular positions and subsequently obtain shoulder rhythm models.

5.5.5 Repeated Measures and Inter-trial Variability

The inter-trial variability or reliability of the methods could not be tested. The main reason for this was to ensure that the collection period was not excessively long. The overhead postures, particularly the ones that involved maximum axial rotation of the humerus were reportedly uncomfortable, and the participants sometimes had trouble keeping their arm elevated for all four trials. Therefore, fatigue may have limited some of the maximum elevation angles and axial rotations achieved, but it would be more problematic if repetitions of each posture were performed. If each posture was repeated and the average global positions of the reflective markers were used to calculate positions of the shoulder bones, it would reduce the effect of measurement error when determining the shoulder and clavicular angles. Repeated measurements would also cause the error and variability between measurements to drop (Barnett et al., 1999), although this was not measured in the current study.

5.5.6 Fatigue

Fatigue, especially near the end of the protocol may have altered the scapular kinematics and thus affected the shoulder rhythm. Fatigue of upper trapezius, lower trapezius, serratus anterior and the middle deltoid muscles monitored using electromyography has been shown to increase scapular upward rotation over arm elevation from 60^o to 150^o (McQuade, Dawson and Smidt, 1995). Measures were taken to prevent fatigue as much as possible in the current study, such as excluding multiple trials of each posture and rest was provided between all postures. Therefore, it is unlikely that fatigue influenced the shoulder rhythm in the current investigation.

5.5.7 Effect of Load and Velocity

The current study did not examine the effect of load on the shoulder rhythm. The effect of moderate loads on the shoulder rhythm has previously been found to be negligible (Hogfors, 1991; de Groot, van Woensel and van der Helm, 1999). de Groot et al. (1999) examined loads of up to 2.9Kg. Similarly, investigations of arm velocity on the shoulder rhythm show that the shoulder rhythm obtained during static movements can be extrapolated to dynamic movement (de Groot et al., 1998). However, it is likely that some jobs place higher loads and require higher velocity movements than those examined by de Groot et al. (1998). Therefore, the prediction models obtained in the current study must be validated for these extreme tasks.

5.6 Future Directions

Future studies on shoulder rhythm should include participants from a more diverse population. If a greater range of age and body types is included, a more definitive conclusion can be made in terms of whether or not participant characteristics have a significant effect on the shoulder rhythm. It would also be ideal to have real-time calculation of thoracohumeral angles during data collection to reduce the error between the externally measured and calculated thoracohumeral angles. To ensure more accurate measurements of thoracohumeral angles, position of the trunk should also be constrained to prevent tilt and rotation. Future studies should also extend the plane of elevation to across-body plane of elevation, so that the scapular and clavicular bone positions can be estimated during across-body reaching tasks.

The first part of the investigation involved developing regression models of the shoulder rhythm. In the future, it is desired that these models can be incorporated into a biomechanical model such as the Dickerson shoulder model (Dickerson et al., 2007). Using the externally measured positions of the arm and the trunk, the models allow the predictions of the positions of the scapula and the clavicle, during postures experienced in workplaces. To ensure that these models accurately depict the geometry of the shoulder complex, future studies will be focused on validating the regression models by comparing the bone orientations obtained from participants that were not included when determining the prediction models to the bone orientations obtained using the prediction models.

Determining how the shoulder rhythm models attained in this study compare with the shoulder rhythm in people affected by shoulder pathology would give more insight into the causes of shoulder pathology. The results in the current study provide a standard record of normal scapular movement for a wide range of humeral postures, and since altered scapular kinematics have been seen in people with shoulder impingement (Ludewig et al., 2009), detecting the differences between normal healthy shoulder rhythm and the shoulder rhythm of people with shoulder pathology can help determine the mechanisms or causes of shoulder pathology. The comparison between normal or healthy and altered shoulder kinematics can also help develop treatments that are focused on restoring normal shoulder kinematics. Since participants with discomfort may not be able to attain all the arm postures studied in the current investigation, this may be limited to postures that do not include the extreme thoracohumeral angles.

The inter-trial variability or reliability of the different methods of determining scapular position could not be tested in the current investigation due to time constraints. An accurate tool for measuring scapular angles may not be the most reliable tool. Inter-trial variability measures are required to determine reliability of methods and this will provide more information about which method should be used to externally measure scapular position. In some instances, reliability of the scapular tracking methods may be of particular importance, such as in clinical studies when comparing pre- and post-treatment scapular angles.

VI. CONCLUSIONS

Predictive biomechanical models of the shoulder complex are frequently used to simulate postures and to calculate structural loads placed on the shoulder to answer a range of applied questions. The structural loads are often used in applications such as identification of risk factors in workplaces to reduce the prevalence of shoulder discomfort and disorders and to reduce the financial burden placed on companies through lost productivity and rehabilitation costs. An accurate representation of the shoulder geometry is required to accurately estimate structural loads and to correctly identify risk factors. Since scapular and clavicular positions are difficult to measure externally, particularly in an applied setting, the current research quantified the shoulder rhythm to allow the estimation of the position of the scapula and the clavicle using externally measurable thoracohumeral orientations. The results of this investigation also provide a record of normal shoulder kinematics that can be used to compare results of future studies focused on shoulder pathology. Determining altered kinematics can also help identify the causes of shoulder pathology and give more insight into developing treatment plans focused on restoring normal kinematics.

To ensure accurate representation of the shoulder geometry for a full range of humeral motion, the shoulder rhythm was quantified using static arm postures that spread over minimum to 180^o of arm elevation in planes of elevation that ranged from the frontal plane to the sagittal plane and included full range of axial rotation of the humerus. The advantages of the models obtained are that they are simple and parsimonious, the overhead arm postures were included and that the scapular and clavicular orientations can also be estimated for axially rotated humeral postures. To facilitate comparison of the results from this study to future research, the bony landmarks, local and joint coordinate systems and Euler rotation sequences used in the current research are based on the standards outlined by ISB for reporting human joint motion (Wu et al., 2005).

Linear models were identified as appropriate and parsimonious for all scapular and clavicular angles except clavicular elevation, where a quadratic model was obtained. Elevation angle was the largest contributor to lateral rotation and posterior tilt of the scapula, while plane of elevation was the largest contributor to retraction/protraction of the scapula. Arm elevation was the largest contributor to all clavicular angles and the clavicle elevated, retracted and rotated backwards with arm elevation. Scapular tilt and clavicular retraction were overestimated compared to previous research.

The current research also contrasted the performance of non-invasive methods of determining scapular position by comparing the measurements obtained using an AMC and a scapular locator to those obtained using a stylus. Using the stylus as the gold-standard, the scapular locator and the AMC were found to underestimate lateral rotation, especially at low elevation angles, but the AMC resembled the stylus measurements more closely than the scapular locator. The AMC and the locator both overestimated posterior tilt at high elevation angles and underestimated posterior tilt at low elevation angles compared to the stylus. The largest difference between the methods occurred in retraction/protraction. The scapular locator consistently overestimated protraction across elevation angle, plane of elevation and axial rotation of the humerus. The AMC underestimated protraction in the frontal plane at low elevation angle but overestimated it at all other postures. The overestimation of scapular protraction by the AMC increased with plane of elevation, internal rotation and elevation angle. As a result, the AMC may be more influenced by the soft-tissue when determining scapular retraction/protraction of the scapula. Soft-tissue was an inherent limitation of the study that also prevented the scapular locator from being aligned with the anatomical landmarks of the scapula and it may have also influenced the accuracy of digitization with the stylus by increasing the distance between the tip of the stylus and the anatomical landmarks. Overall, across all three scapular rotations, it is recommended to use AMC rather than the scapular locator. However, the protraction obtained using the AMC, especially in the sagittal plane must be interpreted with caution.

The current study was the first study to quantify shoulder rhythm and compare methods of measuring shoulder position for the full range of humeral elevation and axially rotation in multiple planes. Future studies should focus on validating the shoulder rhythm models. The reliability of the non-invasive methods should also be addressed to provide more insight into which method should be used for externally measuring scapular positions.

REFERENCES

An K.N., Browne A.O., Korinek S., Tanaka S. & Morrey B.F. (1991). Three-dimensional kinematics of glenohumeral elevation. *Journal of Orthopaedic Research*, 9: 143-149.

Bagg S.D. & Forrest W.J. (1988). A biomechanical analysis of scapular rotation during arm abduction in the scapular plane. *American Journal of Physical Medicine and Rehabilitation*, 67, 238-245.

Barnett N.D., Duncan R.D.D. & Johnson G.R. (1999). The measurement of three dimensional scapulohumeral kinematics – a study of reliability. *Clinical Biomechanics,* 14, 287-290.

Bernard B.P. (1997). Musculoskeletal disorders and workplace factors: a critical review of epidemiologic evidence for work-related disorders of the neck, upper extremity, and low back. Cincinnati: National Institute of Occupational Safety and Health.

Bourne D.A., Choo A.M.T., Regan W.D., MacIntyre D.L. & Oxland T.R. (2007). Three-dimensional rotation of the scapula during functional movements; An *in vivo* study in healthy volunteers. *Journal of Shoulder and Elbow Surgery*,16, 150-162.

Bourne D., Choo A., Regan W., MacIntyre, D. & Oxland, T. (2009). Accuracy of digitization of bony landmarks for measuring change in scapular attitude. *Journal of Engineering in Medicine,* 223, 349-361.

Braman J.P., Engel S.C., LaPrade R.F. & Ludewig P.M. (2009). In vivo assessment of scapulohumeral rhythm during unconstrained overhead reaching in asymptomatic subjects. *Journal of Shoulder and Elbow Surgery*, 18, 960-967.

Browne A.O., Hoffmeyer P., Tanaka S., An K.N. & Morrey B.F. (1990). Glenohumeral elevation studied in three dimensions. *Journal of Bone and Joint Surgery – Series B*, 72: 843-845.

Codman, E.A. (1934). The Shoulder, Boston, USA: Thomas Todd Co.

de Groot J.H. (1997). The variability of shoulder motions recorded by means of palpation. *Clinical Biomechanics,* 12:461-472.

de Groot J.H. (1999). The Scapula-humeral rhythm: effects of 2-D roentgen projection. *Clinical Biomechanics,* 14: 63-68.

de Groot J.H. & Brand R. (2001). A three-dimensional regression model of the shoulder rhythm. *Clinical Biomechanics,* 16: 735-743.

de Groot J.H., Valstar E.R. & Arwert H.J. (1998). Velocity effect on the scapula-humeral rhythm. *Clinical Biomechanics,* 13: 593-602.

de Groot J.H., Woensel W. & van der Helm F.C.T. (1999). Effect of different arm loads on the position of the scapula in abduction postures. *Clinical Biomechanics,* 14: 309-314.

Dickerson C.R. (2005). *A biomechanical analysis of shoulder loading and effort during load transfer tasks* (Doctoral dissertation). University of Michigan, Michigan.

Dickerson C.R., Chaffin D.B. & Hughes R.E. (2007). A mathematical musculoskeletal shoulder model for proactive ergonomic analysis. *Computer Methods in Biomechanics and Biomedical Engineering,* 10, 389-400.

Doody S.G., Freedman L. & Waterland J.C. (1970). Shoulder movements during abduction in the scapular plane. *Archives of Physical Medicine and Rehabilitation,* 51, 595-604.

Ebaugh D.D., McClure P.W. & Karduna A.R. (2005). Three-dimensional scapulothoracic motion during active and passive arm elevation. *Clinical Biomechanics,* 20, 700-709.

Ebaugh D.D. & Spinelli B.A., (2010). Scapulothoracic motion and muscle activity during the raising and lowering phases of an overhead reaching task. *Journal of Electromyography and Kinesiology*, 20, 199-205.

Freedman L. & Munro R.R. (1966). Abduction of the arm in the scapular plane: scapular and glenohumeral movements: a roentgenographic study. *The Journal of Bone and Joint Surgery,* 48, 1503-1510.

Fung M., Kato S., Barrance P.J., Elias J.J., McFarland E.G., Nobuhara K. & Chao E.Y. (2001). Scapular and clavicular kinematics during humeral elevation: A study with cadavers. *Journal of Shoulder and Elbow Surgery,* 10 (3), 278-285.

Gomes P.F., Sesselmann M., Faria C.D.C.M., Araújo P.A. & Faria C.D.C.M. (2010). Measurement of scapular kinematiscs with the moiré fringe projection technique. *Journal of Biomechanics,* 43, 1215-1219.

Graichen H., Stammberger T., Bonel H., Haubner M., Englmeier K.H., Reiser M. & Eckstein F. (2000). Magnetic resonance based motion analysis of the shoulder during elevation. *Clinical Orthopedics and Related Research,* 370, 154-163.

Grieve J.R. & Dickerson C.R. (2008). Overhead work: identification of evidence-based exposure guidelines. *Occupational Ergonomics* 8, 53-66.

Gibson M.H., Goebel, G.V., Jordan T.M., Kegerre S. and Worrell T.W. (1995). A reliability study of measurement techniques to determine static scapular position. *Journal of Orthopedics and Sports Physical Therapy,* 21, 100-106.

Hebert L.J., Moffet H., McFadyen B.J. & St-Vincent G. (2000). A method of measuring three-dimensional scapular attitudes using the optotrak probing system. *Clinical Biomechanics,* 15, 1-8.

Hogfors C., Sigholm G. & Herberts P. (1987). Biomechanical model of the human shoulder joing I: elements. *Journal of Biomechanics,* 20, 157-166.

Hogfors C., Peterson B., Sigholm G. & Herberts P. (1991). Biomechanical model of the human shoulder joint –II. The shoulder Rhythm. *Journal of Biomechanics,* 24, 699-709.

Holzbaur K.R.S, Murray W.M. & Delp S.L. (2005). A model of the upper extremity for simulating musculoskeletal surgery and analyzing neuromuscular control. *Annals of biomedical Engineering,* 33, 829-840.

Inman V.T., Saunders M. & Abbott L.C. (1944). Observations on the function of the shoulder joint. *The Journal of Bone and Joint Surgery,* 26, 1-30.

Johnson G.R., Stuart P.R. & Mitchell S. (1993). A method for the measurement of three-dimensional scapular movement. *Clinical Biomechanics,* 8, 269-273.

Johnston T.B. (1937). The movements of the shoulder joint. *British Journal of Surgery,* 25, 255-260.

Karduna A.R., McClure P.W. & Michener L.A. (2000). Scapular kinematics: effects of altering the Euler angle sequence of rotations. *Journal of Biomechanics,* 33, 1063-1068.

Karduna A.R., McClure P.W., Michener L.A. & Sennett B. (2001). Dynamic measurements of three-dimensional scapular kinematics: a validation study. *Journal of Biomedical Engineering*, 123, 184-190.

Karlsson D. & Peterson B. (1992). Towards a model for force predictions in the human shoulder. *Journal of Biomechanics*, 25, 189-199.

Kibler W.B. (1998). The role of the scapula in athletic shoulder function. *The American Journal of Sports Medicine,* 26: 325-337.

Kibler W.B. & McMullen J. (2003). Scapular dyskinesis and its relation to shoulder pain. *Journal of American Academy of Orthopedic Surgeons,* 11, 142-151.

Klopcar N. & Lenarcic J. (2006). Bilateral and unilateral shoulder girdle kinematics during humeral elevation. *Clinical Biomechanics,* 21, S20-S26.

Koh T.J., Grabiner M.D. & Brems J.J. (1998). Three-dimensional in vivo kinematics of the shoulder during humeral elevation. *Journal of Applied Biomechanics,* 14, 312-326.

Kondo M., Tazoe S., Yamada M. (1984). Changes of the tilting angle of the scapula following elevation of the arm. *Nippon Seikeigeka Gakkai Zasshi, 60, 175-185.*

Laumann U. (1987). Kinesiology of the shoulder joint. In Koelbel R., Helbig B. & Blauth W. (Eds). *Shoulder Replacement (pp. 23-31),* Berlin: Springer-Verlag.

Leffert R.D. & Gumley G. (1987). The relationship between dead arm syndrome and thoracic outlet syndrome. *Clinical Orthopedic and Related Research s,* 223, 20-31.

Lempereur M., Brochard S., Burdin V., & Remy-neris O. (2010). Difference between palpation and optoelectronics recording of scapular motion. *Computer Methods in Biomechanics and Biomedical Engineering,* 13: 48-57.

Lucas D.B. (1973). Biomechanics of the shoulder joint. *Archives of Surgery,* 107, 425-432.

Ludewig P.M., Cook T.M. & Nawoczenski D.A. (1996). Three-dimensional scapular orientation and muscle activity of selected positions of humeral elevation. *Journal of Orthopedic and Sports Physical Therapy,* 24, 57-65.

Ludewig P.M. & Cook T.M. (2000). Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. *Physical Therapy,* 8, 276-291.

Ludewig P.M., Cook T.M.C. & Shields R.K. (2002). Comparison of surface sensor and bone-fixed measurement of humeral motion. *Journal of Applied Biomechanics*, 18, 163-170.

Ludewig P.M., Behrens S.A., Meyer S.M., Spoden S.M. & Wilson L.A. (2004). Three-dimensional clavicular motion during arm elevation: reliability and descriptive data. *Journal of Orthopedic and Sports Physical Therapy*, 34, 140-149.

Ludewig P.M., Phadke V., Braman J.P., Hassett D.R., Cieminski F.J. & LaPrade R.F. (2009). Motion of the shoulder complex during multiplanar humeral elevation. *The Journal of Bone and Joint Surgery,* 91, 378-389.

Lukasiewics A.C., McClure P., Michener L., Pratt N. & Sennett B. (1999). Comparison of 3-dimensional scapular position and orientation between subjects with and without shoulder impingement. *Journal of Orthopedic and Sports Physical Therapy,* 29, 574-583.

Lundberg A. (1996). On the use of bone and skin markers in kinematics research. *Human Movement Science*, 15, 411-422.

Magermans D.J., Chadwick E.K.J., Veeger H.E.J.&van der Helm F.C.T. (1995). Requirements for upper extremity motions during activities of daily living. *Clinical Biomechanics,* 20: 591-599.

Makhsous M. (1999). Improvements, Validation and Adaptation of a Shoulder Model (Doctoral Dissertation). Chalmers University of Technology, Goteborg, Sweden.

Mani L. & Gerr F. (2000). Work-related upper extremity musculoskeletal disorders. *Primary Care: Clinics in Office Practice.* 27: 845-864.

Matias R. & Pascoal A.G. (2006). The unstable shoulder in arm elevation: a three-dimensional and electromyographic study in subjects with glenohumeral instability. *Clinical Biomechanics,* 21, S39-44.

McClure P.W., Michener L.A., Sennett B.J. & Karduna A.R. (2001). Direct 3-dimensional measurement of scapular kinematics during dynamic movments in vivo. *Journal of Shoulder and Elbow Surgery,* 10, 269-277.

McClure P.W., Michener L.A & Karduna A.R. (2006). Shoulder function and 3-dimensional scapular kinematics in people with and without shoulder impingement syndrome. *Physical Therapy,* 86: 1075 – 1090.

McGill S., Cholewicki J. & Peach J.P. (1997). Methodological considerations for using inductive sensors (3SPACE ISOTRAK) to monitor 3-D orthopaedic joint motion. *Clinical Biomechanics,* 12, 190-194.

McQuade K.J., Dawson J. & Smidt G.L. (1995). Scapulothoracic muscle fatigue associated with alterations in scapulohumeral rhythm kinematics during maximum resistive shoulder elevation. *Journal of Orthopaedic and Sports Physical Therapy,* 28: 74-80.

McQuade K.J. & Smidt G.L. (1998). Dynamic scapulohumeral rhythm: the effects of external resistance during elevation of the arm in the scapular plane. Journal of Orthopedic and Sports Physical Therapy, 27, 125-131.

Meskers C.G.M., Vermeulen H.M., de Groot, J.H., van der Helm F.C.T. & Rozing P.M. (1998). 3D shoulder position measurements using a six-degree-of-freedom electromagnetic tracking device. *Clinical Biomechanics,* 13, 280-292.

Meskers C.G.M., van de Sande M.A.J. & de Groot JH. (2007). Comparison between trip and skin-fixed recording of scapular motion. *Journal of Biomechanics,* 40, 941-946.

Michiels I. & Grevenstein J. (1995). Kinematics of shoulder abduction in the scapular plane. *Clinical Biomechanics,* 10, 137-143.

Neer C.S. (1983). Impingement lesions. *Clinical Orthopedics and Related Research,* 173, 70-77.

Nussbaum M.A. & Zhang X. (2000). Heuristics for locating upper extremity joint centers for a reduced set of surface markers. *Human Movement Science,* 19, 797-816.

Oyama S., Myers J.B., Wassinger C.A. & Pehart S.M. (2010). Three-dimensional scapular and clavicular kinematics and scapular muscle activity during retraction exercises. *The Journal of Orthopaedic and Sport Physical Therapy,* 40: 169-179.

Ozaki J. (1990). Glenohumeral movements of the involuntary inferior and multidirectional instability. *Clinical Orthopedic and Related Research s,* 238, 107-111.

Paletta G.A., Warner J.J.P., Warren R.F., Deutsch A. & Altchek D.W. (1997). Shoulder kinematics with 2-plane x-ray evaluation in patients with anterior instability or rotator cuff tearing. *Journal of Shoulder and Elbow Surgery,* 6, 516-527.

Pascoal A.G., van der Helm F.F.C.T, Correia P.P. & Carita I. (2000). Effects of different arm external loads on the 136capula-humeral rhythm. *Clinical Biomechanics,* 15, S21-24.

Picco B.R., Fischer S.L. & Dickerson C.R. (2010). Quantifying scapula orientation and its influence on maximal hand force capability and shoulder muscle activity. *Clinical Biomechanics,* 25, 29-36.

Poppen N.K. & Walker P.S. (1976). Normal and abnormal motion of the shoulder. *The Journal of Bone and Joint Surgery,* 58, 195-201.

Pronk G.M. & van der Helm F.C.T. (1991). The palpator: an instrument for measuring the position of bones in three dimensions. *Journal of Medical Engineering and Technology,* 15, 15-20.

Rockwood C.A. Jr., Matsen F.A. III, Wirth M.A. & Lippitt S.B. (2009). *The shoulder* (4th edition). Philadelphia, USA: Saunders Elsevier.

Sagano J., Magee D. & Katayose M. (2006). The effect of glenohumeral rotation on scapular upward rotation in different positions of scapular-plane elevation. *Journal of Sport Rehabilitation*, 15, 144-155.

Solem-Bertoft E., Thuomas K.A. and Westerberg C.E. (1993). The influence of scapular retraction and protraction on the width of the subacromial space: an MRI study. *Clinical Orthopedics and Related Research,* 99-103.

Statistics Canada. (2009). Canada’s population estimates: Age and Sex.

Szucs K.A. & Borstad J.D. (2010 July). Capturing 3D clavicle kinematics: validation of surface sensor. Paper presented at the *International Shoulder Group Shoulder Biomechanics Conference Proceedings,* University of Minnesota, Minneapolis, MN.

T’Jonck L., Lysens R. and Grasse G. (1996). Measurements of scapular position and rotation: a reliability study. *Physiotherapy Research International,* 1, 148-158.

Van Andel C., van Hutten K., Eversdijk M., Veeger D. & Harlaar J. (2009). Recording scapular motion using an acromion cluster. *Gait and Posture,* 29, 123-128.

Van Andel C., Wolterbeek N., Doorenbosch C.A.M., Veeger D. & Harlaar J. (2008). Complete 3D kinematics of upper extremity functional tasks. *Gait and Posture,* 27: 120-127.

Van der Helm F.C.T. (1994). Analysis of the kinematic and dynamic behavior of the shoulder mechanism. *Journal of Biomechanics,* 27, 527-550.

Van der Helm F.C.T. & Pronk GM. (1995). Three-dimensional recording and description of motions of the shoulder mechanism. *Journal of Biomechanical Engineering,* 117, 27-40.

Van der Helm F.C.T. (1996). A standardized protocol for motion recordings of the shoulder. In veeger H.E.J., van der Helm F.C.T. and Rozing P.M. (Eds.), *Proceedings of the First Conference of the International Shoulder Group* (pp. 1-7), Maastricht, Netherlands: Shaker Publishing.

Veeger H.E.J., van der Helm F.C.T. & Rozendal R.H. (1993). Orientation of the scapula in a simulated wheelchair push. *Clinical Biomechanics,* 8, 81-90.

Warner J.J.P., Micheli L.J., Arslanian L.E., Kennedy J. & Kennedy R. (1992). Scapulothoracic motion in normal shoulders and shoulders with glenohumeral instability and impingement syndrome. *Clinical Orthopedics and Related Research,* 285, 191-199.

Warner M.B, Chappell P.H. & Stokes M.J. (2010, July) A comparison between the acromion marker cluster and scapular locator techniques for measuring scapular kinematics during upper limb elevation and lowering. Paper presented at the *International Shoulder Group Shoulder Biomechanics Conference Proceedings,* University of Minnesota, Minneapolis, MN.

Winter D.A. (2009). *Biomechanics and Motor Control of Human Movement* (4th edition). New Jersey, USA: John Wiley and Sons, Inc.

Wu G., van der Helm F.C.T., Veeger H.E.J., Makhsous M., Van Roy P., Anglin C., Nagels J., Karduna A.R., McQuade K., Wang X., Werner F.W. & Buchholz B. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion. – Part II: shoulder, elbow, wrist and hand. *Journal of Biomechanics,* 38, 981-992.

APPENDIX A

Table 42: The Euler rotation sequences for bone rotations as standardized by ISB (Wu et al., 2005).

Segment	Rotation Sequence
Motions of the thorax relative to the global coordinate system **Z-X-Y**	e1: axis coincident with the Z_g-axis of the global coordinate system. *Rotation (α_{GT}):* flexion (negative) or extension (positive) e3: axis fixed to the thorax and coincident with the Yt-axis of the thorax coordinate system. *Rotation (γ_{GT}):* axial rotation to the left (positive) or to the right (negative). E2: common axis perpendicular to e1 and e3, i.e. the rotated X_t-axis of the thorax. *Rotation (β_{GT}):* lateral flexion rotation of the thorax, to the right is positive, to the left is negative.
Motion of the Clavicle Relative to the thorax (SC joint) **Y-X-Z**	e1: axis fixed to the thorax and coincident with the Y_t-axis of the thorax coordinate system. *Rotation (γ_{SC}):* retraction (negative) or protraction (positive). E3: axis fixed to the clavicle and coincident with the Z_c-axis of the clavicle coordinate system. *Rotation (α_{SC}):* axial rotation of the clavicle; rotation of the top backwards is positive and forward is negative. E2: common axis perpendicular to e1 and e3, the rotated X_c-axis. *Rotation (β_{SC}):* elevation (negative) or depression (positive).
Motion of the scapula relative to the thorax (motion at the ST joint) **Y-X-Z**	e1: axis fixed to the thorax and coincident with the Y_t-axis of the thorax coordinate system. *Rotation (γ_{ST}):* retraction (negative) or protraction (positive) e3: axis fixed to the scapula and coincident with the Z_s-axis of the scapular coordinate system. *Rotation (α_{ST}):* anterior (negative) or posterior (positive) tilt. E2: common axis perpendicular to e1 and e3. *Rotation (β_{ST})*: lateral (negative) or medial (positive) rotation.
Motion of the humerus relative to the thorax (thoracohumeral rotations) **Y-X-Y**	e1: axis fixed to the thorax and coincident with the Y_t-axis of the thorax coordinate system. *Rotation (γ_{TH1}):* GH plane of elevation (0^o is abduction, 90^o is forward flexion) e3: axial rotation around the Y_h-axis. *Rotation (γ_{TH2}):* GH-axial rotation, internal (positive) or external (negative) rotation e2: axis fixed to the humerus and coincident with the X_h-axis of the humerus coordinate system. *Rotation (β_{TH})*: elevation (negative)

Table 43: The Euler rotation sequences for joint rotations as standardized by ISB (Wu et al., 2005).

Segment	Rotation Sequence
Motion for the SC joint (Clavicle relative to the thorax) **Y-X-Z**	Same as the segment rotation of the clavicle relative to the thorax since the proximal coordinate system of the clavicle is the thorax.
Motion for the AC joint (Scapula relative to the clavicle) **Y-X-Z**	e1: axis fixed to the clavicle and coincident with the Y_c-axis of the clavicle coordinate system. *Rotation (γ_{AC}):* AC retraction (negative) or AC protraction (positive). E3: axis fixed to the scapula and coincident with the Z_s-axis of the scapular coordinate system (scapular spine). *Rotation (α_{AC}):* AC-anterior (negative) or AC-posterior (positive) tilt. E2: common axis perpendicular to e1 and e3, the rotated X_s-axis of the scapula coordinate system. *Rotation (β_{AC})*: AC-lateral (negative) or AC-medial (positive) rotation.
Motion at the GH joint (humerus relative to the scapula) **Y-X-Y**	e1: axis fixed to the scapula and coincident with the Y_s-axis of the scapular coordinate system *Rotation (γ_{GH1}):* GH plane of elevation e3: axial rotation around the Y_h-axis. *Rotation (γ_{GH2}):* GH-axial rotation, internal (positive) or external (negative) rotation e2: axis fixed to the humerus and coincident with the X_h-axis of the humerus coordinate system. *Rotation (β_{GH})*: GH elevation (negative)

APPENDIX B

Table 44: The r^2 and the RMS errors of the models obtained and the full-factorial models obtained if the interactions that did not provide additional variance explanation of greater than 0.02 were not excluded to make the models parsimonious.

Segment	**Angle**	**Obtained Parsimonious Prediction Models**		**Full-Factorial model**	
		r^2	**RMS Error**	**r^2**	**RMS Error**
Scapula	Lateral/medial rotation	0.80	5.26°	0.80	5.17°
	Anterior/posterior tilt	0.82	6.54°	0.83	6.32°
	Retraction/protraction	0.60	6.31°	0.60	6.31°
Clavicle	Elevation/depression	0.74	3.24°	0.74	3.20°
	Retraction protraction	0.89	5.11°	0.91	4.66°
	Axial rotation	0.84	3.50°	0.85	3.45°

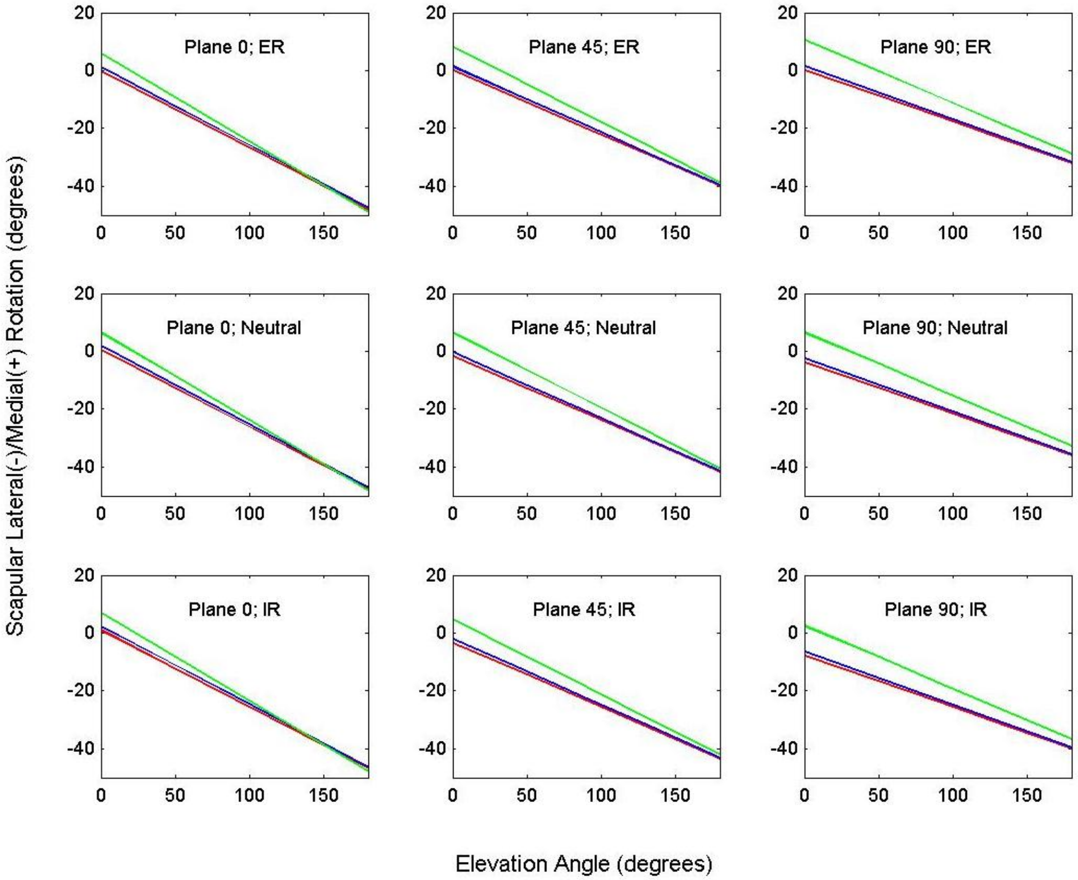


Figure 29: The interaction effect between method of measuring scapular position and elevation angle on lateral/medial rotation of the scapula. The measurements obtained using the stylus (red), AMC (blue) and locator (green) are plotted at 0°, 45° and 90° planes of elevation with the humerus axially rotated 45° externally (ER), neutral and 45° internally (IR).

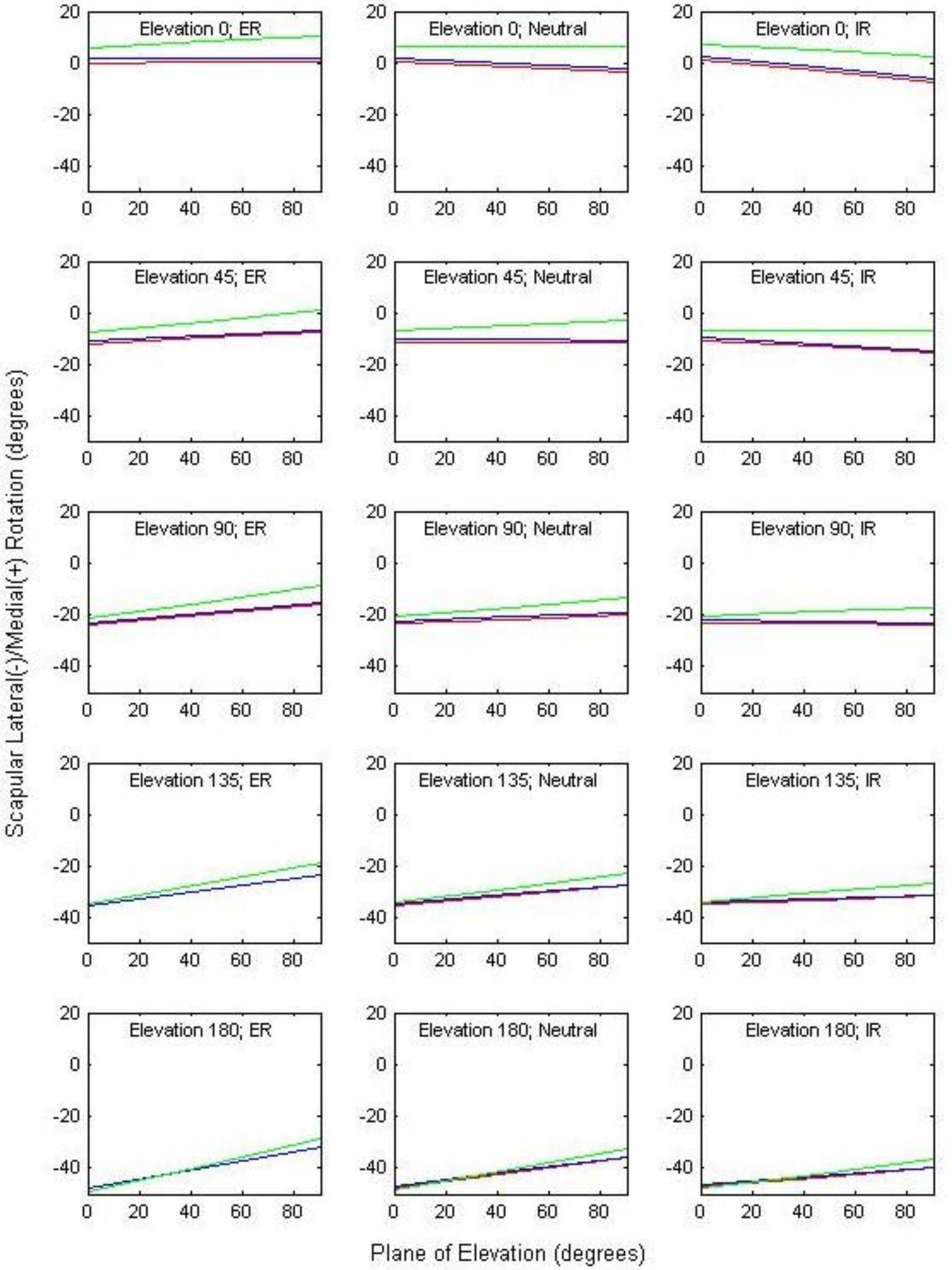


Figure 30: The interaction effect between method of measuring scapular position and plane of elevation on lateral/medial rotation of the scapula. The measurements obtained using the stylus (red), AMC (blue) and locator (green) are plotted at 0^o, 45^o 90^o, 135^o and 180^o elevation angles with the humerus axially rotated 45^o externally (ER), neutral and 45^o internally (IR).

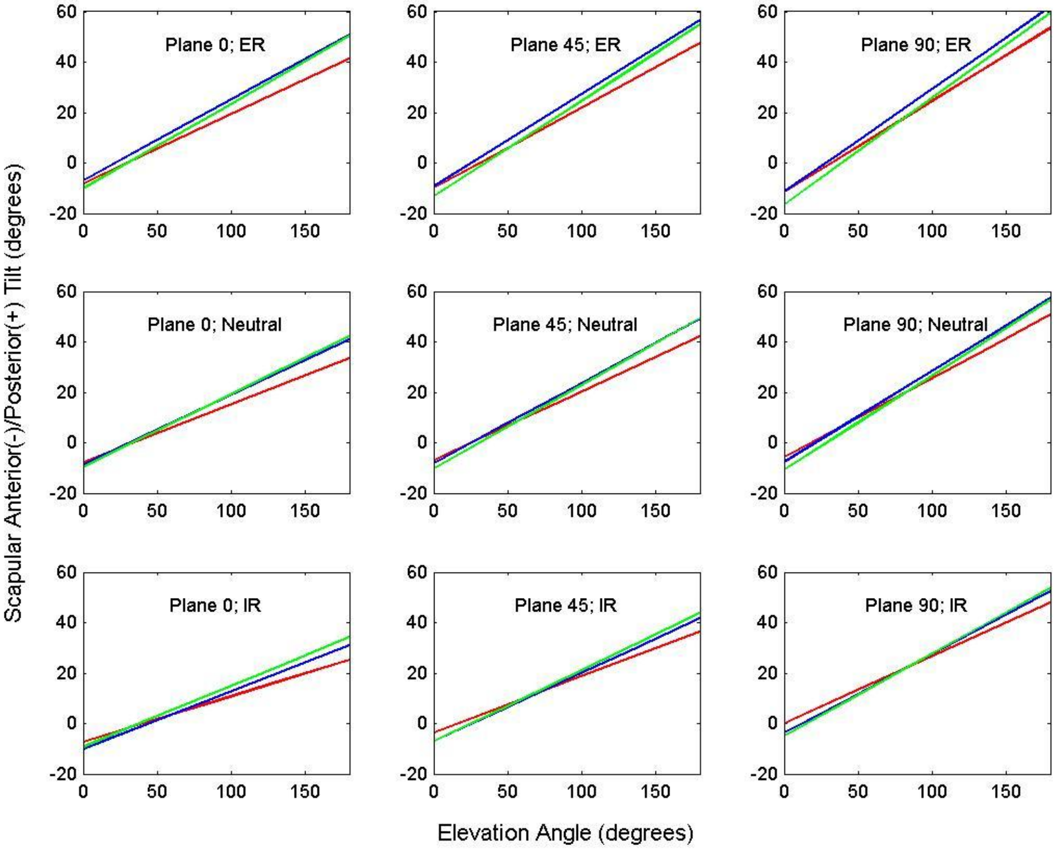


Figure 31: The interaction effect between the method of measuring scapular position and elevation angle on the anterior/posterior tilt of the scapula. The measurements obtained using the stylus (red), AMC (blue) and locator (green) are plotted at 0°, 45° and 90° planes of elevation with the humerus axially rotated 45° externally (ER), neutral and 45° internally (IR).

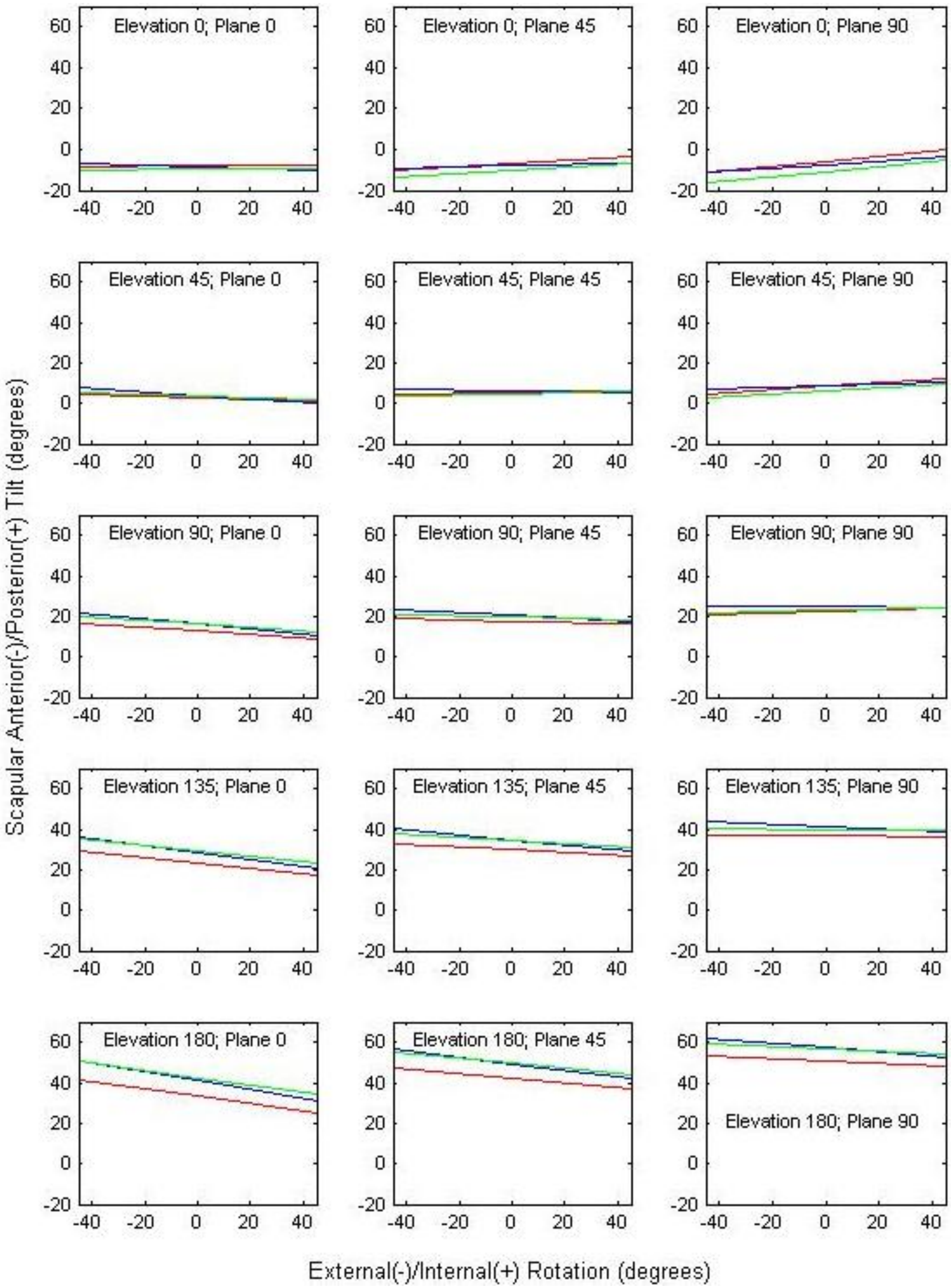


Figure 32: The interaction effect between method of measuring scapular position and axial rotation of the humerus on anterior/posterior tilt of the scapula. The measurements obtained using the stylus (red), AMC (blue) and locator (green) are plotted at 0^o, 45^o, 90^o, 135^o and 180^o elevation angles in frontal (0^o), 45^o to frontal and sagittal plane (90^o) of elevation.

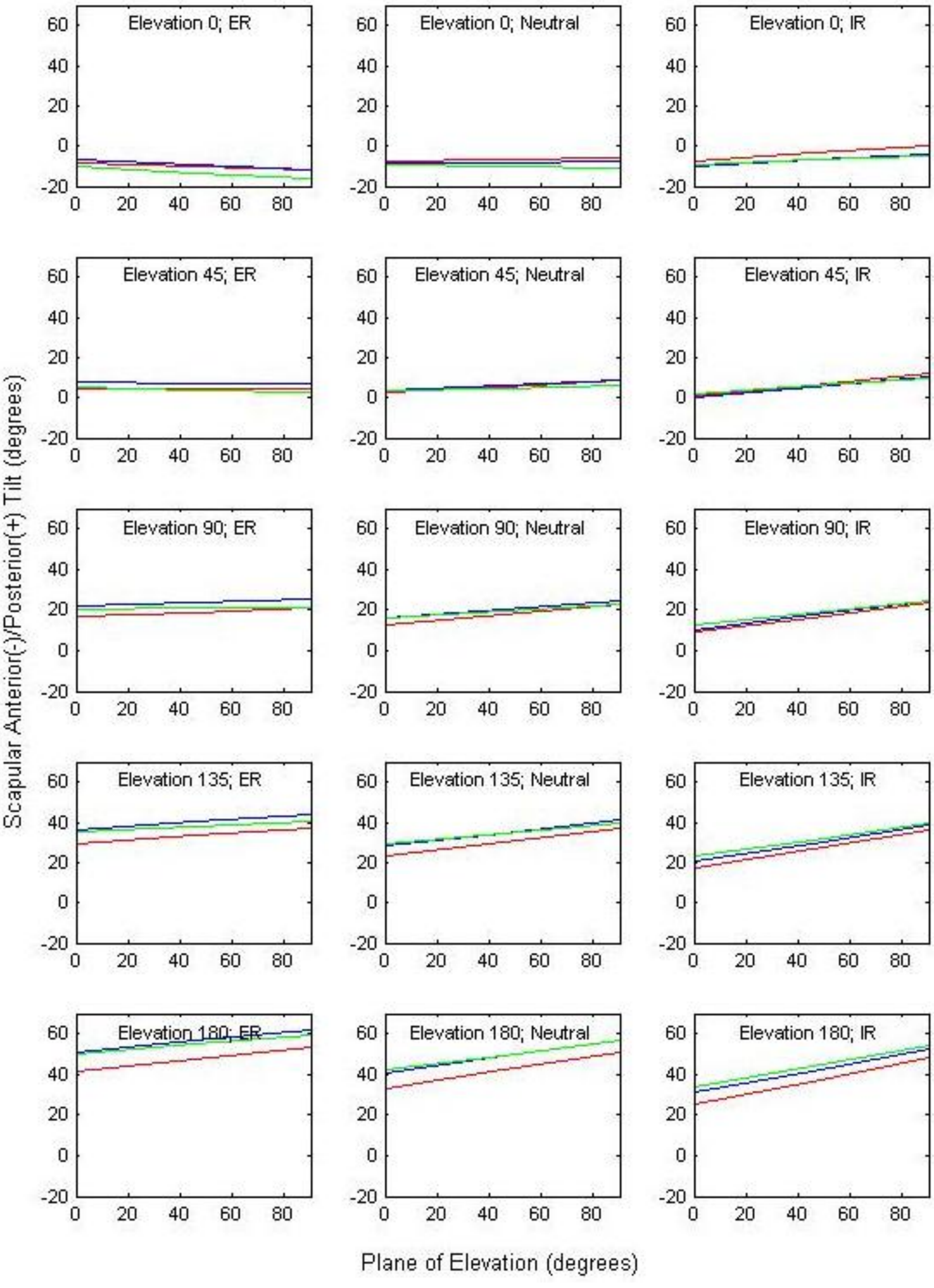


Figure 33: The interaction between method of measuring scapular position and the plane of elevation on anterior/posterior tilt of the scapula. The measurements obtained using the stylus (red), AMC (blue) and locator (green) are plotted at 0°, 45°, 90°, 135° and 180° elevation angles with the humerus axially rotated 45° externally (ER), neutral and 45° internally (IR).

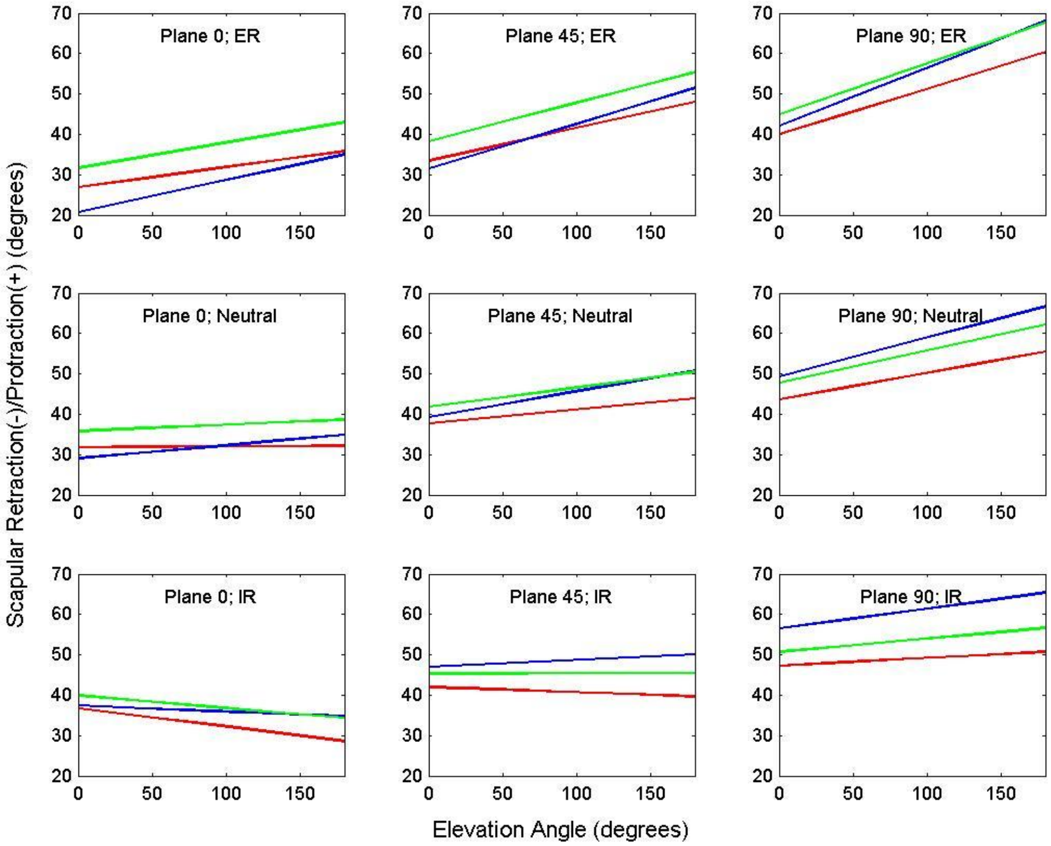


Figure 34: The interaction effect between method of measuring scapular position and elevation angle on retraction/protraction of the scapula. The measurements obtained using the stylus (red), AMC (blue) and locator (green) are plotted at 0°, 45°, and 90° planes of elevation with the humerus axially rotated 45° externally (ER), neutral and 45° internally (IR).

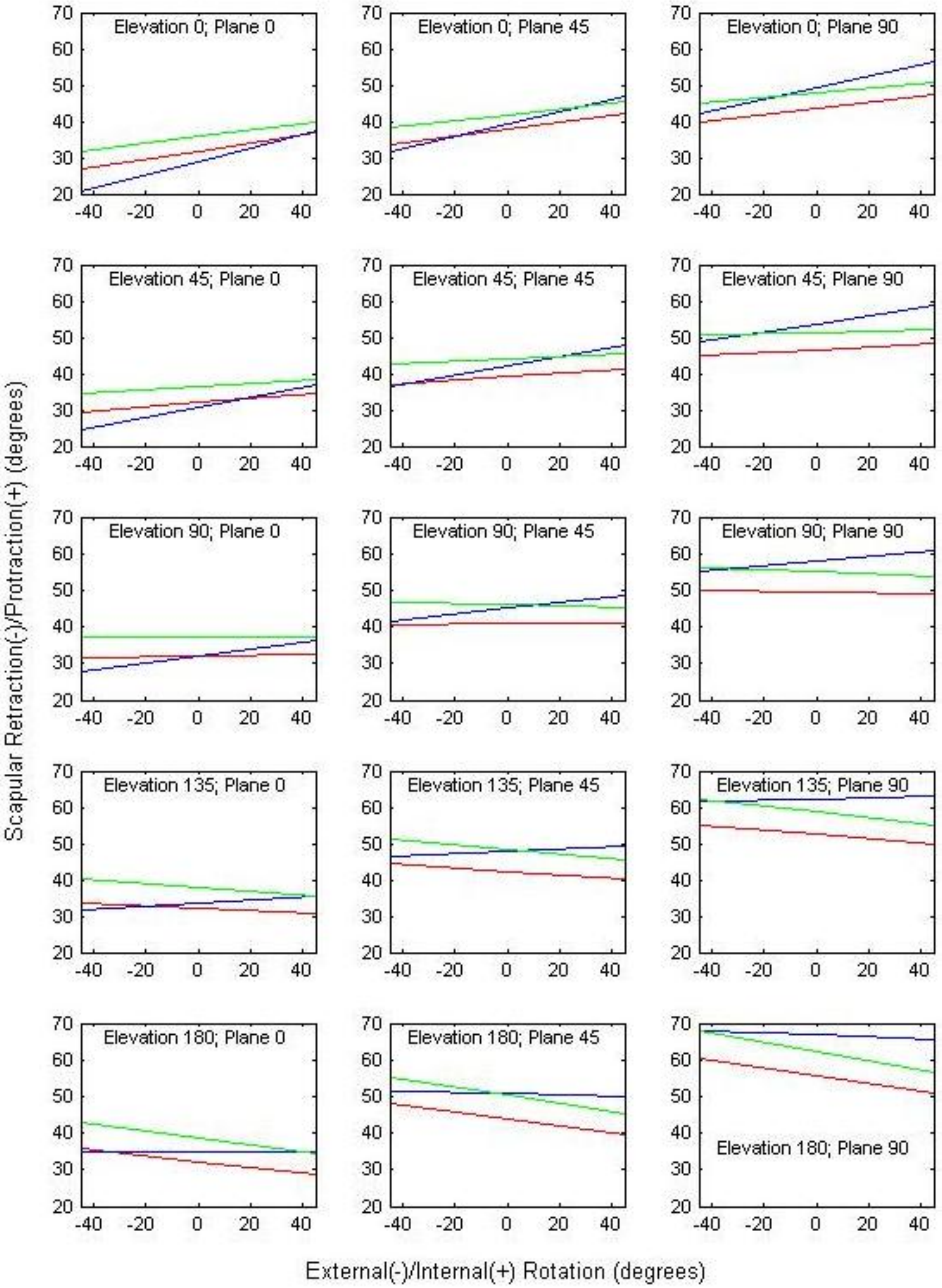


Figure 35: The interaction effect between method of scapular tracking and axial rotation of the humerus on scapular retraction/protraction. The measurements obtained using the stylus (red), AMC (blue) and locator (green) are plotted at 0^o, 45^o, 90^o, 135^o and 180^o elevation angles in frontal (0^o), 45^o to frontal plane and sagittal plane (90^o) of elevation.

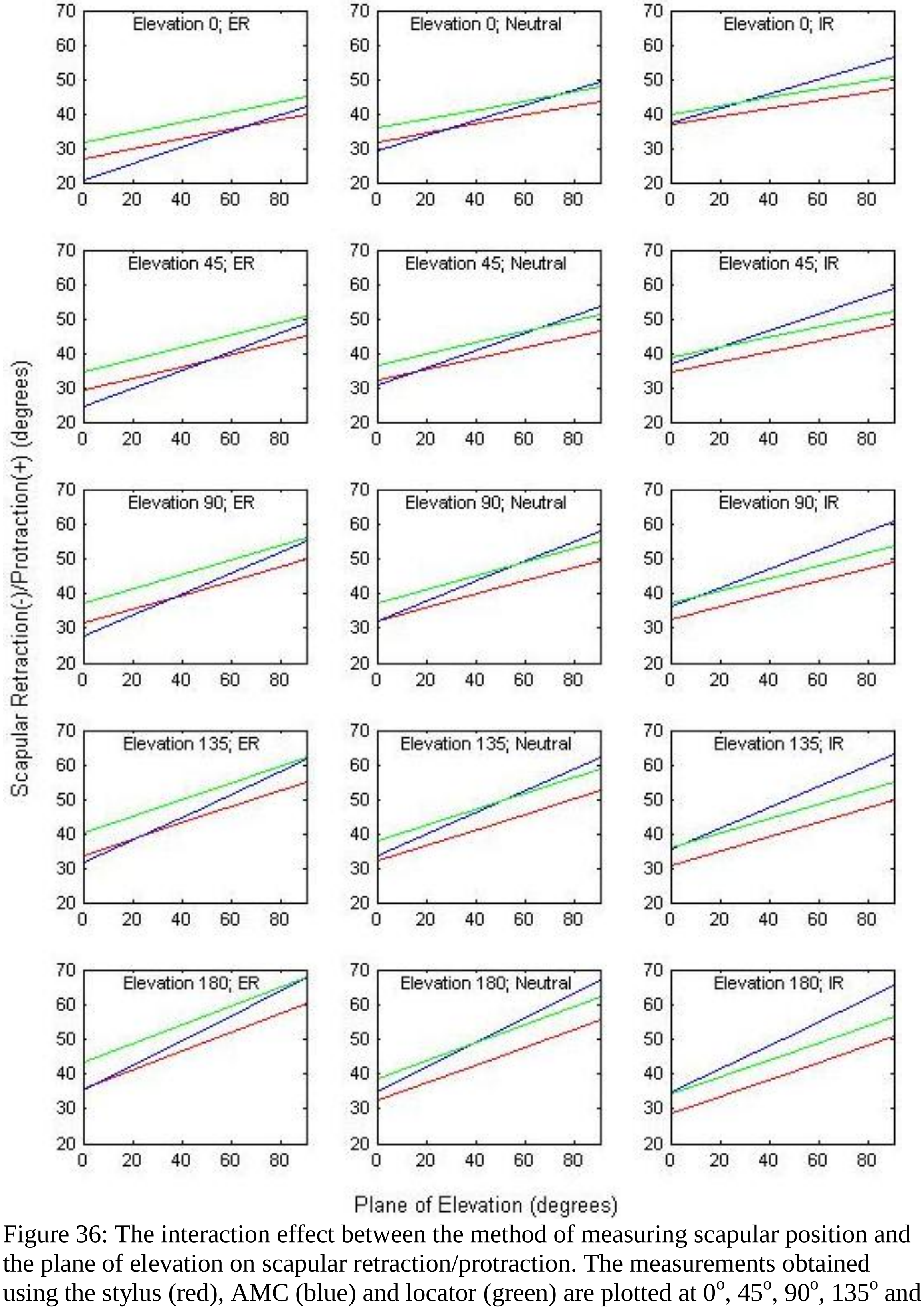


Figure 36: The interaction effect between the method of measuring scapular position and the plane of elevation on scapular retraction/protraction. The measurements obtained using the stylus (red), AMC (blue) and locator (green) are plotted at 0°, 45°, 90°, 135° and 180° elevation angles with the humerus axially rotated 45° externally (ER), neutral and 45° internally (IR).