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Functional Analysis of the Shoulder Complex in Healthy and Pathological Subjects using Three-Dimensional Motion Analysis Techniques

by

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Abstract

Motion capture is increasingly being used to assess the upper limb. The earliest study of the upper limb performed at Cardiff University was an investigative study using retro-reflective markers attached to the skin overlying the bony landmarks of the thorax, clavicle, scapula, and humerus. Throughout the course of the current study this initial model and the experimental protocol have been revised. Particular attention was paid to accurate measurement of the kinematics of the scapula. The original model used markers placed directly over the bony landmarks of the scapula to track its movement. In this study two alternative methods were assessed: a scapula locator, which is considered the "gold standard" in non-invasive scapula tracking, but can only be used during static measurements; and an acromion marker cluster, which can be used to assess dynamic movements of the shoulder. It was found that markers attached directly to the skin overlying the scapula bony landmarks can only be used to assess the level of glenohumeral elevation for arm elevations up to 80° during forward flexion. The acromion marker cluster was found to be suitable for tracking the movement of the scapula in most cases, except that it underestimated glenohumeral elevation during forward flexion due to a necessary design constraint.

The first two applications of the model assessed the hypothesis that common activities of daily living can be performed without the capacity for full physiological range of motion of the scapulothoracic and glenohumeral articulations. It was found that there is an excess capacity of glenohumeral joint elevation not required for the majority of everyday tasks. However it was also found that there is no excess capacity in lateral rotation of the scapulothoracic articulation.

Finally ethical approval was obtained to assess subjects with shoulder pathologies. Subjects were recruited from three different cohorts: mid-shaft clavicle fractures; subjects with one or more previous glenohumeral dislocations; and subjects with multi-directional instability. It was found that the method was able to distinguish between healthy subjects and patient cohorts, and also potentially between different patient cohorts.

This study has served to develop the methods necessary to assess the kinematics of healthy and pathological shoulders and has provided preliminary results on the functionality of three patient cohorts.

Acknowledgements

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Abbreviations

AA	Angulus Acromialis
AC	Acromioclavicular
ACl	Acromion (marker) Cluster
ACS	Anatomical Coordinate System
ADL	Activities (of) Daily Living
AI	Angulus Inferior
BB	Biceps Belly
BMI	Body Mass Index
BI	Brachioradialis Insertion
CF	Clavicle Fracture
C7	(Spinous process of the) 7th Cervical (vertebrae)
DI	Deltoid Insertion
EL	Lateral Epicondyle
EM	Medial Epicondyle
FOU	Forward Outward Upward
GCS	Global Coordinate System
GH	Glenohumeral
GHD	Glenohumeral Dislocator
GHJ	Centre of glenohumeral rotation
IHA	Instantaneous Helical Axis
IMEMP	Institute of Medical Engineering and Medical Physics
IJ	Insicura Jugularis
ISB	International Society (of) Biomechanics
LCS	Local Coordinate System

M:F	(Ratio of) Male (to) Female
MDI	Multi-Directional Instability
OA	Osteoarthritic Knee Function
PC	Processus Coracoideus
PoE	Plane of Elevation
PU	Proximal Ulna
PX	Processus Xiphoideus
QTM	Qualisys Track Manager
RC	Rotator Cuff
RMSE	Root Mean Square Error
ROM	Range Of Motion
RS	Radial Styloid
SC	Sternoclavicular
SL	Scapula Locator
ST	Scapulothoracic
SCoRE	Symmetrical Centre of Rotation Estimation
T8	(Spinous process of the) 8th Thoracic (vertebra)
TCS	Technical Coordinate System
TG	Thorax (relative to the) Global (co-ordinate system)
TKR	Total Knee Replacement
TS	Trigonum Spinae
tsv	tab separated variable
US	Ulnar Styloid
wrt	with respect to

Symbols

°	Degrees of rotation
α	Rotation of a body about helical axis
α	Cutoff significance value in statistical hypothesis testing
α	Rotation about the Z-axis in the I.S.B. recommendations
β	Rotation about the X-axis in the I.S.B. recommendations
γ	Rotation about the Y-axis in the I.S.B. recommendations
λ	Position of a body along a helical axis
$[L]$	Location Vector
$[R]$	Rotation Matrix
R^2	Coefficient of determination
$[T]$	Transformation Matrix

Chapter 1

Background and Literature Review

1.1 Introduction

The shoulder complex has a larger range of motion (ROM) than any other joint complex in the human body, due to the synchronous rotations of four distinct articulations. This extended mobility comes at a cost of decreased stability, particularly of the glenohumeral joint, whose stability is maintained rather tenuously by the surrounding musculature. As a result, the shoulder complex is prone to a wide variety of pathologies, with the glenohumeral joint particularly prone to dislocations and subluxations.

Advances in 3D motion analysis techniques have led to a wider adoption of motion capture as a viable method of assessing the functionality of the shoulder complex,

during activities of daily living [1, 2, 3] and for numerous clinical investigations

such as: post-operative assessment of shoulder arthroplasty [4, 5]; assessment

of subjects with frozen shoulder [6, 7] and osteoarthritis [7]; assessments of the

functionality of the upper limb in stroke patients [8, 9, 10]; and assessment of

subjects with glenohumeral instability [11] including multi-directional instability

[12]. Similar techniques have also been used for quantitative analysis of the neck

and upper limb [13]; to assess children with hemiplegia [14]; and for a variety of

studies which measured the kinematics of the shoulder complex during wheelchair

usage by: able bodied subjects [15, 16, 17]; paraplegic and tetraplegic subjects

[18, 19]; subjects with shoulder impingement [20]; and subjects with spinal cord

injury [21].

The Cardiff University Motion Analysis Laboratory has a strong background in

assessing the functionality of the lower limb, including studies of the hip [22], and

knee [23, 24]. Recent research has focused on the development and implementation

of an objective classification tool to interpret the data outputted by motion anal-

ysis [25, 26, 27, 28]. The tool was developed to aid orthopaedic surgeons during

pre- and post-operative analysis of total knee replacement patients, by providing

a visual output of a patients pathology, and quantify the benefit derived from the

prosthesis.

Based on these experiences, and through consultations with upper limb orthopaedic

surgeons with an interest in biomechanics, it was decided to branch out into motion

analysis studies of the upper limb.

The first study of the upper limb carried out at Cardiff University was a one off investigative study in 2005, which was presented at the World Congress of Biomechanics in 2006 [29]. Retro-reflective markers were attached to the skin overlying the bony landmarks of the thorax, clavicle, scapula, and humerus. Anatomical coordinate systems and joint rotations were calculated according to the International Society of Biomechanics (I.S.B.) recommended standards [30].

The study reported in this thesis builds on this early work to provide the first comprehensive investigation of the upper limb carried out at Cardiff University. The aim of this study was to develop a motion analysis protocol to assess the functionality of the shoulder complex in healthy and pathological subjects. To address this aim, the studies described in this thesis were undertaken to explore the following key objectives:

Objective 1. Determine a layout of 8 Qualisys Pro-Reflex (MCU 1000) (www.qualisys.com) cameras which can track the movement of the markers used to generate the anatomical co-ordinate systems and technical co-ordinate systems of the shoulder complex throughout its full range of movement.

Objective 2. Introduce a scapula locator into the protocol.

Hypothesis 1: Skin-mounted scapula markers, as used in the original incarnation of the shoulder model, do not have the same accuracy as a scapula locator when measuring the kinematics of the shoulder complex.

Objective 3. Determine the most suitable method to dynamically track the scapula in healthy subjects.

Hypothesis 2: An acromion marker cluster can be used to dynamically track the movement of the scapula during ROM and functional tasks in healthy subjects.

Objective 4. Determine the extent of the shoulder complex's full ROM that is used to perform everyday functional tasks.

Hypothesis 3: Common upper limb activities of daily living can be performed without the capacity for full physiological range of motion of the the individual articulations of the shoulder complex.

Objective 5. Use a scapula locator to compare patient and healthy kinematics during static elevations.

Hypothesis 4: A scapula locator can be used to differentiate between the kinematic profiles of healthy and patient cohorts during arm elevation.

1.2 Shoulder Anatomy

1.2.1 The Bones and Muscles of the Shoulder Complex

The shoulder complex is comprised of three bones: the clavicle; the scapula; and the humerus [31] (Fig. 1.1), as well as associated muscles, ligaments and tendons.

The clavicle (Fig. 1.2) is an 's-shaped' double curved bone which serves as the only bony connection between the upper limb and the thorax. It is located directly above the first rib, articulating medially with the manubrium of the sternum at the sternoclavicular joint (section 1.3.1), and laterally with the acromion of the

Clavicle

Scapula

Humerus

Radius

Ulna

Carpus

Metacarpus

Phalanges

Scapular Acromion

Scapular Coracoid process

Humeral Great tubercle

Humeral head

Humeral Lesser tubercle

Humeral Coronoid fossa

Humeral Radial fossa

Humeral Lateral epicondyle

Humeral Medial epicondyle

Humeral Capitulum

Humeral Trochlea

Radius head

Flexor digitorum sublimis

Spinator

Styloid Process

FIGURE 1.1: The bones of the human upper limb. Reproduced from commons.wikimedia.org

scapula at the acromioclavicular joint (section 1.3.2) [32]. It has a rounded medial end and a flattened lateral end. It contributes to power, positioning, stability and protects neurovascular structures.

The scapula connects the clavicle with the humerus [32]. It is held in position by the clavicle, allowing the arm to hang freely. On the anterior surface of the scapula (Fig. 1.3) is the subscapular fossa, which is concave in shape and serves as the attachment of the subscapularis muscle (Fig. 1.8), which facilitates the scapulothoracic articulation (section 1.3.4). The posterior surface of the scapula
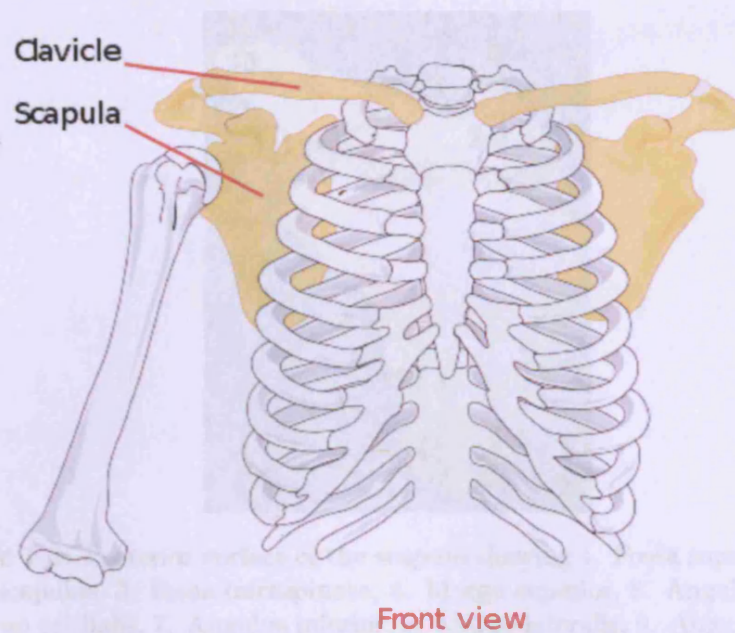
FIGURE 1.2: The pectoral girdle including the clavicle and the scapula. Reproduced from commons.wikimedia.org

(Fig. 1.4) is divided into two parts by the scapular spine: the supraspinatous fossa and the infraspinatous fossa. These two fossae serve as the origins of the supraspinatous and infraspinatous muscles respectively (Fig. 1.8).
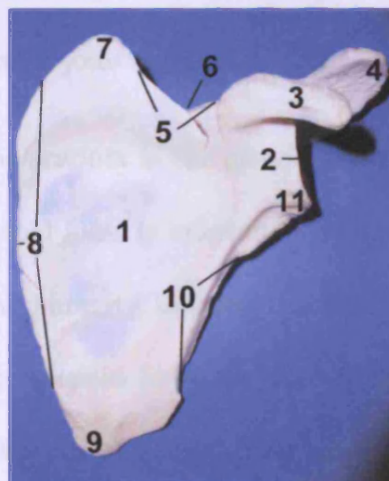
FIGURE 1.3: Anterior surface of the scapula showing 1. Fossa subscapularis, 2. Angulus lateralis with Cavitas glenoidalis, 3. Processus coracoideus, 4. Acromion, 5. Margo superior, 6. Incisura scapulae, 7. Angulus superior, 8. Margo medialis, 9. Angulus inferior, 10. Margo lateralis, 11. Tuberculum infraglenoidale. Reproduced from commons.wikimedia.org.
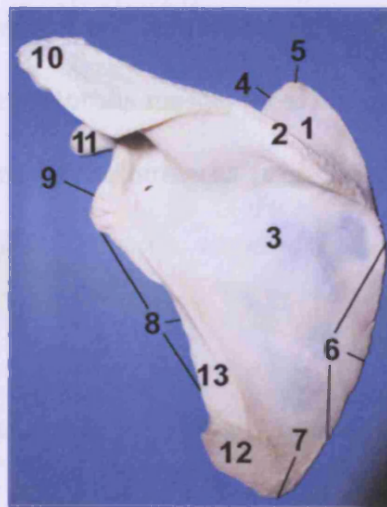
FIGURE 1.4: Posterior surface of the scapula showing 1. Fossa supraspinata, 2. Spina scapulae, 3. Fossa infraspinata, 4. Margo superior, 5. Angulus superior, 6. Margo medialis, 7. Angulus inferior, 8. Margo lateralis, 9. Angulus lateralis, 10. Acromion, 11. Processus coracoideus, 12. Orgin of Musculus teres major, 13. Origin of Musculus teres minor. Reproduced from commons.wikimedia.org.

The medial border of the scapula serves as the attachment of the serratus anterior, the second muscle of the scapulothoracic articulation (section 1.3.4).

The acromion process is a continuation of the scapular spine extending laterally over the glenoid fossa and hooking over it anteriorly. It articulates with the clavicle to form the acromioclavicular joint (section 1.3.2).

On the lateral angle of the scapula is the glenoid fossa, a shallow cavity with an articular surface. The glenoid fossa is orientated laterally and anteriorly. It articulates with the head of the humerus forming the glenohumeral joint [32] (section 1.3.3). The margins of the glenoid fossa are slightly raised and give attachment to the glenoid labrum, a fibrocartilaginous structure, which deepens the fossa to provide extra stability for the glenohumeral joint.

The humerus (Fig. 1.5) is the long bone in the arm and forelimb that connects the scapula and the radius, connecting the glenohumeral joint (section 1.3.3) and

the elbow joint [32]. Movement of the humerus is greatly assisted by its numerous

muscle attachments. The pectoralis major, teres major and latissimus dorsi, work

to adduct and medially rotate the humerus (Fig. 1.6).

FIGURE 1.5: The humerus. Reproduced from commons.wikimedia.org.
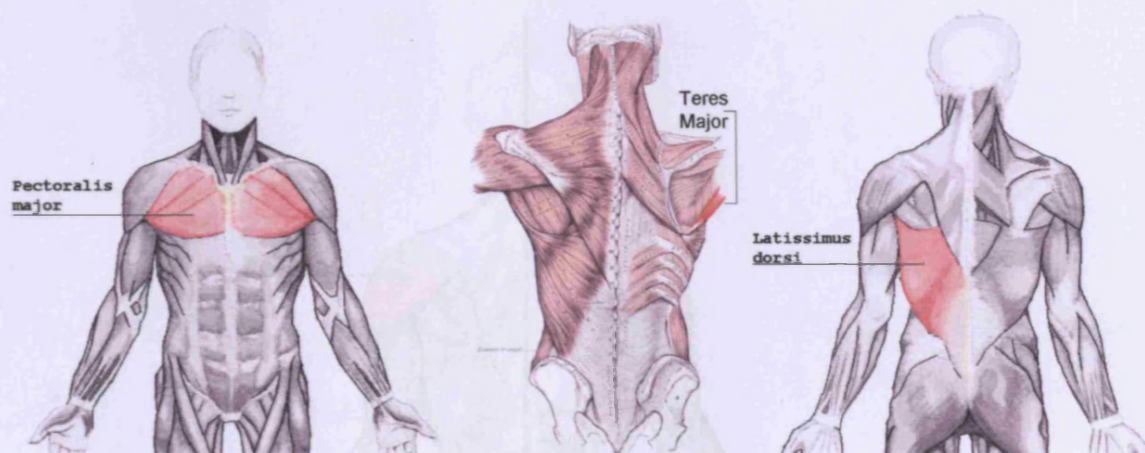
FIGURE 1.6: The pectoralis major, teres major, and latissimus dorsi help to adduct and medially rotate the humerus. Reproduced from commons.wikimedia.org

The deltoid muscle (Fig. 1.7) assists with several movements such as abduction,

extension, and rotation of the humerus [33]. It forms the rounded contour of the

shoulder. It arises in three distinct sets of fibres: the anterior fibres from the

anterior border and upper surface of the lateral clavicle; the middle fibres from

the lateral margin and upper surface of the acromion; and the posterior fibres

from the lower lip of the posterior border of the spine of the scapula. The fibres

converge to form a thick tendon which inserts into the V-shaped deltoid tuberosity

on the lateral aspect of the humerus. When all the fibres contract simultaneously,

the deltoid is responsible for arm abduction in the frontal plane (the arm must be internally rotated). When the arm is externally rotated, the anterior fibres are involved in shoulder abduction. They also assist the pectoralis major during forward flexion. The posterior fibres are strongly involved in transverse extension. The posterior deltoid is also the primary shoulder hyperextensor. The lateral fibers are involved in shoulder abduction when the shoulder is internally rotated, and transverse abduction when the shoulder is externally rotated.
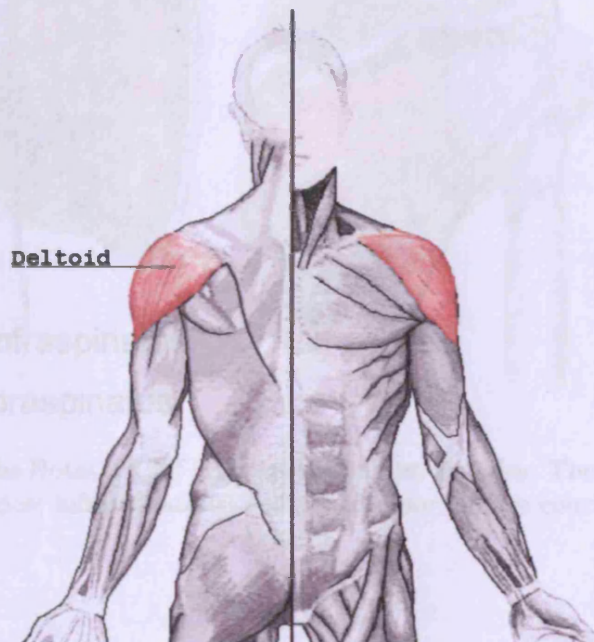
FIGURE 1.7: The deltoid muscle assists with several movements of the humerus including abduction, extension, and rotation of the humerus. Reproduced from commons.wikimedia.org

The rotator cuff (RC) consists of four muscles (and their associated tendons): the supraspinatous; the infraspinatous; teres minor; and the subscapularis [33] (Fig. 1.8). Each of the muscles arise from the scapula and attach to the humerus via a series of tendons, forming a cuff at the GH joint. During arm abduction, the RC compresses the GH joint to allow the deltoid to further elevate the arm without dislocating the humerus. During arm flexion, the infraspinatus and the subscapularis

help to stabilise the joint. During extension, the subscapularis and supraspinatus help to stabilise the joint, while during external rotation the subscapularis alone helps to maintain joint stability. The four muscles of the RC, together with teres major and the deltoid comprise the six scapulohumeral muscles.
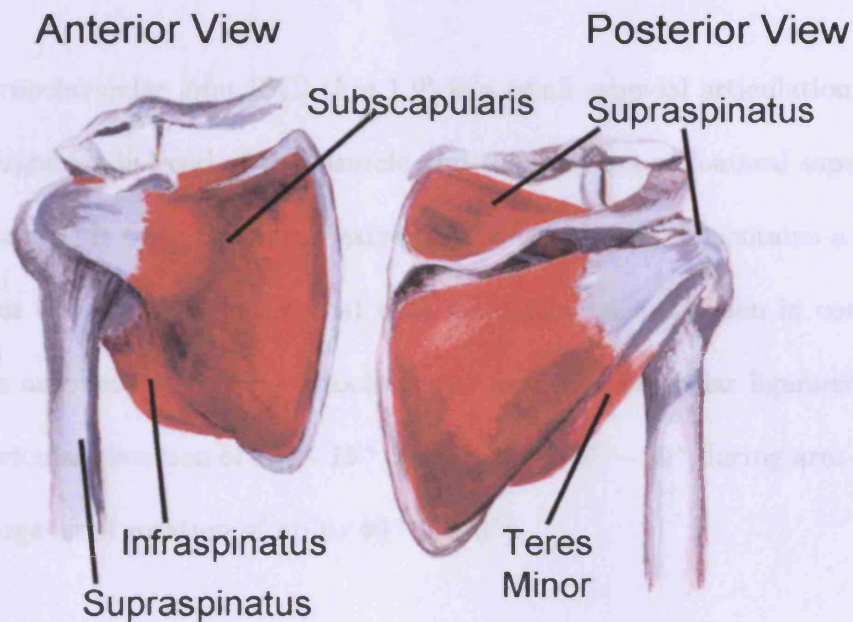
FIGURE 1.8: The Rotator Cuff is comprised of four muscles: The subscapularis; the supraspinatous; infraspinatous; and teres minor. Image courtesy of Audrey Lovern.

1.3 The Articulations of the Shoulder Complex

The three bones of the shoulder complex - the clavicle, the scapula, and the humerus, together with the thorax and the associated musculature, ligaments and tendons of the shoulder complex, combine to form four distinct articulations: the sternoclavicular joint (SC); the acromioclavicular joint (AC); the glenohumeral joint (GH); and the scapulothoracic articulation (ST). These four articulations act synchronously to provide a larger range of motion (ROM) than any of the

individual articulations alone and than any other joint complex in the human body.

1.3.1 The Sternoclavicular Joint

The sternoclavicular joint (SC) (Fig.1.9) is a small synovial articulation between the enlarged medial end of the clavicle and the most superoloateral aspect of the maunubrium. It links the upper extremity to the thorax. It contains a fibrocartilaginous articular disc (meniscus) that maintains joint cohesion in conjunction with the anterior, posterior, costoclavicular and interclavicular ligaments. It allows clavicular elevation of 11 ° - 15 °, retraction of 15 ° - 29 ° during arm elevation and a large axial rotation of up to 40 ° [34, 35].

1.3.2 The Acromioclavicular Joint

The acromioclavicular (AC) joint (Fig. 1.10) is a small synovial joint between the medial surface of the acromion and the lateral end of the clavicle. It allows movement in the anteroposterior and vertical planes together with some axial rotation. A weak fibrous capsule encloses the joint and is reinforced superiorly by the AC ligament. The AC ligament restrains axial rotation and posterior translation of the clavicle. The majority of the joints vertical stability is provided by the coracoclavicular ligament which connects the clavicle with the coracoid process of the scapula. It has a maximum elevation 30 ° - 40 ° [2, 36].

The AC joint allows for elevation/depression, anduction/abduction and medial (downward) lateral (upward) rotation of the scapula [1,13].
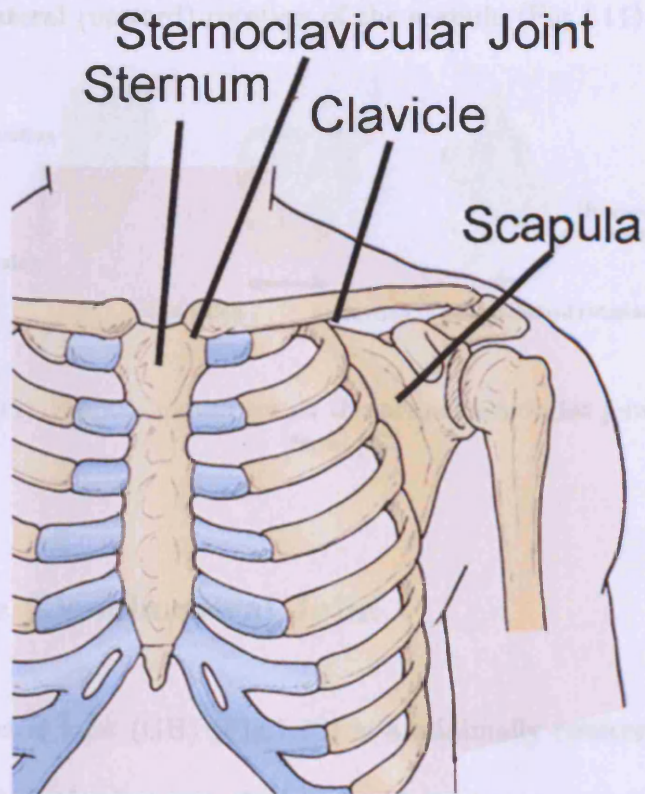
FIGURE 1.9: The sternoclavicular joint. Reproduced from eazyfizzy.co.il

1.3.3 The Glenohumeral Joint

The glenohumeral joint (GH) is a multiaxial, minimally constrained synovial ball and socket articulation between the glenoid fossa (a concave articular surface) and the glenoid head of the humerus. The glenohumeral articulation of the proximal humerus forms a 130°arc. The glenoid fossa is quite shallow, only able to contain approximately 1/4th the surface of the humeral head. The depth of the glenoid is increased by the glenoid labrum, a cartilage rim which attempts to improve stability. Due to the small contact area between the two articulating surfaces of the humeral head and the shallowness of the glenoid fossa, the GH has a large ROM capable of flexion/extension, abduction/adduction, internal/external rotation and circumduction. The GH joint accounts for 120° of the elevation, approximately ⅔ of the shoulder complex's full ROM [1, 8, 13]. The GH joint relies mostly on soft tissue rather than bony structures for its stability, utilising static and dynamic

FIGURE 1.10: The acromioclavicular Joint. Reproduced from www.shoulderdoc.co.uk

The AC joint allows for elevation/depression, adduction/abduction and medial (downward)/lateral (upward) rotation of the scapula (Fig.1.11).
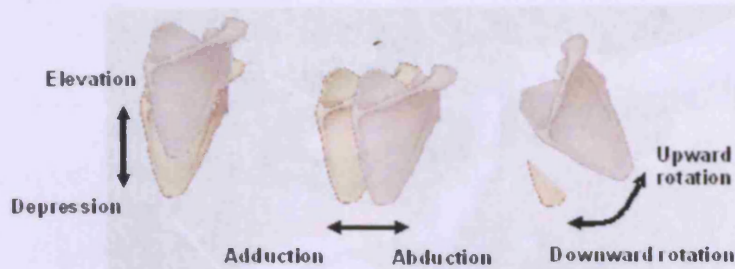
FIGURE 1.11: Scapula movement at the acromioclavicular joint. Reproduced from [37]

1.3.3 The Glenohumeral Joint

The glenohumeral joint (GH) (Fig.1.12) is a minimally constrained synovial ball and socket articulation between the humeral head (a convex articular surface) and the glenoid fossa of the scapula. The articular surface of the proximal humerus forms a 120° arc. The glenoid fossa is quite shallow, only able to contain approximately $\frac{1}{3}$ the diameter of the humeral head. The depth of the glenoid is increased by the glenoid labrum, a cartilaginous surface which helps improve stability. Due to the small contact area between the two articulating surfaces of the humeral head and the shallowness of the glenoid fossa, the GH has a large ROM capable of flexion/extension, abduction/adduction, internal/external rotation and circumduction. The GH joint accounts for 120° of full arm elevation, approximately $\frac{2}{3}$ of the shoulder complex's full elevation [2, 35]. The GH joint relies mainly on soft tissue structures to provide stability. The lack of bony stability and the wide

range of motion permitted by the loose ligamentous and capsular reinforcement leave the GH joint especially prone to dislocations and subluxations.
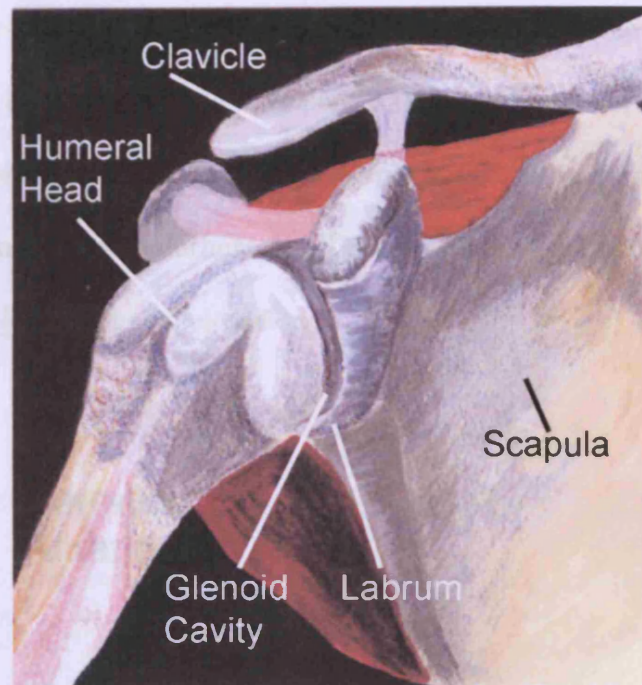
FIGURE 1.12: Glenohumeral joint. Image courtesy of Audrey Lovern.

1.3.4 The Scapulothoracic Articulation

The scapula and thorax are separated by two muscles - the subscapularis (Fig. 1.8) and the serratus anterior (Fig. 1.13). The serratus anterior originates on the surface of the upper eight or nine ribs at the side of the chest and inserts along the entire anterior length of the medial border of the scapula. It is largely responsible for the protraction of the scapula, i.e. pulling of the scapula forward and around the rib cage. It also assists in rotating the glenoid fossa upward enabling higher arm elevations and helps to stabilise the scapula. The subscapularis attaches anteriorly to the scapula at the subscapular fossa and inserts into the lesser tubercle

of the humerus and the front of the capsule of the GH joint. The two muscles glide along one another to provide greatly enhanced mobility to the shoulder complex. The only other connection between the scapula and the thorax is at the AC joint. This allows for a wide scapular ROM including protraction/retraction, elevation/depression and axial rotation. Elevation of the arm involves motion at both the GH and the scapulothoracic (ST) articulation. ST motion accounts for approximately $\frac{1}{3}$ of total arm elevation [7, 38].
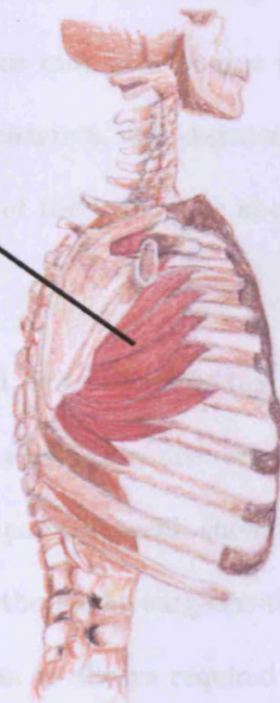
FIGURE 1.13: The serratus anterior glides against the subscapularis to form the scapulothoracic articulation. Image courtesy of Audrey Lovern.

1.4 Shoulder Pathologies

The extended mobility of the shoulder complex comes at a cost of decreased stability leaving it prone to a wide range of pathologies such as: impingement of the GH

joint; rotator cuff tears; AC joint dislocation; and (multi-directional) instability and dislocation of the glenohumeral joint. It is also prone to further complications unrelated to its ROM such as fractures of the clavicle and humerus.

Impingement is believed to be caused by a reduction in the subacromial space leaving an inadequate volume for the clearance of the RC tendons as the arm is elevated. This reduction is believed to be caused by abnormal superior or anterior translations of the humeral head in the glenoid and abnormal scapular motions [39]. The reduced space may also be due to anatomical abnormalities, repetitive eccentric overload, ischaemia, and degeneration of the RC tendons [40, 41]. Frequent or sustained use of the arm at or above head height is also a risk factor.

If impingement is left untreated, it can lead to tears of the RC. The tendons of the RC run under the acromion where they are very vulnerable to being damaged. A tear to the RC results in a painful, weak shoulder. Through personal communications with upper limb orthopaedic surgeons the author was informed that magnetic resonance imaging scan is always required to confirm diagnosis and to determine the size of the tear. If the tear is small, it is treated conservatively with a sling and physiotherapy. Operative repair may be performed arthroscopically or through an open procedure, or sometimes a combination of the two. RC repair involves suturing the torn tendon back onto the humerus using bone anchors. In cases where the tear is too large to be repaired, physiotherapy can be used to train the surrounding muscles to compensate for the RC deficiency. Alternatively a shoulder replacement may be recommended.

AC joint dislocation is usually caused by a fall directly onto the point of the shoulder. The scapula is forced downwards and the clavicle appears prominent. Treatment is either conservative or surgical dependant on the severity of the injury according to the Rookwood Scale (Fig. 1.14).

(a) AC joint sprain (Type 1)

(b) AC joint ligaments torn (Type 2)

(c) 100% dislocation (Type 3)

(d) Clavicle dislocated backward (Type 4)

(e) > 100% dislocation (Type 5)

(f) Clavicle under coracoid (Type 6)
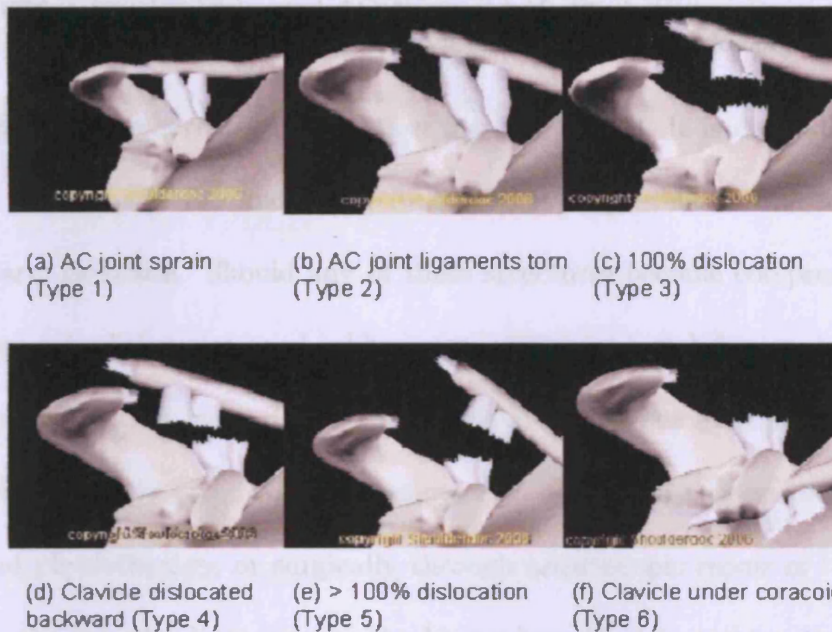
FIGURE 1.14: Rookwood classification of AC joint dislocation. (a) the joint is sprained, (b) the AC ligaments only are torn, (c) there is a 100% dislocation (d) the clavicle has been dislocated backward (e) the dislocation is greater than 100%, (f) the clavicle is underneath the coracoid. Reproduced from www.shoulderdoc.org

AC dislocations types 1 and 2 are always treated conservatively through the use of a sling and physiotherapy. Types 4, 5 and 6 are always treated operatively. There is much debate amongst clinicians as to the best treatment for type 3 dislocations. They are usually treated operatively, but many surgeons advocate conservative treatment with the later option of surgery [42]. Common surgical procedures include the use of a braided polyester material to replace the damaged ligament(s) (Fig. 1.15).
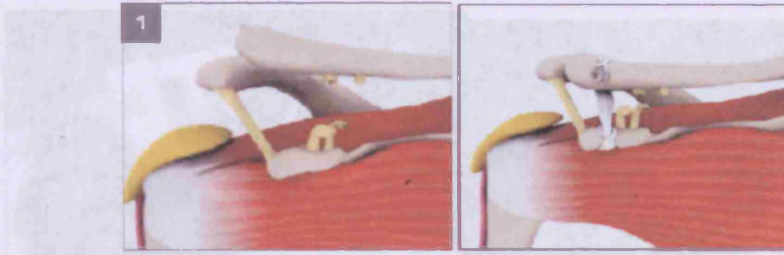
FIGURE 1.15: (a) Dislocated AC Joint; (b) Modified Weaver Dunn used to repair dislocation. Reproduced from www.shoulderdoc.org

The GH joint is inherently lax to allow increased ROM. It is dependant on the glenoid labrum, the RC and the deltoid muscle to prevent it from dislocating during arm elevation. Should any of these structures become compromised, the GH is prone to dislocations and subluxations. GH joint instability can be anterior, posterior, inferior, or multi-directional. The GH joint is the most dislocated joint in the human body [43]. GH dislocations can be treated conservatively with a sling and physiotherapy, or surgically through arthroscopic repair of the glenoid labrum, the capsular ligaments or the biceps long head to tighten the shoulder capsule.

Fractures of the clavicle usually occur during an isolated traumatic event, such as a heavy rugby tackle or a road traffic accident, and as such are common in young active individuals [44]. Untreated clavicle fractures can result in a fixed, multiplanar deformity. Non-operative treatment of clavicle fractures has a much higher rate of non-union (15-25%) [45] than operative treatment ($< 1\%$) [46]. The two most common surgical options are plate fixation 1.16 (a) and a smooth intramedullary pin 1.16 (b).
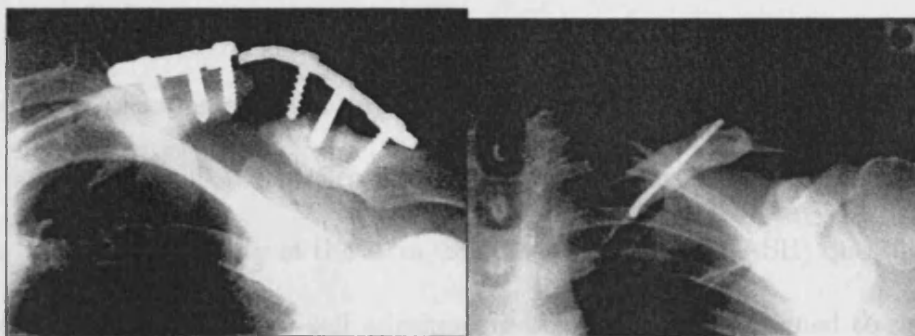
FIGURE 1.16: A clavicle plate (a) or a smooth intramedullary pin (b) are the two most common operative repair methods of a fractured clavicle

1.5 Clinical Diagnosis

Clinically, shoulder pathologies are diagnosed and monitored through a series of observations and physical examinations, such as range of motion testing and subjective strength testing. Orthopaedic surgeons use a series of questionnaires, observations, and physical examinations to determine the extent of the injury and provide an overall score of functionality. This method of assessment is problematic as there are over 20 different upper limb clinical scores in use with no globally adopted standard. Many of the scores contain redundant information [47, 48] and are not equivalent in their assessment of functionality [47]. Amongst the more commonly used scores are the Constant Score [49] (clinician completed), the Oxford Shoulder Score [50] (patient completed), and the American Shoulder and Elbow Surgeons Shoulder Score Index (ASES) [51] (patient completed). In a study of 103 patients treated conservatively for proximal humeral fractures, the Oxford Score and the Constant Score had a correlation coefficient of 0.84 (P <.001). However, the correlation between the Constant and ASES score with a sample group of 70 patients was 0.495, with a coefficient of determination of 0.245, meaning that one

scale explains less than 25% of the variance in the other, rendering cross scale comparisons meaningless [47]. Age is also a confounding variable, particularly when applying the Constant Score [47]. When assessing the functionality of the upper limb, the Disability of the Arm, Shoulder and Hand (DASH) questionnaire [52] is often used. This is a self administered questionnaire designed to measure physical function and symptoms of several musculoskeletal disorders of the upper limb. DASH has been found to be a reliable and valid instrument for assessing shoulder disorders [53] but has been criticised for redundancy in its questions and for not including interviews with patients with the conditions of interest during the item generation phase [48] as physician interpretation of disability consistently differs from patient perception [54, 55, 56].

1.6 Human Kinematics

The position of a rigid body in three-dimensional space is defined by the location of a point on that body and the body's orientation. The human body can be viewed as a series of rigid links connected by joints. Human body parts are not actually rigid structures, but they are assumed to be so to facilitate studies of human motion. Accordingly, human body position can be defined by its location, orientation, and joint configuration (posture) [57].

1.6.1 Defining Body Location and Orientation

The location of a body in space is described by using a co-ordinate method. Various co-ordinate systems can be used, such as Cartesian, oblique, spherical or cylindrical, with the Cartesian co-ordinate system (three orthogonal axes) being the most commonly used.

A co-ordinate method description to define body location is performed in three steps:

1. A Global Co-ordinate System (GCS) is defined

2. A point P in the body is specified. It is convenient to choose the origin of the Local Co-ordinate System (LCS)

3. The location of this point in the GCS is specified

The GCS is by convention described as a right handed orthogonal triad. Usually the positive X axis is horizontal and forward, the positive Y axis vertical and upward, and the positive Z axis horizontal and to the right.

This can cause complications when examining the left and right extremities, as adduction of the right arm is in a positive direction, while adduction of the left arm is in a negative direction. To avoid this complication, a "Forward, Outward, Upward" (FOU) system is recommended, which can be designated as left or right handed.

Three steps are performed to describe body orientation:

1. Define the GCS

2. Attach a LCS to the body

3. Determine the orientation of the LCS relative to the GCS

1.6.1.1 Defining a Local Co-ordinate System in a Rigid Body

A body is considered rigid or solid if the distance between any two points within the body does not change. True rigid bodies are a mathematical abstraction and do not occur in nature. However, it can be a very useful assumption to model something as a rigid body, i.e. a bone.

To fix an orthogonal LCS to a rigid body, the co-ordinates of three non-colinear points within the body must be known. In the example shown in Fig. 1.17 the following routine is performed to fix the reference frame:

1. The cross product of vectors r_1 and r_2 defines the vector r_3 $(r_1 \times r_2 = r_3)$

2. The cross product of vectors r_3 and r_1 defines the vector r_4 $(r_3 \times r_1 = r_4)$

3. Each vector is divided by its own length to determine the unit vectors. The unit vectors of r_1 $\left(\frac{r_1}{|r_1|}\right)$, r_4 $\left(\frac{r_4}{|r_4|}\right)$, and r_3 $\left(\frac{r_3}{|r_3|}\right)$ correspond to the x, y, and z axes of the orthogonal LCS.

The LCS is thus defined by the three mutually orthogonal unit vectors. The orientation of the LCS relative to the GCS describes the orientation of the body in the global reference system.
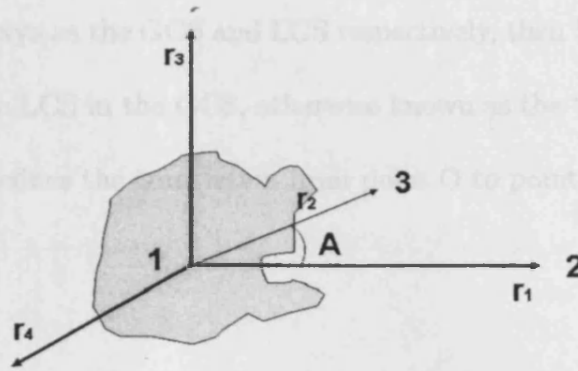
FIGURE 1.17: Within a rigid body of arbitrary dimensions, three points 1,2, and 3 are known. Vectors r_1 and r_2 are from point 1 to points 2 and 3 respectively. Vectors r_3 and r_4 are then determined as cross products. r_1 corresponds to the x-axis of the LCS, r_3 to the y-axis, and r_4 to the z-axis

1.6.2 Defining Body Position and Displacement

The orientation of a moving reference system, fixed within a body, relative to a global reference system can be determined by three methods:

1. The Matrix Method

2. Euler's Method

3. The Helical Axis Method

Using the Matrix Method, both the translation and rotation of a LCS with respect to the global system can be defined. Correspondingly, the translation and rotation

of a LCS relative to a different LCS in another rigid body can be calculated in the same manner.

Taking O-XYZ and o-xyz as the GCS and LCS respectively, then $\mathbf{L}_G$ is the vector giving the origin of the LCS in the GCS, otherwise known as the 'location vector' (Fig. 1.18). $\mathbf{L}_G$ also defines the translation from point O to point o.
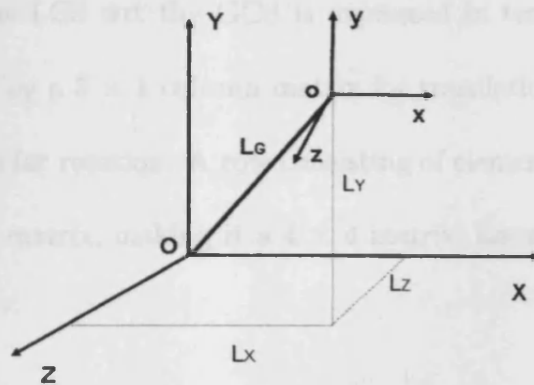
FIGURE 1.18: The three components of the vector **L** define the location of the LCS within the GCS

Each unit vector (**x, y, z**) of the LCS is represented by its components in the GCS. By dividing each component by the length of the vector (which is 1, as it is a unit vector), the cosine of the angle that the vector makes with each of the axes of the GCS is determined. These angles are referred to as the 'direction angles' and the cosines are called the 'direction cosines'. The matrix of direction cosines, also known as the 'rotation matrix' [R] is as follows:

$$[R] = \begin{bmatrix} cos_{X,x} & cos_{X,y} & cos_{X,z} \\ cos_{Y,x} & cos_{Y,y} & cos_{Y,z} \\ cos_{Z,x} & cos_{Z,y} & cos_{Z,z} \end{bmatrix}$$

The columns of [R] are 3 × 1 unit vectors, which correspond to the orientation of the local axes in the global frame. The columns correspond to the axes of the LCS, and the rows match the axes of the GCS.

The position of the LCS wrt the GCS is expressed in terms of translation and rotation described by a 3 × 1 column matrix for translation and a 3 × 3 matrix of direction cosines for rotation. A row consisting of elements (1, 0, 0, 0) is added to homogenise the matrix, making it a 4 × 4 matrix, known as a transformation matrix [T]:

$$[T] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ L_X & cos_{X,x} & cos_{X,y} & cos_{X,z} \\ L_Y & cos_{Y,x} & cos_{Y,y} & cos_{Y,z} \\ L_Z & cos_{Z,x} & cos_{Z,y} & cos_{Z,z} \end{bmatrix}$$

A transformation matrix describes any given position of a LCS relative to the GCS, or potentially relative to any other LCS.

The change of orientation of the body can be also be described with Euler's angles, a sequence of three successive rotations about preset axes from an initial position.

Finite rotations in three-dimensional space are non-commutative. As such, they cannot be considered as vectors.

The general succession for Euler's method is defined as follows:

1. The first rotation is defined relative to an axis in the GCS

2. The second axis of rotation is not fixed w.r.t. the GCS and the LCS, so is commonly called the "floating" axis. It is always orthogonal to the first and third axes. It is denoted by a single prime (')

3. The third rotation is defined with regard to an axis fixed within the rotating body and it is denoted by a double prime (")

The second and third rotations are about local axes transformed by previous rotations. For example, the sequence Yx'y" means that the second rotation is around the local x axis which was previously rotated around the global Y axis; and the third rotation is around the local y axis which was previously rotated around the global Y axis and then around the local x axis.

The final axis in the rotation sequence can be identical to the initial rotation axis (e.g. Xy'x", Zx'z"), or different (e.g. Xy'z", Yx'z"). The term 'Euler's Angles' is often used to denote the use of an **identical** axis, and is referred to as the *two axis system*. The term 'Cardan Angle' is likewise used to denote the use of a **different** final axis. This convention is referred to as the three axis system or the *gyroscopic system*. In total there are 12 sequences of rotations. However the general succession is the same. Six of the sequences are Euler's Angles, and six of

the sequences are Cardan Angles. It is important to realise that the same body orientation measured with various Euler/Cardan sequences gives different angular values.

Euler's/Cardan angles have the advantage of being easily understood, as the angles between two segments of the human body can be measured with a goniometer. However, only the orientation of the segment is defined, meaning that Euler's/Cardan angles do not form a homogeneous system, meaning that translation and rotation must be calculated separately. But, the Euler's/Cardan angles can be expressed as elements of a 3 × 3 rotation matrix, $[R] = [R_1][R_2][R_3]$, where $[R_1],[R_2]$, and $[R_3]$ are the matrices of sequential rotations. An augmented 4 × 4 transformation matrix [T] can be constructed and used as previously discussed in the Matrix Method. The following is an example for a Zy'x" rotation sequence:

$$\left[R\right] = \left[R_Z\right]\left[R_y\right]\left[R_x\right] = \begin{bmatrix} cos\alpha & -sin\alpha & 0 \\ sin\alpha & cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} cos\beta & 0 & sin\beta \\ 0 & 1 & 0 \\ -sin\beta & 0 & cos\beta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\gamma & -sin\gamma \\ 0 & sin\gamma & cos\gamma \end{bmatrix} =$$

$$\begin{bmatrix} cos\alpha cos\beta & cos\alpha sin\beta cos\gamma & cos\alpha sin\beta cos\gamma + sin\alpha sin\gamma \\ sin\alpha cos\beta & sin\alpha sin\beta sin\gamma + cos\alpha cos\gamma & sin\alpha sin\beta cos\gamma - cos\alpha sin\gamma \\ -sin\beta & cos\beta sin\gamma & cos\beta cos\gamma \end{bmatrix}$$

The elements of the combined matrix [R] represent the direction cosines between the axes of the two reference systems, expressed as functions of the Euler's/Cardan

angles. This is known as *decomposition* of the Euler's/Cardan angles, meaning that the axes are decomposed into their projections onto the axes of the global frame. Conversely, when a rotation matrix $[R]$ is given rather than the Euler/Cardan angles, the elements of the matrix can be interpreted in terms of the Euler/Cardan angles if a certain order of rotations is assumed.

When the angle of tilt (about the second rotation axis) is zero, and the first and third axes are parallel, the Euler's/Cardan angles cannot be defined. This results in a *singularity* or *gimbal lock*. If a body is in a singular position, the values of the first and third angles cannot be determined, only their sum (or difference) is measurable, leading to very high errors. This is a very common problem when assessing the GH joint, particularly at low and high levels of arm elevation.

1.6.3 The Helical Method

The helical method, also known as the screw method, allows for the orientation of a body to be described without using arbitrarily chosen axes of rotation. At any given instant during three-dimensional motion, there is a line, referred to as the helical axis, that maintains its position in space. It generally does not lie within the body. The helical method is based on Chasles' theorem, which states that any general motion can be represented as a sequence of translation and rotations. At any given instant, the translation and rotation occur along and around the helical axis. From one instant to the next, the helical axis may change its location in space. The position of the body can be described relative to the helical axis if its position (direction and location) is known.

Helical motion is described by:

1. the position of the helical axis relative to the global frame, i.e.

   the position vector, and

   the unit vector, and

2. the position of the body relative to the helical axis, i.e.

   the position of the body along the axis (λ), and

   the rotation of the body about the axis (α)

1.6.4   Kinematic Modelling of the Upper Limb

Objective kinematic assessment of the upper limb is difficult when compared to lower limb gait analysis due to the large range of path dependant motions of the joints and the numerous non-cyclical unstandardised tasks measured [58]. Accordingly, there are comparatively few studies into the kinematic functionality of the upper limb when compared with the lower limb, which can be easily assessed for repeatable, cyclical movements, i.e. walking.

'The Shoulder: Rupture of the Supraspinatus Tendon and Other Lesions in or about the Subacromial Bursa' published in 1934 by Codman [40] is still prescribed today to trainee orthopaedic surgeons as a definitive guide to the functionality of the shoulder complex. It introduces, amongst other things, the idea of Codman's paradox. During specific motions of the shoulder joint involving two or three sequential arm rotations which do not involve rotation about the longitudinal

axis, an unexplained axial rotation occurs. Take for example an initial position of a subject standing with their arm by their side, palm facing medially and thumb pointing anteriorly. The subject flexes their arm to 180° and then adducts by 180°. The thumb is now pointing posteriorly even though no apparent rotation of the humerus occurred. With the development of mathematical techniques and the increased interest in shoulder kinematics from non-clinicians, Codman's paradox has been further investigated and found to not in fact be a paradox, but to comply with a general law of motion [59, 60]. This is stated as: *"when the long-axis of the arm performs a closed-loop motion by three sequential rotations defined as Codman's rotation, it produces an equivalent axial rotation angle about the long-axis. The equivalent axial rotation angle equals the angle of swing - the second rotation in the three sequential long-axis rotations"* [59].

In 1944 Inman et al. [61] described the motion of the shoulder complex as "...the sum of movement contributed by synchronous participation of (the SC, AC, GH and ST articulations...)". In this very ambitious study, they examined several aspects of the shoulder complex in an effort to derive an overall understanding of its functionality. They compared the scapula, humerus and surrounding musculature of the human shoulder with those of primates to deduce an explanation for the characteristics of the morphology of the human shoulder. They used x-rays and bone pins to perform kinematic analysis, estimated the forces required by each muscle to maintain stability at different elevations, and measured the electrical stimulation of the muscles during movement.

In 1966 Freedman and Munro [62] examined scapular and glenohumeral movement

of 61 subjects in five positions ($0°$, $45°$, $90°$, $135°$, and full elevation) during abduction in the scapular plane using x-rays. This was a change from previous studies which assessed abduction in the coronal plane. The results were compared primarily with those obtained by Inman et al. [61], in the coronal plane. When analysing humeral and scapular movement, lines were drawn on each x-ray to represent the longitudinal axis of the humerus and the orientation of the glenoid fossa, which represented the orientation of the scapula. The glenoid fossa was chosen as it was difficult to discern the medial border of the scapula in most of the images, and it was hard to distinguish the landmarks of the spine of the scapula. For each recorded x-ray image, the angle of the glenoid to the vertical (the scapular angle) and the angle of the humerus to the vertical were recorded. The measured value of glenohumeral elevation was the arm elevation less the scapular elevation. From their study they concluded that on average, there are $3°$ of glenohumeral elevation for every $2°$ of scapula lateral rotation.

In 1976 Poppen and Walker [63] described translations of the humeral head, and instant centres of rotation for the scapula and humerus, for 5 intervals of scapular plane abduction in 15 patients with shoulder pain and a comparison group of healthy individuals. Seven patients displayed an abnormal location of the humeral head instant centre of rotation and 6 patients showed increased translation of the humeral head centre relative to the glenoid. However analysis of the results is complicated as many of the patient sample had numerous shoulder pathologies.

In 1990 Johnson and Anderson [64] developed a three-dimensional measurement technique using an electromagnetic system. The source was mounted on the

humerus and a sensor mounted on the thorax using adhesive tape, enabling measurement of the relative movement of the sternum and the humerus. The authors used two different angular conventions, clinical angles and polar co-ordinates, to report movement. The inadequacies of using clinical angles to define shoulder movement were identified, but it was also highlighted that polar co-ordinates lack any clinical meaning.

The scapulothoracic articulation is responsible for approximately $\frac{1}{3}$ of the shoulder complex's full ROM [7]. Altered scapula kinematics can also be indicative of certain pathology types, for example increased lateral rotation, or "winging" of the scapula in subjects with recurrent glenohumeral dislocations and abnormal scapulo-humeral rhythm in patients with adhesive capsulitis (frozen shoulder) [65]. Accurate in-vivo non-invasive measurement of the kinematics of the scapula is problematic due to the presence of overlying soft tissue. In 1991 Pronk [66] used a single point locator attached to a three dimensional spatial linkage instrument to determine the spatial position of the acromial angle, the root of the scapular spine, and the inferior angle, and thus infer the orientation and position of the scapula. The method was found to be accurate but too time consuming, as the landmarks needed to be identified independently at static increments of elevation.

Johnson et al. [67] expanded on this method by making the assumption that the scapula is a rigid body. They developed a three-pointed locator to determine the locations of the three scapula bony landmarks simultaneously. The scapula locator has been applied since to numerous other studies [12, 35, 39, 65] and it has

now become the gold standard by which other non-invasive methods of scapula tracking are assessed and calibrated [68].

Veeger et al. [15] investigated the three-dimensional movement of the scapula during a simulated wheelchair push to develop a finite element model to study the efficiency of manual wheelchair propulsion. The positions of the trunk and arm were measured using two still-cameras. The co-ordinates of to the anatomical landmarks were reconstructed using a digitisation process and used to establish local co-ordinate systems. The rotation angles were produced using an Euler decomposition (YZX for the scapula and XZY for the humerus).

In 1994 van der Helm [69] developed a finite element model to analyse the kinematic and kinetic behaviour of the shoulder complex. Bony landmark co-ordinates were used to reconstruct the positions of the humerus, clavicle, and scapula which were used as input data to the model. The rotations of the bones were defined from a virtual reference position using Euler angles.

Meskers et al. [65] studied the kinematics of the shoulder complex during abduction and flexion, with an electromagnetic tracking device [70] consisting of three receivers attached to the thorax, scapula and humerus. The thorax receiver was glued to the manubrium, the humerus receiver was mounted on a circular cuff which was attached to the distal humerus, and the scapula receiver was mounted on a scapula locator. Bony landmarks were digitised with a stylus endpoint and their trajectories used to create local co-ordinate systems. Each of the local co-ordinate systems was then related to a technical co-ordinate system provided by the corresponding sensor. Joint rotations were expressed in Euler angles.

In 2005, the I.S.B. [30] issued a set of recommended standards for modelling the shoulder complex. The recommendations were based on the work of Grood and Suntay [71] who developed a methodology to calculate relative movement of two body segments and applied it to the knee. The bones of the body can be viewed as a series of rigid links whose positions can be defined by the location of a point on the bone and the bone's orientation in space [57]. The basic premise is that three non-collinear bony landmarks on a given bone segment are needed to generate a three-dimensional orthogonal co-ordinate system for that bone. The bony landmarks for modelling the shoulder complex as recommended by the I.S.B. [30] are shown in Table 1.1 and Fig. 1.19.

TABLE 1.1: Anatomical Landmarks proposed by the I.S.B.

Thorax	C7	Spinous process of the 7th cervical vertebra
	T8	Spinous process of the 8th thoracic vertebra
	IJ	Deepest point of Incisura Jugularis
	PX	Processus Xiphoideus, most caudal point on the sternum
Clavicle	SC	Most ventral point on the sternoclavicular joint
	AC	Most dorsal point on the acromioclavicular joint
Scapula	TS	Trigonium Spinae, the midpoint of the triangular surface on the medial border of the scapula in line with the scapular spine
	AI	Angulus Inferior, most caudal point of the scapula
	AA	Angulus Acromialis, most laterodorsal point of the scapula
	PC	Most ventral point of processus coracoideus
Humerus	GHJ	Glenohumeral rotation centre (estimated)
	EL	Most caudal point on lateral epicondyle
	EM	Most caudal point on medial epicondyle
Forearm	RS	Most caudal-lateral point on the radial styloid
	US	Most caudal-medial point on the ulnar styloid

It can be useful to describe two types of rotations in the shoulder complex: joint rotation and segment rotation. Joint rotation is the rotation of a bone segment with respect to the proximal articulating segment (e.g. SC, AC, ST and GH joints); whereas segment rotation is the rotation of any segment relative to the
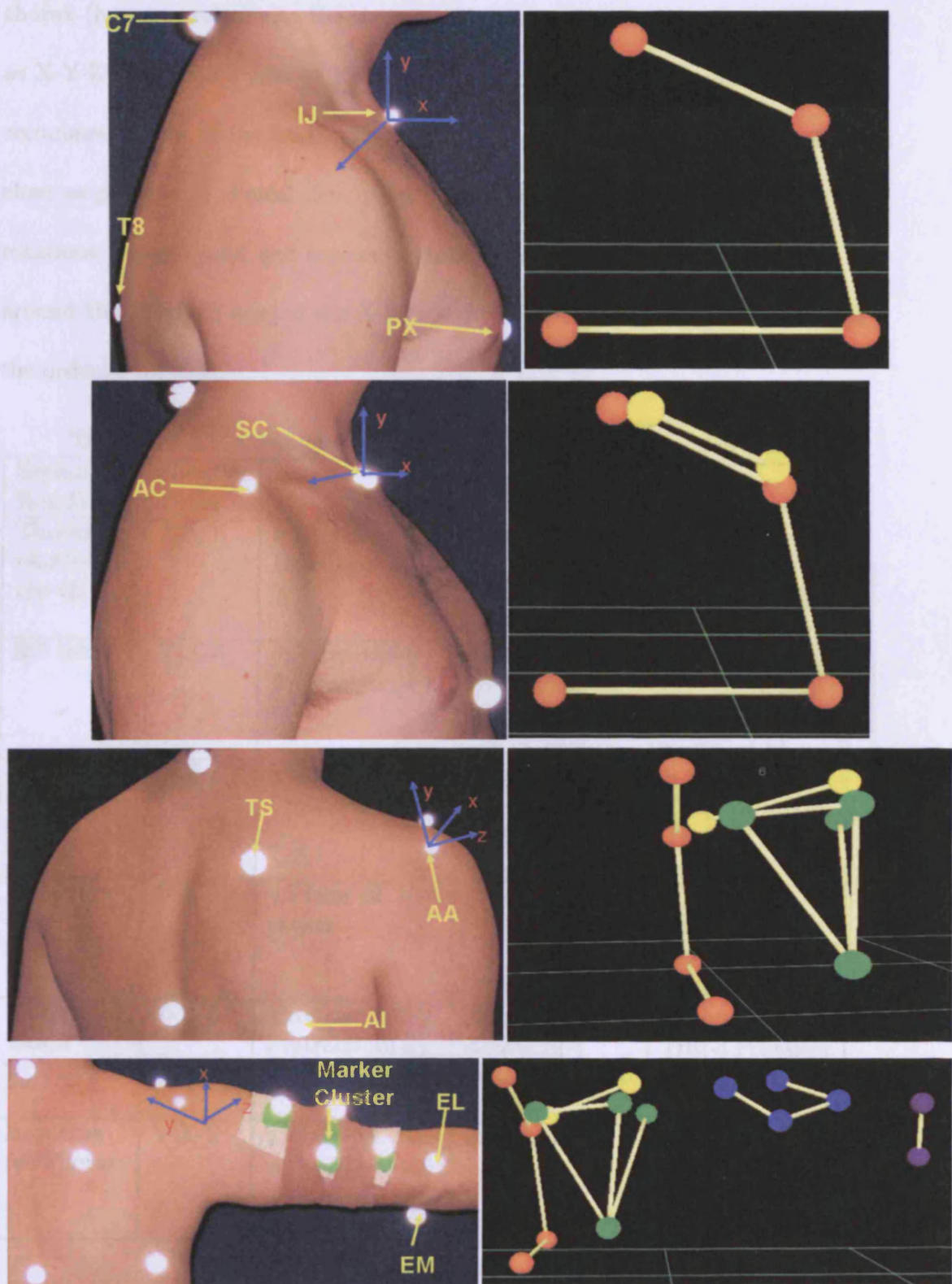
FIGURE 1.19: Marker placement and generation of Anatomical Co-ordinate Systems on the thorax, clavicle, scapula, and humerus as per the I.S.B. recommendations [30].

thorax (humerus relative to the thorax). Many rotation orders are possible such as X-Y-Z in Cardan angles or Y-Z-Y in Euler angles. Rotation orders follow the recommendations of the I.S.B. [30], which were chosen so that angles remain as close as possible to clinical definitions of joint and segment rotations [30]. The rotations for each joint and segment rotation are summarised in Table 1.2. α is around the Z axis, β around the X axis and γ around the Y axis, irrespective of the order of rotation.

TABLE 1.2: I.S.B. recommendations on joint and segment rotation order

Segment Rotation	Rotation Order	Rotation		
Thorax relative to the GCS	Z-X-Y	α:Flexion(-) Extension(+)	β:Left lateral flexion(-) Right lateral Flexion(+)	γ:Right axial rotation(-) Left axial rotation(+)
SC Joint	Y-X-Z	γ:Retraction(-) Protraction(+)	β:Elevation(-) Depression(+)	α:Forward axial rotation(-) Backward axial rotation(+)
AC Joint	Y-X-Z	γ:Retraction(-) Protraction(+)	β:Lateral Rotation(-) Medial Rotation(+)	α:Anterior Tilt(-) Posterior Tilt(+)
GH Joint	Y-X-Y	γ:Plane of Elevation	β:Elevation(-)	γ:External rotation(-) Internal rotation(+)
ST Articulation	Y-X-Z	γ:Retraction(-) Protraction(+)	β:Lateral Rotation(-) Medial Rotation(+)	α:Anterior Tilt(-) Posterior Tilt(+)
Humerus rel Thorax	Y-X-Y	γ:Plane of Elevation	β:Elevation(-)	γ:External axial rotation(-) Internal axial rotation(+)

1.6.5 Ambiguities in the I.S.B. standards

Since the publication of the I.S.B. standards [30] they have been widely adopted by shoulder researchers enabling comparisons between studies carried out in different institutes.

However, the recommendations are intentionally non-exhaustive and leave many of the decisions related to the protocol up to the individual researcher. There are no guidelines given as to which landmarks should be digitised and which are best represented with physical markers. Furthermore, there are no recommendations regarding the placement of technical co-ordinate systems which are related to the local co-ordinate systems produced with digitised markers. As a result there is still a lot of variation in the measurement protocols used in different studies.

1.6.5.1 Modelling the Thorax

The thorax LCS is produced with four markers: IJ, PX, C7, and T8. Many studies prefer to digitise these landmarks and relate them to a TCS on the manubrium, particularly when using electromagnetic apparatus [2, 65], but also when using optical motion capture systems [3]. While other studies prefer to place individual markers on each of the bony landmarks [72].

1.6.5.2 Modelling the Clavicle

Only two landmarks of the clavicle, SC and AC, can be palpated. As a result it is not possible to directly measure the axial rotation of the clavicle. It is possible to

estimate the axial rotation by minimising the rotations at the AC joint [35]. This

is feasible because the longitudinal axis of the clavicle is almost perpendicular to

the scapular plane, meaning that axial rotation of the clavicle and lateral rotation

of the scapula in the scapular plane are equivalent [38]. By applying a clavicle axial

rotation of $60°$, it is possible to reduce AC joint rotations to less than $10°$ [66].

Studies which have implemented these techniques can measure lateral rotations

of the AC joint between 10 and 15 times smaller than those that do not [73]. In

the case of studies which have not used the optimisation techniques, the lateral

rotation of the AC joint is approximately equal to the sum of the measured AC

lateral rotation and the estimated clavicle rotation measured in studies which have

used the optimisation techniques. When using the optimisation techniques, the

SC landmark can be related to a TCS on the manubrium of the thorax, which can

reduce skin artefacts.

The kinematics of the clavicle can also be described by using regression equations

which relate the position and orientation of the clavicle to a given humerus posi-

tion. One such set of regression equations were developed using invasive methods

[74] and are used in the Newcastle Shoulder Musculoskeletal Model [75].

1.6.5.3 Modelling the Scapula

The scapula locator [67] has been applied in numerous studies of upper limb motion

[12, 35, 39, 65] and has now become the gold standard by which other non-invasive

methods of scapula tracking are assessed and calibrated [68]. One limiting factor

of the scapula locator is that it can only be used to take measurements of scapula

orientation during static elevations. Dynamic scapulohumeral rhythm must then be inferred through linear regression equations for the arm reachable workspace [76, 77]. Collecting the data necessary to establish the scapulohumeral rhythm for the arm reachable workspace can be time consuming, and with patient groups where pain and fatigue are major factors, may not always be practical. The scapulohumeral rhythm in healthy subjects has been found to be relatively predictable for healthy subjects [76, 77] but this assumption cannot be made when assessing patient groups.

Alternative methods of directly tracking the dynamic movement of the scapula have been assessed. One option is to place skin markers directly over the bony landmarks of the scapula. This method is extremely prone to errors associated with skin artefacts (see section 1.6.6). It has been found to be effective only for measuring the level of glenohumeral elevation [73] up to arm elevations of 80°.

Two variants of a non-invasive method which use the acromion plateau as the placement site of a TCS were developed and validated by Karduna et al. [78]. The first method simply placed an electromagnetic sensor on the plateau, while the second fixed the sensor to an adjustable plastic jig that fits over the scapular spine and acromion. Both methods were validated against an invasive method which involved pins drilled directly into the scapula. The study found that for up to 120° of arm elevation both methods provided similar results to the invasive method. This was later confirmed by comparison with a scapula locator [68] but the recommendations have since been altered not to supersede arm elevations of 100° [79]. The technique has been widely adopted in other studies [3, 39].

1.6.5.4 Modelling the Humerus

Accurate calculation of the humerus LCS according to the I.S.B. recommendations is dependant on accurate and reliable identification of the glenohumeral centre of rotation (GHJ). It defines the superior point of the y-axis, which is in turn used to calculate the x and y" axes. Therefore, a misplacement of GHJ can alter the entire humerus LCS. This in turn effects the measured rotations of the elbow and wrist joints, as forearm rotations are measured relative the the humerus, and hand movements are in turn measured relative to the forearm [80].

Numerous methods have been reported in the literature to estimate GHJ. These can be categorised into two groups: predictive; and functional methods.

Predictive methods rely on a generic relationship between GHJ and anatomical attributes, such as the positions of particular bony landmarks or anthropometric measurements. The predictive method suggested by the I.S.B. recommendations [30] uses linear regression equations based on the locations of the scapula bony landmarks [81]. This particular method was validated on cadavers and was later found, in vitro, to produce an anterior offset, and to have relatively low reliability [82]. The International Shoulder Group website (www.internationalshouldergroup.org) now contains an updated set of regression equations. Various studies have used this particular predictive model [2, 11, 73]. However many other studies use a variety of unvalidated predictive methods of varying degrees of sophistication. Some use the thorax as the relative proximal segment [14, 83]. Others use the location

of the AC joint as an offset point, where the respective offsets are calculated in a variety of different manners [9, 13, 72, 84, 85, 86].

Functional methods rely on the trajectories of the markers of the upper arm making a sphere about the GHJ, which is located in the proximal segment, the scapula, during a kinematic movement trial. The GH joint is assumed to move as a ball and socket joint with a fixed rotation point in the geometric centre of the humeral head [87]. The functional algorithms can be divided into three sub-categories; 'Sphere fit', 'Helical axis', and 'Transformation algorithm' methods.

Sphere fit methods optimise the centre and radius of the sphere to fit the trajectories of the surface markers [88, 89]. These methods make the assumption that the centre of rotation is stationary in the proximal co-ordinate system, which implies that the calculation is more accurate if the proximal segment is at rest during the kinematic calibration [90].

The helical axis method [91] requires the angular acceleration of the distal segment (the humerus) and the acceleration of the distal segment relative to the proximal segment (the scapula). This is the preferred method of the I.S.B. [30] despite its associated computation time and sensitivity to low angular velocities. It is preferred to the I.S.B. suggested predictive method [81] as it, and other functional methods, can be used in situations where the morphology of the GH has been altered due to injury or surgery [82].

Transformation algorithms rely on the assumption of rigid segment motion [92] to create LCS's from the markers attached to proximal and distal segments. These

methods estimate a single fixed joint centre from the transformations of a LCS into a common reference system in each time frame of the kinematic movement trial [90]. The Symmetrical Centre of Rotation Estimation (SCoRE) [92], is a two sided transformation algorithm which has been shown to be more reliable than the Instantaneous Helical Axis method [93] and has the further advantage of not being susceptible to low angular velocities.

The I.S.B. standards [30] provide no guidelines for the placement of the markers constituting the humerus TCS with regard to representing the movement of the underlying bone or representation of GHJ. The placement of the markers will alter the solution of the functional algorithms used to calculate GHJ [90, 94, 95]. A mechanical linkage comparison found that the accuracy of the sphere fit method was increased when the markers were placed proximally on the segment, close to the joint centre, but for the individual markers to be as far apart as possible [95]. This may not be the case with the helical axis method and SCoRE method. Furthermore, markers on the proximal portion of the humerus are susceptible to larger soft tissue artefacts (see section 1.6.6) than those on the distal segment [72]. The presence of soft tissue artefacts suggest that although the functional methods have been found to be reliable in predicting GHJ [82, 93], the estimate may still be inaccurate. The purpose of the markers used to define the TCS is 1) to represent the motion of the underlying bone, and 2) to reference the location of the segment anatomical landmarks during dynamic motion. The optimum choice of TCS is complicated by these two purposes, as an individual TCS may be suitable for referencing the anatomical landmarks, but unsuitable for representing the motion

of the underlying bone. Conversely, the opposite may be true for a separate

TCS. It has been found that a combination of TCS give the best results. A TCS

placed on the acromion and a TCS-placed on the upper arm were both found

suitable when referencing GHJ. Taking the average position as referenced by each

of these TCS further reduced the errors [96]. The optimal TCS for representing

the motion of long bones such as the humerus has been confirmed as the distal

portion [72, 84, 97, 98]. It can therefore be inferred that three TCS should be

used for maximum accuracy when assessing the kinematics of the GH joint.

1.6.6 Errors Associated with Motion Capture of the Upper Limb

The two most significant errors associated with modelling human body kinematics

are artefacts caused by the presence of soft tissue and the misidentification of

anatomical landmarks [80, 98, 99, 100, 101, 102].

Soft tissue artefacts are caused by the movement of active and passive tissue

between the surface markers and the underlying bone. The magnitude of the asso-

ciated errors are dependant on the marker location [98]. Markers placed directly

over anatomical landmarks are particularly error prone [99]. The most widely used

solution to this alternative is the 'Calibrated Anatomical Systems Technique' [99],

where the positions of the anatomical landmarks of a segment are related to the

positions of three or more non-collinear markers which are positioned on the seg-

ment in a position considered to be least susceptible to artefacts. The positions of

the markers are independent of the anatomy of the underlying bone, and are used to create a TCS. The TCS is then used to reference the positions of the anatomical landmarks throughout the motion, which can now be treated as virtual markers based on their identification during anatomical calibration trials.

The implications of soft tissue artefacts and techniques to minimise them have been discussed previously for the thorax (section 1.6.5.1), the clavicle (section 1.6.5.2), the scapula (section 1.6.5.3) and the humerus (section 1.6.5.4). The humerus in particular is extremely prone to soft tissue artefacts, which can result in internal/external rotation being underestimated by up to 35% [103]. An in-vivo technique to compensate for the soft tissue artefact affecting axial rotation of the humerus has been developed based on the definition of a humerus bone-embedded frame [72]. The orientation of the forearm is used to help determine the axial rotation of the humerus. Using this technique, the root mean square error (RMSE) decreased from 9° to 3°.

The second most common errors in human motion analysis are caused by palpation errors of anatomical landmarks and marker misplacement [99, 100, 102]. In particular to the shoulder, palpation error has been shown to result in errors of 2° when measuring the orientations of the shoulder bones [104].

1.6.7 The Future of Upper Limb Motion Capture?

The publication of the I.S.B. recommended standards [30] was a major step forward in upper extremity motion analysis as it defined a standard, which if adopted,

would allow comparisons to be made between the results collected at different research and clinical centres. The next step is to define a set of standardised protocols with a standardised description. A framework has recently been proposed with the intention of opening discussion. It is composed of two nested flowcharts [105]. The first flowchart (Fig. 1.20) defines what a motion analysis protocol is by pointing out its role in a motion analysis study. The second flowchart (Fig. 1.21) describes the process involved in determining a protocol, emphasising decisions on the joints and/or segments to be investigated, the definition of the anatomical or functional co-ordinate frames as appropriate, the choices available with regard to marker or sensor configuration and the validity of each choice, and a definition of the activities to be measured. Recommendations are also proposed for each step based on the body of knowledge currently available in the literature.

The ultimate aim of kinematic analysis of the shoulder complex in relation to a clinical context is to have a beneficial end effect on patient treatment and improve quality of life, either by providing objective evidence of one treatment's superiority over another, or by enhancing the understanding of upper limb clinicians. The I.S.B. method is an effective means of describing shoulder motion by using a sequence dependant matrix decomposition. However, alternative methods have been proposed which seek to simplify the description of the motions to facilitate understanding amongst clinicians, who if lacking a technical or engineering background, may find the methods used and results obtained difficult to comprehend. One such method is the 'Globe Method' [106, 107, 108].

```
┌─────────────────────────────────────┐
│  1. Define the research question     │
└─────────────────────────────────────┘
                  ↓
┌─────────────────────────────────────┐
│  2. Formulate á set of hypotheses    │
└─────────────────────────────────────┘
                  ↓
┌─────────────────────────────────────┐
│     3. Define the parameters         │
│         to be measured               │
└─────────────────────────────────────┘
                  ↓
┌─────────────────────────────────────┐
│       4. Build the motion            │
│        analysis protocol             │
└─────────────────────────────────────┘
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┌─────────────────────────────────────┐
│     5. Measure the parameters        │
└─────────────────────────────────────┘
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┌─────────────────────────────────────┐
│      6. Statistical analyses         │
│         of the parameters            │
└─────────────────────────────────────┘
                  ↓
┌─────────────────────────────────────┐
│      7. Verify hypotheses to         │
│         conclude study               │
└─────────────────────────────────────┘
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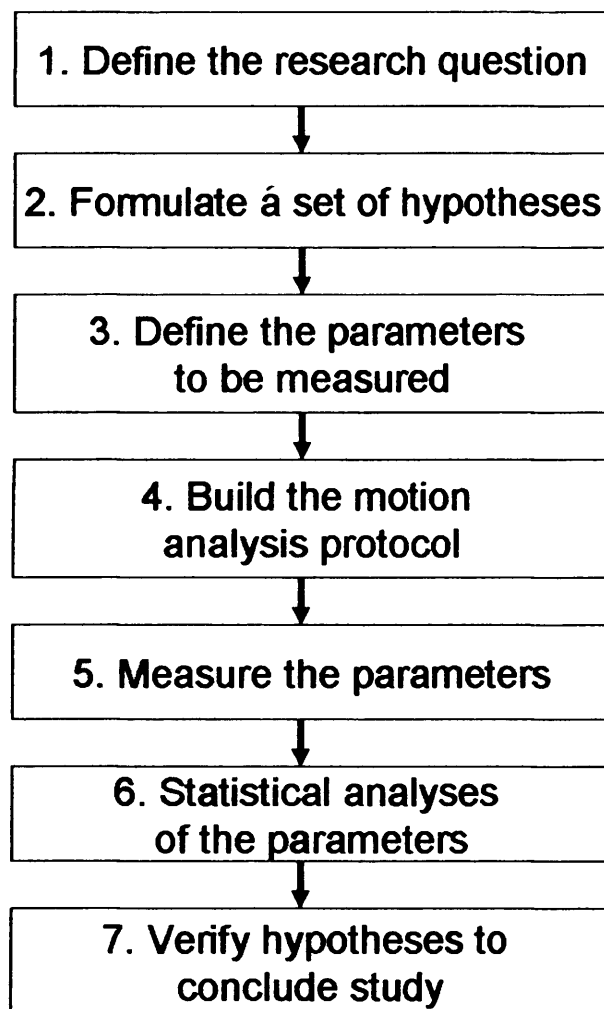
FIGURE 1.20: This flowchart describes the basic steps to develop a motion analysis study, and thus highlight the role of a motion analysis protocol. [105]

The Globe Method superimposes a sphere on the subject with a radius equal to the humeral length and with centre at GHJ. The position of the humerus is measured relative to a base frame located in the trunk. The plane of elevation is the projection of the humerus onto the horizontal plane. Elevation is the angle between the global (trunk) longitudinal axis and the humeral longitudinal axis. Axial rotation of the humerus is described by inclination of the forearm with the global latitude passing through the elbow in a plane tangent to the sphere at the point of the elbow. Figures 1.22 and 1.23 provide a pictorial comparison of the
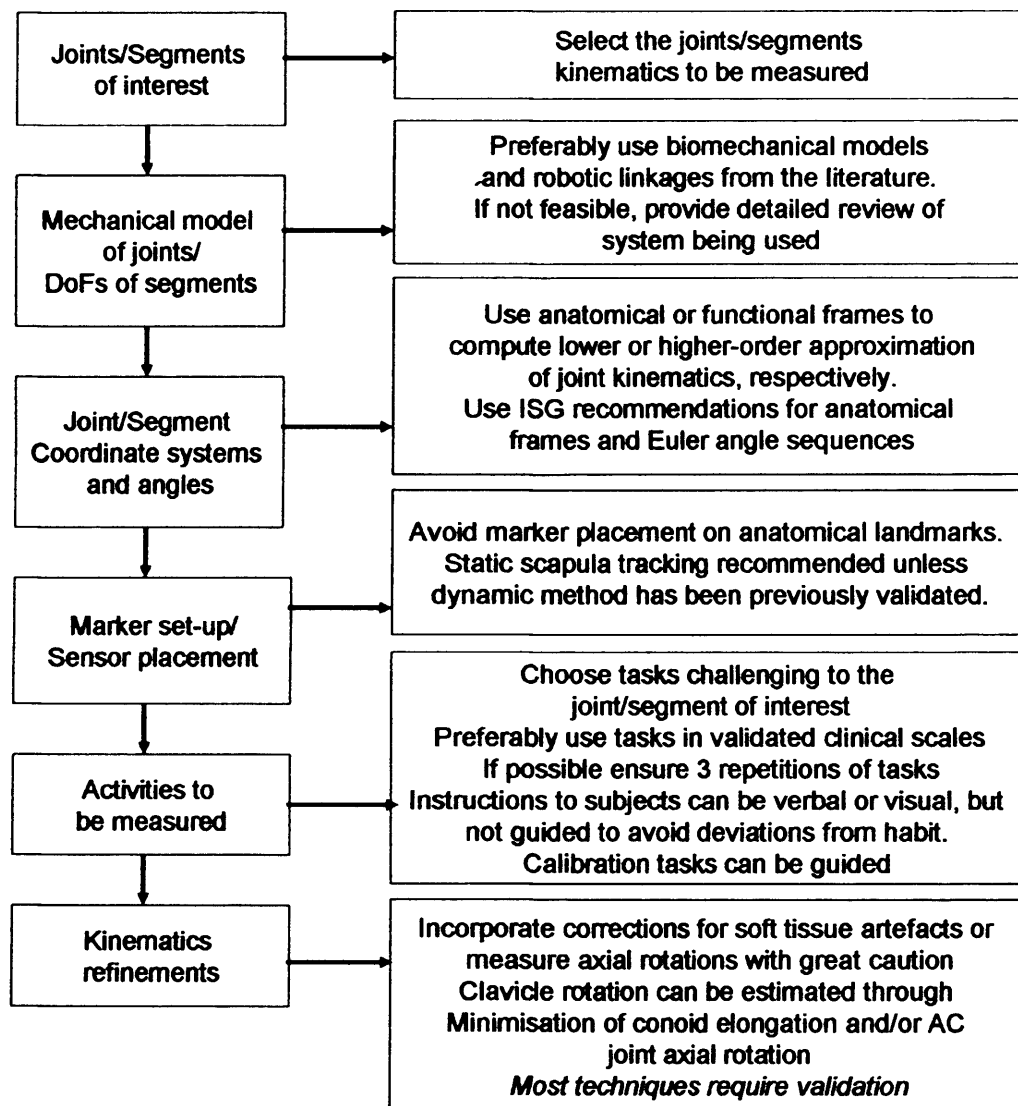
FIGURE 1.21: (a) This flowchart specifies the steps required to build a motion analysis protocol. (b) This flowchart contains basic recommendations and highlights current gaps for each of the steps in (a). [105]

Globe and I.S.B. methods.

Mathematically, the Globe Method is identical to the I.S.B. method [108], but is more intuitive and easier for clinicians to understand as it mimics practical measurement techniques commonly performed by clinicians. An ordered set of numbers is used to describe position, but the measurement of angles is sequence-independent. Any one of the three measurements can be made independently of
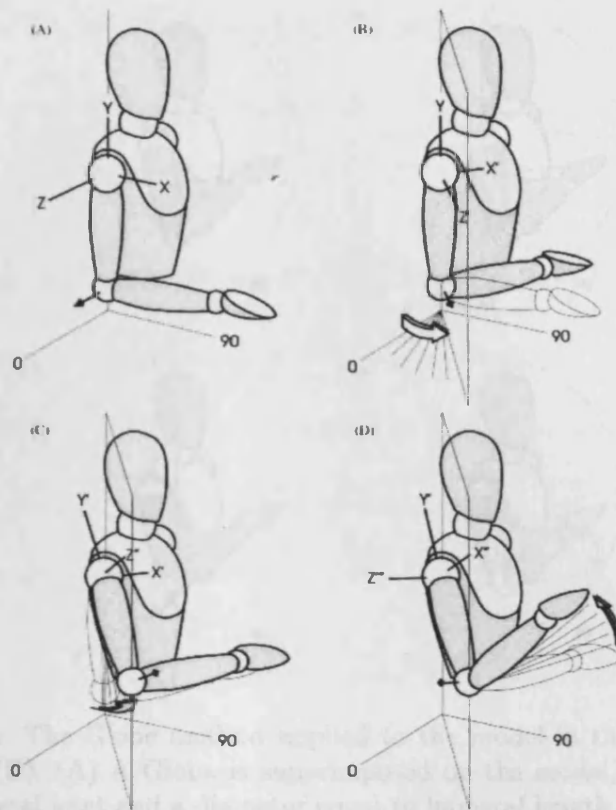
FIGURE 1.22: The I.S.B. method of measuring joint rotations: (A) shows the initial position with a vector pointing laterally (parallel to the humeral Z-axis) at 0° on the XZ plane. (B) The humerus is rotated about its Y-axis until the humeral Z' -axis points to the plane of elevation. (C) The humerus is elevated about its X'-axis. (D) The humerus is externally rotated about its Y'-axis to the final position. The Y'-axis is normal to the plane containing the rotating forearm. Taken directly from [108].

the other with no regard for rotation sequence. When working with physicians in a clinical context, the Globe Method may be more suitable than the I.S.B. method.

1.7 Thesis Summary

The thesis is divided into five chapters.

Chapter 1 contains relevant background information to the study and a literature review.
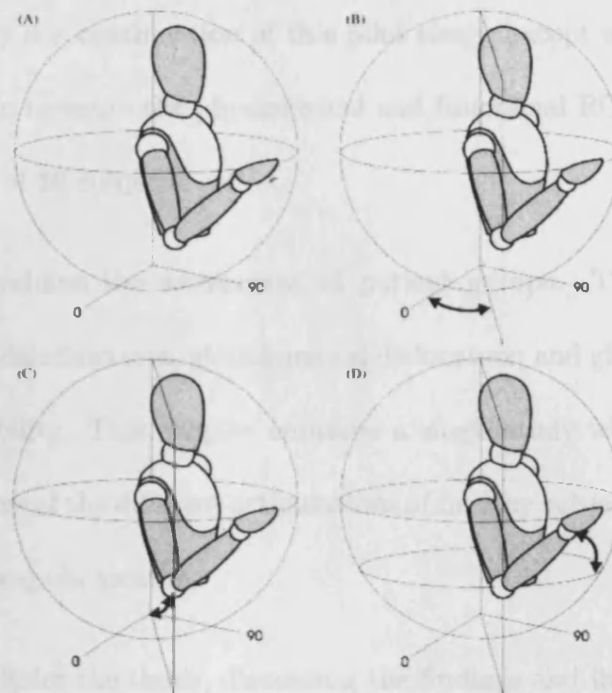
FIGURE 1.23: The Globe method applied to the model in the final position of Fig. 1.22 (D). (A) A Globe is superimposed on the model, with centre at the glenohumeral joint and a diameter equal to humeral length. (B) The plane of elevation is defined as the projection of the humerus onto the horizontal plane. (C) The angle of elevation of the humerus is measured. (D) The forearm rotation is measured as a deviation from the local latitude passing through the elbow joint, in a plane tangent to the sphere at that point. This plane is normal to the longitudinal humeral axis, and is therefore the same as described in Fig. 1.22. Taken directly from [108].

Chapter 2 contains an account of the development and improvement of the methods through two studies. The first study involves a cohort of 10 healthy subjects. The accuracy of skin based markers on the scapula is compared with a scapula locator. The second study assesses the accuracy of an acromion marker cluster against a scapula locator on 16 healthy subjects.

Chapter 3 contains two studies focusing on the applications of the developed methods. The first is a pilot study on five subjects using skin-based scapula markers to determine the differences in functional elevation and physiological elevation of the glenohumeral joint when performing a series of activities of daily living.

The second study is a continuation of this pilot study, except using the acromion marker cluster, to measure the physiological and functional ROM of the GH and ST articulations of 16 subjects.

Chapter 4 introduces the assessment of patient groups. The patient groups assessed are: clavicle fractures; glenohumeral dislocators; and glenohumeral multi-directional instability. This chapter contains a single study which compares the measured rotations of the different articulations of healthy subjects and the patient cohorts using a scapula locator.

Chapter 5 concludes the thesis, discussing the findings and limitations.

Chapter 6 discusses the several avenues for further investigation that have arisen from this study.

All testing, analysis, and software development was done by the author, unless explicitly stated. Where other researchers and colleagues were involved, the level and extent of their contributions have been indicated in the relevant sections.

Fig. 1.24 provides an overview of the thesis structure.

Chapter 1:
Background and
Literature Review

↓

Hypothesis 1 ⟶ **Chapter 2:**
Methods

Study 1: 10 Healthy Subjects
Skin vs. Scapula Locator

Study 2: 16 Healthy Subjects
Scapula Locator vs. Acromion Cluster

↓

Hypothesis 2 ⟶ **Chapter 3:**
Applications

Study 1: 5 Healthy Subjects, Pilot Study
Functional vs. Physiological ROM
(using skin markers on scapula)

Study 2: 16 Healthy Subjects
Functional vs. Physiological ROM
(using acromion marker cluster)

↓

Hypothesis 3 ⟶ **Chapter 4:**
Patients
⟶ Study 1: Healthy vs. Patients
(using Scapula Locator)

↓

Chapter 5:
Conclusions and
Limitations

↓

Chapter 6:
Further Work

FIGURE 1.24: A flowchart providing an overview of the thesis structure

Chapter 2

Development of the Experimental Methods

2.1 Chapter Overview

The first part of this chapter provides an overview of the motion analysis laboratory, including camera positioning and the calibration procedure. The remainder of the chapter is divided into two studies, both of which focus on accurate representation of the kinematics of the scapula. The scapula is involved in three of the four rotations of the shoulder complex: the acromioclavicular joint (AC), the scapulothoracic articulation (ST), and the glenohumeral joint (GH). As such, accurate measurement of the movement of the scapula is of utmost importance when assessing the functionality of the shoulder complex. The first study [73] examines the accuracy of the model as developed by Jones et al. [29], specifically focusing

52

on the use of skin-mounted markers to track the movement of the scapula. It investigates hypothesis 1, that **skin-mounted scapula markers do not have the same accuracy as a scapula locator when measuring the kinematics of the shoulder complex.** The second study uses an alternative means of scapula tracking, a TCS placed on the acromion plateau, which if found to be suitably accurate has the added benefit of being able to track dynamically the movement of the scapula. This study is an investigation of hypothesis 2, that **an acromion marker cluster can be used to dynamically track the movement of the scapula during ROM and functional tasks in healthy and pathological subjects.**

2.2   Equipment Set-up and Calibration

The Cardiff University Motion Analysis Laboratory is equipped with 8 infra-red Qualisys Pro-Reflex MCU 1000 cameras (Fig. 2.1) (www.qualisys.com) with a sampling frequency of 60Hz. Objective 1 of the study was to determine the optimal positioning of the cameras to view all of the retro-reflective markers necessary to model the shoulder complex.

The factors that were considered when doing this were as follows:

- At least two cameras (but preferably three to allow for some redundancy) must be able to see each marker at all times in order to determine its position in three-dimensional space.

- The shoulder complex has a very large ROM. The visible workspace of the cameras needs to be accordingly large to ensure that all markers are visible (by at least two cameras) throughout the shoulder's full ROM

- Cameras need to be positioned to view markers which are placed anteriorly, posteriorly, and laterally.

- The IJ and SC markers are in very close proximity to each other. Both markers needed to be seen clearly at all times to avoid "marker swapping", where the camera system confuses the trajectories of the two markers causing them to overlap.

- Finally, it needed to be possible to assess the left and right arms of each subject without moving the cameras.

Bearing in mind these considerations, and through much trial and error, the optimum positions and heights of each camera were determined. A schematic is provided in Fig. 2.2. This schematic serves as a guideline which was adhered to throughout the entire study. At the start of each trial, the cameras were positioned according to the schematic. A calibration L-frame was then placed on a stool in the centre of the lab (Fig. 2.3). The camera positions were then modified so that the current view of the calibration frame in each view matched the corresponding view from an earlier trial which was known to have suitable camera positioning (Fig.2.4). This camera positioning was maintained throughout the course of the study. Where necessary, the seated positions of the subject being tested could be adjusted, for example when changing from the left to the right shoulder.

Other motion analysis studies of the upper limb, for example in Newcastle University [109], do not document the positioning of the cameras. Through personal communications with the author [109], it was discerned that the cameras were roughly positioned for each independent trial so that the calibration frame could be seen in each view. The heights and distances from the centre of each camera were varied, based on the opinion of the tester, to ensure that the markers would be visible throughout the tasks to be assessed.

In the University of Southampton, through personal communications with the lab manager, it was found that 11 of the 12 cameras are fixed on rails from the ceiling 2.5m above floor level. They are kept in this position for all studies of the lower limb, shoulder, and hand. When assessing the hand, the 12^{th} camera is sometimes suspended above the subject.
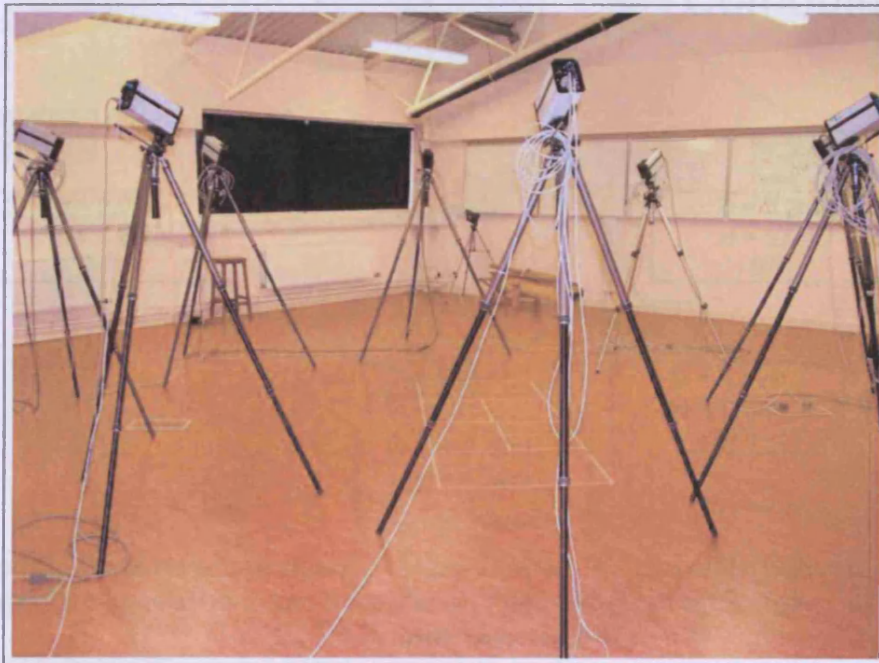
FIGURE 2.1: The Cardiff University Motion Analysis Laboratory
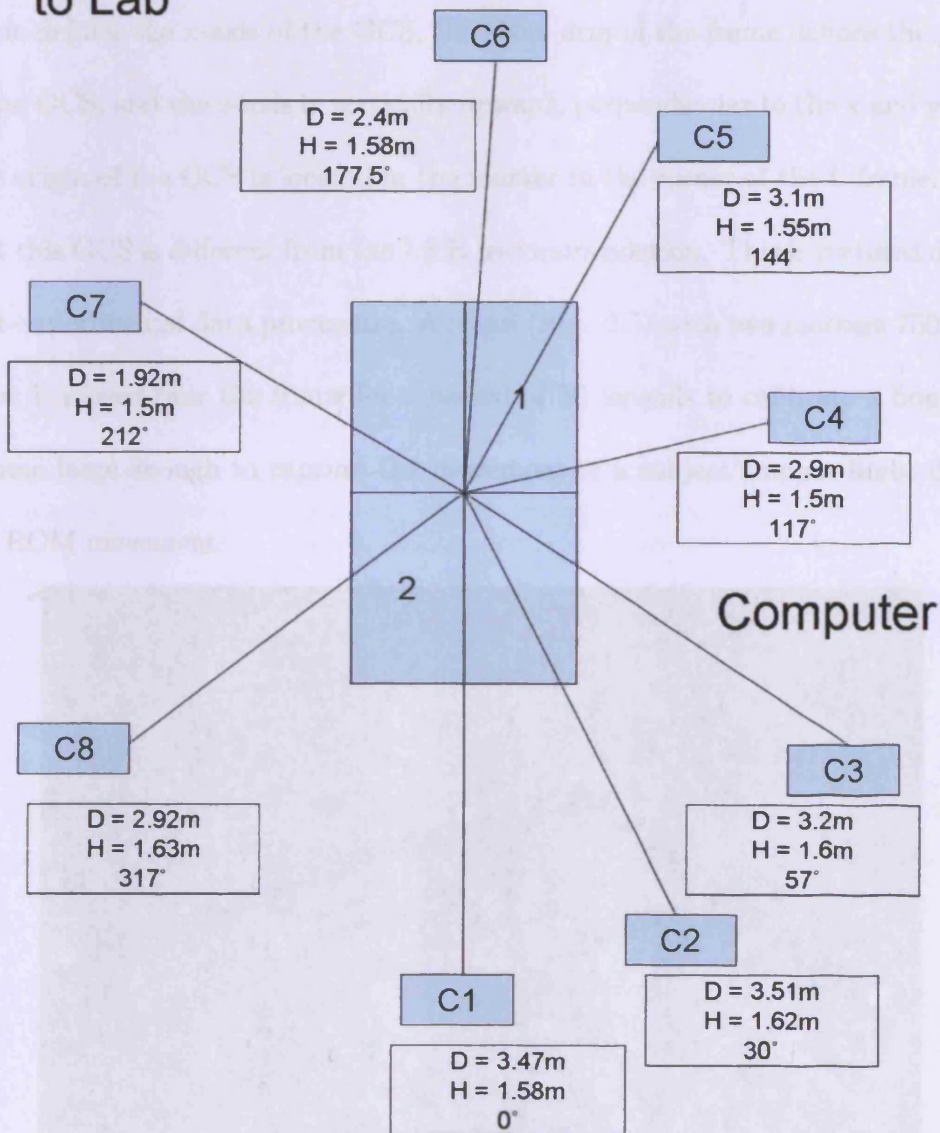
FIGURE 2.2: A schematic showing the positions and heights of the eight cameras during testing relative to two force plates (1 and 2) in the centre of the gait lab. C1-C8 indicate cameras 1-8.

Once the cameras are positioned, the system can be calibrated to define a GCS for the lab. The calibration is performed using a 750mm wand kit provided by Qualisys (www.qualisys.com). An L-shaped calibration frame (Fig. 2.4) is placed on a stool which is placed in the centre of the laboratory. The long arm of the frame defines the x-axis of the GCS, the short arm of the frame defines the y-axis of the GCS, and the z-axis is vertically upward, perpendicular to the x and y axes. The origin of the GCS is located in the marker in the corner of the L-frame. Note that this GCS is different from the I.S.B. recommendation. This is rectified during post-experimental data processing. A wand (Fig. 2.5) with two markers 750.9mm apart is moved over the frame for a period of 30 seconds to calibrate a bounding volume large enough to capture the movement of a subject's upper limbs during full ROM movement.
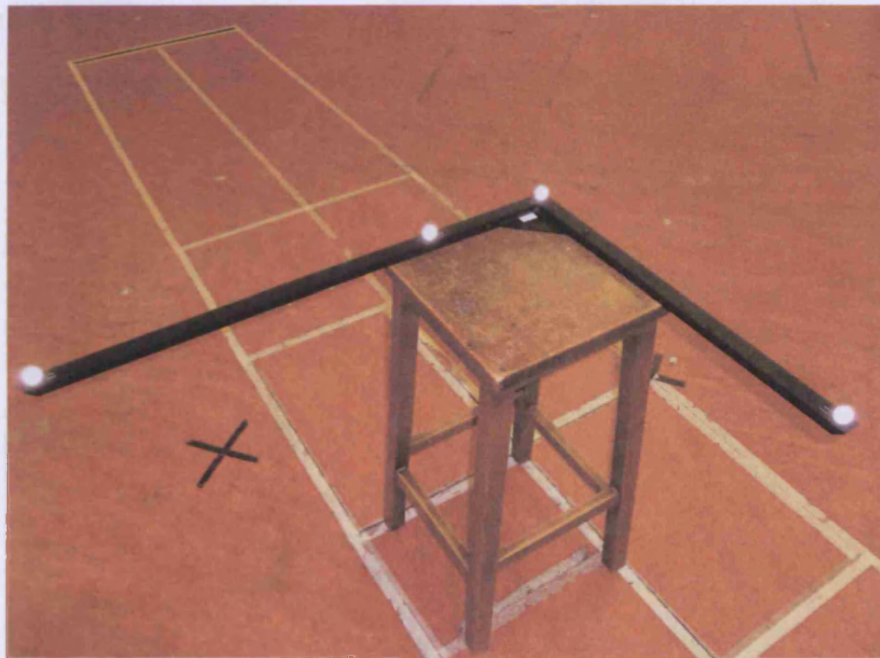
FIGURE 2.3: The calibration frame is used to define the GCS of the laboratory. The long arm of the frame defines the x-axis of the GCS, the short arm of the frame defines the y-axis of the GCS, and the z-axis is vertically upward, perpendicular to the x and y axes. The origin of the GCS is located in the marker in the corner of the L-frame.
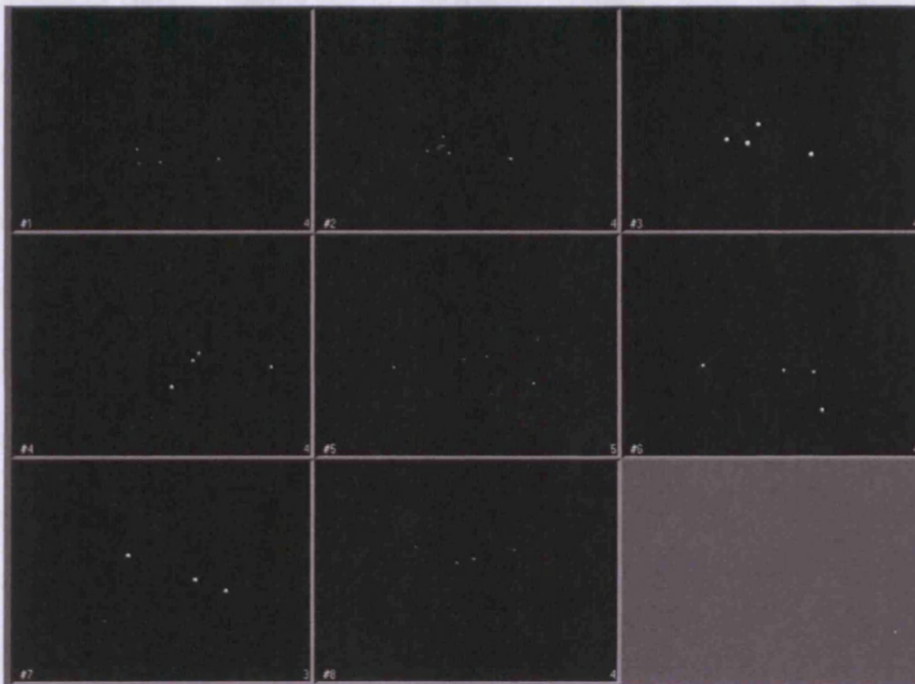
FIGURE 2.4: The calibration frame as viewed in 2D using QTM. Once the cameras have been positioned as per the schematic, this view of the calibration frame from a previous trial is used to fine tune heir positions.
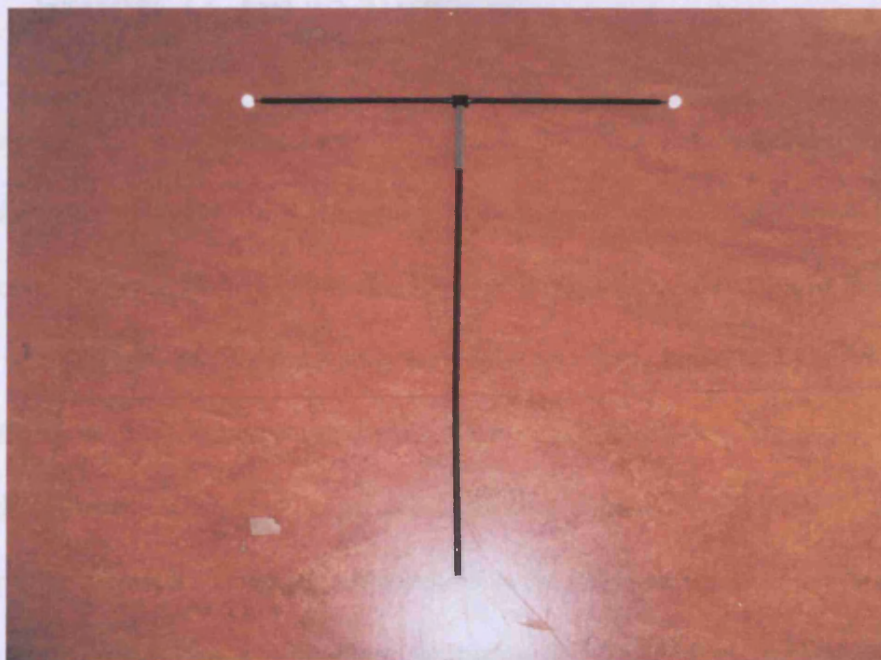
FIGURE 2.5: The calibration wand consists of two markers 750.9mm apart. It is used to define a bounding volume during the calibration.

At the end of the calibration the QTM software outputs a series of residual errors for each camera. The residual errors measure the difference between the sample (the eight cameras) and the estimated function value based on the sample values. From experience it was found that a maximum residual error of 0.7mm resulted in clear image capture. If the residual error of any of the cameras was above this value, the calibration procedure would be repeated. During the trial the system may need to be recalibrated if the quality of image capture decreases. This is most often caused by random noise in the system, which consists of ambient vibration, time drift, and temperature drift in the signal processing circuit [110]. Fluctuations in the ambient temperature of the room (caused by extra people entering the lab, heating systems being turned on etc.) were found to accentuate this effect.

2.3   Study 1: Introduction

Previous motion analysis research at Cardiff University has focused primarily on the assessment of lower limb function, in particular osteoarthritic knee function. The knee joint is modelled using the method described by Grood and Suntay [71] which was designed to facilitate effective communication between biomechanicians and clinicians. The recommended standards of the I.S.B. [30] are largely derived from the Grood and Suntay approach, and it was based on this that the initial attempts by Cardiff University researchers were made to measure shoulder kinematics [29]. Retro-reflective markers were attached to the skin overlying the bony landmarks of the thorax, clavicle, scapula, and humerus. The markers are made of high density foam and were manually coated with retro-reflective sticky tape

by the author and colleagues in the Institute of Medical Engineering and Medical

Physics (IMEMP). The size (diameter in mm) of the markers used to identity

each landmark are provided in Table 2.1. By default, 19.2mm diameter markers

were used to identify all bony landmarks. For bony landmarks that were prone

to "marker swapping" such as SC & IJ, PC, AC & AA, and RS & US, 9.6mm

markers were used to minimise this occurrence.

TABLE 2.1: By default 19.2mm (diameter) markers were used to identify the bony landmarks. 9.6mm markers were used when necessary.

Thorax	C7	19.2mm
	T8	19.2mm
	IJ	9.6mm - due to proximity to SC
	PX	19.2mm
Clavicle	SC	9.6mm - due to proximity to IJ
	AC	9.6mm - due to proximity to PC and AA
Scapula	TS	19.2mm
	AI	19.2mm
	AA	9.6mm - due to proximity to PC and AC
	PC	9.6mm - due to proximity to AA and AC
Humerus	TCS	Green cuff as see in Fig. 2.6a uses 19.2mm markers
	EL	19.2mm
	EM	19.2mm
Forearm	RS	9.6mm - due to proximity to US
	US	9.6mm - due to proximity to RS

Custom software (see Fig. 2.9 for overview) was written using Matlab (The Math-

Works, Inc) to generate the anatomical co-ordinate systems for each bone segment

and to calculate the joint and body segment rotations according to the I.S.B. rec-

ommended standards. The centre of glenohumeral rotation was calculated using

the linear regression equations of Meskers et al. [81]. The regression equations

use the positions of the scapula bony landmarks (AA, AI, TS, PC) to estimate

the centre of rotation in the scapula segment. This point was then used as a third

landmark to generate the humerus anatomical co-ordinate system (ACS). The

humerus ACS was then related to a technical co-ordinate system (TCS) consisting

of four markers. The entire marker set-up can be seen in Fig. 2.6.
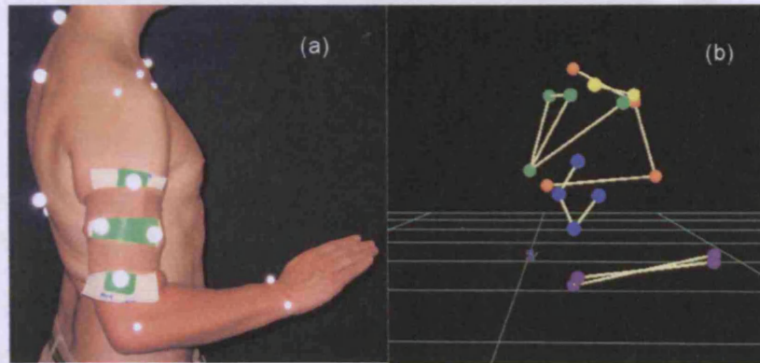
FIGURE 2.6: (a) Subject wearing full marker set-up (b) Qualisys view of markers

The main limitation of this method was the use of skin markers to track the move-

ment of the scapula. As previously discussed, accurate non-invasive measurements

of scapula kinematics is hindered by the presence of active and passive layers of tis-

sue. It was decided to use a scapula locator (Fig. 2.7a) [67], a three pronged device

used to palpate the three bony landmarks of the scapula simultaneously, which is

seen as the 'Gold Standard' of scapula kinematic measurement, to determine the

accuracy of the skin-marker method. One limiting factor of the scapula locator is

that it can only be used to take measurements of scapula orientation during static

elevations. Dynamic scapulohumeral rhythm must then be inferred through linear

regression equations for the arm reachable workspace [76, 77]. Collecting the data

necessary to establish the scapulohumeral rhythm for the arm reachable workspace

can be time consuming, and with patient groups where pain and fatigue are major

factors, is not always practical. It was hoped that by quantifying the inherent

errors in using skin-mounted scapula markers (Fig. 2.7b), it would be possible to
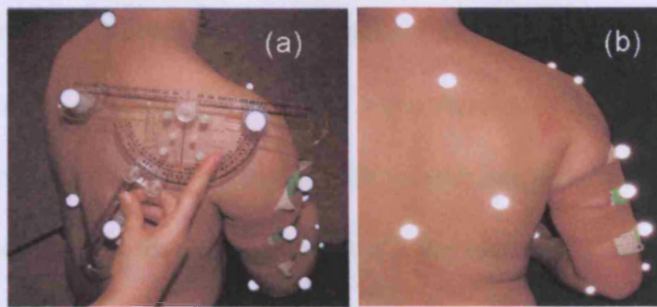
FIGURE 2.7: (a) A scapula locator with markers attached to represent the locations of the three scapula bony landmarks. (b) Markers directly attached to the bony landmarks of the scapula

measure dynamic scapula movement directly, by factoring in the associated errors to the results.

Of the 10 subjects assessed in this study, a colleague (Ms. Lindsay Stroud) assisted during the data collection in the lab for six subjects, and did the analysis for one subject. She also wrote the subroutine to calculate the scapula ACS using a scapula locator as part of her undergraduate dissertation, in which I assisted [111].

2.4 Study 1: Experimental Protocol

Ten subjects (M:F 6:4 mean age 27.5 ± 5.1 years, height 1.71 ± 0.09m, weight 73.7 ± 18.3kg, body mass index (BMI) 25 ± 5.5) were recruited to the study. Subjects were recruited from within the Cardiff School of Engineering. Potential subjects with prior shoulder pathologies or injuries were excluded. Ethical approval was granted by the Cardiff University Research Committee Ethics Panel and informed consent was obtained from each subject prior to the study.

Subjects performed incremental arm elevations in the coronal and sagittal planes with the right arm. Nine of the subjects were right arm dominant. The subject who was left arm dominant was comfortable having her right arm tested as she felt that was "ambidextrous to a certain degree". All elevations were performed with the arm straight and hand pronated. A neutral position anatomical calibration measurement was captured for one second at the start of each trial with the elbow flexed to 90° and the hand pronated (Fig. 2.6). An external reference frame fitted with retro-reflective markers was used to guide arm elevation in the different planes and to assist in post experimental data acquisition (Fig. 2.8). Subjects performed each elevation in increments of 30° of the external frame. Static measurements were taken at each increment using a scapula locator with markers attached to represent each of the three scapula bony landmarks (Fig. 2.7a). Individual skin mounted markers were then attached to each of the scapula bony landmarks (Fig. 2.7b) with the subject in a neutral position measurement (Fig. 2.6a). Elevations in the coronal and sagittal planes were then repeated dynamically using skin mounted markers.
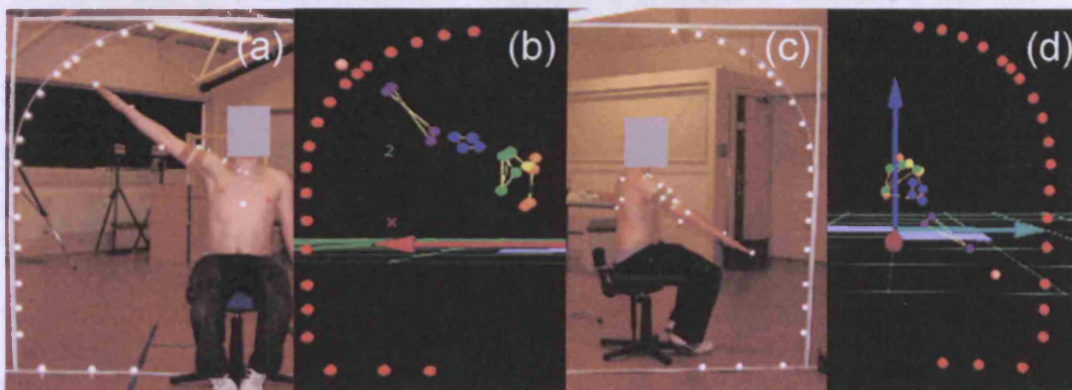
FIGURE 2.8: Subject elevates arm using frame for guidance; (a) coronal plane elevation in the real view, (b) coronal plane elevation in the Qualisys Track Manager (QTM) view, (c) sagittal plane elevation in the real view, (d) sagittal plane elevation in the QTM view.

The positions of each marker on every subject was double-checked by Ms. Lindsay Stroud (and in some later studies also by Mr. Nicholas Ferran) to ensure consistency. In all cases, Ms. Stroud and Mr. Ferran were unaware of the locations selected by the author. When there was a disagreement, the bony landmark in question would be collectively examined until a consensus was reached.

2.5 Study 1: Data Analysis

The data for each marker was exported from QTM as tab separated variable (tsv) files. Columns represent the X,Y, and Z positions of each marker in the GCS. Rows represent time. For example, a one second measurement at 60Hz would have 60 rows of data. A schematic flow diagram of the software used to process the data (using skin-markers on the scapula) is shown in Fig. 2.9. A schematic of the changes made to the software to calculate the rotations of the scapula using a scapula locator is shown in Fig. 2.10. An explanation of the functions and variables used in each of these flow diagrams is available in Tables 2.2 and 2.3.

The software was checked by inserting numerous breakpoints throughout the routines and comparing the outputs with hand calculations and with results of similar studies reported in the literature [65]. The singular value decomposition method was checked by determining the same transformation matrices using the rotation matrix and location vector method.

The static data collected with the scapula locator was used in a similar manner to previous studies [76, 77] to generate multiple linear regression models which
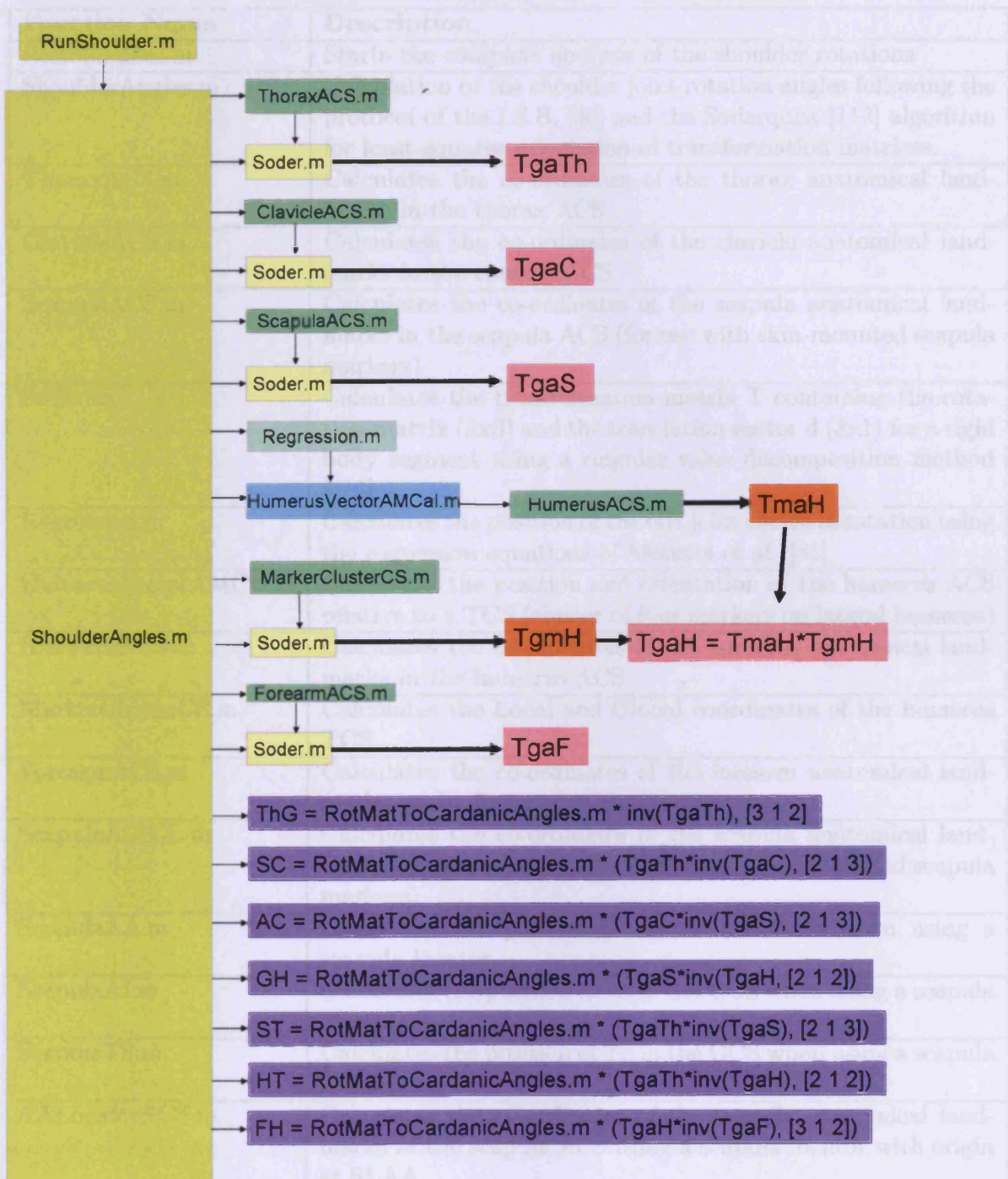
FIGURE 2.9: Schematic of the software used to calculate the rotations of the shoulder complex using skin-markers on the scapula. A description of each function and a glossary of the variables used in the schematic can be found in Tables 2.2 and 2.3.

TABLE 2.2: Description of the functions used in Fig. 2.9 and 2.10

Function Name	Description
RunShoulder.m	Starts the complete analysis of the shoulder rotations
ShoulderAngles.m	Calculation of the shoulder joint rotation angles following the protocol of the I.S.B. [30] and the Soderquist [112] algorithm for least squares calculation of transformation matrices.
ThoraxACS.m	Calculates the co-ordinates of the thorax anatomical landmarks in the thorax ACS
ClavicleACS.m	Calculates the co-ordinates of the clavicle anatomical landmarks in the clavicle ACS
ScapulaACS.m	Calculates the co-ordinates of the scapula anatomical landmarks in the scapula ACS (for use with skin-mounted scapula markers)
Soder.m	Calculates the transformation matrix T containing the rotation matrix (3x3) and the translation vector d (3x1) for a rigid body segment using a singular value decomposition method [112]
Regression.m	Calculates the position of the GH joint centre of rotation using the regression equations of Meskers et al. [81]
HumerusVectorAMCal.m	Calculates the position and orientation of the humerus ACS relative to a TCS (cluster of four markers on lateral humerus)
HumerusACS.m	Calculates the co-ordinates of the humerus anatomical landmarks in the humerus ACS
MarkerClusterCS.m	Calculates the Local and Global coordinates of the humerus TCS
ForearmACS.m	Calculates the co-ordinates of the forearm anatomical landmarks in the forearm ACS
ScapulaACSSL.m	Calculates the co-ordinates of the scapula anatomical landmarks in the scapula ACS (for use with skin-mounted scapula markers)
ScapulaAA.m	Calculates the position of AA in the GCS when using a scapula locator
ScapulaAI.m	Calculates the position of AI in the GCS when using a scapula locator
ScapulaTS.m	Calculates the position of TS in the GCS when using a scapula locator
AALocatorACS.m	Calculates the co-ordinates of the scapula anatomical landmarks in the scapula ACS using a scapula locator with origin at SLAA
AILocatorACS.m	Calculates the co-ordinates of the scapula anatomical landmarks in the scapula ACS using a scapula locator with origin at SLAI
TSLocatorACS.m	Calculates the co-ordinates of the scapula anatomical landmarks in the scapula ACS using a scapula locator with origin at SLTS
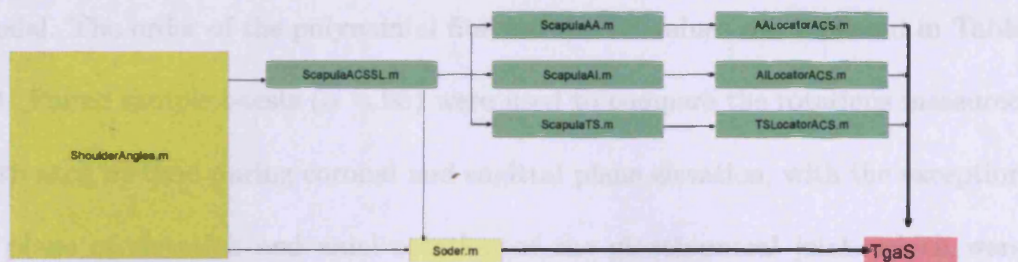
FIGURE 2.10: Schematic of the sub-routine to calculate the rotations of the shoulder complex using the scapula locator. A description of each function and a glossary of the variables used in the schematic can be found in Tables 2.2 and 2.3.

TABLE 2.3: Description of the variables used in Fig. 2.9 and 2.10

Function Name	Description
TgaTh	Transformation matrix from GCS to Thorax ACS
TgaC	Transformation matrix from GCS to Clavicle ACS
TgaS	Transformation matrix from GCS to Scapula ACS
TmaH	Transformation matrix from TCS to Humerus ACS
TgmH	Transformation matrix from GCS to Humerus TCS
TgaH	Transformation matrix from GCS to Humerus ACS
TgaF	Transformation matrix from GCS to Forearm ACS
ThG	Rotations of the thorax relative to the GCS
SC	Rotations of the sternoclavicular joint
AC	Rotations of the acromioclavicular joint
GH	Rotations of the glenohumeral joint
ST	Rotations of the scapulothoracic articulation
HT	Rotations of the humerus relative to the thorax
FH	Rotations of the forearm relative to the humerus (elbow)

predict scapula orientation during dynamic movements based on the position of the humerus relative to the thorax. Joint rotations for the AC joint, the GH joint and the ST articulation were evaluated at each value of humerothoracic elevation, to allow comparison with the data collected dynamically using the skin mounted scapula markers. Polynomial fits of order two to seven were fitted to the entire data set generated by the 10 subjects. The order of the polynomial fits were chosen to maximise the coefficient of determination values (R^2) in each case, which indicates the proportion of variability in each data set that is accounted for by its associated

model. The order of the polynomial fits and the R^2 values can be found in Table

2.4. Paired sample t-tests (α =.05) were used to compare the rotations measured

with each method during coronal and-sagittal plane elevation, with the exception

of plane of elevation and axial rotation of the glenohumeral joint, which were

compared using the Wilcoxon signed rank test, as their difference variables were

not normally distributed.

2.6 Study 1: Results

Complete kinematic descriptions of the shoulder complex were obtained for the

ten shoulders during elevations in the coronal and sagittal planes. To maintain

consistency, all rotations are plotted against elevation of the humerus relative to

the thorax. Polynomials were fitted to the data sets generated by the 10 subjects

(Table 2.4), similar to previous studies [35, 65]. A full set of rotations for the

thorax relative to the global coordinate system (GCS), the SC joint, the AC joint,

the GH joint and the ST articulation are shown for coronal plane elevation (Fig.

2.11) and sagittal plane elevation (Fig. 2.12). Solid lines represent the dynamic

rotations measured directly with the skin mounted markers. Dashed lines represent

the predicted rotations using multiple linear regression models based on static

measurements with the scapula locator.
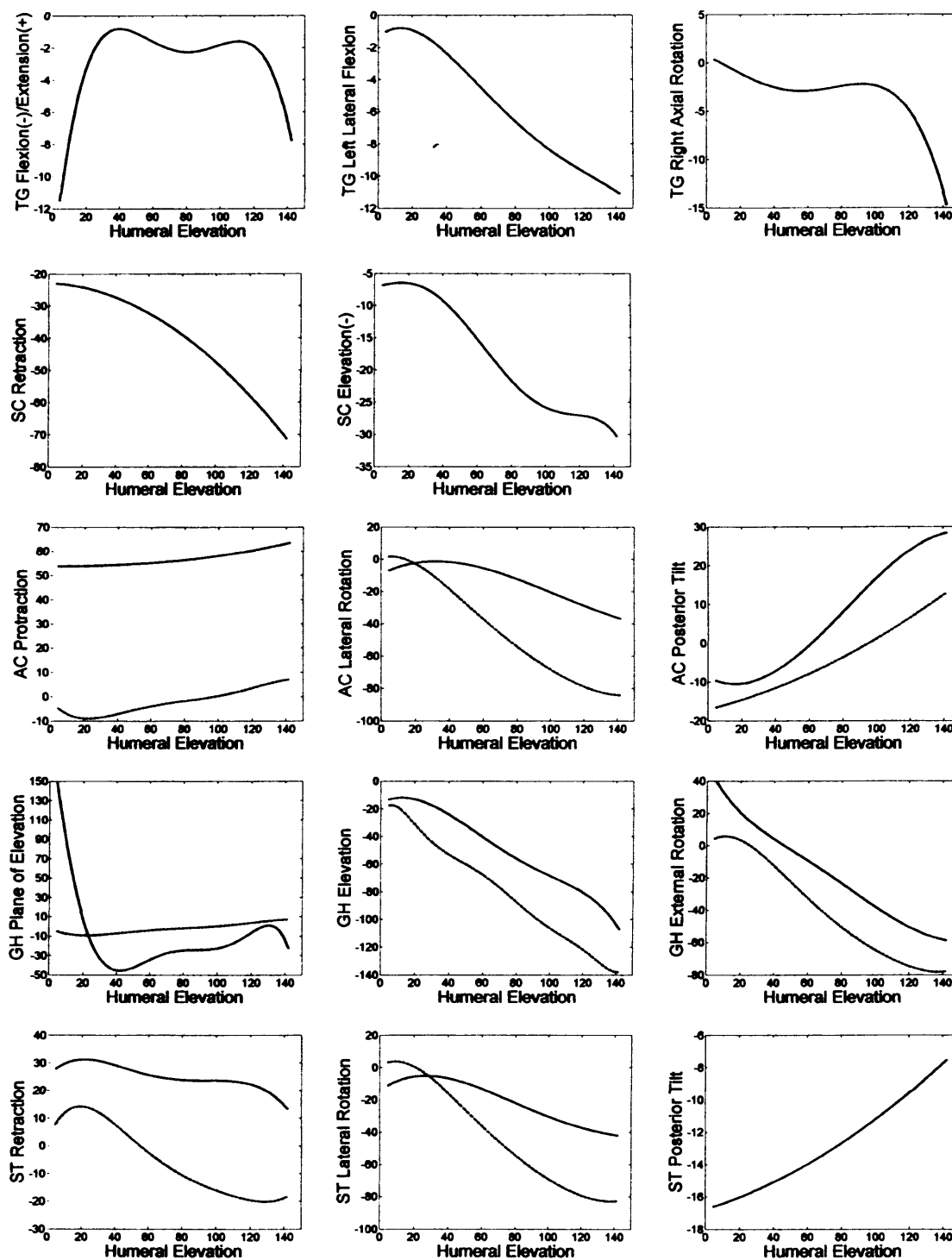
FIGURE 2.11: Polynomial fits to the angles describing the rotations of the thorax relative to the global coordinate system (TG); the sternoclavicular joint (SC); the acromioclavicular joint (AC); the glenohumeral joint (GH) and the scapulothoracic articulation (ST) from a data set of 10 healthy shoulders **during coronal plane elevation**. Subjects have the elbow extended and the hand pronated. Solid line: Dynamic measurements with skin mounted scapula markers. Dashed line: Dynamic motion profiles estimated through multiple linear regression based on static measurements taken with the scapula locator. All rotations measured in degrees (°).

TABLE 2.4: R^2 values for the polynomial fits to the angles describing the rotations of the thorax relative to the GCS; the SC joint; the AC joint; the GH joint; and the ST articulation during humeral elevation in the coronal and sagittal plane for 10 subjects as measured with the scapula locator and scapula mounted skin markers. Figures in brackets represent the order of the polynomial used. * indicates where gimbal lock caused unusually low R^2 values. (See also Figs. 2.11 and 2.12)

	Abduction			Flexion		
Thorax rel GCS	Flexion/ Extension	Lateral Flexion	Axial Rotation	Flexion/ Extension	Lateral Flexion	Axial Rotation
Skin Markers	0.0671 (4)	0.9515 (5)	0.7271 (4)	0.9672 (2)	0.4372 (4)	0.751 (2)
SC Joint	Retraction	Elevation	Axial Rotation	Retraction	Elevation	Axial Rotation
Skin Markers	0.969 (2)	0.9346 (5)	N/A	0.9152 (5)	0.9533 (2)	N/A
AC Joint	Protraction	Lateral Rotation	Posterior Tilt	Protraction	Lateral Rotation	Posterior Tilt
Scapula Locator	0.8898 (5)	0.9983 (5)	0.9361 (2)	0.9435 (5)	0.9961 (5)	0.9762 (4)
Skin Markers	0.9658 (3)	0.9521 (4)	0.9663 (3)	0.7202 (4)	0.9579 (5)	0.9595 (2)
GH Joint	Plane of Elevation	Elevation	External Rotation	Plane of Elevation	Elevation	External Rotation
Scapula Locator	0.8898 (5)	0.9976 (7)	0.9957 (5)	0.9558 (3)	0.9989 (7)	0.8937 (3)
Skin Markers	0.2676* (6)	0.9877 (5)	0.7964 (5)	0.1342* (5)	0.9741 (4)	0.6974 (4)
ST Articulation	Retraction	Lateral Rotation	Posterior Tilt	Retraction	Lateral Rotation	Posterior Tilt
Scapula Locator	0.9467 (5)	0.9967 (5)	N/A	0.8619 (3)	0.9946 (4)	0.8672 (7)
Skin Markers	0.7521 (5)	0.9434 (4)	0.9474 (2)	0.7291 (3)	0.9686 (3)	0.9236 (2)

For the thorax relative to the GCS and for the SC joint, only the data collected during the skin mounted marker trial is shown, as these rotations are unaltered by the different methods of measuring scapula orientation. It is not possible to measure axial rotation of the sternoclavicular joint as only two landmarks on the clavicle can be palpated. For posterior tilt of the scapulothoracic articulation during coronal plane elevation, only the skin marker data is presented, as it was
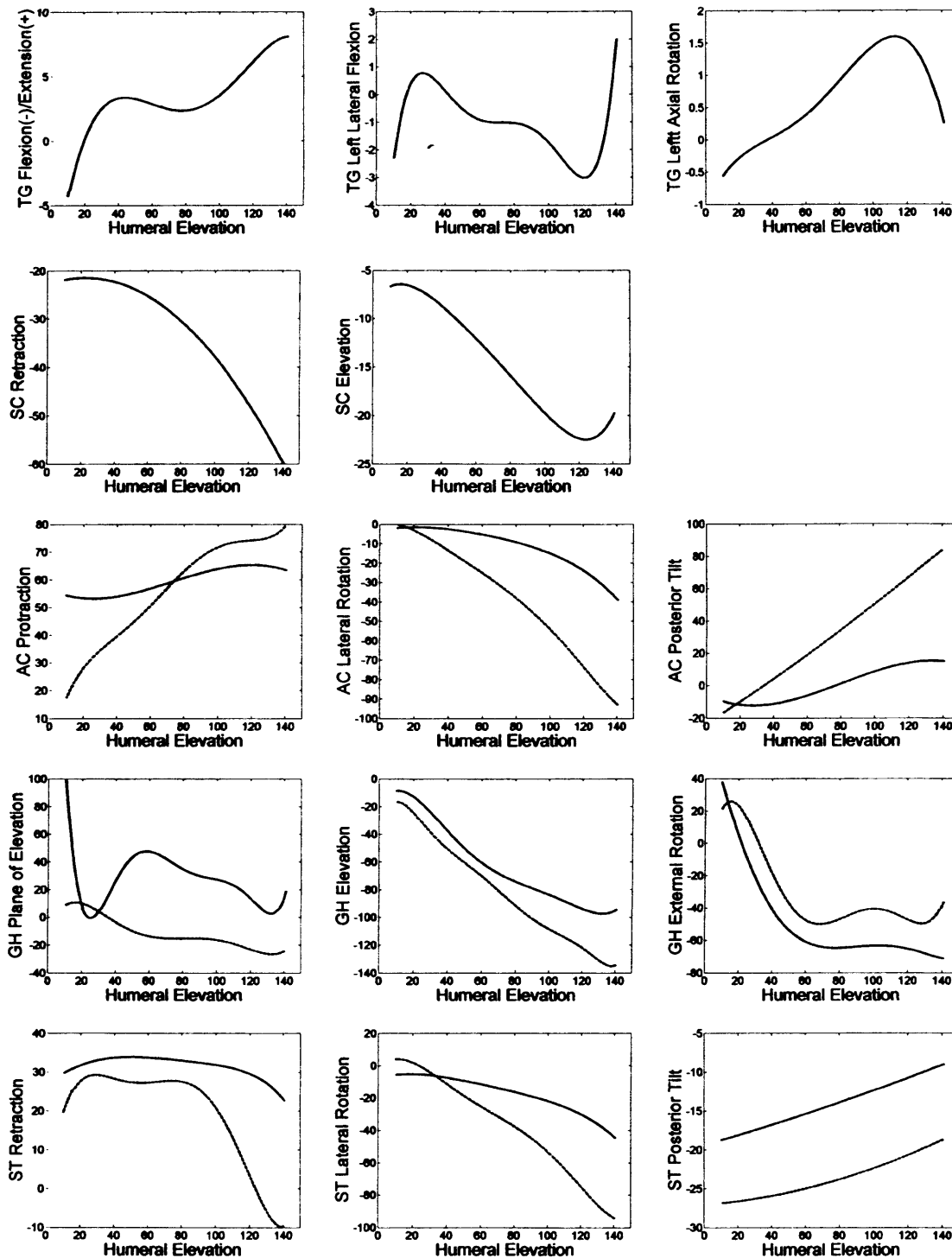
FIGURE 2.12: Polynomial fits to the angles describing the rotations of the thorax relative to the global coordinate system (TG); the sternoclavicular joint (SC); the acromioclavicular joint (AC); the glenohumeral joint (GH) and the scapulothoracic articulation (ST) from a data set of 10 healthy shoulders **during sagittal plane elevation**. Subjects have the elbow extended and the hand pronated. Solid line: Dynamic measurements with skin mounted scapula markers. Dashed line: Dynamic motion profiles estimated through multiple linear regression based on static measurements taken with the scapula locator. All rotations measured in degrees (°)

TABLE 2.5: Pearson correlation values (except where denoted as Spearman *) between the angles describing the rotations of the AC joint; the GH joint; and the ST articulation with the scapula locator (and regression equations) and dynamically with the skin mounted markers during humeral elevation in the coronal plane' and sagittal plane.

	Abduction			Flexion		
AC Joint	Protraction	Lateral Rotation	Posterior Tilt	Protraction	Lateral Rotation	Posterior Tilt
Correlation	0.463	0.624	0.776	0.471	0.745	0.905
GH Joint	Elevation Plane	Elevation	External Rotation	Elevation Plane	Elevation	External Rotation
Correlation	0.416*	0.923	0.693*	0.071*	0.955	0.82*
ST Articu-lation	Retraction	Lateral Rotation	Posterior Tilt	Retraction	Lateral Rotation	Posterior Tilt
Correlation	0.164	0.726	N/A	0.367	0.777	0.56

not possible to generate a significant regression model using the scapula locator data.

The coefficient of determination (R^2) values for each polynomial fit are shown in Table 2.4 to indicate the proportion of variability in each data set that is accounted for by its associated polynomial fit. Correlation values for each rotation as measured by the two different methods are in Table 2.5. The paired sample t-tests and Wilcoxon signed rank tests found that there was a statistically significant difference between measurements with the scapula locator and the skin mounted markers for every rotation during both elevations ($\alpha = .05$). The salient features to note when comparing the rotations measured with the scapula locator and the skin mounted markers are as follows:

For the AC joint:

- For coronal plane elevation, an offset of 60 ° was observed for protraction. For

sagittal plane elevation, the kinematic waveforms for protraction as measured with each method were different. The skin marker method measured a ROM of $10°$, while the scapula locator measured a ROM of $60°$.

- During coronal and sagittal plane elevation, the measured lateral rotations began to deviate after $20°$ of arm elevation. The skin markers underestimated the rotations by over $50°$ as full arm elevation was reached.

- Posterior tilt during coronal plane elevation displayed an initial offset of approximately $7°$, which increased to $16°$ at full arm elevation. This resulted in the skin-marker method underestimating the ROM. During sagittal plane elevation, posterior tilt ROM was underestimated by the skin marker method from $20°$ of arm elevation upwards, reaching a maximum difference of just over $60°$ at full arm elevation.

For the GH joint:

- The main discrepancy when measuring the plane of elevation of the glenohumeral joint during elevation in the coronal and sagittal planes was caused by gimbal lock. This caused an offset greater than $40°$ for coronal plane elevation. During sagittal plane elevation the skin marker method showed an erratic kinematic profile with maximum offsets of approximately $60°$

- Elevation profiles and ROM's in the coronal plane displayed an offset of approximately $30°$ throughout the majority of the movement. During sagittal plane elevation there was an offset of approximately $10°$ up to $70°$ of arm elevation, after which the two waveforms began to diverge. By maximum

arm elevation, the skin marker method underestimated elevation by approximately 35°.

- When measuring axial rotation, an offset of 25° is observed for coronal plane elevation. During sagittal plane elevation there was an initial offset of 10° which gradually increased to 20° by full arm elevation.

For the ST articulation:

- There was an offset of 5° between the two methods when measuring retraction during sagittal plane elevation, up to approximately 75° of arm elevation. For higher elevations the two kinematic profiles deviate causing the skin marker method to underestimate the ROM by approximately 40° by full arm elevation. During coronal plane elevation, there was an initial offset of 17° which gradually increased to 25° at full arm elevation.

- Lateral rotation measured by the skin markers produced different motion profiles during both coronal and sagittal plane elevation. In both cases the measured ROM's were underestimated by the skin marker method by more than 50°

- It was not possible to compare posterior tilt during coronal plane elevation as a significant regression model could not be generated from the scapula locator data. During sagittal plane elevation both methods measured a similar ROM with a 10° offset.

2.7 Study 1: Discussion

The scapula locator is regarded as the optimum method for tracking the movement of the scapula non-invasively [68]. This study objectively explores the motion profiles of the shoulder complex using both the gold standard (the scapula locator), and a simplified option of placing markers directly over the scapula bony landmarks. The aim of this was to determine if skin-markers could be used under any circumstances to track the movement of the scapula, and to introduce the scapula locator to the protocol. Complete kinematic descriptions of the shoulder were obtained for the 10 subjects using both methods of scapula tracking. The recorded motion patterns and ROM's are comparable to those reported in the literature [35, 65] with the exception of the AC joint, particularly lateral rotation, which was between 10 and 15 times larger for both movements. As it is only possible to palpate two bony landmarks on the clavicle, it is not possible to directly measure axial rotation of the clavicle. The discrepancy in measured AC rotations in the current study are due to the previous studies estimating clavicle axial rotation by minimising the rotations at the AC joint (see section 1.6.5.2).

In clinical practice accurate measurement of the lateral rotation of the ST articulation is important as it can be indicative of certain pathology types [65]. The results indicate that the skin marker method is unsuitable for assessing ST lateral rotation, which corroborates Hypothesis 1, "Skin-mounted scapula markers do not have the same accuracy as a scapula locator when measuring the kinematics of the shoulder complex". The simplified scapula marker set was found to be particularly useful for assessing GH elevation up to arm elevations of 80° (Table 2.5).

However measurements of the GH plane of elevation with the skin-marker method were hampered by gimbal lock. Gimbal lock occurs when two of the three rotational axes of the glenohumeral joint are aligned with their pivot axes in a single plane. When this occurs it is no longer possible to represent the orientation of the glenohumeral joint. This is likely to occur at low and high humeral elevations. Due to gimbal lock, there is an offset of $50°$ between the two methods during coronal plane elevation, and the R^2 values of the polynomial fits are low.

2.8 Improvements and Modifications to the Shoulder Model

Following on from this study, a number of modifications were made to the model to enable more accurate measurement of the shoulder kinematics. Particular attention was paid to the humerus and dynamic tracking of the scapula.

2.8.1 Improvements to the Humerus Model

The anatomical coordinate system of the humerus is generated using the medial epicondyle, lateral epicondyle and the centre of glenohumeral rotation. The previous studies estimated the centre of rotation by using linear regression equations which estimate the centre of rotation based on anthropometric properties of the scapula [81]. All further studies will estimate the centre of rotation with the instantaneous helical axis (IHA) method [91] as it has been found by Stokdijk et al.

[82] to be more accurate than the linear regression equations of Meskers et al. [81] and suitable for testing pathologies where the relationship between the scapula and the humerus has been altered. It is also the preferred method of the I.S.B. [30].

The technical coordinate system (TCS) used in the previous chapters to track dynamic movement of the humerus consisted of a moulded plastic cuff with four markers (Fig. 2.6). It was unsuitable for measuring axial rotation of the humerus not only due to soft tissue artefacts [113] but also due to the rigid shape of the TCS which impeded its movement with the underlying bone. The new TCS is derived from markers placed on the deltoid insertion (DI), the insertion of the brachiora-dialis (BI) and the biceps belly (BB) (Fig. 2.13), which provides a more accurate representation of axial rotation and allows compensatory techniques for soft tissue artefacts to be implemented when measurement of humerus axial rotation is of specific concern. 9.6mm markers were used to represent each of these landmarks as it was felt that the increased diameter of the 19.2mm markers would make it more difficult to accurately place the markers on the muscle insertion points.

FIGURE 2.13: Modified Humerus Technical Coordinate System consisting of three markers placed on the insertion of the deltoid (DI), the biceps belly (BB), and the brachioradialis insertion (BI).

The alterations to the humerus TCS including the Matlab subroutines were done by the author. The IHA method was added to the model by Ms. Lindsay Stroud as part of a study to measure GH joint translations, which is not reported in this thesis. A schematic of these changes can be seen in Fig. 2.15.

2.8.2 Dynamic Tracking of the Scapula

The previous study investigated the use of skin based scapula markers and found that they were largely unsuitable for tracking movement of the scapula, the exception being the measurement of GH elevation (particularly during flexion up to 80°). Alternative methods of dynamic scapula tracking were thus investigated.

Two non-invasive methods of dynamic scapula tracking have been pioneered by Karduna et al. [78] (see section 1.6.5.3). Both methods used the acromion plateau of the scapula as a placement site for a TCS and were validated against an invasive technique using bone-pins to directly measure scapula movement. As both methods provided similar results to the invasive method, the simpler of the two methods, placing a sensor directly on the acromion plateau without the use of a plastic jig, has been widely adopted in other studies [3, 39].

For the second study in this chapter, a marker based equivalent was developed. The TCS consists of three markers placed on the acromion plateau of the scapula (Fig. 2.14). This TCS is commonly known as an acromion cluster. The TCS consists of three markers which are used to create an orthogonal co-ordinate system. The three markers are raised on a stalk to enable the cluster to be used at the

same time as a scapula locator. 9.6mm markers were used to minimise the weight

of the cluster.
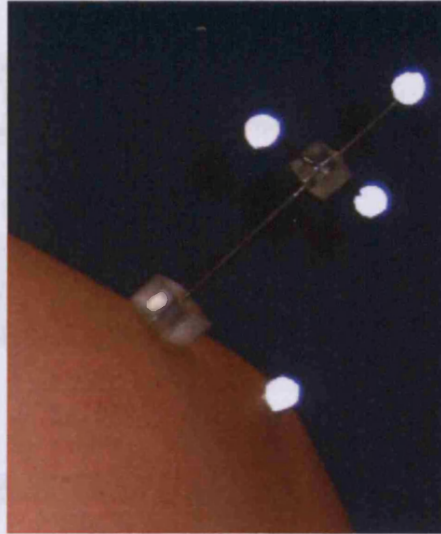
FIGURE 2.14: A scapula technical coordinate system consisting of three markers placed on the acromion plateau, commonly referred to as an acromion cluster.

The development of the acromion marker cluster and the associated Matlab routines were done by the author. A schematic of these changes can be seen in Fig. 2.15.

2.9   Study 2: Experimental Protocol

Sixteen subjects (ten males and six females with a mean age of 24.46 ± 2.23 years, height 1.79 ± 0.05m, weight 78 ± 7.5kg, BMI 22.9 ± 2.1) with no previous history of shoulder pathology or instability in either shoulder were recruited to the study. Subjects performed static arm elevations in increments of 20° in the coronal, scapular, and sagittal planes. Elevations were performed bilaterally, with the thumb pointing upwards for coronal and scapular plane elevation, and with
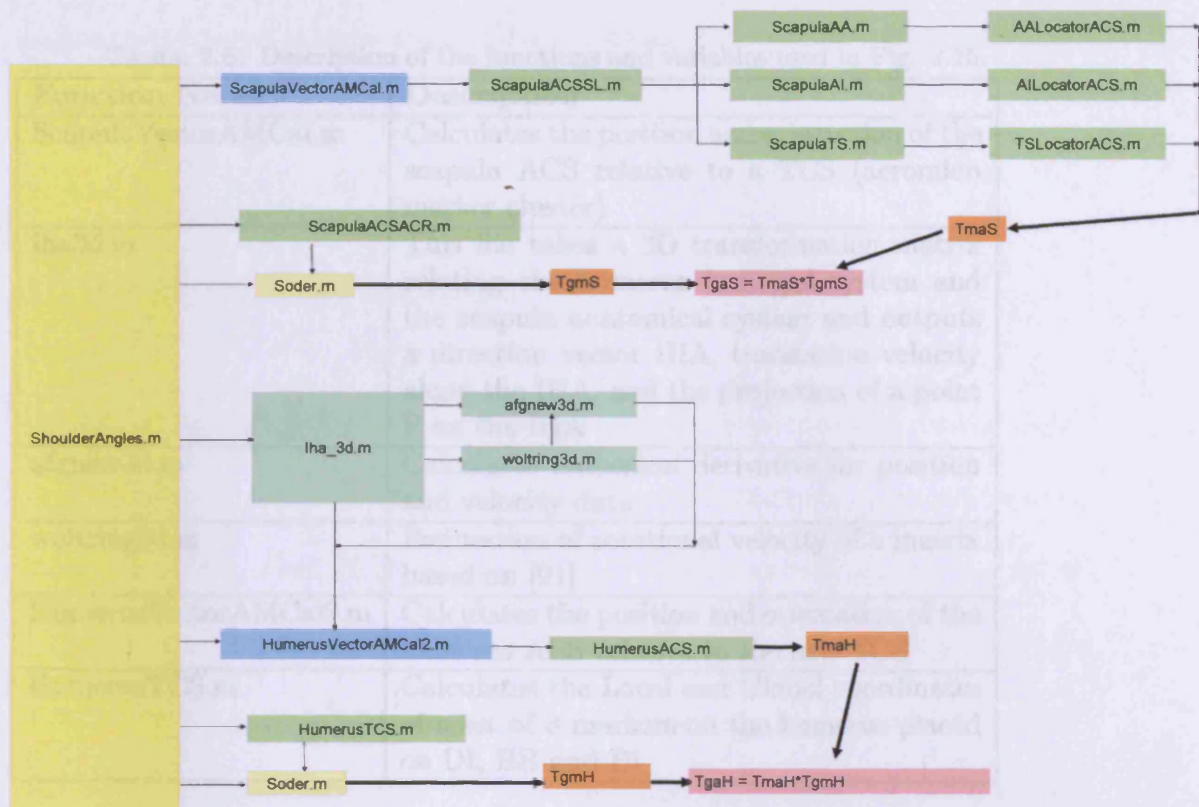
FIGURE 2.15: Schematic of the sub-routine to calculate the rotations of the shoulder complex using an acromion marker cluster, a modified humerus TCS, and the Instantaneous helical axis to calculate the centre of GH rotation. A description of each function and a glossary of the variables used in the schematic can be found in Table 2.6.

the hand pronated for sagittal plane elevation. In all cases, scapula position was measured with an acromion cluster, and with a scapula locator with markers attached to represent each of the scapula bony landmarks. The same external reference frame fitted with retro-reflective markers as in the previous study was used to guide arm elevation in the different planes and assist in post experimental data acquisition.

As in the previous study, a neutral position anatomical calibration measurement was captured for one second at the start of each trial with the elbow flexed to 90° and the hand pronated. The orientation and position of the acromion cluster

TABLE 2.6: Description of the functions and variables used in Fig. 2.15.

Function Name	Description
ScapulaVectorAMCal.m	Calculates the position and orientation of the scapula ACS relative to a TCS (acromion marker cluster)
iha3d.m	This file takes a 3D transformation matrix relating the humerus technical system and the scapula anatomical system and outputs a direction vector IHA, translation velocity along the IHA, and the projection of a point P on the IHA
afgnew3d.m	Calculates numerical derivative for position and velocity data
woltring3d.m	Estimation of rotational velocity of a matrix based on [91]
HumerusVectorAMCal2.m	Calculates the position and orientation of the humerus ACS relative to the new TCS
HumerusTCS.m	Calculates the Local and Global coordinates of a set of 3 markers on the humerus placed on DI, BB and BI

was related to the scapula locator during the neutral position measurement to remove any initial variations when measuring scapula orientation between the two methods.

Anatomical and technical coordinate systems and joint rotations were calculated according to the recommendations of the I.S.B. [30] using a modified version of the software used in the previous study. The centre of glenohumeral rotation was estimated with the instantaneous helical axis method [91]. The humerus ACS was then related to a TCS derived from markers on the deltoid insertion (DI), the biceps belly (BB), and brachioradialis insertion (BI).

All testing was performed with the assistance of either Ms. Lindsay Stroud, or Mr. Nicholas Ferran, who assisted with the data collection of five subjects, to be used in his Orthopaedic Engineering MSc thesis [114]. Ms. Stroud and Mr. Ferran also

assisted with the post-experimental data processing in Qualisys Track Manager (QTM).

2.10 Study 2: Results

Full kinematic descriptions of the shoulder complex were recorded for the right arms of the 16 subjects during static elevations in the frontal, scapular, and sagittal planes. Scapula orientation during the static elevations was measured with a scapula locator, and an acromion marker cluster. To validate the acromion marker cluster, the rotations of the AC joint, ST articulation, and GH joint measured with both techniques are compared. Rotations of SC joint are not reported in this study, as they are not impacted by the method used to measure scapula rotations. However the rotations of the SC joint for this cohort are reported in section 4.4 when they are compared with patient cohorts.

2.10.1 Acromion Cluster compared to Scapula Locator

Figs. 2.16, 2.17, and 2.18 show the rotations of the AC, ST, and GH articulations respectively during coronal, scapular and sagittal plane elevation. The static rotations measured for each articulation were divided into $20°$ increments of humerothoracic elevation ($0° - 20°$; $20° - 40°$; $40° - 60°$; $60° - 80°$; $80° - 100°$; and $100° - 120°$). Solid lines and solid errors bars (standard deviation of the rotations measured for the 16 subjects) represent the rotations measured with the scapula locator. Dashed lines and dashed error bars represent rotations measured

with the acromion marker cluster. This provides a visual reference to determine

what rotations can be measured accurately with the acromion cluster, and during

which levels of arm elevation and planes of elevation this is possible.

Coronal Plane

Scapular Plane

Sagittal Plane
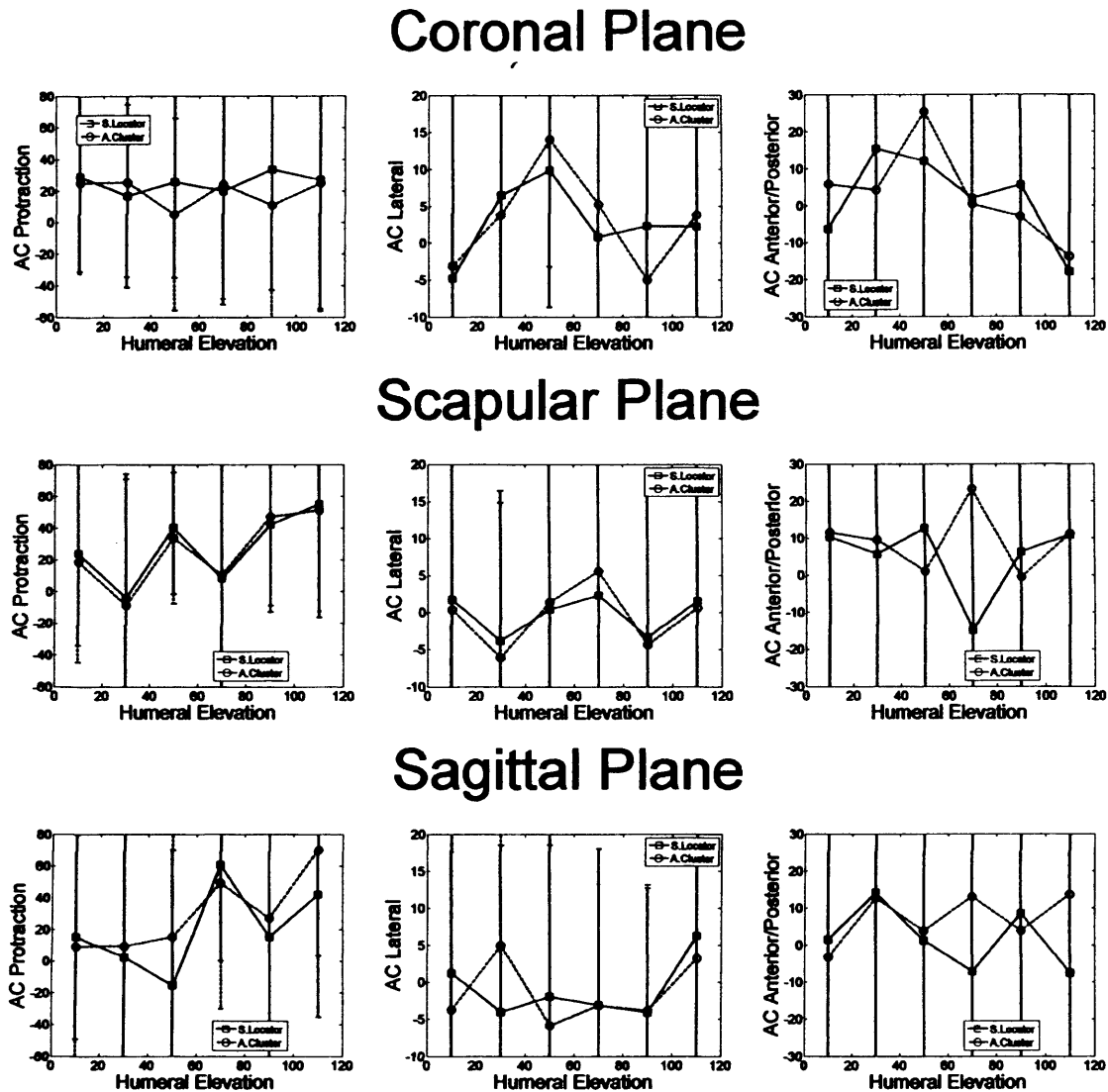
FIGURE 2.16: **The rotations measured for the acromioclavicular joint** were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. Square markers with solid lines and solid error bars represent the rotations (± the standard deviation of the rotations measured for the 16 subjects) measured with the scapula locator. Circular markers with dashed lines and dashed error bars represent the rotations (± the standard deviation of the rotations measured for the 16 subjects) measured with the acromion cluster. The error bars have been truncated to allow greater resolution of the rotations. Untruncated versions of the graphs can be found in Appendix A. All rotations measured in degrees (°).

Coronal Plane
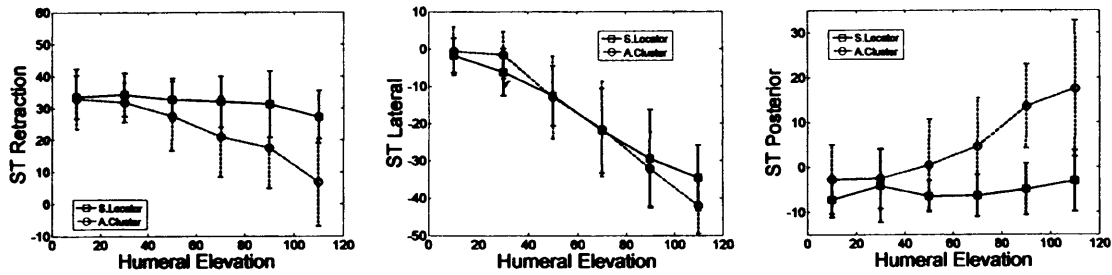
Scapular Plane
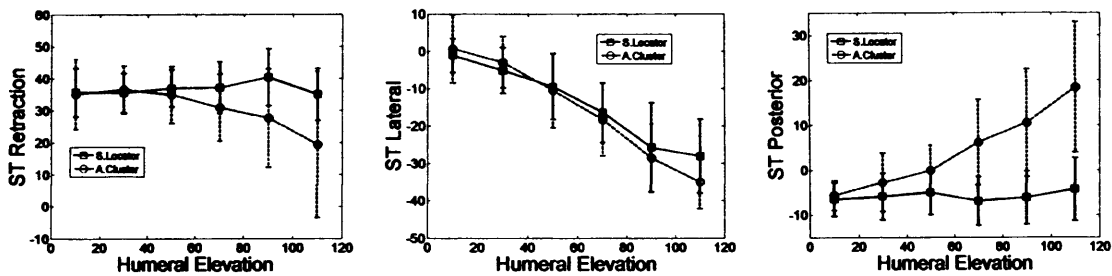
Sagittal Plane
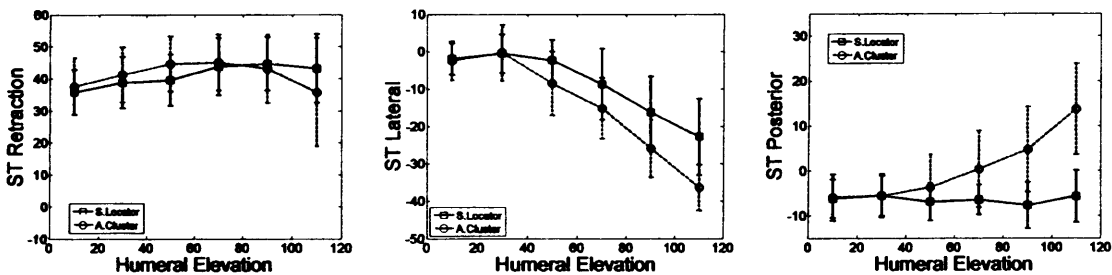
FIGURE 2.17: The rotations measured for the scapulothoracic articulation were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. Square markers with solid lines and solid error bars represent the rotations (± the standard deviation of the rotations measured for the 16 subjects) measured with the scapula locator. Circular markers with dashed lines and dashed error bars represent the rotations (± the standard deviation of the rotations measured for the 16 subjects) measured with the acromion cluster. All rotations measured in degrees (°). Significant differences are highlighted in Table 2.7.
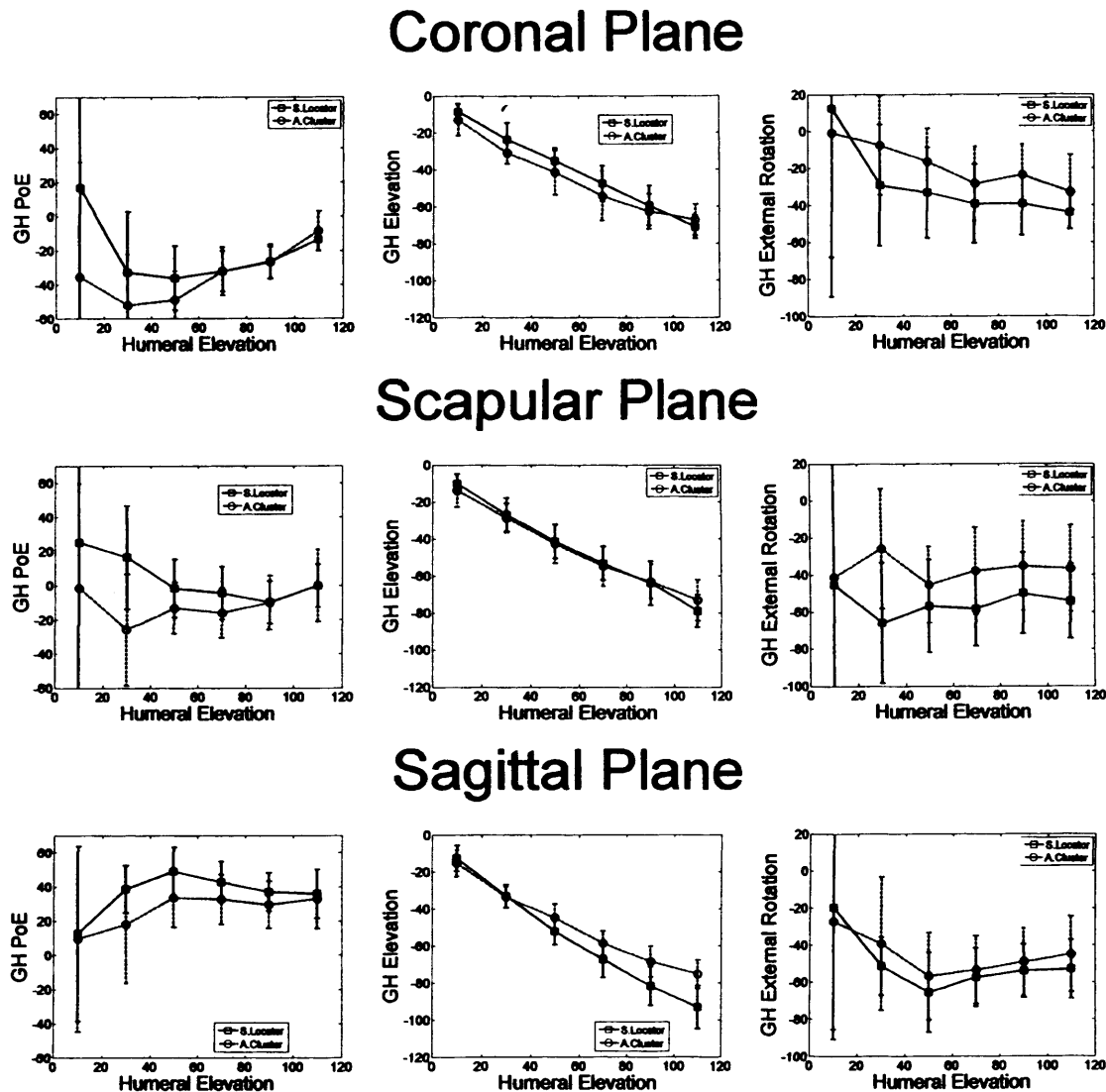
FIGURE 2.18: The rotations measured for the glenohumeral joint were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. Square markers with solid lines and solid error bars represent the rotations (± the standard deviation of the rotations measured for the 16 subjects) measured with the scapula locator. Circular markers with dashed lines and dashed error bars represent the rotations (± the standard deviation of the rotations measured for the 16 subjects) measured with the acromion cluster. Low elevations can result in gimbal lock when measuring the plane of elevation and axial rotation of the GH joint, resulting in overly large error bars. The error bars in these cases have been truncated to allow greater resolution of the remainder of the rotations. All rotations measured in degrees (°). Significant differences are highlighted in Table 2.7.

TABLE 2.7: Significant differences ($\alpha = .05$) between the scapula locator and the acromion cluster when measuring the rotations of the AC, GH, and ST articulations during abduction, scapular abduction, and flexion. The increments of arm elevation where significant differences were noted are marked with an 'X'. It should be noted that the large error bars when measuring the AC joint rotations resulted in insignificant differences despite being large in magnitude. AC1 = Protraction, AC2 = Lateral Rotation, AC3 = Posterior Tilt, GH1 = Plane of Elevation, GH2 = Elevation, GH3 = Axial Rotation, ST1 = Retraction, ST2 = Lateral Rotation, ST3 = Posterior Tilt

Abduction									
	AC1	AC2	AC3	GH1	GH2	GH3	ST1	ST2	ST3
0° - 20°				X	X				X
20° - 40°					X				
40° - 60°				X					X
60° - 80°						X	X		X
80° - 100°							X		X
100° - 120°						X	X	X	X

Scapular Abduction									
	AC1	AC2	AC3	GH1	GH2	GH3	ST1	ST2	ST3
0° - 20°					X				
20° - 40°				X		X			
40° - 60°				X					X
60° - 80°						X			X
80° - 100°						X	X		X
100° - 120°									X

Flexion									
	AC1	AC2	AC3	GH1	GH2	GH3	ST1	ST2	ST3
0° - 20°									
20° - 40°									
40° - 60°				X	X		X	X	
60° - 80°				X	X			X	X
80° - 100°				X	X			X	X
100° - 120°					X			X	X

Wilcoxon signed-ranks tests were used to compare the rotations measured with the scapula locator and acromion cluster during each of the increments. Table 2.7 shows which elevation increments show a statistically significant difference for each rotation between the two methods during abduction, scapular abduction, and flexion respectively ($\alpha=.05$). The salient features to note when comparing the acromion cluster with the scapula locator are discussed in section 2.11.2.

2.11 Study 2: Discussion

2.11.1 Protocol Changes ,

In the first study in this chapter (section 2.4), arm elevations were performed uni-laterally. This could result in increased lateral flexion and axial rotation of the thorax during elevation. This affect was offset when measuring joint rotations by plotting them against elevation of the humerus relative to the thorax. Nevertheless, it was decided to assess subjects bi-laterally from this study onwards.

Also, during the elevations in the coronal and scapular planes, subjects now point their thumbs upwards, as opposed to the previous studies, where the hand was pronated. This was changed to facilitate easier arm elevation, and will result in larger values of GH external rotation than previous studies.

2.11.2 Discussion of Results

The salient features to note when comparing the measured rotations for each ar-ticulation are discussed below.

For the AC joint: There were no significant differences between the two methods when measuring the rotations of the AC joint. Mean values and standard devia-tions in both cases were similar in size, indicating that the spread of the data was approximately equal with both methods. However, the standard deviations were also very large, meaning that little information can be derived from cross-method

comparisons. The primary reason for this is believed to be skin-artefacts. The two bony landmarks of the clavicle lie on the SC joint and the AC joint, both of which are extremely susceptible to skin artefacts, causing large variations in the measured rotations. However, even considering the presence of skin-artefacts, the errors appear to be extremely large and the author advises that these results are accepted with caution.

For the GH joint:

- The measured values for the GH plane of elevation are heavily affected by gimbal lock during low arm elevations (section 2.7). At higher elevations, there were still some statistically significant differences, but these are largely due to offsets in the measured data (Fig. 2.18). The magnitudes of the measured rotations, and the standard deviations of each method, were all approximately equal, making the acromion cluster useful for measuring changes in plane of elevation over the range of a movement.

- During abduction and scapular plane abduction, there are significant differences in the values measured for GH elevation during low arm elevations. However on examining Fig. 2.18, these differences are quite small, and the magnitude of the elevation measured with both techniques is very similar up to the 80° - 100° increment. This is in agreement with a previous study using a similar measurement protocol [79]. During flexion however a different trend is noted. The two techniques are in accord up to 40° of arm elevation, after which point the acromion cluster begins to underestimate GH elevation. This is because arm elevation in the sagittal plane is less

reliant on ST lateral rotation, which is a relatively reliable rotation to measure non-invasively, and more reliant on ST posterior tilt and to a lesser degree ST retraction. Both of these rotations are very difficult to measure non-invasively, even with a scapula locator, and as a result are not reported in many studies. An examination of Fig. 2.17 highlights the inadequacy of the acromion cluster when measuring the posterior tilt of the scapula. The acromion cluster overestimates the level of ST posterior tilt, resulting in GH elevation being underestimated. The reason for this occurrence is discussed in the next set of bullet points on the ST articulation.

- Measurements of axial rotation of the GH joint are heavily effected by gimbal lock during low arm elevations for both methods. For higher arm elevations, during abduction and scapular abduction, there are some significant differences, but there is also an almost constant offset between the two methods. During flexion there are no statistically significant differences.

For the ST articulation:

- During abduction, the acromion cluster begins to overestimate retraction of the ST articulation from 60° of arm elevation upwards. During scapular plane abduction, there was only a statistically significant difference during the 80° - 100° increment of arm elevation. However it should be noted that the two measurements begin to deviate from 60° onwards, and that the acromion cluster measurements have a much larger standard deviation, which has possibly skewed the results of the statistical analysis. During

flexion however, both methods are quite comparable. The magnitude of retraction required during flexion is larger than that required during abduction, and there is less contraction of the trapezius during flexion, resulting in a thinner layer of tissue between the cluster and the scapula, allowing a more representative measurement of scapula movement.

- Lateral rotation of the scapula during abduction shows no significant differences up to $100°$ of arm elevation, and no significant differences at all during scapular abduction. During flexion, the two methods diverge by approximately $10°$ from $40°$ of arm elevation upwards. Between $60°$ and $100°$ of arm elevation, this divergence remains almost constant.

- For all elevations, the acromion cluster overestimates the posterior tilt of the ST articulation from approximately $40°$ of arm elevation upwards. This is of particular importance during forward flexion, as it results in an underestimation of GH elevation. The main reason for this discrepancy is the physical dimensions of the acromion cluster. One of the necessary design inputs was to be able to use the cluster at the same time as the scapula locator. This necessitated that the three markers protrude vertically above the scapula locator, causing an increased moment arm which led to a perceived increase in scapulothoracic posterior tilt.

To summarise, the primary situation when the accuracy of the acromion cluster is of major concern is when measuring the posterior tilt of the ST articulation (and as a consequence, the elevation of the GH joint during forward flexion). It is believed that this is largely due to a necessary design compromise to validate the cluster.

The stalk which holds the three markers was made larger than necessary to make the markers visible while using a scapula locator. The extra moment arm caused by this increased length in the stalk has resulted in an overestimation of the values of ST posterior tilt and lateral rotation, particularly during forward flexion. Based on the conclusions of this study, it is recommended to modify the cluster to reduce the moment arm, i.e., to make the stalk supporting the markers shorter, and to consider using the cluster independently of a scapula locator. Another point to note is that the acromion cluster is unsuitable for measuring ST retraction during abduction and scapular abduction. However this rotation plays a small role in both of these movements and in most practical applications can safely be ignored. During forward flexion, where ST retraction is more important, the acromion cluster does measure this rotation more accurately.

The acromion cluster does not provide a perfect representation of dynamic scapula movement, but it is an improvement on the use of skin markers, and with due consideration to its limitations, is an extremely useful tool to assess shoulder kinematics during dynamic movements, such as activities of daily living, as is seen in the next chapter.

Chapter 3

Applications of the Model

3.1 Chapter Overview

This chapter contains two studies focusing on applications of the shoulder model, assessing hypothesis three, that **common upper limb activities of daily living can be performed without the capacity for full physiological range of motion of the the individual articulations of the shoulder complex.** The first study [115] is a pilot study on five healthy subjects. The sample size was kept intentionally small as the study was merely a pilot study to determine the efficacy of skin-mounted scapula markers when assessing ADL, as the previous chapter showed that skin-mounted markers were only suitable for tracking GH elevation, primarily for arm elevations of less than $80°$ and close to forward flexion. As such, the analysis of this study focuses solely on the elevation of the GH joint during tasks which assess ROM and a series of everyday functional tasks. The study primarily serves as a precursor to the second study which is a continuation of the

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pilot study, on 16 subjects (the same 16 subjects as used in the previous chapter to assess the AC cluster against the scapula locator), using the acromion marker cluster to assess the physiological and functional ROM of the ST articulation and GH joint. This study has two purposes. The first is to apply the acromion marker cluster to the measurement of functional tasks, and the second is to further investigate hypothesis three, by examining the GH and ST articulations.

3.2 Study 1: Introduction

The measurement of a subject's maximum arm elevation constitutes an important component of many of the clinical scores used to determine an overall score of functionality (see section 1.5). The previous chapter investigated the use of skin-mounted markers to track the dynamic movement of the scapula and found that the method is suitable for measuring the elevation of the glenohumeral joint during movements close to flexion. Following from lower limb function where the hip, knee and ankle have a substantially larger normal physiological ROM than that required during gait [116], it is hypothesised that common upper limb activities of daily living can be performed without the capacity for full physiological range of motion of the glenohumeral joint.

Kinematic assessment of the upper limb and inter-study comparisons are difficult when compared to gait analysis due to the large range of path dependant motions of the articulations and the numerous unstandardised tasks [58]. Kinematic modelling of the upper limb requires in vivo data on the most frequently performed

tasks. Unlike gait analysis, this requires careful selection of the activities believed

to be most common and relevant to the subject group of interest [1]. This selection

process can be very subjective, as what is deemed important to one individual is of

no significance to another, based on factors such as age, occupation, level of phys-

ical/sporting activity and even the ergonomic factors of an individual household

or workplace. This level of subjectivity is reflected in the wide range of activities

assessed in various studies [1, 2, 3, 117, 118, 119, 120]. For this study the stan-

dardised tasks of the Newcastle Shoulder Group (Table 3.1) [1] were chosen after

consultation with an upper limb orthopaedic consultant, as they cover a general

range of daily activities necessary for independent living which are considered rel-

evant to the majority of subjects. The activities are related to personal hygiene,

feeding, and handling of everyday objects. The data collected can also be used as

inputs for future studies with the Newcastle Shoulder Musculoskeletal Model [75].

The simplified marker set of the previous study (scapula markers placed directly

over the bony landmarks) was used to track the movement of the scapula of five

healthy subjects during ROM tasks and ADL. Analysis is focused singularly on the

elevation of the glenohumeral joint. The measured values for the other rotations

can be found in Appendix B.

Ms. Lindsay Stroud and Mr. Nicholas Ferran assisted with the data collection

and post-experimental data processing in QTM.
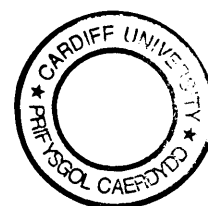
3.3 Study 1: Experimental Protocols

Five right arm dominant subjects (two males and three females with a mean age of 23 ± 1 years, height 1.68 ± 0.05m, weight 62.6 ± 5.8kg, BMI 22.2 ± 1.6) with no previous history of pathology or instability in either shoulder were assessed for full ROM and 10 functional tasks of daily living (Table 3.1) [1] for both arms. All subjects were right arm dominant and were instructed to perform the tasks at a speed and manner with which they felt comfortable. Each shoulder was assessed unilaterally with joint rotations calculated using the same software as in section 2.4. Each task began and finished in the "neutral position". The neutral position is defined as the arm by the side, elbow flexed to 90° and hand pronated (Fig. 2.6). Abduction and scapular plane abduction were performed uni laterally with the hand supinated. Forward flexion was performed uni laterally with the hand pronated. Internal rotation was performed by reaching as far up the back as possible with the thumb pointing upwards. External rotation was measured with the arm by the side, elbow flexed to 90°, thumb pointing upward and rotating the arm laterally about the longitudinal axis of the humerus.

Ethical approval for the study was granted by the University Research Ethics Panel and informed consent was obtained from each subject prior to the study.

3.3.1 Data Processing

Anatomical co-ordinate systems were generated for each subject and joint and segment rotations were calculated according to the recommendations of the I.S.B.

TABLE 3.1: Activities of Daily Living [1]

Reach to opposite ax-illa	Drink from mug
Reach to opposite side of neck	Answer telephone
Reach to side and back of head	Brush opposite side of head
Eat with hand to mouth	Lift block (20N) to shoulder height
Eat with spoon	Lift block (20N) to head height

[30]. The centre of glenohumeral rotation was calculated using the linear regression equations of Meskers et al. [81]. The anatomical co-ordinate system of the humerus was related to a technical co-ordinate system on the lateral humerus which was used to track dynamic humerus movements (Fig. 2.13).

Paired sample t-tests ($\alpha=.05$) were used to compare the elevation of the GH joint required to perform each task with the left and right arm. A Wilcoxon signed-rank test was used to compare the tasks where the difference variable was not normally distributed. Friedman tests were used to compare the level of GH elevation necessary to perform full elevation in the scapular plane and to perform each task, as the samples were related, and not all difference variables were normally distributed.

The difference variable for each task was assessed for normality based on the values of the mean, median, skew, kurtosis and the shape of the resulting histogram. Normality was accepted if the mean was approximately equal to the median, and if the skew and kurtosis were between -1 and +1. In cases where the skewness and kurtosis were between -3 and -1 or +1 and +3 then normality was accepted if the

histogram approximated a normal distribution.

3.4   Study 1: Results

Complete kinematic descriptions of the shoulder were obtained for the 10 shoulders

during abduction, scapular plane abduction, flexion, internal rotation, external

rotation, and the 10 tasks of daily living.

The four most demanding tasks based on the level of GH elevation required to

perform them were: touching the side and back of the head; brushing the opposite

side of the head; lifting an object to shoulder height; and lifting an object to

head height, as can be seen in Fig. 3.1. To perform these four tasks **with the**

right arm required 74%, 58%, 58% and 70% respectively of the glenohumeral

elevation required for full elevation in the scapular plane. To perform these four

tasks **with the left arm** required 83%, 62%, 64% and 72% respectively of the

glenohumeral elevation required for full elevation in the scapular plane. Friedman

tests showed that for both arms, these values were significantly different ($\alpha=0.5$)

from full physiological GH elevation. There was also a significant difference found

in the glenohumeral elevation required for full scapular abduction and to touch the

side and back of the head (the task that required the largest elevation) for both

the left and right ($\alpha=.05$) shoulder when using a Wilcoxon signed rank test. The

mean glenohumeral elevation required to perform each task with the left and right

arms were compared using paired sample t-tests on the normally distributed data

and the Wilcoxon signed-rank test on the non-normal data. The tests revealed

that only one of the tasks, touching the side and back of the head (right arm 72.59 ± 8.77°, left arm 82.11 ± 8.48°, α=.001), showed a statistically significant difference (see Table 3.2) between left and right shoulders.
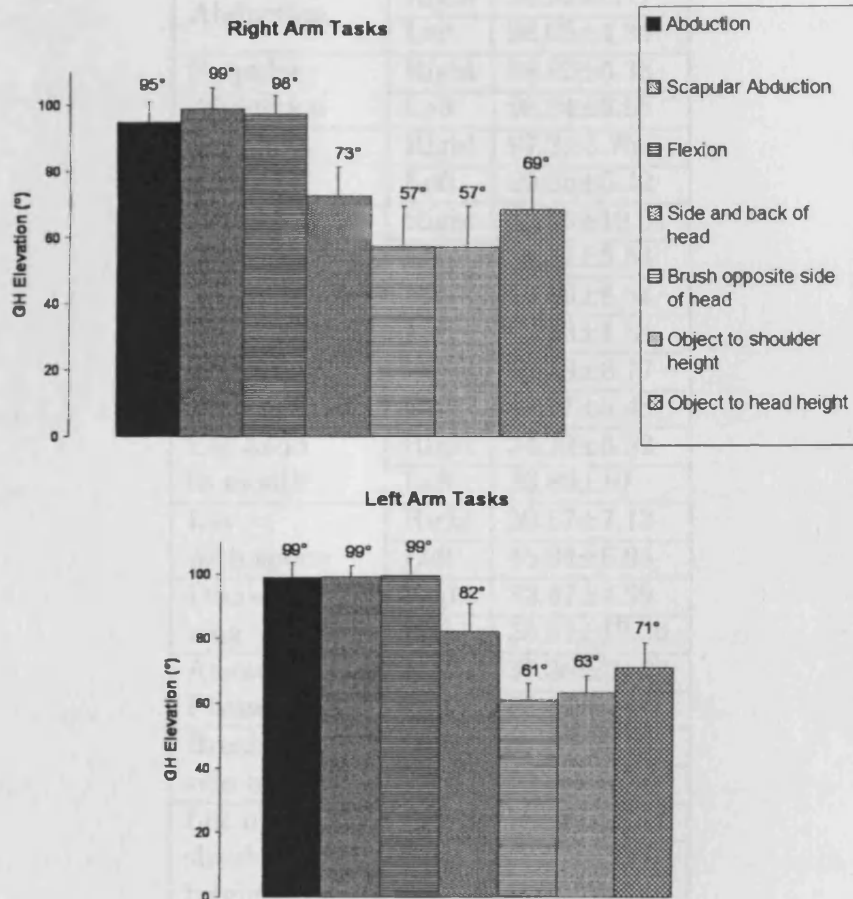
FIGURE 3.1: Average glenohumeral elevation required by five subjects to perform abduction, scapular abduction, flexion, touching the side and back of the head, brushing the opposite side of the head, lift a 20N object to shoulder height and lift a 20N object to head height. (a) Right arm (n=5), (b) left arm (n=5)

3.5 Study 1: Discussion

This pilot study of five subjects objectively explored the required elevation of the glenohumeral joint in healthy subjects during maximum arm elevation and

TABLE 3.2: Average glenohumeral elevation (°) required to perform a series of range of motion tasks and activities of daily living with the left and right arm (n=5) and the left and right arm combined (n=10).

Task	Arm	Mean±SD (°)
Abduction	Right	94.92±6.17
	Left	98.65±4.84
Scapular Abduction	Right	98.82±6.38
	Left	98.84±3.65
Flexion	Right	97.2±5.75
	Left	99.36±5.42
Reach Opp. Axilla	Right	32.36±10.61
	Left	35.81±5.54
Reach opp. side of neck	Right	50.39±8.54
	Left	53.63±5.84
Touch side & back of head	Right	72.59±8.77
	Left	82.11±8.48
Eat hand to mouth	Right	34.13±8.32
	Left	36.89±10
Eat with spoon	Right	39.57±7.13
	Left	45.94±6.95
Drink from mug	Right	32.47±4.99
	Left	33.57±12.36
Answer Phone	Right	37.36±10.22
	Left	36.62±4.6
Brush opp. side of head	Right	57.3±12.29
	Left	60.86±5.27
Lift object to shoulder height	Right	56.98±12.51
	Left	63.09±5.29
Lift object to head height	Right	68.83±9.84
	Left	70.93±7.54

activities of daily living. The results show that to perform the most demanding task, touching the side and back of the head, 83% of maximum glenohumeral elevation was required in the left arm, and 73% was required in the right arm.

These results show that a subjects physiological ROM is not necessarily representative of a patient's ability to perform everyday functional tasks and that there is in accordance with hypothesis three, a significantly different excess capacity of the

glenohumeral joint that is not used during the majority of daily activities. Loss of this excess range of motion should not affect an individuals ability to perform a range of everyday tasks. These findings are similar to studies of the lower limb which have shown that the functional range of motion required of the hip, knee and ankle during walking and sitting is significantly (statistically) lower than the normal values obtainable in healthy subjects [116].

The study is limited by the use of skin mounted scapula markers. The previous chapter showed that this method underestimated lateral rotation of the scapulothoracic articulation by approximately 50° when compared with a scapula locator. Thus, compensatory motions of the acromioclavicular joint and scapulothoracic articulation could not be accurately reported. It is also worth noting that in some research [113] and clinical [121] settings, it can be useful to assess motion of the arm only, without considering the motions of the clavicle and scapula. The study was also limited by the use of linear regression [81, 82] equations to determine the centre of GH rotation, and of the use of a moulded cuff as a humerus TCS (see section 2.8.1). The next study further examines applications of the shoulder model, but with the improvements of: dynamic tracking of the scapula with the acromion cluster; a humerus TCS derived from markers placed on the deltoid insertion, the biceps belly, and the brachioradialis insertion; and estimating the centre of GH rotation using the instantaneous helical axis method [91].

3.6   Study 2: Introduction

This next study builds on the previous one, and runs parallel to the structure of Chapter 2 by introducing the acromion cluster as a means of measuring scapula kinematics during functional tasks. As the acromion cluster provides a greater degree of accuracy when measuring the rotations of the scapula, it allows a more thorough assessment of hypothesis three, that common upper limb activities of daily living can be performed without the capacity for full physiological range of motion of the individual articulations of the shoulder complex.

3.7   Study 2: Experimental Protocols

The same sixteen healthy subjects(ten males and six females with a mean age of 24.46 $\pm$ 2.23 years, height 1.79 $\pm$ 0.05m, weight 78 $\pm$ 7.5kg, BMI 22.9 $\pm$ 2.1) as used for the study in section 2.9 were assessed. Subjects were assessed for 12 ADL and four ROM tasks (Table 3.3, Figs. 3.2 and 3.3). The numbers in brackets in Table 3.3 represent the number of subjects used in the analysis of the corresponding task. Measurements were discarded primarily due to marker occlusion. Tasks number 4, 7, and 15 were introduced after five subjects had been tested.

All subjects were instructed to perform the tasks at a speed and manner with which they felt comfortable. Each shoulder was assessed unilaterally with joint rotations calculated using the same software as in section 2.9. Each task began and finished
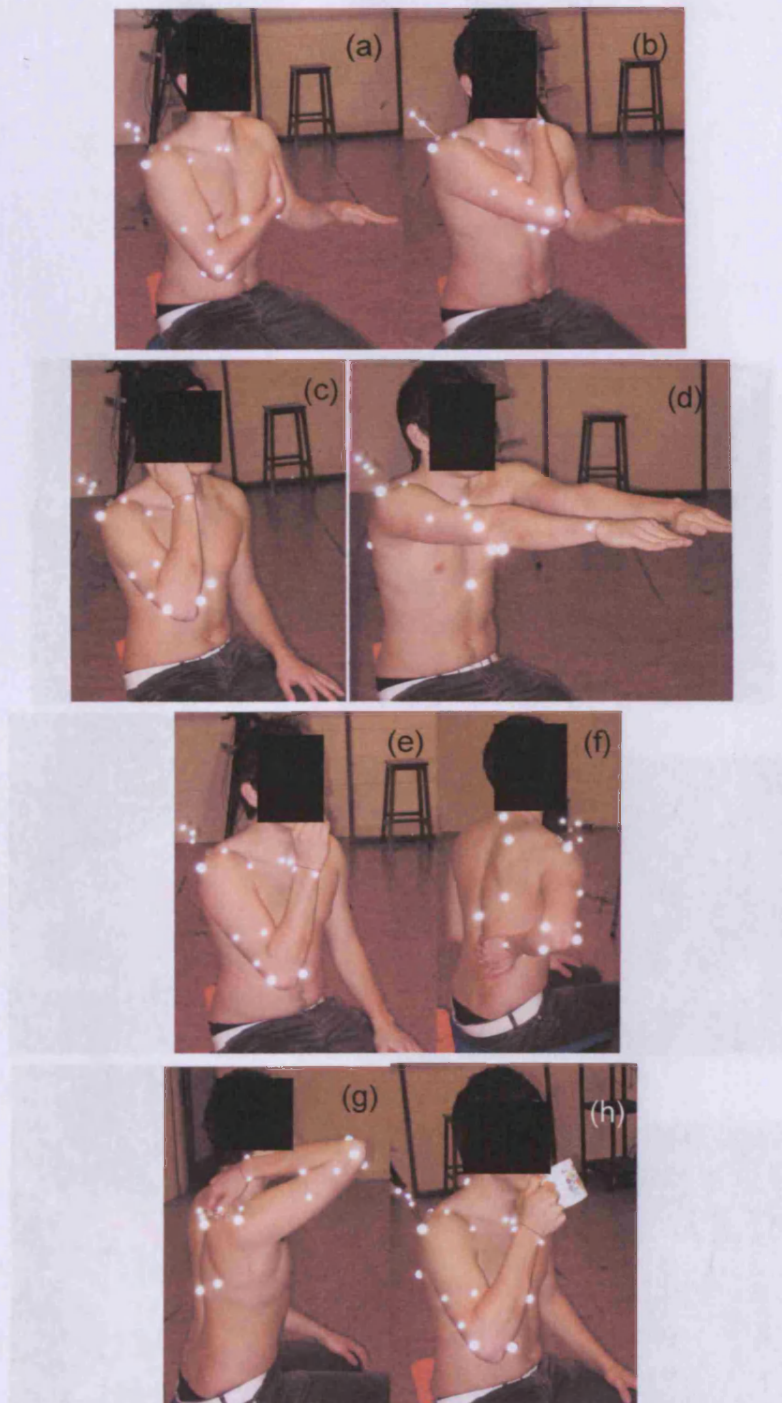
FIGURE 3.2: Activities of daily living and range of motion tasks. (a) Reach to opposite axilla, (b) Reach to opposite side of neck, (c) Reach to side and back of head, (d) Reach forward, (e) Eat with hand to mouth, (f) Clean lower back, (g) Wash upper back, (h) Drink from mug.
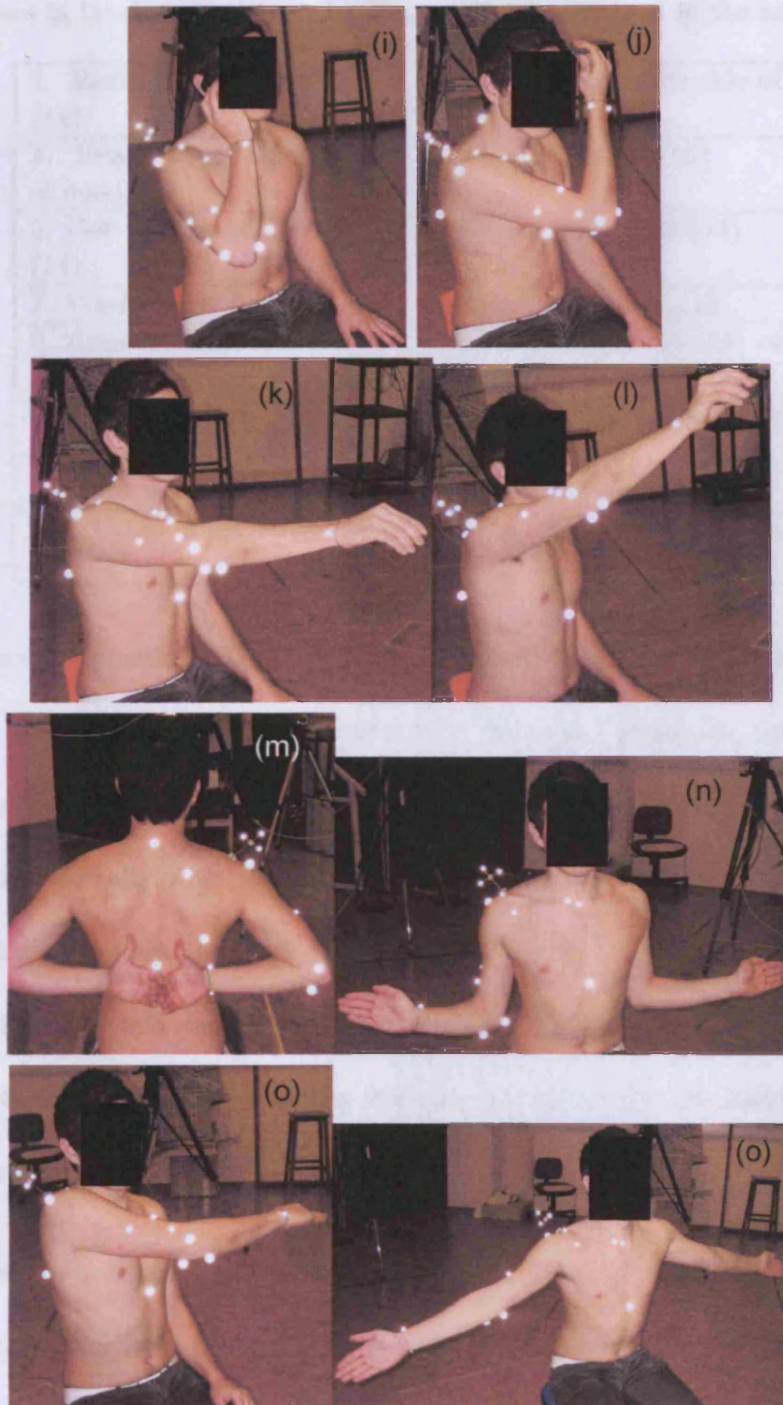
FIGURE 3.3: Activities of daily living and range of motion tasks. (i) Answer telephone, (j) Brush opposite side of head, (k) Lift object (20N) to shoulder height, (l) Lift object (20N) to head height, (m) Internal rotation, (n) External rotation, (o) Cross chest adduction, (p) Scapular plane elevation.

TABLE 3.3: Activities of Daily Living and Range of Motion tasks assessed. The numbers in brackets represent the number of subjects used in the analysis of the corresponding task.

1. Reach to opposite axilla (14)	2. Reach to opposite side of neck (15)
3. Reach to side and back of head (12)	4. Reach forward (10)
5. Eat with hand to mouth (14)	6. Clean lower back (14)
7. Wash upper back (6)	8. Drink from mug (15)
9. Answer telephone (16)	10. Brush opposite side of head (15)
11. Lift object (20N) to shoulder height (15)	12. Lift object (20N) to head height (16)
13. Internal rotation (14)	14. External rotation (16)
15. Cross chest adduction (11)	16. Scapular plane elevation (14)

in the "neutral position".The neutral position is defined as in previous studies with the arm by the side, elbow flexed to 90° and hand pronated. Scapular plane abduction was performed bilaterally with the hand supinated. Forward flexion was performed bilaterally with the hand pronated. Internal rotation was performed by reaching as far up the back as possible with the thumb pointing upwards. External rotation was measured with the arm by the side, elbow flexed to 90°, thumb pointing upward and rotating the arm laterally about the longitudinal axis of the humerus.

Anatomical co-ordinate systems were generated for each subject and joint and segment rotations were calculated according to the recommendations of the International Society of Biomechanics [30]. The centre of glenohumeral rotation was calculated using the instantaneous helical axis method [91]. The anatomical co-ordinate system of the humerus was related to a technical co-ordinate system on the lateral humerus derived from markers placed on the deltoid insertion, the

biceps belly, and brachioradialis insertion.

3.8 Study 2: Results

Kinematic descriptions of the shoulder were obtained for the 16 shoulders during

each of the 16 tasks. Friedman tests were used to determine if there were significant

differences in the magnitude of the rotations required of the GH joint and the ST

articulation to perform full physiological ROM and the functional tasks assessed.

There were no significant differences when measuring the GH plane of elevation,

and GH internal/external rotation (Fig. 3.4).

FIGURE 3.4: On each box, the central mark is the median rotation, the edges of the box are the 25^{th} and 75^{th} percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually as '+'. (a) GH plane of elevation, (b) GH internal rotation, (c) GH external rotation. T1 - Reach opposite axilla; T2 - Reach to opposite side of neck; T3 - Touch side and back of head; T4 - Reach forward; T5 - Eat with hand to mouth; T6 - Clean lower back; T7 - Wash upper back; T10 - Brush opposite side of head; T13 - Internal rotation; T14 - External rotation; T15 - Cross chest adduction. Full table of tasks can be found in Table 3.3.

Significant differences were found when assessing GH elevation, and all three ST

rotations. Task 7, washing the upper back, shows extremely large values for ST

retraction, (Fig. 3.5a). However, even when discarding this task, significant dif-

ferences are still observed (Fig. 3.5b). It is worth noting however, that if each

movement is compared individually with cross chest adduction (Task 15) using

Wilcoxon signed rank tests, no statistically significant differences were observed.

The Friedman test corrects for multiple comparisons in this instance.
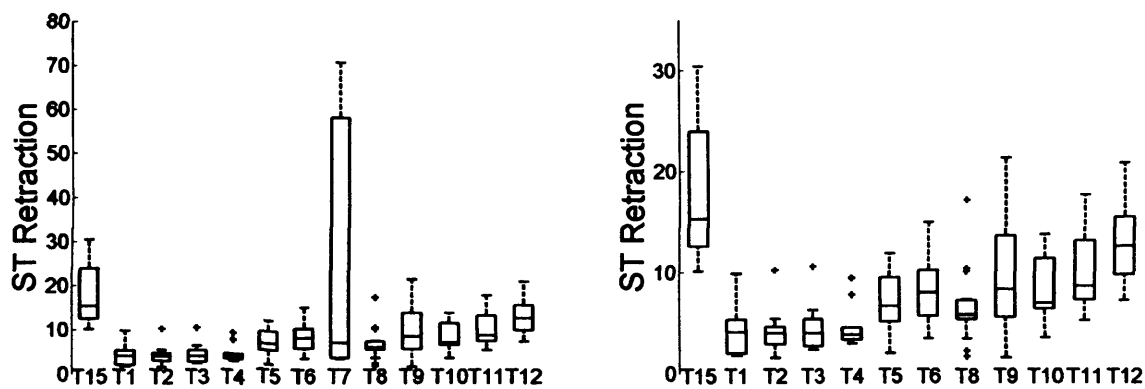
FIGURE 3.5: On each box, the central mark is the median rotation, the edges
of the box are the 25^{th} and 75^{th} percentiles, the whiskers extend to the most
extreme data points not considered outliers, and outliers are plotted individually
as '+'. (a) ST retraction, (b) ST retraction with task 7 removed for clarity. T1
- Reach opposite axilla; T2 - Reach to opposite side of neck; T3 - Touch side
and back of head; T4 - Reach forward; T5 - Eat with hand to mouth; T6 - Clean
lower back; T7 - Wash upper back; T8 - Drink from mug; T9 - Answer phone;
T10 - Brush opposite side of head; T11 - Lift block to shoulder height; T12 -
Lift block to head height; T15 - Cross chest adduction. Full table of tasks can
be found in Table 3.3.

Task 7, washing the upper back, again provides extreme values of ST posterior tilt

(Fig. 3.6a). With the removal of Task 7, significant differences were still observed

(Fig. 3.6b).

When measuring lateral rotation of the ST articulation, it is interesting to note

that lifting an object to head height required a larger rotation than scapular plane

abduction (Fig. 3.7a). This would suggest that the necessary muscle activation

to lift a 20N object resulted in a larger lateral rotation. However a Friedman

test comparing scapular abduction, washing the upper back, lifting a 20N object
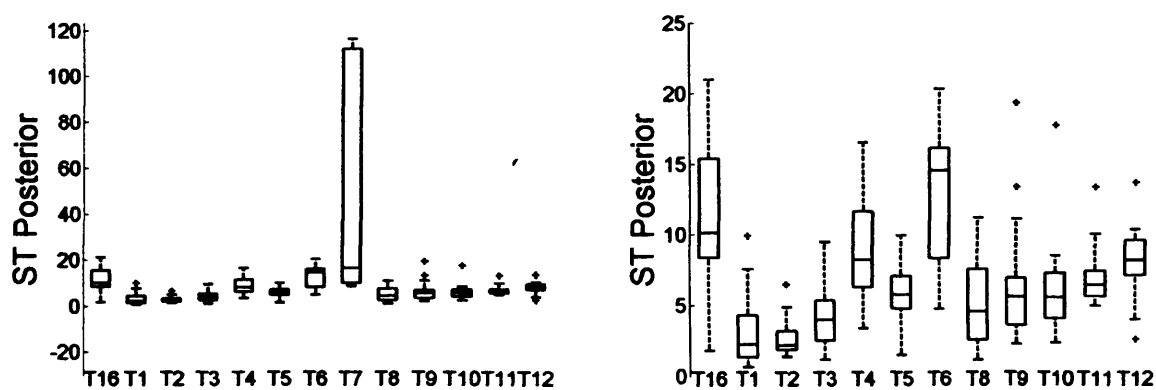
FIGURE 3.6: On each box, the central mark is the median rotation, the edges of the box are the 25^{th} and 75^{th} percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually as '+'. (a) ST posterior tilt, (b) ST posterior tilt with task 7 removed for clarity. T1 - Reach opposite axilla; T2 - Reach to opposite side of neck; T3 - Touch side and back of head; T4 - Reach forward; T5 - Eat with hand to mouth; T6 - Clean lower back; T7 - Wash upper back; T8 - Drink from mug; T9 - Answer phone; T10 - Brush opposite side of head; T11 - Lift block to shoulder height; T12 - Lift block to head height; T16 - Scapular plane abduction. Full table of tasks can be found in Table 3.3.

to shoulder height, and lifting an object to head height found no statistically significant differences.

Analysis of the GH joint corroborated the findings of the previous study, that there is an excess capacity of the GH elevation which is unnecessary for the majority of functional tasks. Friedman tests with and without Task 7, washing the upper back (which has a large spread of data due to the fewer samples used), showed that there was a statistically significant difference between the GH elevation required to perform full arm elevation and the GH elevation required for the functional tasks (Fig. 3.7b).
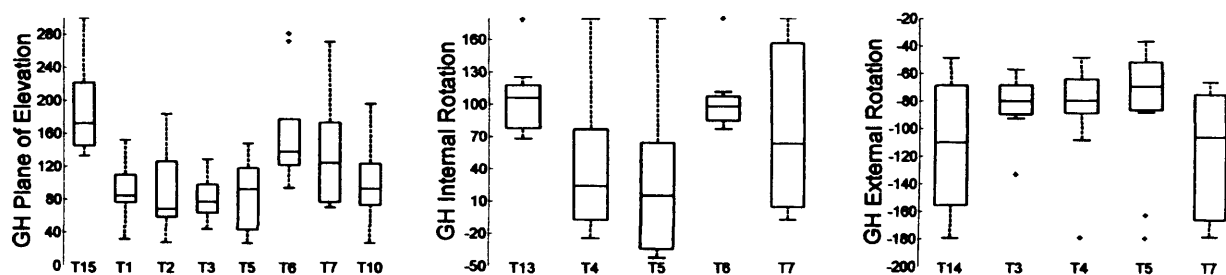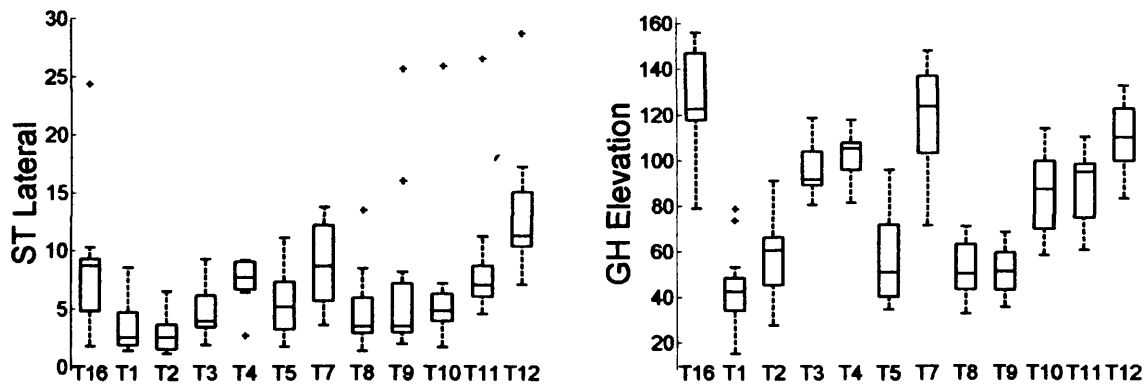
FIGURE 3.7: On each box, the central mark is the median rotation, the edges of the box are the 25^{th} and 75^{th} percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually as '+'. (a) ST lateral rotation, (b) GH elevation. T1 - Reach opposite axilla; T2 - Reach to opposite side of neck; T3 - Touch side and back of head; T4 - Reach forward; T5 - Eat with hand to mouth; T7 - Wash upper back; T8 - Drink from mug; T9 - Answer phone; T10 - Brush opposite side of head; T11 - Lift block to shoulder height; T12 - Lift block to head height; T16 - Scapular plane abduction. Full table of tasks can be found in Table 3.3.

3.8.1 Male vs. Female

Wilcoxon signed-rank tests were used to compare the rotations measured for the male and female subjects during each activity. The rotations of the GH and ST articulations were compared for every task. It was found, that for the current cohort (10 males, 6 females), there were no significant differences for any of the rotations.

3.9 Study 2: Discussion

This study objectively measured the rotations of the GH and ST articulations during ROM tasks (scapular plane abduction, cross chest adduction, internal/external rotation) and during a series of everyday functional tasks. The results found that

for the GH joint, there was no significant excess capacity of physiological axial rotation and plane of elevation movement. For GH elevation, there was a significant difference between the elevation required for full arm elevation, which is in agreement with the first study in this chapter.

The results showed that for retraction of the ST articulation, the physiological ROM was significantly greater than the functional ROM. The benchmark task used to measure ST retraction was cross chest adduction, to avoid the risk of the acromion cluster overestimating this rotation at higher elevations.

The analysis of ST lateral rotation showed that lifting an object to head height required a larger ROM than full scapular abduction, indicating that increased muscle activation may have resulted in a larger rotation. However the difference was not significant. Furthermore this finding is somewhat limited by the inherent limitations of the acromion cluster, which can only be used to measure scapula movement accurately up to $100°$ of arm elevation. The majority of ST lateral rotation occurs after $120°$ of arm elevation. It is therefore possible that this rotation has not been accurately reported, thus it is believed that there is an excess physiological range for ST lateral rotation, that has not been measured.

The results of the ST posterior tilt analysis show that there is a significant difference between the physiological and functional ROM. However the study in section 2.9 showed that the AC cluster overestimated ST posterior tilt, increasingly so at higher elevations.

The functional tasks assessed were altered from the first study at the discretion

of the author. The "Eat with a spoon" task was removed, as the information collected is made redundant by the "Eat with hand to mouth" and "Drink from mug" tasks. Two functional tasks related to hygiene were added: "Wash upper back" and "Wash lower back". Both tasks were added due to their importance in everyday independent living and also because of the physical challenges in doing them. Washing the upper back requires a high degree of arm elevation and washing the lower back requires a large amount of internal rotation. The final functional task added was to "Reach as far forward as possible". This was added for the functional relevance of reaching for everyday objects. Cross chest adduction was added as a ROM task to assess GH plane of elevation and the ST rotations.

Analysis of the type presented in this chapter may prove useful to clinicians by providing information on the function of the healthy shoulder, providing a baseline when assessing patients both pre and post surgery. This has implications for clinical practice, litigation cases and insurance settlements as a patient's ability to perform maximum elevation is commonly assessed as an indicator of their ability to return to physical activity.

In conclusion, bearing in mind the limitations of the methodology previously discussed, these two studies found that everyday functional tasks of daily living can be performed without the full capacity of GH elevation, but require full capacity of GH rotation and plane of elevation. It was also found that full capacity of ST lateral rotation is required to perform the tasks, but there is an excess capacity of retraction and posterior tilt of the ST articulation. With regard to hypothesis

three, that common upper limb ADL can be performed without the full physiological ROM of the individual articulations, based on these findings, this is only partially true.

3.10 Comparisons with other studies

A previous study by Magermans et al. [2] used a six degree-of-freedom electromagnetic tracking device to obtain 3D descriptions of the ROM and ADL of the shoulder and elbow of 24 female subjects with no previous history of shoulder pathology or instability. Due to the inherent difficulties in dynamic tracking of the scapula, the measurements were taken in an incremental quasi-static mode. This allowed for high accuracy in the measured joint rotations, but is very time consuming and not truly representative of the manner in which ADL are performed in everyday situations. This study found that during scapular plane abduction and forward flexion, arm elevation was brought about by approximately $80°$ glenohumeral elevation, compared to approximately $99°$ in the first study in this chapter, and $120°$ in the current study. The current study contained four comparable tasks: combing the hair; washing the axilla; eating; and reaching forward. For each task, the measured ST lateral rotations were consistently lower, while the GH plane of elevation and GH elevation were slightly higher. The first study of this chapter recorded lower levels of glenohumeral elevation during each of the comparable ADL (touching the opposite axilla, eating with a spoon and combing the hair).

A more recent study by van Andel et al. [3] used an active LED-marker motion capture system with three cameras to assess 10 healthy subjects. The aim of the study was to develop a standardisation protocol for 3D motion capture of the upper extremity for clinical application which would form the basis for the development of an upper extremity analysis report, the upper limb equivalent of the gait analysis report. The protocol consisted of four ADL and six ROM tasks. The dynamic movement of the scapula was tracked using a sensor placed on the acromion plateau which has been found to be reliable for arm elevations up to $120°$ [68, 78] but it is recommended not to exceed arm elevations of $100°$ [79]. Of the four ADL tasks assessed, all of them are comparable with ADL assessed in study 2 of this chapter, while three of them are comparable with ADL assessed in the first study (hand to contra lateral shoulder; hand to mouth/drinking; and combing the hair). Glenohumeral rotations were not reported in the van Andel study. Humerus movements were instead reported relative to the thorax. The humerus elevation required to drink from a mug was identical to the first study of this chapter $(44°)$ but less than that (not significantly) measured in the second study $(58°)$. The magnitude of axial rotation is also larger in the current study by approximately $40°$. $33.7°$ of humeral elevation was required to touch the contralateral shoulder, which is similar to the current study $(35°)$. The first study of this chapter required $18.57°$ and $28.77°$ (right and left arms respectively). This difference is most likely caused by the variations in the protocol. The study by van Andel et al. required subjects to touch the contralateral vicinity of the acromioclavicular joint, whereas the current study required subjects to touch the contralateral axilla, which is lower, and would thus require less arm elevation. The magnitude of axial rotation

required of the humerus in the the current study and the van Andel study were also similar (between 30° and 40° in both studies). For the hair combing task, the studies in this chapter asked subjects to comb the opposite side of their head, at the side, close to the ear, which required elevations of 49° and 60° respectively in the first study, and 76° in the current study. The van Andel study had a slightly different protocol, where subjects combed the top of the head, resulting in slightly higher elevations of 83°. The current study also required a larger axial rotation of the humerus, as the brush stroke was on the opposite side of the head. The hand to back pocket task is very similar to the washing the lower back task in the current study. Both studies found similar levels of HT elevation (approx 50°) and humerus internal rotation (100°).

Chapter 4

Patient Study

4.1 Introduction

Motion capture has become an increasingly used tool to assess the functionality
of the upper limb in pathological subjects, as discussed in section 1.1. Ethical
approval to recruit and test NHS treated patients with any shoulder pathology was
granted by the South Wales Research Ethics Committee REC No: 08/WSE02/37
(see Appendix D). Based on consultations with orthopaedic surgeons as to what
patient groups may benefit from motion capture assessment, and the availability
of suitable patients, subjects from the following cohorts were recruited:

- Glenohumeral Dislocation and Subluxation

- Clavicle Fractures

- Multi-Directional Instability

The clinical questions that were raised during these consultations were:

- Is it possible to use motion analysis to detect factors that may predispose a first time GH dislocator to become a recurrent dislocator?

- Is there a difference in the functional outcomes of clavicle fracture subjects who are treated with clavicle pins or fracture fixation plates?

- Is it possible to detect altered motion patterns in subjects with MDI?

This chapter is a preliminary study which only begins to address these questions. It focuses on the application of the scapula locator to assess pathological shoulder functionality and compare it to a healthy cohort. This relates to Objective 5 and is an investigation of hypothesis 4, that **a scapula locator can be used to differentiate between the kinematic profiles of healthy and patient cohorts during arm elevation.** This study was designed to investigate the potential of the technique to be beneficial in the diagnosis and prognosis of specific pathologies.

4.2 Patient Cohort Overview

In total 17 patients were recruited to the study. Fifteen of these had uni-lateral shoulder pathologies, while two had bilateral pathologies, totalling 19 shoulders for analysis.

The clavicle fracture cohort consisted of 5 uni-lateral subjects (M:F 4:1 mean age 27.3 $\pm$ 9.3 years, height 1.7 $\pm$ 0.06m, weight 77.6 $\pm$ 10.8kg, BMI 26 $\pm$ 1.9). The

GH dislocator group consisted of five uni-lateral subjects and one bilateral subject

(M:F 6:0 mean age 24.3 ± 3.7 years, height 1.79 ± 0.06m, weight 78 ± 7.5kg,

BMI 22.9 ± 2.1), providing seven shoulders in total. The MDI group consisted

of five unilateral subjects and one bilateral subject (M:F 3:3 mean age 26.1 ±

7.2 years, height 1.7 ± 0.12m, weight 74 ± 12.8kg, BMI 25.7 ± 3.9), also giving

seven shoulders in total. Full details for each of the cohorts are provided in Tables

4.1, 4.2, and 4.3, including scores for the Oxford Shoulder Score/Oxford Shoulder

Instability Score, the Constant Score where applicable, and the Beightons score

to quantify joint laxity and hypermobility for the MDI patients.

The Oxford Shoulder Score [50] and the Oxford Shoulder Instability Score [122]

measure a patient's subjective assessment of pain and ADL. The questionnaire

contains 12 entries, each with five optional responses, ranging from no pain/no

difficulty performing a task to maximum pain/difficulty. Four of the questions are

related to pain, eight are related to ADL. Scores are added to give a single score,

with 12 being a perfect score, and 60 being the worst score.

The Constant score [49] is commonly used to assess functional outcome following

treatment. It combines a subjective assessment of the patient's perception of pain

and function (15 and 20 points respectively) along with an objective measurement

of ROM and strength (40 and 25 points respectively). Low scores denote significant

pain and poor function. It has been found to be unsuitable for assessing subjects

with GH instability as even subjects with a high level of laxity tend to achieve high

scores [123, 124]. It is instead recommended to use a tool which is specific to GH

instability, such as the Oxford Shoulder Instability Score. As such the Constant

score has not been reported for the GH dislocator group. It has however been

reported for the MDI group, as they were scored by a medical student as part of

a separate study.

TABLE 4.1: Overview of patient details from the clavicle fracture cohort. Patients have been anonymised and any revealing data removed. 'L' and 'R' refer to 'Left' and 'Right' respectively, and indicate which arm is injured.

Patient Number	Treatment	Constant Score	Oxford Shoulder Score	Other relevant information
1 L	Clavicle plate (removed)	83	29	Martial arts injury. Weakness and numbness in shoulder. 3 years since treatment
2 R	Plate fixation	50	22	Awaiting removal of plate - discomfort. 10 months since treatment
3 R	Pin fixation (removed).	84	40	Full recovery. 2 years since treatment
4 L	Plate fixation (still in place)	64	17	Fell from horse. Still has weakness. 6 months since treatment
5 R	Pin fixation. Removed.	92	15	18 months since treatment

The control group for consists of the same 16 subjects assessed in sections 2.9 and

3.6, consisting of sixteen subjects (ten males and six females with a mean age of

24.46 ± 2.23 years) with no previous history of shoulder pathology or instability

in either shoulder.

TABLE 4.2: Overview of patient details from the glenohumeral dislocator cohort. Patients have been anonymised and any revealing data removed. 'L' and 'R' refer to 'Left' and 'Right' respectively, and indicate which arm is injured.

Patient Number	Treatment	Oxford Shoulder Instability Score	Other relevant information
6 L	Conservative	36	Three dislocations. Also: fractured humerus; fractured radius; fractured ulna; AC dislocation type 3 (managed conservatively). AC dislocation causes pain. 6 months since last dislocation
6 R	Conservative	15	Two dislocations. Broken radius. 15 months since last dislocation
7 L	Conservative	49	Five anterior dislocations, one posterior dislocation. All playing rugby in single season. 10 months since last dislocation
8 L	Arthroscopy and stabilisation	20	Six dislocations prior to surgery. 6 months since treatment
9 R	Conservative	25	Two sporting dislocations. 8 months since last dislocation
10 L	Conservative followed by surgery	36	Three dislocations managed conservatively before surgery. Post surgery dislocated many times before starting yoga six years prior to assessment. Has only dislocated three times since then, most recently 18 months ago.
11 L	Conservative	17	Dislocated shoulder once in bike accident 4 years ago. Also fractured clavicle but no surgery required

TABLE 4.3: Overview of patient details from the multi-directional instability cohort. Patients have been anonymiséd and any revealing data removed. 'L' and 'R' refer to 'Left' and 'Right' respectively, and indicate which arm is injured.

Patient Number	Treatment	Constant Score	Oxford Shoulder Instability Score Score	Beightons Score	Other relevant information
12 L	Capsular shrinkage	89	21	N/A	Exacerbated by rugby and American football. Reduced since surgery 3 years ago
12 R	Capsular shrinkage	88	26	N/A	Subluxes in bed most nights despite surgery 3 years ago. Exacerbated by rugby and American football
13 R	Conservative	78.6	26	7/9	Instability due to fall at work. Dislocates and/or subluxates regularly
14 L	Conservative	87.1	24	7/9	Last dislocation 8 months ago
15 L	Conservative	73.25		4/9	Has not dislocated recently
16 R	Conservative	88.75	42	0/9	last dislocation 18 months ago
17 R	Conservative	90.1	42	6/9	Last dislocation 2 years ago

4.3   Comparing Healthy and Patient cohorts with

a scapula locator

Subjects from each cohort performed static arm elevations in increments of $20°$

in the coronal, scapular, and sagittal planes. Elevations were performed bilater-

ally, with the thumb pointing upwards for coronal and scapular plane elevation,

and with the hand pronated for sagittal plane elevation. Scapula position and

orientation was measured at each increment using a scapula locator with markers

attached to represent each of the scapula bony landmarks. The same external ref-

erence frame fitted with retro-reflective markers as in the previous study [73] was

used to guide arm elevation in the different planes and assist in post experimental

data acquisition.

As in previous studies, a neutral position anatomical calibration measurement was

captured for one second at the start of each trial with the elbow flexed to $90°$ and

the hand pronated. All calculations for the different segment ACS's and TCS's,

and the joint and segment rotations were calculated as per the previous studies

and to the recommendations of the I.S.B [30]. The PX marker was digitised for

four of the female subjects; three from the MDI cohort, and one from the clavicle

fracture cohort, to avoid marker occlusion. The Matlab subroutine to perform this

was written by the author.

4.4   Results

Full kinematic descriptions of the shoulder complex were recorded for the injured

arms of each patient and for the right arm of the healthy cohort during static

elevations in the coronal, scapular, and sagittal planes.

4.4.1   Clavicle Fracture Cohort

Figs. 4.1 - 4.4 show the rotations of the SC, AC, ST, and GH articulations respec-

tively during coronal, scapular and sagittal plane elevation for the clavicle fracture

cohort compared with the healthy cohort. The static rotations measured for each

articulation were divided into $20°$ increments of humerothoracic elevation ($0°$ -

$20°$; $20°$ - $40°$; $40°$ - $60°$; $60°$ - $80°$; $80°$ - $100°$; and $100°$ - $120°$). Solid lines

and solid errors bars (standard deviation of the rotations measured for the sample

group) represent the rotations measured for the healthy cohort. Dashed lines and

error bars represent the rotations measured for each patient cohort. These graphs

provide a visual reference as to how the clavicle fracture patient cohort varies from

the healthy cohort.

A summary of the significant differences for the healthy cohort vs. the clavicle

fracture cohort can be found in Table 4.4. Full statistical analysis of the entire

cohort can be found in section 4.4.4, specifically in Tables 4.7 and 4.8.

Coronal Plane
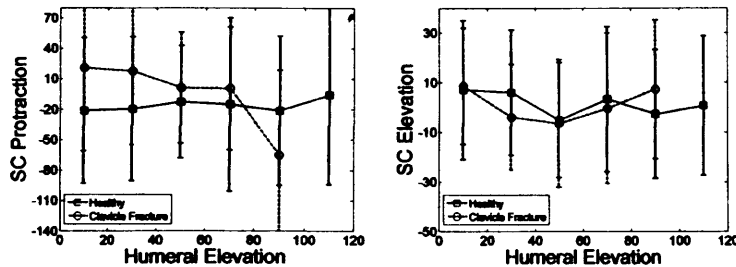
Scapular Plane
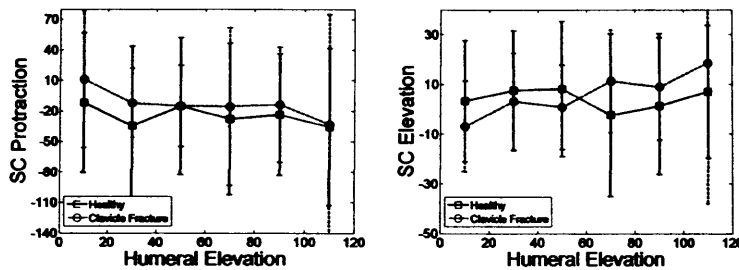
Sagittal Plane

FIGURE 4.1: **Healthy cohort vs. Clavicle fracture cohort. The rotations measured for the sternoclavicular joint** were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. **Square markers with solid lines and solid error bars represent the rotations of the healthy cohort** (± the standard deviation of the rotations measured for the sample group). **Circular markers with dashed lines and dashed error bars represent the rotations of the clavicle fracture cohort** (± the standard deviation of the rotations measured for the sample group). All rotations measured with a scapula locator. The error bars have been truncated to allow greater resolution of the rotations. Untruncated versions of the graphs can be found in Appendix C. All rotations measured in degrees (°).

Coronal Plane

Scapular Plane

Sagittal Plane

FIGURE 4.2: **Healthy cohort vs. Clavicle fracture cohort. The rotations measured for the acromioclavicular joint** were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. **Square markers with solid lines and solid error bars represent the rotations of the healthy cohort** (± the standard deviation of the rotations measured for the sample group). **Circular markers with dashed lines and dashed error bars represent the rotations of the clavicle fracture cohort** (± the standard deviation of the rotations measured for the sample group). All rotations measured with a scapula locator. The error bars have been truncated to allow greater resolution of the rotations. Untruncated versions of the graphs can be found in Appendix C. All rotations measured in degrees (°).

Coronal Plane

Scapular Plane

Sagittal Plane

FIGURE 4.3: **Healthy cohort vs. Clavicle fracture cohort. The rotations measured for the glenohumeral joint** were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. **Square markers with solid lines and solid error bars represent the rotations of the healthy cohort** (± the standard deviation of the rotations measured for the sample group). **Circular markers with dashed lines and dashed error bars represent the rotations of the clavicle fracture cohort** (± the standard deviation of the rotations measured for the sample group). All rotations measured with a scapula locator. All rotations measured in degrees (°). Significant differences have been highlighted in Table 4.7.

Coronal Plane
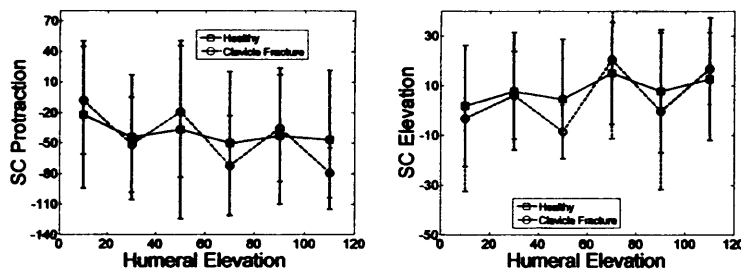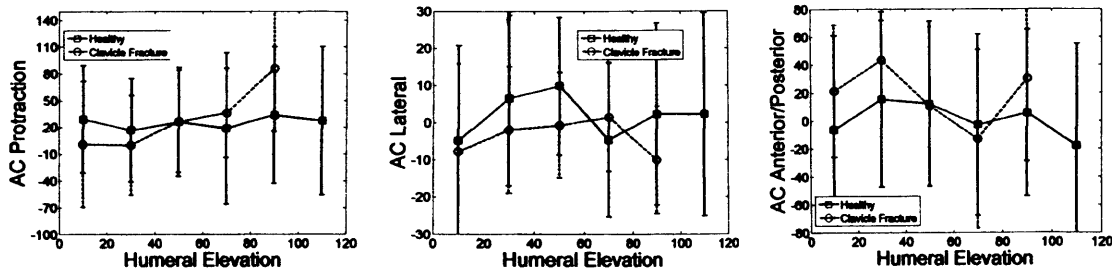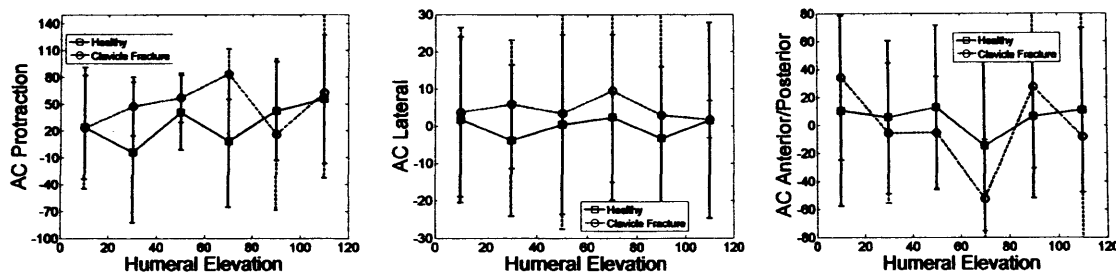

Scapular Plane

Sagittal Plane

FIGURE 4.4: **Healthy cohort vs. Clavicle fracture cohort. The rotations measured for the scapulothoracic articulation** were divided into $20°$ increments of humerothoracic elevation ($0°$ - $20°$; $20°$ - $40°$; $40°$ - $60°$; $60°$ - $80°$; $80°$ - $100°$; and $100°$ - $120°$. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. **Square markers with solid lines and solid error bars represent the rotations of the healthy cohort** ($\pm$ the standard deviation of the rotations measured for the sample group). **Circular markers with dashed lines and dashed error bars represent the rotations of the clavicle fracture cohort** ($\pm$ the standard deviation of the rotations measured for the sample group). All rotations measured with a scapula locator. All rotations measured in degrees ($°$). Significant differences have been highlighted in Table 4.7.

TABLE 4.4: Mann-Whitney U tests ($\alpha=.05$) were used to compare each patient cohort and the healthy cohort. Full results can be seen in Tables 4.7 and 4.8. The current table is provided as a quick reference for when the clavicle fracture cohort differs significantly from the healthy cohort. GH1 = GH Plane of Elevation, GH2 = GH Elevation, GH3 = GH Axial Rotation, ST1 = ST Retraction, ST2 = ST Lateral Rotation, ST3 = ST Posterior Tilt.

Abduction
ST1 20° - 40°
Scapular Abduction
ST1 0° - 20°
ST1 20° - 40°
ST3 60° - 80°
Flexion
ST1 0° - 20°
ST3 20° - 40°

4.4.2 Glenohumeral Dislocator Cohort

Figs. 4.5 - 4.8 show the rotations of the SC, AC, ST, and GH articulations respectively during coronal, scapular and sagittal plane elevation for the GH dislocator cohort compared with the healthy cohort. The static rotations measured for each articulation were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°). Solid lines and solid errors bars (standard deviation of the rotations measured for the sample group) represent the rotations measured for the healthy cohort. Dashed lines and error bars represent the rotations measured for the glenohumeral dislocator cohort. These graphs provide a visual reference as to how the glenohumeral dislocator cohort varies from the healthy cohort.

A summary of the significant differences for the healthy cohort vs. the glenohumeral dislocator cohort can be found in Table 4.5. Full statistical analysis of the entire cohort can be found in section 4.4.4, specifically in Tables 4.7 and 4.8.

Coronal Plane
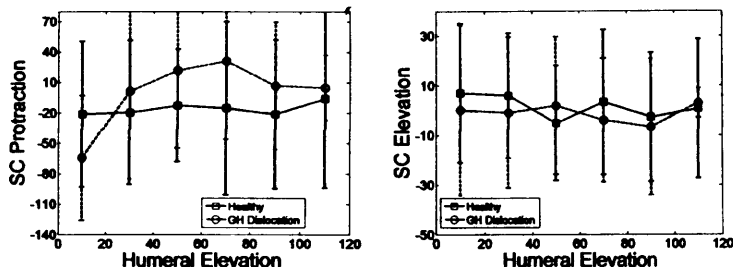
Scapular Plane
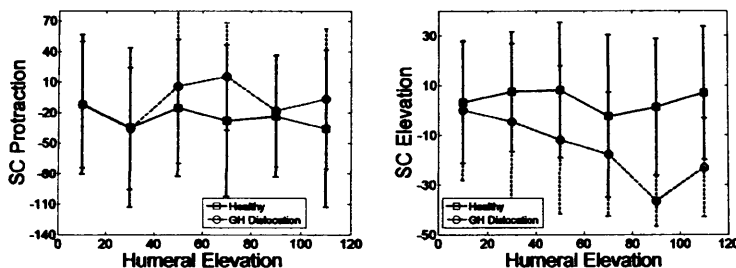
Sagittal Plane
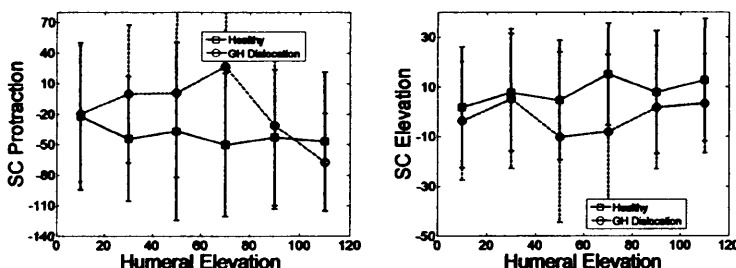
FIGURE 4.5: **Healthy cohort vs. glenohumeral dislocation cohort. The rotations measured for the sternoclavicular joint** were divided into $20°$ increments of humerothoracic elevation ($0° - 20°$; $20° - 40°$; $40° - 60°$; $60° - 80°$; $80° - 100°$; and $100° - 120°$. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. **Square markers with solid lines and solid error bars represent the rotations of the healthy cohort** ($\pm$ the standard deviation of the rotations measured for the sample group). **Circular markers with dashed lines and dashed error bars represent the rotations of the glenohumeral dislocation cohort** ($\pm$ the standard deviation of the rotations measured for the sample group). All rotations measured with a scapula locator. The error bars have been truncated to allow greater resolution of the rotations. Untruncated versions of the graphs can be found in Appendix C. All rotations measured in degrees ($°$).
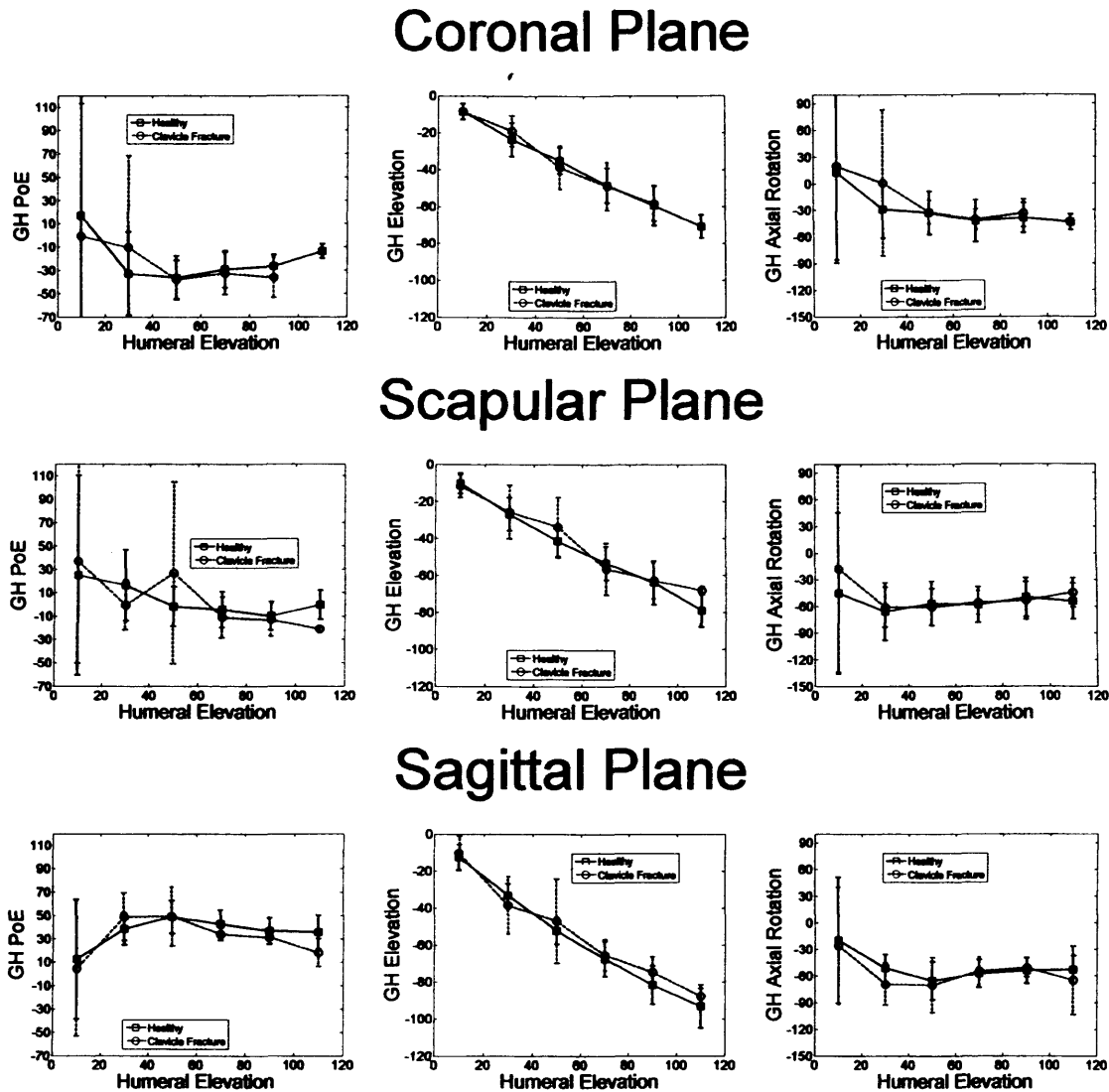
Coronal Plane

Scapular Plane

Sagittal Plane

FIGURE 4.6: **Healthy cohort vs. glenohumeral dislocation cohort. The rotations measured for the acromioclavicular joint** were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. **Square markers with solid lines and solid error bars represent the rotations of the healthy cohort** (± the standard deviation of the rotations measured for the sample group). **Circular markers with dashed lines and dashed error bars represent the rotations of the glenohumeral dislocation cohort** (± the standard deviation of the rotations measured for the sample group). All rotations measured with a scapula locator. The error bars have been truncated to allow greater resolution of the rotations. Untruncated versions of the graphs can be found in Appendix C. All rotations measured in degrees (°).

Coronal Plane

Scapular Plane

Sagittal Plane

FIGURE 4.7: **Healthy cohort vs. glenohumeral dislocation cohort.The rotations measured for the glenohumeral joint** were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. **Square markers with solid lines and solid error bars represent the rotations of the healthy cohort** (± the standard deviation of the rotations measured for the sample group). **Circular markers with dashed lines and dashed error bars represent the rotations of the glenohumeral dislocation cohort** (± the standard deviation of the rotations measured for the sample group). All rotations measured with a scapula locator. All rotations measured in degrees (°). Significant differences have been highlighted in Table 4.7.

Coronal Plane

Scapular Plane

Sagittal Plane

FIGURE 4.8: **Healthy cohort vs. glenohumeral dislocation cohort. The rotations measured for the scapulothoracic articulation** were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. **Square markers with solid lines and solid error bars represent the rotations of the healthy cohort** (± the standard deviation of the rotations measured for the sample group). **Circular markers with dashed lines and dashed error bars represent the rotations of the glenohumeral dislocation cohort** (± the standard deviation of the rotations measured for the sample group). All rotations measured with a scapula locator. All rotations measured in degrees (°). Significant differences have been highlighted in Table 4.7.

TABLE 4.5: Mann-Whitney U tests (α=.05) were used to compare each patient cohort and the healthy cohort. Full results can be seen in Tables 4.7 and 4.8. The current table is provided as a quick reference for when the glenohumeral dislocator cohort differs significantly from the healthy cohort. GH1 = GH Plane of Elevation, GH2 = GH Elevation, GH3 = GH Axial Rotation, ST1 = ST Retraction, ST2 = ST Lateral Rotation, ST3 = ST Posterior Tilt.

Abduction
GH1 80° - 100°
ST1 0° - 20°
ST2 20° - 40°
Scapular Abduction
ST1 0° - 20°
ST3 0° - 20°
ST3 60° - 80°
Flexion
GH1 40° - 60°
GH1 60° - 80°
GH3 20° - 40°
GH3 40° - 60°
GH3 60° - 80°
ST1 0° - 20°
ST1 40° - 60°
ST3 0° - 20°
ST3 60° - 80°

TABLE 4.6: Mann-Whitney U tests (α=.05) were used to compare each patient cohort and the healthy cohort. Full results can be seen in Tables 4.7 and 4.8. The current table is provided as a quick reference for when the MDI cohort differs significantly from the healthy cohort. GH1 = GH Plane of Elevation, GH2 = GH Elevation, GH3 = GH Axial Rotation, ST1 = ST Retraction, ST2 = ST Lateral Rotation, ST3 = ST Posterior Tilt.

Abduction
GH2 20° - 40°
Scapular Abduction
ST1 0° - 20°
Flexion
GH3 20° - 40°
GH3 60° - 80°
ST2 20° - 40°

4.4.3 Multi-Directional Instability Cohort

Figs. 4.9 - 4.12 show the rotations of the SC, AC, ST, and GH articulations respectively during coronal, scapular and sagittal plane elevation for the MDI cohort compared with the healthy cohort. The static rotations measured for each articulation were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°). Solid lines and solid errors bars (standard deviation of the rotations measured for the sample group) represent the rotations measured for the healthy cohort. Dashed lines and error bars represent the rotations measured for MDI cohort. These graphs provide a visual reference as to how the MDI cohort varies from the healthy cohort.

A summary of the significant differences for the healthy cohort vs. the MDI cohort can be found in Table 4.6. Full statistical analysis of the entire cohort can be found in section 4.4.4, specifically in Tables 4.7 and 4.8.

Coronal Plane
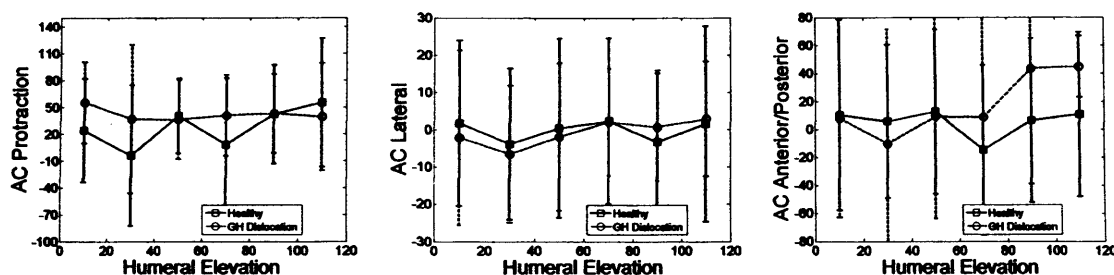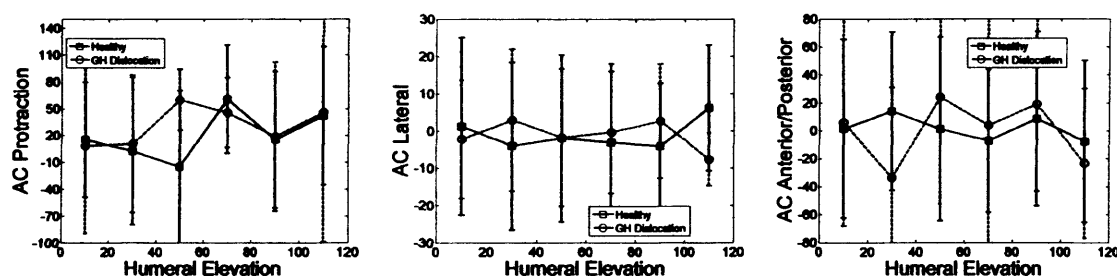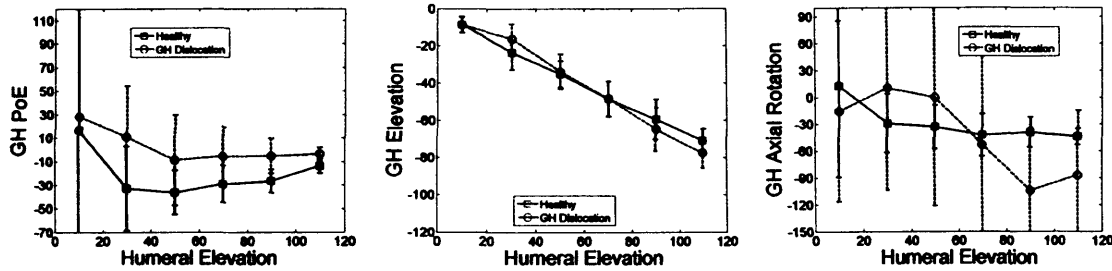

Scapular Plane

Sagittal Plane
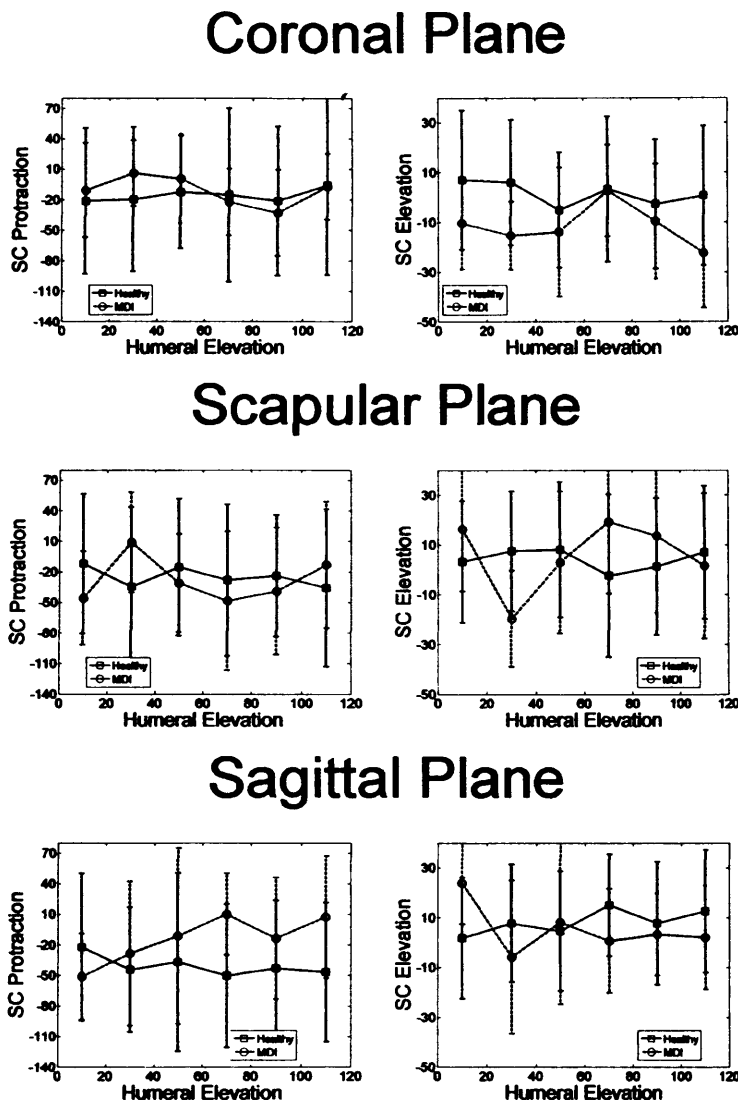
FIGURE 4.9: **Healthy cohort vs. MDI cohort. The rotations measured for the sternoclavicular joint** were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. **Square markers with solid lines and solid error bars represent the rotations of the healthy cohort** (± the standard deviation of the rotations measured for the sample group). **Circular markers with dashed lines and dashed error bars represent the rotations of the Multi Directional Instability cohort** (± the standard deviation of the rotations measured for the sample group). All rotations measured with a scapula locator. The error bars have been truncated to allow greater resolution of the rotations. Untruncated versions of the graphs can be found in Appendix C. All rotations measured in degrees (°).
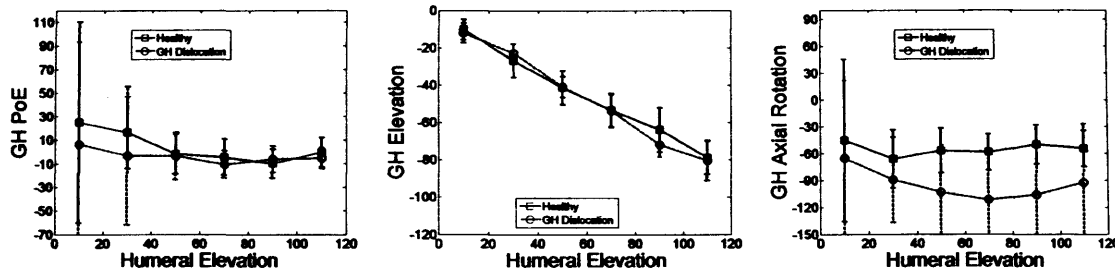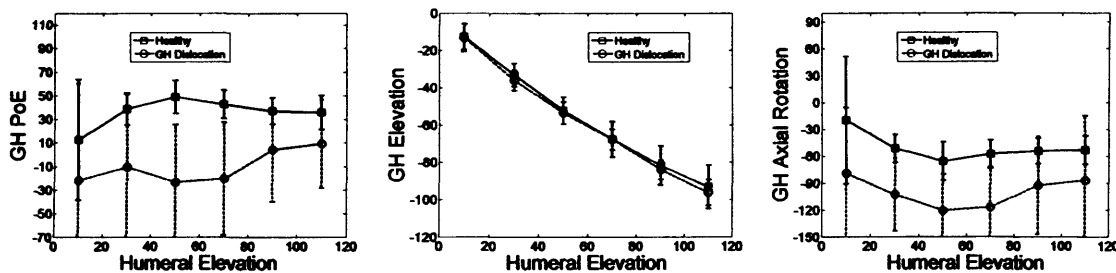
Coronal Plane

Scapular Plane

Sagittal Plane

FIGURE 4.10: **Healthy cohort vs. MDI cohort. The rotations measured for the acromioclavicular joint** were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. **Square markers with solid lines and solid error bars represent the rotations of the healthy cohort** (± the standard deviation of the rotations measured for the sample group). **Circular markers with dashed lines and dashed error bars represent the rotations of the Multi Directional Instability cohort** (± the standard deviation of the rotations measured for the sample group). All rotations measured with a scapula locator. The error bars have been truncated to allow greater resolution of the rotations. Untruncated versions of the graphs can be found in Appendix C. All rotations measured in degrees (°).

Coronal Plane

Scapular Plane

Sagittal Plane

FIGURE 4.11: **Healthy cohort vs. MDI cohort. The rotations measured for the glenohumeral joint** were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. **Square markers with solid lines and solid error bars represent the rotations of the healthy cohort** (± the standard deviation of the rotations measured for the sample group). **Circular markers with dashed lines and dashed error bars represent the rotations of the Multi Directional Instability cohort** (± the standard deviation of the rotations measured for the sample group). All rotations measured with a scapula locator. All rotations measured in degrees (°). Significant differences have been highlighted in Table 4.7.
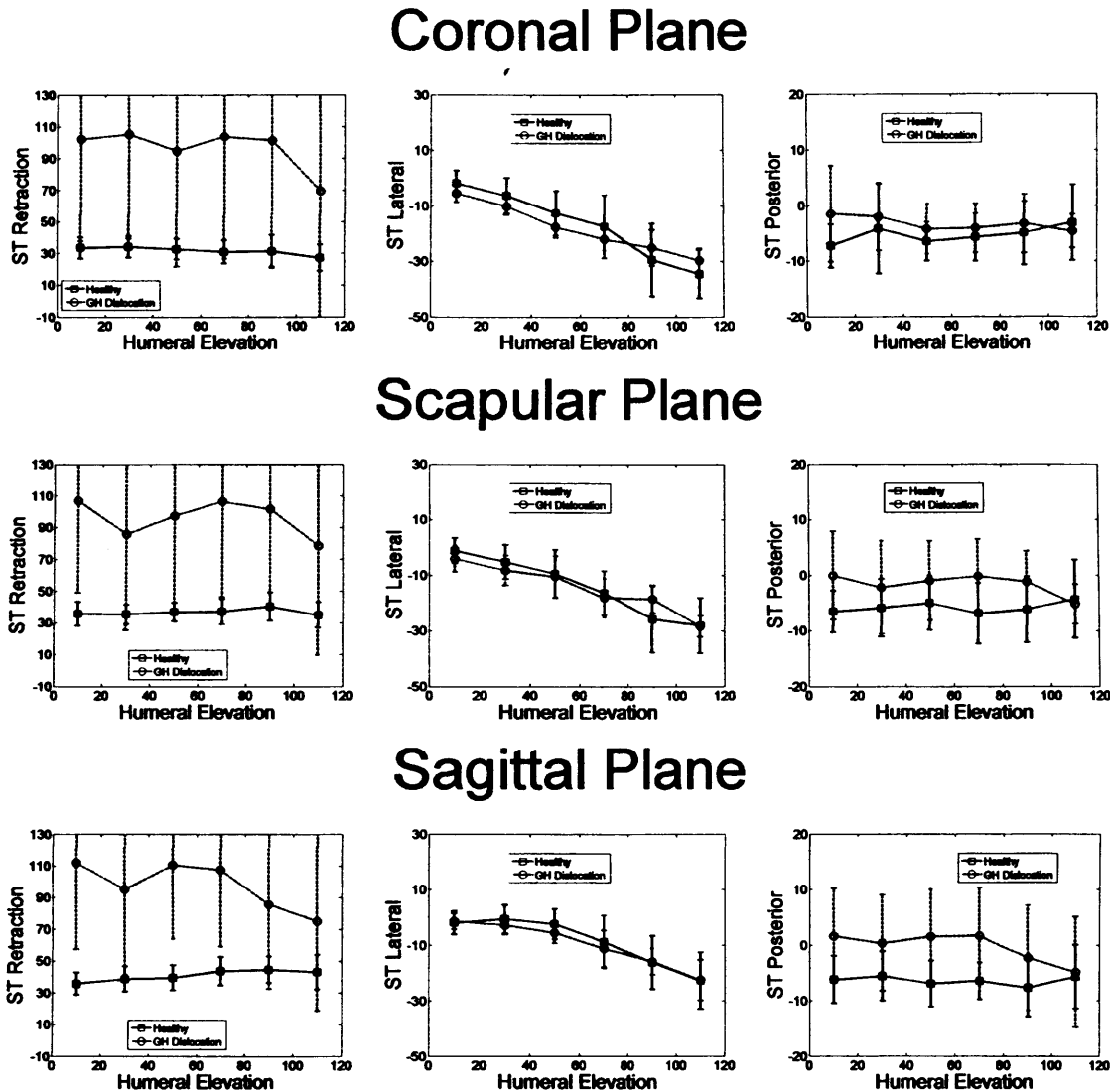
Coronal Plane

Scapular Plane

Sagittal Plane

FIGURE 4.12: **Healthy cohort vs. MDI cohort. The rotations measured for the scapulothoracic articulation** were divided into $20°$ increments of humerothoracic elevation ($0°$ - $20°$; $20°$ - $40°$; $40°$ - $60°$; $60°$ - $80°$; $80°$ - $100°$; and $100°$ - $120°$. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. **Square markers with solid lines and solid error bars represent the rotations of the healthy cohort** ($\pm$ the standard deviation of the rotations measured for the sample group). **Circular markers with dashed lines and dashed error bars represent the rotations of the Multi Directional Instability cohort** ($\pm$ the standard deviation of the rotations measured for the sample group). All rotations measured with a scapula locator. All rotations measured in degrees ($°$). Significant differences have been highlighted in Table 4.7.

4.4.4   Cross-Cohort Comparisons

Kruskal-Wallis tests, a non-parametric equivalent of ANOVA, were used to compare the rotations of each articulation of each cohort during each of the increments. Table 4.7 shows which elevation increments show a statistically significant difference for each rotation between the four cohorts during abduction, scapular abduction, and flexion respectively $(\alpha=.05)$. The salient features to note when comparing the four cohorts are discussed in section 4.5.

There is no consensus amongst statisticians as to the most appropriate post-hoc test for a Kruskal-Wallis test which rejects the null hypothesis. For the measurements where it was found that there were statistically significant differences, Mann-Whitney U tests have been used to determine which pairs are significantly different, as recommended in [125]. The results of these are tabulated in Table 4.8.

4.5   Discussion

This study was the first exploratory investigation of subjects with shoulder pathologies in the Cardiff University Motion Analysis Laboratory. The successful application for the ethical approval for the study was completed entirely by the author over the course of several months. Once ethical approval was granted, patient recruitment was still a very difficult task. Patients who were deemed to have suitable shoulder pathologies were contacted by registrars based in Cardiff. They then gave verbal consent to be contacted by the author. Subjects with traumatic uni-lateral

TABLE 4.7: Significant differences ($\alpha=.05$) between the clavicle fracture, GH dislocator, MDI, and healthy cohorts as measured with Kruskal-Wallis tests when measuring the rotations of the SC, AC, GH, and ST articulations during abduction, scapular abduction, and flexion. The increments of arm elevation where significant differences were noted are marked with an 'X'. SC1 = SC Protraction, SC2 = SC Elevation AC1 = AC Protraction, AC2 = AC Lateral Rotation, AC3 = AC Posterior Tilt, GH1 = GH Plane of Elevation, GH2 = GH Elevation, GH3 = GH Axial Rotation, ST1 = ST Retraction, ST2 = ST Lateral Rotation, ST3 = ST Posterior Tilt. It should be noted the the error bars for the SC and AC rotations were very large, resulting in statistically insignificant differences. Table 4.8 identifies the pairs responsible for the significant differences in noted this table. It should e noted that the measurements for the SC and AC articulations have very large error bars. Therefore the differences are insignificant even if large in magnitude.

Abduction											
	SC1	SC2	AC1	AC2	AC3	GH1	GH2	GH3	ST1	ST2	ST3
0° - 20°									X		
20° - 40°							X		X	X	
40° - 60°											
60° - 80°											
80° - 100°						X			X		
100° - 120°											

Scapular Abduction											
	SC1	SC2	AC1	AC2	AC3	GH1	GH2	GH3	ST1	ST2	ST3
0° - 20°									X		X
20° - 40°									X		
40° - 60°											
60° - 80°											X
80° - 100°											
100° - 120°											

Flexion											
	SC1	SC2	AC1	AC2	AC3	GH1	GH2	GH3	ST1	ST2	ST3
0° - 20°									X		X
20° - 40°								X		X	X
40° - 60°						X		X	X		
60° - 80°						X		X			X
80° - 100°											
100° - 120°											

TABLE 4.8: Mann-Whitney U tests (α=.05) were used to determine which pairs of cohorts were responsible for the significant differences noted in Table 4.7. GH1 = GH Plane of Elevation, GH2 = GH Elevation, GH3 = GH Axial Rotation, ST1 = ST Retraction, ST2 = ST Lateral Rotation, ST3 = ST Posterior Tilt. H = Healthy cohort, CF = Clavicle Fracture cohort, GHD = Glenohumeral Dislocator cohort, MDI = Multi-directional instability cohort.

	Significant Difference between:
Abduction	
GH1 80° - 100°	H & GHD; CF & GHD
GH2 20° - 40°	H & MDI
ST1 0° - 20°	H & GHD
ST1 20° - 40°	H & CF
ST1 80° - 100°	CF & MDI
ST2 20° - 40°	H & GHD
Scapular Abduction	
ST1 0° - 20°	H & CF; H & GHD; H & MDI
ST1 20° - 40°	H & CF
ST3 0° - 20°	H & GHD; CF & GHD; GHD & MDI
ST3 60° - 80°	H & CF; H & GHD; CF & GHD
Flexion	
GH1 40° - 60°	H & GHD
GH1 60° - 80°	H & GHD
GH3 20° - 40°	H & GHD; H & MDI
GH3 40° - 60°	H & GHD; CF & GHD
GH3 60° - 80°	H & GHD; H & MDI; CF & GHD
ST1 0° - 20°	H & CF; H & GHD
ST1 40° - 60°	H & GHD
ST2 20° - 40°	H & MDI; CF & MDI; GHD & MDI
ST3 0° - 20°	H & GHD; CF & GHD; GHD & MDI
ST3 20° - 40°	H & CF; CF & GHD
ST3 60° - 80°	H & GHD; GHD & MDI

shoulder pathologies are primarily young and active, with full time jobs, children to raise, hobbies etc. In most cases, eligible subjects were unable or unwilling to take part in the study. This is in sharp contrast to previous research in Cardiff University on subjects with total knee replacement (TKR) or total hip arthroplasty (THA), who are older, usually retired, and more inclined to give their time. As a result, it was only possible to recruit 11 patients directly from NHS sources. The remaining six were friends, colleagues, and acquaintances who happened to

have suitable shoulder pathologies.

The scapula locator was used in this study as it is regarded as the gold standard for tracking the movement of the scapula, and hence the shoulder complex, non-invasively [68]. This study objectively explored the motion profiles of four cohorts (healthy, clavicle fracture, GH dislocator, and multi-directional instability) and attempted to determine if and how the kinematic profiles between cohorts differ, and thus determine if motion capture is a valid tool to assess shoulder functionality.

The salient features to note when comparing the measured rotations for each articulation for each cohort as summarised in Tables 4.7 and 4.8 are as follows:

For the SC joint and AC joint:

Statistically there were no significant differences between any of the cohorts when measuring the rotations of the SC and AC joints. However the error bars were very large due to the prevalence of skin-artefacts which undermines the findings of the statistical analysis and highlights the challenges and limitations when using the current method to assess these rotations. Even considering the presence of skin-artefacts, the errors appear to be extremely large and the author advises that these results are accepted with caution.

The Clavicle Fracture Cohort:

The clavicle fracture cohort differ from the healthy cohort primarily when measuring retraction of the ST articulation (ST1) during low arm elevations (abduction $20°$ - $40°$ arm elevation, scapular abduction $0°$ - $20°$ arm elevation, flexion $0°$ -

20° arm elevation). This rotation also differs from the measured values for the MDI cohort for coronal plane elevations of 80° - 100°.

ST posterior tilt (ST3) differs from the healthy cohort and GH dislocator cohort during sagittal plane elevations of 20° - 40°.

The GH Dislocator Cohort:

The measured values for GH plane of elevation differ from the healthy cohort (and clavicle fracture cohort) for coronal plane elevations of 80° - 100°, and sagittal plane elevations (healthy cohort only) of 40° - 80°.

Axial rotation of the GH joint differs from the healthy cohort during sagittal plane elevations of 20° - 80°. They also differ from the clavicle fracture cohort for elevations of 40° - 80°.

Retraction of the ST articulation differs from the healthy cohort during elevations of 0° - 20° in all planes and during elevations of 40° - 60° in the sagittal plane only.

Posterior tilt of the ST articulation differs from all other cohorts during scapular plane elevation and sagittal plane elevation of 0° - 20°. During sagittal plane elevation of 60° - 80° this rotation also differs from the healthy and MDI cohorts.

One of only two cases in the entire study where there is a significant difference between any of the cohorts for the values measured for ST lateral rotation is between the GH dislocator cohort and the healthy cohort for am elevations of 20° - 40° in the coronal plane.

The MDI Cohort:

The values for GH elevation during coronal plane arm elevations of $20°$ - $40°$ differed from the healthy cohort. This is the only case in the entire study where there was an observed difference when measuring GH elevation. Axial rotation of the GH joint differed from the healthy cohort during arm elevations of $20°$ - $40°$ and $60°$ - $80°$ in the sagittal plane.

ST retraction differs from the healthy cohort during arm elevations of $0°$ - $20°$ in the scapular plane. As previously mentioned when discussing the clavicle fracture cohort, the measured values for the MDI cohort for ST retraction during abduction of $80°$ - $100°$ differ from the clavicle fracture cohort.

ST lateral rotation differs from every other cohort during flexion of $20°$ - $40°$. This is the second of the two instances in the entire study where any difference in ST lateral rotation is noted.

These findings are limited by the fact that the entire healthy cohort were assessed on their dominant right arm only, whereas some of the patient subjects were assessed on their injured non-dominant arms. Study 1 of Chapter 3 found that there was only one task that differed significantly between the left and right arms, nevertheless, future studies should consider this and collect data from the non-dominant arm of healthy subjects.

In total, there were 21 observed significant differences between the four cohorts (Table 4.7). All of these differences were measured in rotations of the GH and ST articulations, where there were a possible 108 differences to be measured. This

equates to 19.44% of all measurements of the GH and ST articulations reporting a significant difference. Table 4.8 provides a breakdown of which individual pairings were responsible for these differences: The 21 observed significant differences in Table 4.7 actually consists of 39 paired differences. Of these 39 differences, 26 were between the healthy cohort and any of the remaining pathological cohorts. This would suggest that the motion analysis protocol is able to distinguish between healthy and pathological subjects (hypothesis four). The remaining 13 differences were between the patient cohorts. This would suggest that the method is also capable of distinguishing between individual pathologies, but possibly to a lesser extent than between healthy and patient cohorts. However the sample sizes are quite small, so further testing is warranted. Furthermore, the significant differences were primarily observed for retraction and posterior tilt of the ST articulation, which are the most difficult rotations to accurately measure.

There has been a relatively small amount of research to assess the kinematics of subjects with pathological shoulders. Many studies indicate that there is a large amount of inter-subject variability, and large variations from the kinematic profiles of healthy cohorts [126, 127, 128].

Studies which have assessed frozen shoulders focused primarily on the movement of the humerus. One such study compared 10 patients who had been diagnosed with frozen shoulder with a control group of 10 healthy shoulders so as to describe humeral motion in frozen shoulder subjects and to determine if there was a consistent pattern of capsular restriction [129]. This study used an electromagnetic tracking system and scapula movement was tacked by placing a sensor on the

acromion plateau. The study concluded that affected patients had a decreased humeral ROM (with a large variation within the sample), but no capsular pattern of movement was elucidated. A′ separate study assessed the kinematics of the affected and non-affected shoulder in frozen shoulder patients before and after physiotherapy [6]. As in the previous study [129] an electromagnetic tracking system was used. The scapula was tracked with a scapula locator. The study was able to detect differences between the affected and the non-affected arms, primarily the increased lateral rotation of the scapula during low arm elevations. The study was also able to detect improvements over time (3 months).

A study using MRI of 20 subjects with impingement syndrome reported that only approximately 25% of subjects showed an increase in scapulo-humeral kinematics and that overall there was no significant change in the shoulder complex kinematics compared to a healthy cohort of 14 [130]. In another study [128], 52 construction workers who routinely perform overhead activities were recruited. Electromagnetic sensors were used the track the dynamic movement of the scapula and the humerus. Subjects who displayed symptoms of impingement showed a decrease in scapulothoracic lateral rotation.

The kinematic profiles of subjects with reverse shoulder prostheses have also been investigated [126, 127]. One study [127] reported that subjects with reverse prostheses had a 24% increase in scapular lateral rotation compared to healthy subjects. A separate study [126] assessed 12 patients performing a series of ADL against a control group of 10 healthy subjects. It was found that the patient group was able to complete most of the tasks (none were able to wash their lower

back), but did so with a much more variable ROM than the control group. The

time taken to complete each task by the patient group was also longer and more

variable than the control group.

Chapter 5

Conclusions and Limitations

In this chapter a summary of the findings of each study and how these findings

relate to the stated objectives and hypotheses is provided.

5.1 Conclusions

5.1.1 Chapter 2, Study 1

Comparing skin-markers and a scapula locator for tracking the move-ment of the scapula on healthy subjects.

In this study the right shoulders of 10 healthy subjects were assessed during static

arm elevations in the coronal and sagittal planes. Scapula rotations were measured

using skin-mounted scapula markers and with a scapula locator. The first objective

of the study was to determine the optimal camera positions to view all of the retro-reflective markers during full ROM. This was successfully achieved and is summarised in Fig. 2.2.

The hypothesis being assessed in this study was that *Skin-mounted scapula markers do not have the same accuracy as a scapula locator when measuring the kinematics of the shoulder complex*, while the main objective was to *Introduce a scapula locator into the protocol.*

The study concluded that skin-markers were only suitable for measuring GH elevation for movements close to flexion, and for arm elevations up to $80°$. This meant that the scapula locator was the most viable method of accurately measuring scapula rotations. However the scapula locator is limited in that it can only be used for static measurements. It was therefore decided to further research means of accurate dynamic scapula tracking.

5.1.2   Chapter 2, Study 2

The objective of this study was to *to determine a viable means of dynamic scapula tracking.* The hypothesis behind this objective was that *An acromion marker cluster can be used to dynamically track the movement of the scapula during ROM and functional tasks.*

The study confirmed that within known limitations, the acromion cluster is a very useful tool for tracking dynamic scapula movement. The accuracy of the cluster is primarily of concern when measuring the posterior tilt of the ST articulation.

This rotation is not often reported in the literature, but the overestimation by the cluster of this rotation causes a subsequent underestimation of GH elevation during forward flexion. It is recomnfended to modify the cluster to reduce the moment arm which causes this overestimation.

5.1.3 Chapter 3, Study 1 and Study 2

The objective of these two studies was to *determine the extent of the shoulder complex's full physiological ROM that is required to perform a series of everyday functional tasks.* The hypothesis behind this was that *common upper limb activities of daily living can be performed without the capacity for full physiological range of motion of the the individual articulations of the shoulder complex.*

The first study was a pilot study of five subjects which used the simplified skin-marker method to track scapula rotations. As such only the elevations of the GH joint could be measured accurately. The study concluded that there is a significantly different excess capacity of GH elevation which is not necessary for many everyday tasks.

The second study was a continuation of this first study, but with numerous improvements to the model, most notably the use of an acromion marker cluster to track the movement of the scapula, allowing the rotations of the ST articulation to also be assessed. The results of this study were in agreement with those of the first study, that there is a significantly different excess capacity of elevation of the GH joint which is unnecessary for many everyday tasks, but not in axial rotation

or plane of elevation movement. The study also found that there was no excess capacity in the physiological lateral rotation of the ST articulation. However it must be borne in mind that the acrómion cluster can only accurately measure rotations up to 100° of arm elevation, and that the majority of ST lateral rotation occurs after 120° of arm elevation. It is therefore very likely that the majority of ST lateral rotation required during full arm elevation has not been reported in this study.

5.1.4 Chapter 4

In this chapter patient cohorts were introduced to the study. It is important to note that this is the first study of pathological shoulder cohorts to be carried out at Cardiff University, and that ethical approval first had to be sought by the author. This process took several months to complete. Cohorts assessed were: subjects with clavicle fracture; subjects with a previous GH dislocation; and subjects with MDI.

The objective of the study was to *use a scapula locator to compare patient and healthy kinematics during static elevations.* The hypothesis underlying this objective was that *a scapula locator can be used to differentiate between subject and patient groups and determine when compensatory mechanicisms are being used to elevate the arm.* It was found that the motion analysis protocol could distinguish between healthy subjects and pathological subjects, and also possibly between

the different patient cohorts. However a limitation of this inference are the sample sizes used, as there were 16 healthy shoulders, but only seven GH dislocator shoulder, seven MDI shoulders, and five clavicle fracture shoulders.

In conclusion, this thesis has served to develop the methods necessary to assess the kinematics of healthy and pathological shoulders and has opened the way for several avenues of further investigation, which are discussed in the next chapter.

Chapter 6

Further Work

This study has highlighted and provoked several areas for improvement and investigation. Further possible work arising from this thesis can be divided into five categories:

1. Repeatability and Reliability

2. Improvements to the Model

3. Applications of the model to wider cohorts

4. Musculoskeletal Modelling

5. Objective Classification to aid diagnosis, prognosis, and post-treatment monitoring

6.1 Repeatability and Reliability

During testing, the positions of each marker were double-checked by Ms. Lindsay Stroud (and in some studies also by Mr. Nicholas Ferran) to ensure consistency. In all cases, Ms. Stroud and Mr. Ferran were unaware of the locations selected by the author. When there was a disagreement, the bony landmark in question would be collectively examined until a concesus was reached. In addition to this measure of due diligence, a repeatability and reliability study was recently carried out. Three testers (the author, Lindsay Stroud, and Nicholas Ferran) placed and replaced a full set of markers three times on one subject. After each marker placement, the subject performed ROM arm movements. At the time of writing the results of this study are unavailable but are expected to be published at a later date.

6.2 Model Improvements

There are several subtle improvements that can be made to the model that may lead to more accurate representations of the shoulder complex's rotations.

The Thorax

The thorax co-ordinate system is generated from two vertebrae (C7 and T8) and the superior and inferior aspects of the sternum, IJ and PX respectively. Currently each landmark is represented by a physical marker. This can cause skin artefacts on C7 and IJ and issues of marker occlusion on IJ and PX during cross chest adduction, and tasks which require a degree of cross chest adduction, i.e.

reaching to the opposite axilla. Also, when measuring a subjects range of internal rotation (or assessing the task "Wash the lower back"), The T8 marker can often be occluded.

One possible solution to the skin artefact and occlusion of T8 problems is to place a TCS on the manubrium of the sternum, and relate the points of the thorax ACS to this TCS. However the TCS may still be occluded during tasks requiring cross chest adduction, therefore a combination of the two systems may be most appropriate.

The Clavicle

The SC and AC joints of the clavicle are currently represented by two physical markers. The SC marker is very prone to skin artefact errors so it is suggested that for future studies its position is related to a thorax TCS if available. The AC joint will still need be identified with a marker but with some post-experimental modifications. A plane can be created through the AC marker perpendicular to the z-axis of the clavicle which corresponds to the unit vector between SC and AC. The location of AC can then be translated along this line by a distance equal to the radius of the marker representing it. This will prevent under estimation of the clavicle length and elevation angle.

As it is only possible to palpate two markers on the clavicle, it is not possible to measure clavicle axial rotation. As a result, the rotations of the clavicle (SC joint and AC joint) are largely ignored in studies of the upper limb, unless they are of specific importance. Optimisation techniques to estimate clavicle axial rotation

by minimising the lateral rotation of the AC joint are commonly used to simplify matters [35]. It may be worthwhile adding this to the Cardiff model.

The Scapula

Following the validation studies of the acromion cluster in this thesis, it is suggested to redesign the acromion cluster without the design constraint of being used at the same time as the scapula locator. This would allow the struts holding the markers to be much smaller, or possibly removed altogether, enabling more accurate representation of the scapula rotations, particularly ST posterior tilt and lateral rotation, and as a result, GH elevation during forward flexion.

The Humerus

Accurate estimation of GHJ is necessary to construct the humerus ACS. Currently the IHA method [91] as recommended in the I.S.B. recommendations [30] is used. However the Symmetrical Centre of Rotation Estimation (SCoRE) [92], a two sided transformation algorithm, has been shown to be more reliable than the IHA method [93] and has the further advantage of not being susceptible to low angular velocities. See section 1.6.5.4.

The position of GHJ is currently related to a TCS on the lateral humerus. An MRI validation study concluded that the optimum solution is to use the average values of GHJ based on two TCS's. The first placed on the acromion plateau, and the second placed on the proximal humerus [131].

Measurement of humeral axial rotation is extremely prone to soft tissue artefacts, which can result in an underestimation of up to 35% [103]. An in vivo technique has been assessed which uses the orientation of the forearm to adjust for the measured rotation values, such that US and RS (the ulnar and radial styloids) are used to determine the rotation of the humerus [72].

6.3 Applications of the Model

During the course of this study, ethical approval was successfully obtained to assess subjects with any shoulder pathology in the motion analysis lab. The two main constraints on the study were time - the approval process was long and slow, with the first patient eventually being tested in October 2008; and the availability and willingness of patients to be tested in the limited time frame. Now that approval has been granted, it would be interesting to assess patients from wider cohorts, such as:

- A study is already underway assessing subjects with irreparable RC tears (tears which are too large to be treated operatively) to objectively determine the efficacy of physiotherapy techniques.

- Hemiplegic stroke sufferers

- Kinematics of the upper limb during wheelchair use

- Upper limb kinematics of subjects with cerebral palsy, possibly to assess efficacy of physiotherapy treatments which use botulinum toxin (botox)

- Paediatric studies, either of healthy children, or of children suffering from cerebral palsy or other neuromuscular disorders

During personal communications with numerous orthopaedic surgeons based in the Cardiff area, a recurring element was the difficulty in accurate diagnosis and prognosis of shoulder pathologies using standard clinical methods. The techniques developed throughout this study, the ethical approval acquired, and the studies on the three patient cohorts have formed a strong foundation for further studies to address these issues. By gathering further patient data it will be possible to do a full statistical analysis comparing different patient cohorts (and non-pathological cohorts). This may elucidate previously unknown properties of the kinematic waveforms of the shoulder complex of the different cohorts. There are two potential ways in which this data could be used. Firstly, the motion analysis protocol could be stripped down to specifically examine these properties (perhaps by performing a single or small number of tasks) to differentiate between cohorts quickly and effectively. Secondly, depending on the nature of the findings, it may be possible to develop a number of clinical tests which can aid diagnosis and prognosis, but do not require a motion capture system.

It may also be interesting to assess the techniques of overhead throwing athletes, however the dimensions of the lab would not be suitable, so testing would need to be off-site. It may be possible to assess the shoulder rotations of other high performance athletes on site, for example rowers.

Finally there is scope for research projects which assess everyday workplace/leisure ergonomics, for example repetitive strain injuries caused by the use of computers, doing manual labour, or playing an instrument.

6.4 Musculoskeletal Modelling

The data collected can be used as input data for musculoskeletal models, for example the Newcastle Shoulder Musculoskeletal Model [75], an inverse dynamic model which is used to predict muscle and joint contact forces and moment arms for healthy and pathological subjects based on the input joint and segment rotations.

When using kinematic data in a musculoskeletal model, it is important to scale the data to the individual to be assessed [132], i.e. to compensate for natural variations within the sample group such as arm length, height, weight etc. There are a number of different scaling methods which can be used to scale a musculoskeletal model to an individual anatomy, such as: uniform scaling where an entire model is scaled using a single factor such as BMI or arm length [133]; and intra-segmental scaling where each segment (i.e. thorax, clavicle, scapula, and humerus) are scaled uniformly based on their respective lengths [133].

6.5 Objective Classification

An objective classification tool to assess osteoarthritic (OA) knee function of patients pre and post TKR surgery has been developed in Cardiff University

[25, 26, 27, 28]. The classifier is trained to recognise healthy subjects from subjects with advanced knee OA by examining key variables. The variables can either be manually selected, or principal component analysis can be used to highlight the variables which contribute the most to the variability between the two cohorts. The tool then makes use of the Dempster Shafer theory of evidence [134, 135] to develop a visual output which shows the progress of post-operative TKR patients, i.e. over a period of time. Patients are plotted as a point on the simplex plot (Fig. 6.1). Their post-treatment progress from an OA state towards a healthy state can be tracked over a period of time with repeated testing. The classifier has also been applied to subjects with THA [22] to emphasise the wider potential of the tool.
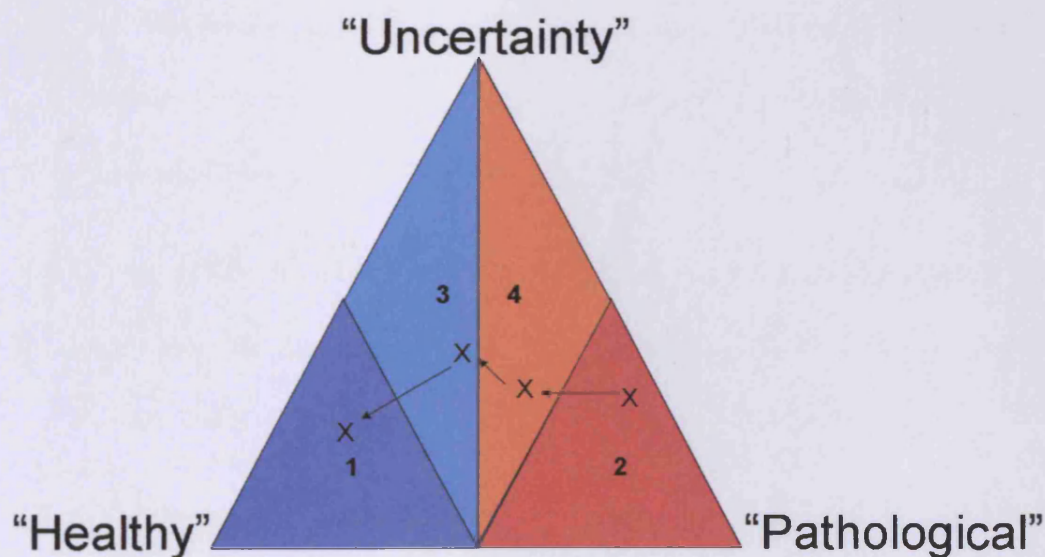
FIGURE 6.1: Classification of shoulder pathologies using the Dempster-Shafer theory of evidence. A combination of a patients functional variables produces a point on the simplex plot. Sections 1 and 2 are dominant classifications, "healthy" and "pathological" respectively, sections 3 and 4 are non-dominant classifications of "healthy" and "pathological" subjects. The closer a point is to the base-line, the more certain the diagnosis

It would be very interesting to apply the classifier to shoulder pathologies. However, it would require at least 25 patients from a single cohort to be worthwhile.

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Appendix A: AC Error Bars

Untruncated (Chapter 2)
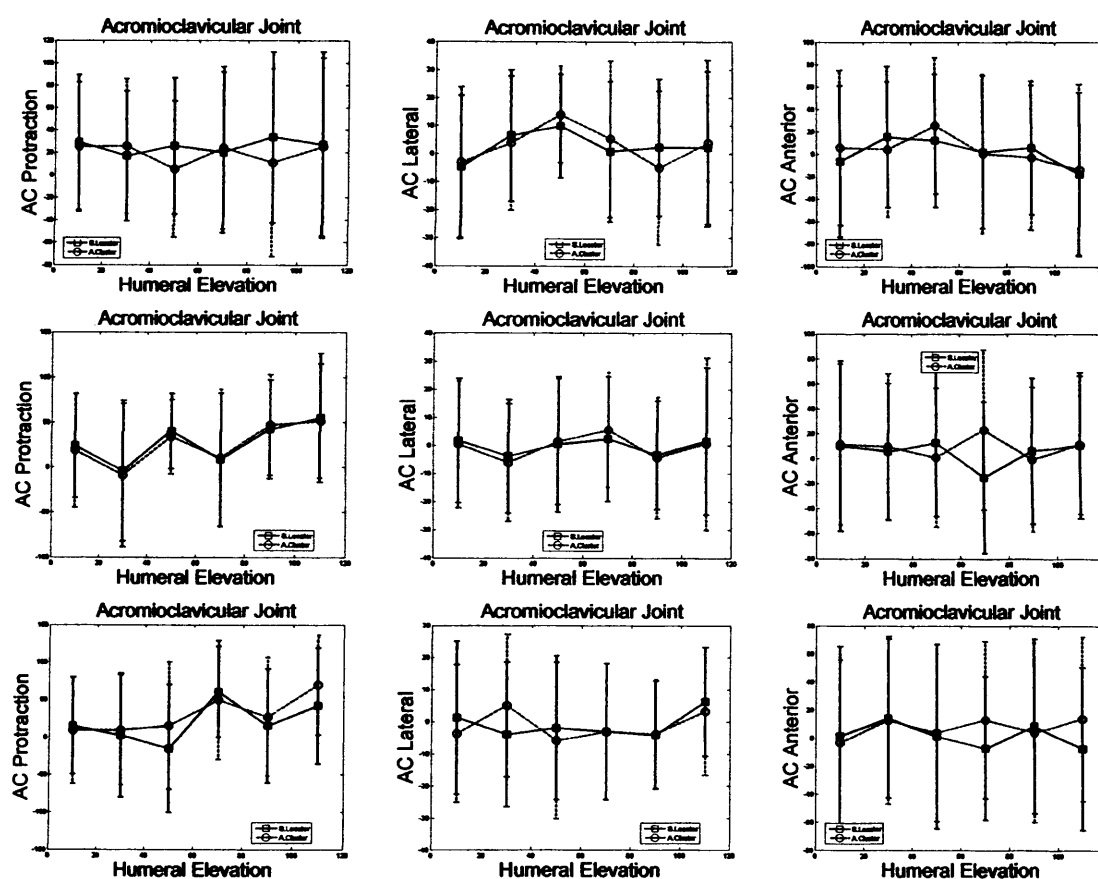
FIGURE 2: **The rotations measured for the acromioclavicular joint** were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. Square markers with solid lines and solid error bars represent the rotations (± the standard deviation) measured with the scapula locator. Circular markers with dashed lines and dashed error bars represent the rotations (± the standard deviation) measured with the acromion cluster. The error bars are untruncated to allow greater resolution of the rotations. All rotations measured in degrees (°).

Appendix B: Chapter 3: Study 1:

Full Results

TABLE 1: Mean rotations ± standard deviation of the sternoclavicular (SC), acromioclavicular (AC), and scapulothoracic (ST) articulations (°) required to perform a series of range of motion tasks and activities of daily living with the right arm (n=5).

Task	SC Ret/Pro	SC Elevation	AC Ret/Pro	AC Elevation	AC Axial	ST Ret/Pro	ST Lateral	ST Ant/Post
Abduction	41.16±4.96	22.01±3.94	12.44±3.55	39.96±2.80	40.76±11.83	13.01±2.57	42.50±4.92	10.85±3.06
Scapular Abduction	43.54±3.85	19.25±2.55	16.93±3.47	36.84±4.65	36.80±11.49	15.08±6.53	38.68±4.53	14.25±3.54
Flexion	50.92±5.49	22.67±4.05	16.43±3.28	36.87±5.25	37.37±6.78	29.05±8.13	38.78±6.43	15.69±3.14
External Rotation	12.16±4.95	2.78±2.62	4.35±1.96	4.72±2.81	3.76±2.85	14.84±4.34	5.81±3.37	2.33±0.82
Internal Rotation	22.40±5.17	10.20±3.58	5.48±1.49	10.02±3.30	10.83±1.70	17.88±6.56	12.74±3.27	4.64±2.25
Reach Opposite Axilla	15.09±3.89	19.89±5.51	8.25±2.09	9.52±7.21	22.72±4.46	21.97±5.51	14.41±8.47	5.79±1.34
Reach Opposite side of neck	11.14±7.73	18.88±5.70	10.12±6.09	11.63±4.80	22.64±6.71	16.80±5.01	17.86±4.03	6.58±3.86
Touch side and back of head	27.84±3.72	14.77±2.62	9.09±2.31	24.09±2.19	29.23±6.03	13.46±5.59	29.18±2.90	12.73±2.65
Eat with hand to mouth	8.17±4.38	5.87±2.49	6.13±2.72	6.28±1.29	7.04±1.91	9.06±3.78	8.51±.55	2.33±1.02
Eat with spoon	11.67±4.34	12.37±5.06	4.50±1.14	14.14±3.26	16.42±5.78	6.04±3.20	19.99±4.66	4.83±2.91
Drink from mug	13.90±6.86	13.31±4.08	5.44±2.10	15.62±3.91	18.23±6.11	9.99±5.00	21.34±3.46	6.11±2.01
Answer Phone	12.86±6.29	7.15±2.60	4.43±1.66	8.83±3.14	9.66±3.61	9.54±6.18	12.06±3.69	3.62±1.44
Brush opposite side of head	13.33±7.03	18.91±7.57	11.40±5.20	10.88±2.57	22.78±8.26	21.21±6.03	16.97±3.94	6.59±3.28
Lift weight to shoulder height	16.89±8.16	27.32±10.23	8.99±1.81	17.51±4.07	29.74±11.01	24.17±6.10	24.20±5.48	6.00±1.48
Lift weight to head height	17.65±3.85	31.07±9.12	9.68±2.27	21.93±3.55	34.78±9.77	26.67±7.13	28.79±4.66	7.25±0.98

TABLE 2: Mean rotations ± standard deviation of the sternoclavicular (SC), acromioclavicular (AC), and scapulothoracic (ST) articulations (°) required to perform a series of range of motion tasks and activities of daily living with the left arm (n=5).

Task	SC Ret/Pro	SC Elevation	AC Ret/Pro	AC Elevation	AC Axial	ST Ret/Pro	ST Lateral	ST Ant/-Post
Abduction	38.49±4.47	20.63±6.30	16.04±5.78	34.78±8.16	34.28±8.48	12.67±7.28	37.25±7.82	10.00±3.83
Scapular Abduction	36.62±5.56	20.38±6.84	17.06±5.20	32.74±8.67	31.98±9.92	14.07±4.37	35.09±6.81	10.17±4.22
Flexion	42.02±5.79	22.31±4.08	15.96±4.80	32.63±4.91	31.92±6.41	21.43±7.07	36.05±4.26	11.69±4.03
External Rotation	13.06±4.65	6.31±1.13	3.22±2.77	4.27±1.14	6.17±1.84	14.51±7.79	7.60±1.78	2.89±0.97
Internal Rotation	18.69±2.06	10.17±3.70	6.26±2.74	8.92±2.08	9.14±3.81	15.38±3.68	11.62±3.83	5.30±0.55
Reach Opposite Axilla	16.53±5.93	12.29±4.90	6.10±2.82	7.70±4.19	15.15±6.10	20.44±3.56	11.70±4.93	5.05±1.67
Reach Opposite side of neck	13.17±2.87	18.89±7.17	6.99±1.78	10.36±4.23	21.11±8.40	18.70±6.33	18.36±5.38	4.81±2.19
Touch side and back of head	28.73±4.29	14.32±6.62	12.67±3.63	21.77±7.24	24.82±7.50	13.34±5.33	25.45±8.83	10.42±1.88
Eat with hand to mouth	8.56±4.55	7.84±2.95	7.62±3.15	7.72±5.59	9.85±5.18	8.51±4.68	9.91±6.50	3.80±1.55
Eat with spoon	17.60±7.57	13.78±4.69	7.52±3.65	14.99±5.41	17.96±6.05	8.69±5.76	20.65±6.76	5.84±2.24
Drink from mug	15.57±9.32	15.68±4.36	8.43±4.63	14.05±4.18	20.14±5.63	8.12±4.41	20.23±5.71	6.01±2.63
Answer Phone	13.91±6.60	8.93±2.45	6.76±2.24	8.85±2.90	10.57±3.45	10.91±7.31	11.97±4.40	3.84±1.43
Brush Opposite side of head	9.73±4.30	18.31±10.13	11.68±4.40	14.65±8.66	22.70±11.73	18.26±5.95	19.29±9.71	5.46±1.83
Lift weight to shoulder height	11.71±3.64	21.66±8.93	10.72±4.70	14.73±5.11	23.55±7.83	21.06±9.23	21.81±6.20	5.58±2.03
Lift weight to head height	18.19±2.73	28.69±8.43	12.16±4.79	22.09±6.04	31.27±7.88	21.67±9.18	30.20±4.84	6.85±1.56

TABLE 3: Mean rotations ± standard deviation of the Glenohumeral joint (GH), Humerothoracic articulation (HT), and Forearm relative to humerus (FH) (elbow joint)(°) required to perform a series of range of motion tasks and activities of daily living with the right arm (n=5).

Task	GH Elevation Plane	GH Elevation	GH Axial	HT Elevation Plane	HT Elevation	HT Axial	FH Flexion	FH Axial
Abduction	215.84±137.94	95.80±5.10	218.61±136.29	187.96±154.19	137.91±13.24	199.65±139.38	-	-
Scapular Abduction	192.23±149.25	98.68±6.53	199.01±147.02	183.84±159.76	136.07±9.46	198.88±146.96	-	
Flexion	200.45±142.97	97.56±5.61	206.37±136.01	118.08±29.62	128.84±9.28	132.54±24.53	-	-
External Rotation	61.92±18.86	9.71±1.64	50.19±11.86	42.73±5.49	6.13±0.46	27.73±23.10	14.12±9.38	93.48±12.4
Internal Rotation	54.60±28.99	47.22±12.48	70.47±35.68	35.03±11.58	48.49±12.34	62.73±14.13	59.02±20.34	-
Reach Opposite Axilla	170.77±24.81	27.60±12.83	127.53±25.56	140.53±20.26	18.57±13.18	68.07±19.06	24.13±22.24	133.16±17.9
Reach Opposite side of neck	182.20±92.60	47.73±6.69	162.29±111.41	144.70±28.91	41.52±8.94	84.12±27.68	33.37±5.02	147.50±13.8
Touch side and back of head	172.62±158.54	68.67±3.56	176.95±148.24	94.43±35.83	89.50±2.72	104.68±32.61	59.19±10.29	56.45±14.20
Eat with hand to mouth	124.74±40.53	32.67±9.13	115.47±39.52	107.66±19.04	23.60±5.82	90.40±19.57	90.00±11.24	108.87±14.68
Eat with spoon	109.09±70.11	35.81±6.10	115.84±65.53	84.58±32.57	47.17±4.94	85.68±25.23	86.20±18.98	104.26±41.63
Drink from mug	117.03±45.09	31.65±5.36	123.87±41.29	98.11±26.02	43.37±6.68	94.17±21.63	78.67±13.05	102.38±9.67
Answer Phone	122.75±53.50	35.13±10.26	120.35±54.83	97.00±21.83	32.00±10.73	91.75±24.47	89.65±16.14	117.77±11.55
Brush Opposite side of head	143.19±35.43	52.51±5.47	124.67±43.19	146.74±18.80	48.94±8.54	97.65±22.24	54.61±7.74	125.27±16.50

TABLE 4: Mean rotations ± standard deviation of the Glenohumeral joint (GH), Humerothoracic articulation (HT), and Forearm relative to humerus (FH) (elbow joint)(°) required to perform a series of range of motion tasks and activities of daily living with the left arm (n=5).

Task	GH Elevation Plane	GH Elevation	GH Axial	HT Elevation Plane	HT Elevation	HT Axial	FH Flexion	FH Axial
Abduction	223.93±159.68	98.70±4.82	242.12±160.63	103.04±35.08	135.02±7.88	127.60±25.53		-
Scapular Abduction	241.17±145.46	98.98±3.74	247.84±151.12	123.99±40.25	132.61±9.33	130.47±42.79	-	-
Flexion	208.26±139.69	99.54±5.49	204.05±139.38	134.30±18.80	128.05±6.50	130.48±19.38	-	-
External Rotation	176.93±167.59	12.37±7.15	168.50±172.52	43.50±16.04	10.43±3.44	44.59±21.68	31.15±16.02	112.16±25.13
Internal Rotation	119.67±136.43	46.02±14.14	130.01±118.50	47.93±38.82	53.19±13.23	79.02±30.69	100.80±53.45	-
Reach Opposite Axilla	215.38±132.46	35.92±5.57	191.16±153.32	158.08±18.96	28.77±4.92	95.74±17.39	26.62±8.74	135.05±9.31
Reach Opposite side of neck	211.73±119.92	53.88±6.04	187.90±141.98	167.28±31.66	45.95±5.16	106.32±27.24	35.11±8.78	150.23±12.45
Touch side and back of head	157.08±131.35	82.30±8.76	166.19±128.12	120.09±33.03	99.44±6.88	126.57±29.88	63.04±12.11	89.03±35.47
Eat with hand to mouth	168.67±118.13	37.07±9.80	165.48±118.69	127.07±24.78	33.46±11.16	114.82±22.03	92.08±15.53	118.73±17.67
Eat with spoon	198.16±154.73	45.99±6.99	201.08±152.34	117.87±33.86	59.13±10.65	120.07±25.25	86.82±22.28	145.31±117.56
Drink from mug	161.31±122.31	33.62±12.33	166.40±120.37	112.13±30.91	43.90±11.92	116.15±29.86	76.61±12.96	106.25±16.46
Answer Phone	209.51±131.94	36.71±4.59	207.73±132.10	124.26±26.39	35.40±6.01	119.19±24.52	99.10±28.28	113.19±3.85
Brush Opposite side of head	206.38±99.46	60.96±5.19	186.88±112.93	165.38±18.63	59.59±7.02	118.39±27.52	54.81±18.99	125.44±21.80

Appendix C: SC and AC Error

Bars Untruncated (Chapter 4)

Coronal Plane

Scapular Plane

Sagittal Plane

FIGURE 3: **The rotations measured for the sternooclavicular joint** were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. **Square markers with solid lines and solid error bars represent the rotations of the healthy cohort** (± the standard deviation). **Circular markers with dashed lines and dashed error bars represent the rotations of the clavicle fracture cohort** (± the standard deviation). All rotations measured with a scapula locator. The error bars are untruncated. All rotations measured in degrees (°).

Coronal Plane

Scapular Plane

Sagittal Plane

FIGURE 4: **The rotations measured for the acromioclavicular joint** were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. **Square markers with solid lines and solid error bars represent the rotations of the healthy cohort (± the standard deviation). Circular markers with dashed lines and dashed error bars represent the rotations of the clavicle fracture cohort (± the standard deviation).** All rotations measured with a scapula locator. The error bars are untruncated. All rotations measured in degrees (°).

Coronal Plane

Scapular Plane

Sagittal Plane

FIGURE 5: **The rotations measured for the sternooclavicular joint** were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. **Square markers with solid lines and solid error bars represent the rotations of the healthy cohort (± the standard deviation). Circular markers with dashed lines and dashed error bars represent the rotations of the glenohumeral dislocation cohort (± the standard deviation).** All rotations measured with a scapula locator. The error bars are untruncated. All rotations measured in degrees (°).
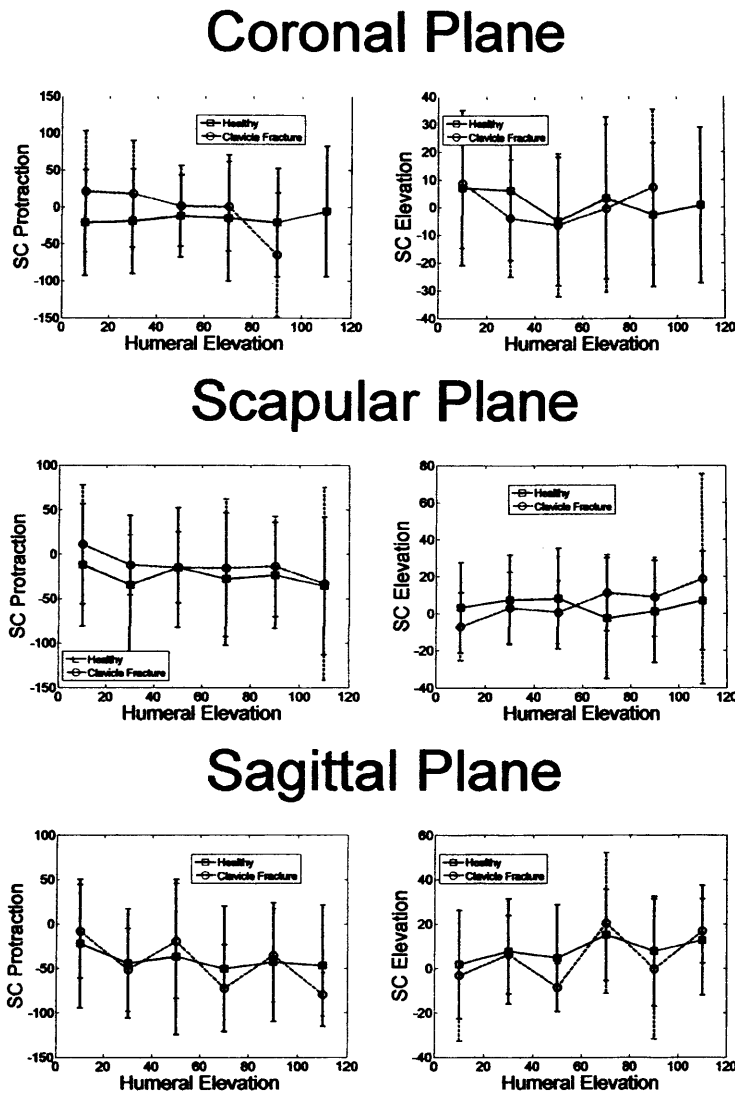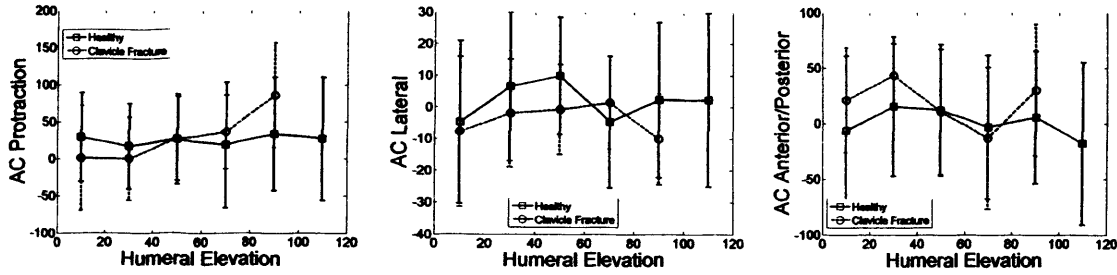
Coronal Plane

Scapular Plane

Sagittal Plane

FIGURE 6: **The rotations measured for the acromioclavicular joint** were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. **Square markers with solid lines and solid error bars represent the rotations of the healthy cohort (± the standard deviation). Circular markers with dashed lines and dashed error bars represent the rotations of the glenohumeral dislocation cohort (± the standard deviation). All rotations measured with a scapula locator. The error bars are untruncated. All rotations measured in degrees (°).
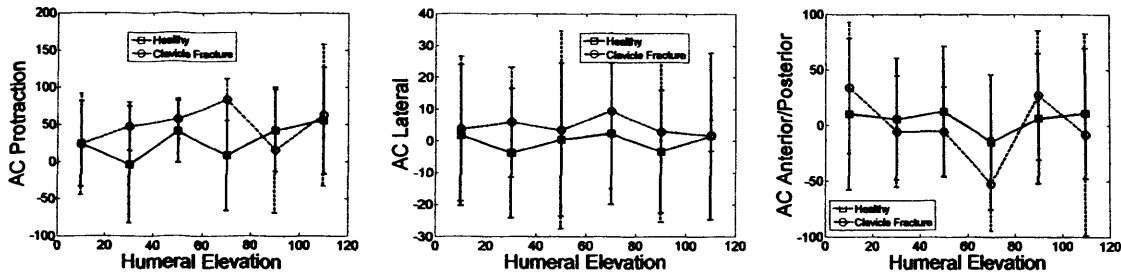
Coronal Plane

Scapular Plane

Sagittal Plane

FIGURE 7: **The rotations measured for the sternooclavicular joint** were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. **Square markers with solid lines and solid error bars represent the rotations of the healthy cohort (± the standard deviation). Circular markers with dashed lines and dashed error bars represent the rotations of the Multi Directional Instability cohort (± the standard deviation).** All rotations measured with a scapula locator. The error bars are untruncated. All rotations measured in degrees (°).

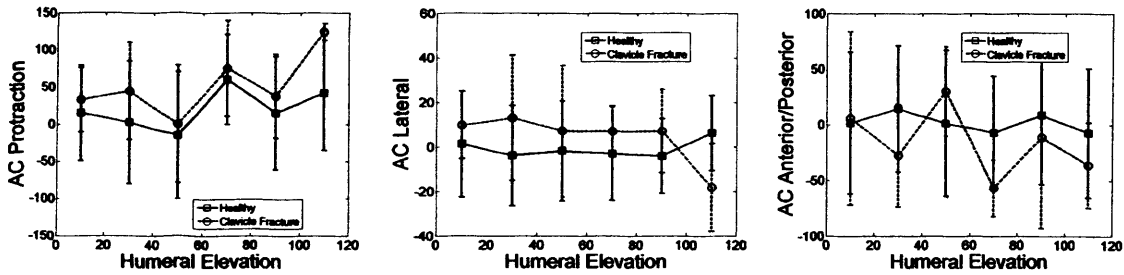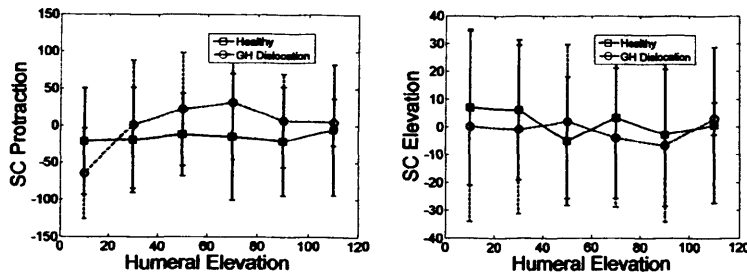# Coronal Plane

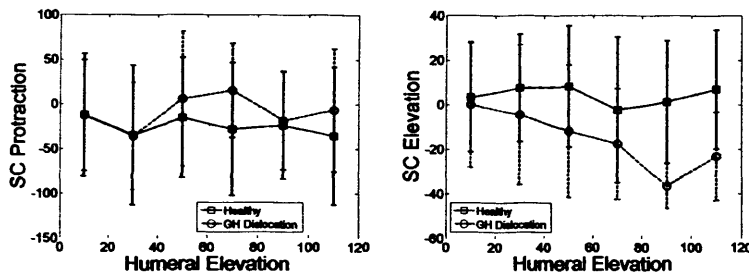# Scapular Plane

Sagittal Plane

FIGURE 8: **The rotations measured for the acromioclavicular joint** were divided into 20° increments of humerothoracic elevation (0° - 20°; 20° - 40°; 40° - 60°; 60° - 80°; 80° - 100°; and 100° - 120°. The first row of graphs are the rotations measured for coronal plane elevation, the second for scapular plane elevation, and the third sagittal plane elevation. **Square markers with solid lines and solid error bars represent the rotations of the healthy cohort (± the standard deviation). Circular markers with dashed lines and dashed error bars represent the rotations of the Multi Directional Instability cohort** (± the standard deviation). All rotations measured with a scapula locator. The error bars are untruncated. All rotations measured in degrees (°).
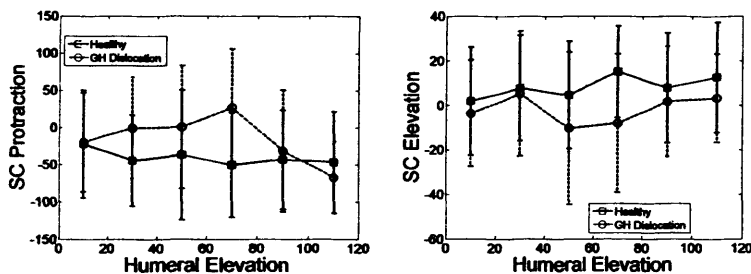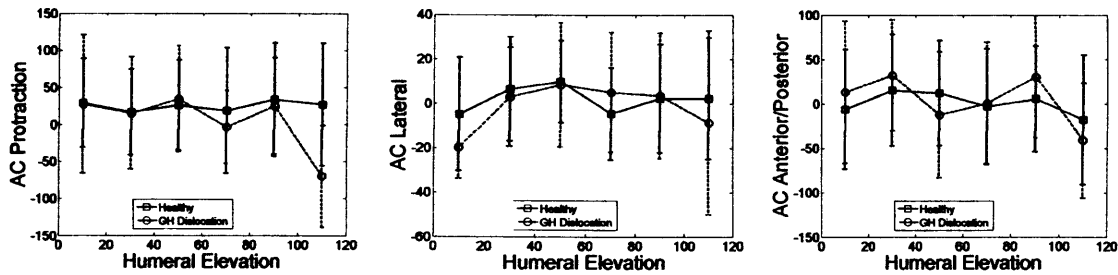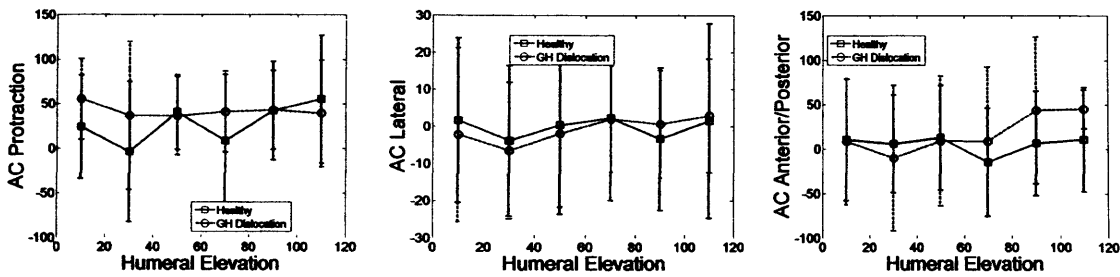
Appendix D: Ethical Approval

Application

South East Wales Research Ethics Committee Panel B

EMAILED: Holt@cardiff.ac.uk

07 September 2010

Dr. Catherine Holt
Cardiff School of Engineering
Queen's Buildings, The Parade
Cardiff
CF24 3AA

Dear Dr. Holt

Study title:	**Assessment of shoulder function in healthy and pathological subjects using three dimensional motion analysis techniques.**
REC reference:	**08/WSE02/37**
Protocol number:	**SPON525-08**

Thank you for sending the progress report for the above study dated 24 August 2010. The report will be reviewed by the Chair of the Research Ethics Committee, and I will let you know if any further information is requested.

The favourable ethical opinion for the study continues to apply for the duration of the research.

08/WSE02/37:	**Please quote this number on all correspondence**

Yours sincerely

Joanne Love
Committee Co-ordinator

Copy to: R&D office for Cardiff University
                   R&D office for Cardiff and Vale NHS Trust

APPLICANT'S CHECKLIST

All studies except clinical trials of investigational medicinal products

REC Ref:	
Short Title of Study:	Shoulder Trauma Study v1.01
CI Name:	Dr. Catherine Holt
Sponsor:	Cardiff University

Please complete this checklist and send it with your application

- Send ONE copy of each document (except where stated)
- ALL accompanying documents must bear version numbers and dates (except where stated)
- When collating please do NOT staple documents as they will need to be photocopied.

Document	Enclosed?	Date	Version	Office use
Covering letter on headed paper	⦿ Yes ○ No	12/05/2008		
NHS REC Application Form, Parts A&B	Mandatory	12/05/2008		
Site–Specific Information Form (for SSA)	⦿ Yes ○ No	12/05/2008		
Research protocol or project proposal (6 copies)	Mandatory	18/02/2008	1	
Summary C.V. for Chief Investigator (CI)	Mandatory	12/05/2008		
Summary C.V. for supervisor (student research)	○ Yes ⦿ No			
Research participant information sheet (PIS)	⦿ Yes ○ No	18/02/2008	1	
Research participant consent form	⦿ Yes ○ No	18/02/2008	1	
Letters of invitation to participants	⦿ Yes ○ No	18/02/2008	1	
GP/Consultant information sheets or letters	○ Yes ⦿ No			
Statement of indemnity arrangements	⦿ Yes ○ No	18/02/2008		
Letter from sponsor	⦿ Yes ○ No	18/02/2008		
Letter from statistician	○ Yes ⦿ No			
Letter from funder	○ Yes ⦿ No			
Referees' or other scientific critique report	○ Yes ⦿ No			
Summary, synopsis or diagram (flowchart) of protocol in non–technical language	○ Yes ⦿ No			
Interview schedules or topic guides for participants	○ Yes ⦿ No			
Validated questionnaire	⦿ Yes ○ No			
Non–validated questionnaire	○ Yes ⦿ No			
Copies of advertisement material for research participants, e.g. posters, newspaper adverts, website. For video or audio cassettes, please also provide the printed script.	○ Yes ⦿ No			

WELCOME TO THE NHS RESEARCH ETHICS COMMITTEE APPLICATION FORM

An application form specific to your project will be created from the answers you give to the following questions.

---

1. Is your project an audit or service evaluation?

O Yes   ⊙ No

---

2. Select one research category from the list below:

O Clinical trials of investigational medicinal products
O Clinical investigations or other studies of medical devices
⊙ Other clinical trial or clinical investigation
O Research administering questionnaires/interviews for quantitative analysis, or using mixed quantitative/qualitative methodology
O Research involving qualitative methods only
O Research limited to working with human tissue samples and/or data
O Research tissue bank

If your work does not fit any of these categories, select the option below:

O Other research

2a . Please answer the following questions:

a) Does the study involve the use of any ionising radiation?	O Yes	⊙ No
b) Will you be taking new human tissue samples?	O Yes	⊙ No
c) Will you be using existing human tissue samples?	O Yes	⊙ No

---

3. Is your research confined to one site?

O Yes   ⊙ No

---

4. Does your research involve work with prisoners?

O Yes   ⊙ No

---

5. Do you plan to include in this research adults unable to consent for themselves through physical or mental incapacity?

O Yes   ⊙ No

---

6. Is the study, or any part of the study, being undertaken as an educational project?

⊙ Yes   O No

6a. Is the project being undertaken in part fulfilment of a PhD or other doctorate?

⦿ Yes   ◯ No

NHS Research Ethics Committee NHS
Application form

This form should be completed by the Chief Investigator, after reading the guidance notes. See glossary for clarification of different terms in the application form.

Short title and version number: (maximum 70 characters – this will be inserted as header on all forms)
Shoulder Trauma Study v1.01

Name of NHS Research Ethics Committee to which application for ethical review is being made:
South East Wales

Project reference number from above REC:
Submission date:

PART A: Introduction

A1. Title of the research

Full title: Assessment of shoulder function in healthy and pathological subjects using three dimensional motion analysis techniques.

Key words: Shoulder, motion analysis, three dimensional

A2. Chief Investigator

Title:	Dr.
Forename/Initials:	Catherine
Surname:	Holt
Post:	Royal Academy of Engineering/Leverhulme Trust Senior Research Fellow, Senior Lecturer in Biomechanics
Qualifications:	BEng PhD CEng FIMechE
Organisation:	Cardiff University
Work Address:	Cardiff School of Engineering
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A copy of a current CV (maximum 2 pages of A4) for the Chief Investigator must be submitted with the application

A3. Proposed study dates and duration

Start date: 01/07/2008
End date: 30/06/2013
Duration: Years: 5 ; Months: 0

A4. Primary purpose of the research: *(Tick as appropriate)*

☐ Commercial product development and/or licensing
☑ Publicly funded trial or scientific investigation
☑ Educational qualification
☑ Establishing a database/data storage facility
☐ Other

Question(s) 5 disabled.

A6. Does this research require site–specific assessment (SSA)? (Advice can be found in the guidance notes on this topic.)

⦿ Yes ◯ No

If No, please justify:

If Yes, an application for SSA should be made for each research site on the Site–Specific Information Form and submitted to the relevant local Research Ethics Committee. Do not apply for SSA at sites other than the lead site until the main application has been booked for review and validated by the main Research Ethics Committee.

Management approval to proceed with the research will be required from the R&D office for each NHS care organisation in which research procedures are undertaken. This applies whether or not the research is exempt from SSA. R&D applications in England, Wales and Scotland should be made using the Site–Specific Information Form.

PART A: Section 1

A7. What is the principal research question/objective? *(Must be in language comprehensible to a lay person.)*

Use of three dimensional motion analysis techniques to establish differences between the motion profiles of healthy shoulders and injured/pathological/unstable shoulders.

This will aid in the development of a non–invasive diagnostic tool for clinical use which can also be used to assess functional outcomes of treatment.

A8. What are the secondary research questions/objectives? *(If applicable, must be in language comprehensible to a lay person.)*

To use the data gathered to aid prognosis of various shoulder pathologies and determine which treatment methods are more successful under particular circumstances.

A9. What is the scientific justification for the research? What is the background? Why is this an area of importance?*(Must be in language comprehensible to a lay person.)*

The shoulder complex is the most versatile joint complex in the human body. Due to the increased mobility and decreased stability of the shoulder complex, it is prone to a wide range of pathologies.

Orthopaedic surgeons use a range of observations and physical examinations to decide on the type and extent of a patient's shoulder injury. Due to the wide range of possible injuries, this can be far from straightforward and is largely based on the surgeons experience with similar cases, their training and area of expertise.

It is felt that surgeons could benefit from further understanding of the movement of the shoulder complex to aid in understanding the causes and associated problems of particular shoulder disorders for clinical evaluation and rehabilitation purposes.

Examples of applications of this research are:
(a)determining whether there is a functional difference in shoulder motion between patients treated conservatively or surgically for shortened mid–shaft clavicle fractures.
(b)determining whether first time shoulder dislocators have abnormal shoulder motion which could predict their risk of becoming recurrent dislocators.

A10-1. Give a full summary of the purpose, design and methodology of the planned research, including a brief explanation of the theoretical framework that informs it. It should be clear exactly what will happen to the research participant, how many times and in what order.

This section must be completed in language comprehensible to the lay person. It must also be self–standing as it will be replicated in any applications for site–specific assessment on the Site–Specific Information Form. Do not simply reproduce or refer to the protocol. Further guidance is available in the guidance notes.

Purpose of Planned Research:

The purpose of the planned research is to gather kinematic and kinetic data of the shoulder complex from patients with shoulder pathologies or trauma pre–treatment and post–treatment.
This data will be compared with data collected from healthy volunteers' shoulders with the intent of analyzing the differences so as to establish a non–invasive diagnostic tool.
The prognosis of different treatment methods will also be assessed.

Methodology of Planned Research:

Subjects will be assessed in the Human Motion Analysis Laboratory, Cardiff School of Engineering a maximum of four times at intervals of 6 weeks, 3 months, 6 months and 12 months post injury/treatment, in the Cardiff School of Engineering Human Motion Analysis Laboratory. The sessions will last a maximum of three hours, including taking of consent, explanation of laboratory etc.
With some pathology subgroups, two sessions each of two hours may suffice.

Patient selection:

– Patients presenting to Cardiff & Vale NHS Trust with shoulder pathology such as shortened mid–shaft clavicle fractures and first time shoulder dislocators.
– As per usual patients will be clinically and radiographically assessed, and will be assessed, scored, and treated by shoulder physiotherapists.
– Patients will give consent for contact by Cardiff University PhD students

Consent Process:
Potential patients will be selected by Mr. Nicholas Ferran and Mr. Richard Evans during clinics at Cardiff & Vale NHS Trust. They will give verbal consent to be contacted by Cardiff University PhD students Barry Lovern or Lindsay Stroud, who will provide the patients with further information and an information pack. Willing patients will then be recruited to the trial. Upon arrival at the Motion Analysis Laboratory, patients will have the entire protocol explained to them. It will be made clear that they are free to withdraw from the trial at any time and that their participation in the trial will not affect their relationship with the NHS in any way. Once patients are satisfied and wish to participate in the trial, informed consent will be obtained.

Anonymization:
Once patients are enrolled in the trial, they will be assigned a reference number which will be used as their identifier throughout the trial and for purposes of data analysis. A master copy of patient contact information and relevant reference numbers will be encrypted and stored on password protected Cardiff University computers to allow future contact with patients.
Any written/printed files will be stored in locked filing cabinets.

Data Collection:

Five patients from each subgroup (for e.g. midline clavicle shaft fracture conservative or operative, and first time dislocators) will be recruited for a pilot study.
Patients' range of motion for flexion–extension, abduction–adduction and internal–external rotation of the shoulder complex will be assessed.
Their abilities to perform activities of daily living (such as combing hair, taking hand to mouth and raising hand above head height) will also be assessed.
Joint strength will be assessed with the aid of a dynamometer.

Participants will be asked to remove their upper garments excluding bra in the case of females. The process will be conducted with utmost professionalism to maintain a comfortable environment for both parties. Female patients will be asked to wear a sports bra or other appropriate garment to the laboratory sessions.

During the session, participants will have reflective markers attached to bony landmarks of the arm and torso using double sided tape. This is to allow the calculation of segment and joint rotations using the recommended standards of the International Society of Biomechanics.

The reflective markers will be placed as follows:
• On the thorax: insicura jugularis and xiphoideus process on the sternum and the 7th cervical vertebra and 8th thoracic vertebra on the spine.
• On the clavicle: the sternoclavicular joint and the acromioclavicular joint.
• On the scapula: the acromion angle, the trigonum spinae, the inferior angle and the coroidal process.
• On the humerus: the medial epicondyle and the lateral epicondyle.
• On the forearm: the ulnar styloid and the radial styloid.

A marker cluster will also be placed on the upper arm using self–adhesive Coban tape.

The patients will then be instructed to perform the activities previously described.

The markers will then be removed and an electromagnetic tracking device in tandem with a scapula locator

(a 3 pointed rigid device used to palpate the bony landmarks of the scapula) will be used to determine the orientation of one bone segment relative to another.

During this phase, the participants will be asked to use a supporting brace which minimises rotation of the forearm by holding the elbow flexed at 90°. The brace will be secured to the elbow using Velcro. Receivers will be mounted onto the participants using double sided tape and self adhesive tape at the following sites:
• Thorax receiver fixed to the sternum, between the incisura jugularis and the   xiphoideus process
•   A second thorax receiver fixed to the 7th cervical vertebra
• Humerus receiver fixed to the supporting brace.
• Scapula receiver mounted on a three pin device which aids in the identification of the acromion angle, the trigonum spinae, and the inferior angle.

With the subject in a resting position, a stylus receiver will be used to identify the bony landmarks of the shoulder complex:
• On the thorax: incisura jugularis and xiphoideus process on the sternum and the 7th cervical vertebra and 8th thoracic vertebra on the spine.
• On the clavicle: the sternoclavicular joint and the acromioclavicular joint.
• On the scapula: the acromion angle, the trigonum spinae, the inferior angle and the coroidal process.
• On the humerus: the medial epicondyle and the lateral epicondyle.
• On the forearm: the ulnar styloid and the radial styloid.

The patients will then be instructed to perform full range of motion (within the confines of their injury/pathology and comfort level) for elevation in the negative 30 degree plane (behind the patient), elevation in the 0 degree plane (abduction), elevation in the scapular plane (approximately 30 degree), elevation in the 60 degree plane, elevation in the 90 degree plane (flexion) and when patients are able, elevation in a plane beyond 90 degrees.

Measurements of shoulder position will be taken at increments of 10–30 degrees with patients remaining still during this time. Adequate rest time will be provided when necessary.

Patients will be recorded using audiovisual cameras during the laboratory sessions. This is to allow re–assessment of results as a quality assurance measure.
Audiovisual files will be digitally stored on password protected Cardiff University computer drives. Patient faces will be digitally masked prior to saving files.

Based on the findings from the pilot study, the measurement protocol will be finalised and the statistical model validated.

Data Storage:
Soft copy data will be stored and encrypted on password protected drives in Cardiff University.
Printed data will be stored in locked filing cabinets in Cardiff University.

Data Analysis:
Body segment and joint coordinate systems will be established and joint and segment rotations calculated according to the recommendations of the International Society of Biomechanics.

When appropriate, parametric statistical analysis (t–test, ANOVA) will be performed. In other cases non–parametric analysis will be implemented.

The statistical analysis is necessarily exploratory and this is reflected in the study. We will be initially exploring the efficacy of applying motion analysis techniques to a number of traumas and pathologies to determine which may benefit from further study.   This assessment will be made in terms of defining the usefulness of the functional analysis for a particular shoulder problem and the practical application of the measurement protocols to larger cohorts of patients.   This will then include an assessment by the collaborating engineers, surgeons and physiotherapists as to the practical nature of continuing recruitment of patients for specific shoulder problems in terms of value of the assessment compared to existing assessments and possible correlations with qualitative outcome scores such as the Oxford Shoulder Score and the Oxford Shoulder Instability Score. Cohorts will be split into groups based on type of pathology (or healthy) and rehabilitation regime, i.e. surgically managed vs. conservatively managed. If a correlation of shoulder function is found within the various groups, then we will apply for   an amendment to include more patients of that subgroup in the study in order to develop powerful statistical techniques for objective classification. A Dempster Shafer theory of evidence, linear discriminant analysis and artificial neural

networking will be used to train a classifier to objectively categorise the various patient cohorts.

A10-2. In which parts of the research have patients, members of the public or service users been involved?

☐ As user–researchers
☐ As members of a research project group
☐ As advisor to a project
☐ As members of a departmental or other wider research strategy group
☑ None of the above

Please provide brief details if applicable:

A10-3. Could the research lead to the development of a new product/process or the generation of intellectual property?

○ Yes   ○ No   ◉ Not sure

A11. Will any intervention or procedure, which would normally be considered a part of routine care, be withheld from the research participants?

○ Yes   ◉ No

A12. Give details of any clinical intervention(s) or procedure(s) to be received by research participants over and above those which would normally be considered a part of routine clinical care.*(These include uses of medicinal products or devices, other medical treatments or assessments, mental health interventions, imaging investigations and taking samples of human biological material.)*

Additional Intervention	Average number per participant		Average time taken (mins/hours/days)	Details of additional intervention or procedure, who will undertake it, and what training they have received.
	Routine Care	Research		

A13. Give details of any non–clinical research–related intervention(s) or procedure(s).*(These include interviews, non–clinical observations and use of questionnaires.)*

Additional Intervention	Average number per participant	Average time taken (mins/hours/days)	Details of additional intervention or procedure, who will undertake it, and what training they have received.
Face to Face Interview	4	20 mins	Upon arriving at the Cardiff Motion Analysis Lab for the first time, PhD student Barry Lovern or Lindsay Stroud, will explain how the lab works and what will be happening during that session. Informed consent will then be obtained. (S)he will then ask for details of any previous injuries or problems with the upper limb or spine, aside from the condition which is currently being analysed and take a series of anthropometric measurements of the upper limb and record the patients height and weight. Participants will be asked to fill out the Oxford Shoulder Score.

Face to Face Interview	1	20 mins	Mr. Nicholas Ferran / Mr. Richard Evans will inform patients about the trial and obtain verbal consent for the patient to be contacted by either Mr. Barry Lovern or Ms. Lindsay Stroud.

A14. Will individual or group interviews/questionnaires discuss any topics or issues that might be sensitive, embarrassing or upsetting, or is it possible that criminal or other disclosures requiring action could take place during the study (e.g. during interviews/group discussions, or use of screening tests for drugs)?

○ Yes ⊙ No

The Information Sheet should make it clear under what circumstances action may be taken.

A15. What is the expected total duration of participation in the study for each participant?

One year post recruitment with up to four sessions of at most three hours each in the Motion Laboratory. Twelve hours in total in Laboratory.

A16. What are the potential adverse effects, risks or hazards for research participants either from giving or withholding medications, devices, ionising radiation, or from other interventions (including non–clinical)?

None.

A17. What is the potential for pain, discomfort, distress, inconvenience or changes to lifestyle for research participants?

Patients will need to make several visits to Motion Laboratory with sessions lasting up to three hours. Regular rests and breaks will be provided throughout motion analysis sessions.

Patients will need to remove upper garments to allow the attachment of the markers.
Female patients will be asked to wear a sports bra or other suitable garment.

There may be very minor, very transient discomfort when removing double sided tape from skin.

A18. What is the potential for benefit to research participants?

Research participants may benefit from early diagnosis of abnormal biomechanics which may allow targeting of treatment.

A19. What is the potential for adverse effects, risks or hazards, pain, discomfort, distress, or inconvenience to the researchers themselves? *(if any)*

None

A20. How will potential participants in the study be (i) identified, (ii) approached and (iii) recruited?
Give details for cases and controls separately if appropriate:

(i) Mr. Richard Evans and Mr. Nicholas Ferran will identify and approach potential participants during outpatient clinics.

(ii) Patients will give verbal consent to Mr. Ferran or Mr. Evans to be contacted by Mr. Lovern or Ms. Stroud.

Patient contact details will be passed to Mr. Lovern and Ms. Stroud via email.

(iii) Mr. Lovern or Ms. Stroud will phone the potential patients, explain the procedure, and send them an info pack. Once the patient has had an opportunity to read the info pack, willing patients will then be recruited to the trial.

A21. Where research participants will be recruited via advertisement, give specific details.

☑ Not Applicable

If applicable, enclose a copy of the advertisement/radio script/website/video for television (with a version number and date).

A22. What are the principal inclusion criteria? *(Please justify)*

– Unilateral isolated shoulder girdle bony/soft tissue injury
  – such as shortened mid–shaft clavicle fractures or first time shoulder   dislocation.

The contralateral uninjured shoulder will be assessed to serve as a patient specific indicator of recovery.
In clinic, both surgeons and physiotherapists observe the contralateral shoulder to assess pathology, trauma and rehabilitation as it serves as a patient specific comparator for dysfunction and recovery.

A23. What are the principal exclusion criteria? *(Please justify)*

– Patients with pre–existing shoulder pathology prior to injury
– Patients unable to consent for themselves

A24. Will the participants be from any of the following groups? *(Tick as appropriate)*

☐ Children under 16
☐ Adults with learning disabilities
☐ Adults who are unconscious or very severely ill
☐ Adults who have a terminal illness
☐ Adults in emergency situations
☐ Adults with mental illness (particularly if detained under Mental Health Legislation)
☐ Adults with dementia
☐ Prisoners
☐ Young Offenders
☐ Adults in Scotland who are unable to consent for themselves
☐ Healthy Volunteers
☐ Those who could be considered to have a particularly dependent relationship with the investigator, e.g. those in care homes, medical students
☐ Other vulnerable groups

Justify their inclusion.

☑ No participants from any of the above groups

A25. Will any research participants be recruited who are involved in existing research or have recently been involved in any research prior to recruitment?

⦿ Yes   ○ No   ○ Not Known

If Yes, give details and justify their inclusion. If Not Known, what steps will you take to find out?

Patients may be recruited from the ongoing RCT of clavicle fracture management at Cardiff & Vale NHS Trust (REC Reference number 05/WSE04/161). These patients may be included because their inclusion criteria is similar. Motion analysis would also benefit analysis of the outcome of clinical interventions and may add further weight to argue for or against a given intervention.

A26. Will informed consent be obtained from the research participants?

⦿ Yes   ○ No

If Yes, give details of who will take consent and how it will be done. Give details of any particular steps to provide information (in addition to a written information sheet) e.g. videos, interactive material.

If participants are to be recruited from any of the potentially vulnerable groups listed in A24, give details of extra steps taken to assure their protection. Describe any arrangements to be made for obtaining consent from a legal representative.

If consent is not to be obtained, please explain why not.

R. Evans or N. Ferran will obtain verbal consent for patients to be contacted by PhD students B. Lovern or L. Stroud.

B. Lovern or L. Stroud will take consent prior to the first session in the lab.

Written info sheet and verbal explanation will be only ways of providing information.

Copies of the written information and all other explanatory material should accompany this application.

A27. Will a signed record of consent be obtained?

⦿ Yes   ○ No

If Yes, attach a copy of the information sheet to be used, with a version number and date.

A28. How long will the participant have to decide whether to take part in the research?

Approximately 1 week from receiving the information pack from Cardiff University.

A29. What arrangements have been made for participants who might not adequately understand verbal explanations or written information given in English, or who have special communication needs? *(e.g. translation, use of interpreters etc.)*

None

A30. What arrangements are in place to ensure participants receive any information that becomes available during the course of the research that may be relevant to their continued participation?

Participants will be appraised verbally or via leaflet about any new information relevant to the study.

A30–1. What steps would you take if a participant, who has given informed consent, loses capacity to consent during the study? *Tick one option only.*

⦿ The participant would be withdrawn from the study. Data or tissue which is not identifiable to the research team may be retained. Any identifiable data or tissue would be anonymised or disposed of.

◯ The participant would be withdrawn from the study. Identifiable data or tissue already collected with consent would be retained and used in the study.

◯ The participant would continue to be included in the study.

◯ Not applicable – informed consent will not be sought from any participants in this research.

Further details:

A31. Does this study have or require approval of the Patient Information Advisory Group (PIAG) or other bodies with a similar remit? *(see the guidance notes)*

◯ Yes   ⦿ No

A32a. Will the research participants' General Practitioner (and/or any other health professional responsible for their care) be informed that they are taking part in the study?

◯ Yes   ⦿ No

If Yes, enclose a copy of the information sheet/letter for the GP/health professional with a version number and date.

A32b. Will permission be sought from the research participants to inform their GP or other health professional before this is done?

◯ Yes   ⦿ No

If No to either question, explain why not

> GP's will not be routinely contacted as part of the trial. GP's will be kept up to date on the patients medical management by the medical team at Cardiff & Vale NHS Trust. Participation in the trial does not affect medical management.

It should be made clear in the patient information sheet if the research participant's GP/health professional will be informed.

A33. Will individual research participants receive any payments for taking part in this research?

◯ Yes   ⦿ No

A34. Will individual research participants receive *reimbursement of expenses* or any other *incentives or benefits* for taking part in this research?

⦿ Yes   ◯ No

If Yes, indicate how much and on what basis this has been decided:

> Parking will be provided and local travel expenses may be reimbursed if requested.

A35. Insurance/indemnity to meet potential legal liabilities

Note: References in this question to NHS indemnity schemes include equivalent schemes provided by Health and Personal Social Services (HPSS) in Northern Ireland.

A35-1. What arrangements will be made for insurance and/or indemnity to meet the potential legal liability of the _sponsor(s)_ for harm to participants arising from the _management of the research_?

Note: Where a NHS organisation has agreed to act as the sponsor, indemnity is provided through NHS schemes. Indicate if this applies (there is no need to provide documentary evidence). For all other sponsors, describe the arrangements and provide evidence.

○ NHS indemnity scheme will apply

◉ Other insurance or indemnity arrangements will apply (give details below)

> Cardiff University has agreed to sponsor the project, subject to COREC approval. The reference number is SPON525-08.
> The University's standard insurance covers (Professional Indemnity and Public Liability) apply to this research and cover all University staff and students involved in the project.

Please enclose a copy of relevant documents.

A35-2. What arrangements will be made for insurance and/or indemnity to meet the potential legal liability of the _sponsor(s) or employer(s)_ for harm to participants arising from the _design of the research_?

Note: Where researchers with substantive NHS employment contracts have designed the research, indemnity is provided through NHS schemes. Indicate if this applies (there is no need to provide documentary evidence). For other protocol authors (e.g. company employees, university members), describe the arrangements and provide evidence.

○ NHS indemnity scheme will apply to all protocol authors

◉ Other insurance or indemnity arrangements will apply (give details below)

> Some of the researchers have substantive employment contracts, so indemnity is provided through NHS schemes.
>
> But for the other protocol authors:
> Cardiff University has agreed to sponsor the project, subject to COREC approval. The reference number is SPON525-08
> The University's standard insurance covers (Professional Indemnity and Public Liability) apply to this research and cover all University staff and students involved in the project.

Please enclose a copy of relevant documents.

A35-3. What arrangements will be made for insurance and/or indemnity to meet the potential legal liability of _investigators/collaborators_ and, where applicable, _Site Management Organisations_, arising from harm to participants in the _conduct of the research_?

Note: Where the participants are NHS patients, indemnity is provided through NHS schemes or through professional indemnity. Indicate if this applies to the whole of the study (there is no need to provide documentary evidence). Where non-NHS sites are to be included in the research, including private practices, describe the arrangements which will be made at these sites and provide evidence.

○ All participants will be recruited at NHS sites and NHS indemnity scheme or professional indemnity will apply

◉ Research includes non-NHS sites (give details of insurance/indemnity arrangements for these sites below)

> All patients are NHS patients and are recruited at the NHS site, therefore indemnity is provided through NHS schemes.

Non–NHS sites are to be used:
Cardiff University has agreed to sponsor the project, subject to COREC approval. The reference number is
SPON525–08

Please enclose a copy of relevant documents.

A36. Has the sponsor(s) made arrangements for payment of compensation in the event of harm to the research participants where no legal liability arises?

○ Yes ◉ No

If Yes, give details of the compensation policy:

Please enclose a copy of relevant documents.

A37. How is it intended the results of the study will be reported and disseminated? *(Tick as appropriate)*

☑ Peer reviewed scientific journals
☑ Internal report
☑ Conference presentation
☐ Other publication
☐ Submission to regulatory authorities
☐ Access to raw data and right to publish freely by all investigators in study or by Independent Steering Committee on behalf of all investigators
☐ Written feedback to research participants
☐ Presentation to participants or relevant community groups
☑ Other/none e.g. Cochrane Review, University Library

If other/none of the above, give details and justify:

PhD Theses of Barry Lovern and Lindsay Stroud which will be available in the Cardiff University library.

A38. How will the results of research be made available to research participants and communities from which they are drawn?

The results will be disseminated to the participants verbally and if appropriate, through leaflets. Significant results may also be published in local media and disseminated to communities.

A39. Will the research involve any of the following activities at any stage (including identification of potential research participants)? *(Tick as appropriate)*

☐ Examination of medical records by those outside the NHS, or within the NHS by those who would not normally have access
☑ Electronic transfer by magnetic or optical media, e–mail or computer networks
☑ Sharing of data with other organisations
☐ Export of data outside the European Union
☑ Use of personal addresses, postcodes, faxes, e–mails or telephone numbers
☐ Publication of direct quotations from respondents
☐ Publication of data that might allow identification of individuals

☑ Use of audio/visual recording devices

☑ Storage of personal data on any of the following:

☐ Manual files including X-rays

☑ NHS computers

☐ Home or other personal computers

☑ University computers

☐ Private company computers

☐ Laptop computers

Further details:

After patients have verbally consented to either Mr. Nicholas Ferran or Mr. Richard Evans to be contacted by Cardiff University, patient contact details will be passed onto PhD students Lindsay Stroud and Barry Lovern via email.
Once patients are enrolled in the trial, they will be assigned a reference number which will be used as their identifier throughout the trial and for purposes of data analysis. A master copy of patient contact information and relevant reference numbers will be   encrypted and stored on password protected Cardiff University computers to allow future contact with patients.
Any written/printed files will be stored in locked filing cabinets.

Patients will be recorded using audiovisual cameras during the laboratory sessions. This is to allow re-assessment of results as a quality assurance measure.
Audiovisual files will be digitally stored on password protected Cardiff University computer drives. Patient faces will be digitally masked prior to saving files.

A40. What measures have been put in place to ensure confidentiality of personal data? Give details of whether any encryption or other anonymisation procedures have been used and at what stage:

Once patients are enrolled in the trial, they will be assigned a reference number which will be used as their identifier throughout the trial and for purposes of data analysis. A master copy of patient contact information and relevant reference numbers will be kept to allow future contact with patients.
All soft copy files will be stored and encrypted on password protected Cardiff University computers.
Any written/printed files will be stored in locked filing cabinets.

A41. Where will the analysis of the data from the study take place and by whom will it be undertaken?

The data will be analysed in the Cardiff School of Engineering, Cardiff University by Barry Lovern, Lindsay Stroud and Nicholas Ferran.

A42. Who will have control of and act as the custodian for the data generated by the study?

Dr. Catherine Holt

A43. Who will have access to research participants' or potential research participants' health records or other personal information? *Where access is by individuals outside the normal clinical team, justify and say whether consent will be sought.*

Mr Richard Evans and Mr Nicholas Ferran (NHS Medical Staff)

A44. For how long will data from the study be stored?

10 Years 0 Months

Give details of where they will be stored, who will have access and the custodial arrangements for the data:

The data will be stored for the duration of the trial and for at least five years thereafter.

The data will be encrypted and stored on password protected drives on Cardiff University computers.
Printed data will be kept in locked filing cabinets in Cardiff University.
Access to records will be granted to researchers assisting with the running of the trial and data analysis.
Dr. Catherine Holt will be the custodian of the data.

A45-1. How has the scientific quality of the research been assessed? *(Tick as appropriate)*

☐ Independent external review
☐ Review within a company
☐ Review within a multi–centre research group
☐ Review within the Chief Investigator's institution or host organisation
☑ Review within the research team
☑ Review by educational supervisor
☐ Other

Justify and describe the review process and outcome. If the review has been undertaken but not seen by the researcher, give details of the body which has undertaken the review:

The project proposal has been reviewed by
Chris Shaw, Cardiff University Research Governance Coordinator
Cardiff University
Research And Commercial Division
30–36 Newport Road
Cardiff
CF24 0DE

Chris has approved the proposal and provided a SPON reference number, SPON525–08.

The project has been accepted for sponsorship by Kathy Pittard Davis, the Head of Research Policy
Management subject to COREC approval

The project has been approved by the
Cardiff and Vale NHS Trust
R&D Trust Director (Prof MF Scanlon)
Joint University/Trust Peer and Risk Review Committee
Radnor House
UHW
Cardiff CF14 4XW

A45-2. How have the statistical aspects of the research been reviewed? *(Tick as appropriate)*

☐ Review by independent statistician commissioned by funder or sponsor
☐ Other review by independent statistician
☐ Review by company statistician
☐ Review by a statistician within the Chief Investigator's institution
☐ Review by a statistician within the research team or multi–centre group
☑ Review by educational supervisor
☐ Other review by individual with relevant statistical expertise

In all cases give details below of the individual responsible for reviewing the statistical aspects. If advice has been provided

in confidence, give details of the department and institution concerned.

	Title:	Forename/Initials:	Surname:
	Dr.	Catherine	Holt

Department:	Department of Mechanical, Medical and Manufacturing Engineering
Institution:	Cardiff University
Work Address:	Cardiff School of Engineering
	Cardiff University
	Queen's Buildings, The Parade
Postcode:	CF24 3AA
Telephone:	00 44 (0)29 2087 4533
Fax:	00 44 (0)29 2087 4939
Mobile:	00 44 (0)7963371492
E–mail:	holt@cardiff.ac.uk

Please enclose a copy of any available comments or reports from a statistician.

Question(s) 46–47 disabled.

A48. What is the primary outcome measure for the study?

The purpose of the planned research is to gather kinematic and kinetic data of the shoulder complex from patients with shoulder pathologies or trauma pre–treatment and post–treatment.

This data will be compared with data collected from healthy volunteers' shoulders with the intent of analyzing the differences so as to establish a non–invasive diagnostic tool.
The prognosis of different treatment methods will also be assessed.

A49. What are the secondary outcome measures? *(if any)*

Patient data will be compared with outcome scores from the Oxford Shoulder Score (or Oxford Shoulder Instability Score when appropriate) to determine if there is any correlation between the Oxford Shoulder Score and patient kinematics and kinetics.

A50. How many participants will be recruited?
If there is more than one group, state how many participants will be recruited in each group. For international studies, say how many participants will be recruited in the UK and in total.

Initially 5 patients will be recruited from each sub study: for example clavicle fractures operated, clavicle fractures conservatively managed, and first time dislocators.

These patients will serve as a pilot study to finalise the measurement protocol and statistical analysis required within each subgroup.

After this, it is hoped to recruit as many patients as possible to strengthen the diagnostic tool.

A51. How was the number of participants decided upon?

We initially intend to recruit 5 patients per group to validate the 3D model and perform pilot statistics and will recruit further patients thereafter.

If a formal sample size calculation was used, indicate how this was done, giving sufficient information to justify and reproduce the calculation.

A52. Will participants be allocated to groups at random?

○ Yes   ◉ No

A53. Describe the methods of analysis (statistical or other appropriate methods, e.g. for qualitative research) by which the data will be evaluated to meet the study objectives.

When appropriate, parametric statistical analysis (t–test, ANOVA) will be performed. In other cases non–parametric analysis will be implemented.

The statistical analysis is necessarily exploratory and this is reflected in the study. We will be initially exploring the efficacy of applying motion analysis techniques to a number of traumas and pathologies to determine which may benefit from further study.   This assessment will be made in terms of defining the usefulness of the functional analysis for a particular shoulder problem and the practical application of the measurement protocols to larger cohorts of patients.   This will then include an assessment by the collaborating engineers, surgeons and physiotherapists as to the practical nature of continuing recruitment of patients for specific shoulder problems in terms of value of the assessment compared to existing assessments and possible correlations with qualitative outcome scores such as the Oxford Shoulder Score and the Oxford Shoulder Instability Score. Cohorts will be split into groups based on type of pathology (or healthy) and rehabilitation regime, i.e. surgically managed vs. conservatively managed. If a correlation of shoulder function is found within the various groups, then we will apply for   an amendment to include more patients of that subgroup in the study in order to develop powerful statistical techniques for objective classification. A Dempster Shafer theory of evidence, linear discriminant analysis and artificial neural networking will be used to train a classifier to objectively categorise the various patient cohorts.

A54. Where will the research take place? *(Tick as appropriate)*

☑ UK
☐ Other states in European Union
☐ Other countries in European Economic Area
☐ Other

If Other, give details:

A55. Has this or a similar application been previously rejected by a Research Ethics Committee in the UK, the European Union or the European Economic Area?

○ Yes   ◉ No

A56. In how many and what type of host organisations (NHS or other) in the UK is it intended the proposed study will take place?

Indicate the type of organisation by ticking the box and give approximate numbers if known:

	Number of organisations
☑ Acute teaching NHS Trusts	1
☐ Acute NHS Trusts	
☐ NHS Primary Care Trusts or Local Health Boards in Wales	
☐ NHS Trusts providing mental healthcare	
☐ NHS Health Boards in Scotland	
☐ HPSS Trusts in Northern Ireland	
☐ GP Practices	
☐ NHS Care Trusts	
☐ Social care organisations	
☐ Prisons	
☐ Independent hospitals	
☑ Educational establishments	1
☐ Independent research units	
☐ Other (give details)	

Other:

A57. What arrangements are in place for monitoring and auditing the conduct of the research?

The PI will manage the research via regular fortnightly meetings with the other investigators to ensure the focus of the study is maintained and that all ethical issues are addressed and guidelines adhered to. Day–to–day running of the trial will be controlled on the basis of continued availability of the PI to deal with unexpected occurrences and patient issues.

A57a. Will a data monitoring committee be convened?

○ Yes ◉ No

If Yes, details of membership of the data monitoring committee (DMC), its standard operating procedures and summaries of reports of interim analyses to the DMC must be forwarded to the NHS Research Ethics Committee which gives a favourable opinion of the study.

What are the criteria for electively stopping the trial or other research prematurely?

Lack of funding
Inability to validate the model
Lack of patients willing to participate
Lack of personnel to carry out the trial and the analysis

A58. Has external funding for the research been secured?

○ Yes ◉ No

If No, what arrangements are being made to cover any costs of the research? If no external funding is being sought, please say so:

No external funding is being sought.

A59. Has the funder of the research agreed to act as sponsor as set out in the Research Governance Framework?

○ Yes ● No

Has the employer of the Chief Investigator agreed to act as sponsor of the research?

● Yes ○ No

Lead sponsor *(must be completed in all cases)*

Name of organisation which will act as the lead sponsor for the research:

Cardiff University

Status:

○ NHS or HPSS care organisation ● Academic ○ Pharmaceutical industry ○ Medical device industry ○ Other

If Other, please specify:

Address:	Cardiff University
	Cardiff
	Wales, UK
Post Code:	CF10 3XQ
Telephone:	+44 (0)29 208 74000
Fax:	00 44 (0)29 2087 4939
Mobile:	
E-mail:	holt@cardiff.ac.uk

Sponsor's UK contact point for correspondence with the main REC *(must be completed in all cases)*

Title: Dr	Forename/Initials: Catherine	Surname: Holt

Work Address:	Cardiff School of Engineering
	Cardiff University
	Queen's Buildings, The Parade
Post Code:	CF24 3AA
Telephone:	00 44 (0)29 2087 4533
Fax:	00 44 (0)29 2087 4939
Mobile:	
E-mail:	holt@cardiff.ac.uk

Co-sponsors

Are there any co-sponsors for this research?

○ Yes ● No

A60. Has any responsibility for the research been delegated to a subcontractor?

O Yes ⊙ No

A61. Will individual *researchers* receive any personal payment over and above normal salary for undertaking this research?

O Yes ⊙ No

A62. Will individual *researchers* receive any other benefits or incentives for taking part in this research?

O Yes ⊙ No

A63. Will the host organisation or the researcher's department(s) or institution(s) receive any payment or benefits in excess of the costs of undertaking the research?

O Yes ⊙ No

A64. Does the Chief Investigator or any other investigator/collaborator have any direct personal involvement (e.g. financial, share–holding, personal relationship etc.) in the organisations sponsoring or funding the research that may give rise to a possible conflict of interest?

O Yes ⊙ No

A65. Research reference numbers: *(give any relevant references for your study):*

Applicant's/organisation's own reference number, e.g. R&D (if available): SPON525–08
Sponsor's/protocol number: SPON525–08
Funder's reference number: N/A
International Standard Randomised Controlled Trial Number (ISRCTN): N/A
ClinicalTrials.gov Identifier (NCT number): N/A
Project website: N/A

A66. Other key investigators/collaborators *(all grant co–applicants or protocol co–authors should be listed)*

Title: Mr   Forename/Initials: Richard   Surname: Evans

Post: Consultant Orthopaedic Surgeon
Qualifications: FRCS (Tr. & Orth)
Organisation: Cardiff & Vale NHS Trust
Work Address: University Hospital of Wales
                          Heath Park
                          Cardiff
Postcode: CF14 4XW
Telephone: 02920 745371
Fax: 02920 744206

Mobile:

E-mail: lorraine.timmons@cardiffandvale.wales.nhs.uk

Title: Mr.   Forename/Initials: Nicholas A.   Surname: Ferran

Post: Trauma Research Fellow

Qualifications: MBBS, MRCSEd.

Organisation: Cardiff & Vale NHS Trust

Work Address: University Hospital of Wales

Heath Park

Cardiff

Postcode: CF14 4XW

Telephone: 02920-748034

Fax: 02920-744206

Mobile:

E-mail: nferran@uku.co.uk

Title: Mr.   Forename/Initials: Barry   Surname: Lovern

Post: PhD Student

Qualifications: BEng Biomedical Engineering

Organisation: Cardiff University

Work Address: Room 3.20, South Building

Cardiff School of Engineering

Queens Buildings, Cardiff University

Postcode: CF24 3AA

Telephone: 02920874000ext77900

Fax: +44 (0)29 2087 4939

Mobile:

E-mail: lovernb@cf.ac.uk

Title: MS.   Forename/Initials: Lindsay   Surname: Stroud

Post: PhD Student

Qualifications: BEng Medical Engineering

Organisation: Cardiff University

Work Address: Room 3.20, South Building

Cardiff School of Engineering

Queens Buildings, Cardiff University

Postcode: CF24 3AA

Telephone: 02920874000ext77900

Fax: +44 (0)29 2087 4939

Mobile:

E-mail: stroudla@cf.ac.uk

A67. What arrangements are being made for continued provision of the intervention for participants, if appropriate, once the research has finished? *May apply to any clinical intervention, including a drug, medical device, mental health intervention, complementary therapy, physiotherapy, dietary manipulation, lifestyle change, etc.*

Cardiff & Vale NHS Trust will continue the clinical management of the patient as per usual.

PART A: Summary of Ethical Issues

A68. Overview of the research

To provide all the information required by the REC, we ask a number of specific questions. This section invites you to give an overview using language comprehensible to lay reviewers and members of the public. Please read the guidance notes for advice on this section.

A68-1. Lay summary. *Please provide a brief summary of the research (maximum 300 words) in lay language. This summary will be published on the website of the National Research Ethics Service following the ethical review.*

The shoulder complex consists of four articulations: the sternoclavicular joint, the acromioclavicular joint, the glenohumeral joint and the scapulothoracic articulation. These four articulations combine to provide a larger range of movement than any other joint complex in the human body. As a result, the shoulder is susceptible to a wide range of pathologies, injuries and instabilities. Clinical diagnosis can be difficult as it is based on the individual surgeons prior experience and training. Many pathologies exhibit similar symptoms but require different treatment modes. As a result, a medical imaging scan is often necessary to confirm diagnosis, increasing waiting times significantly. Even with correct diagnosis, it is difficult to determine which treatment mode is most effective for different pathologies. It is believed that clinical diagnosis and prognosis could benefit from further understanding of the kinematics of the shoulder complex.

Cardiff University is assessing the kinematic properties of the shoulder complex in healthy and injured subjects in a non-invasive manner. The research is intended to aid in clinical diagnosis and prognosis by providing objective patient data.

Volunteers with a shoulder injury will be asked to attend up to four sessions in the lab, 6 weeks, 3 months, 6 months and 12 months after they receive treatment for their injuries. Reflective markers will be attached to their skin with double sided tape. The movement of the markers is tracked by special cameras in the lab. They will be asked to perform a range of movements such as raising their arm to above head height and to perform everyday tasks such as brushing their hair or answering the telephone.

A68-2. Summary of main issues. *Please summarise the main ethical and design issues arising from the study and say how you have addressed them.*

Data protection
Once patients are enrolled in the trial, they will be assigned a reference number which will be used as their identifier throughout the trial and for purposes of data analysis. A master copy of patient contact information and relevant reference numbers will be stored on password protected Cardiff University computers to allow future contact with patients.
Any written/printed files will be stored in locked filing cabinets.

Time spent in laboratory
Sessions will last up to three hours with a maximum of four sessions. Adequate toilet and rest breaks will be provided to ensure patient comfort.

Video recording of lab session
Patients will be recorded using audiovisual cameras during the laboratory sessions. This is to allow re-assessment of results as a quality assurance measure.
Audiovisual files will be digitally stored on password protected Cardiff University computer drives. Patient faces will be digitally masked prior to saving files.

Removing upper garments

Participants will be asked to remove their upper garments excluding underwear. The process will be conducted with utmost professionalism to maintain a comfortable environment for both parties. Female patients will be asked to wear a sports bra or other appropriate garment to the laboratory sessions.

We would appreciate advice on how to transfer patient contact details between the NHS and Cardiff University after patients have consented to be contacted.
We propose doing this by email but would appreciate the committee's guidance on this.

Question(s) 69 disabled.

PART A: Student Page

A70. Give details of the educational course or degree for which this research is being undertaken:

Name of student:

Barry Lovern and Lindsay Stroud

Name and level of course/degree:

Barry Lovern
"Classification of shoulder function in healthy and pathological subjects using 3D motion analysis techniques"
PhD Mechanical Engineering

Lindsay Stroud
"Functional classification of human joints using motion analysis and objective classifiers"
PhD Mechanical Engineering

Name of educational establishment:

Cardiff University

Name and contact details of educational supervisor:

Dr. Catherine Holt
Cardiff School of Engineering
Cardiff University
Queen's Buildings, The Parade
Cardiff CF24 3AA

00 44 (0)29 2087 4533

A71. Declaration of educational supervisor

I have read and approved both the research proposal and this application for the ethical review. I am satisfied that the scientific content of the research is satisfactory for an educational qualification at this level. I undertake to fulfil the responsibilities of a supervisor as set out in the Research Governance Framework for Health and Social Care.

Signature: ....

Print Name: Catherine A. Holt

Date: 15/05/2008 (dd/mm/yyyy)

A one-page summary of the supervisor's CV should be submitted with the application

PART B: Section 1 – List of proposed research sites

List below all research sites you plan to include in this study. The name of the site is normally the name of the acute NHS Trust, GP practice or other organisation responsible for the care of research participants. In some cases it may be an individual unit, private practice or a consortium – see the guidance notes.

Principal Investigators at other sites should apply to the relevant local Research Ethics Committee for site-specific assessment (SSA) using the Site-Specific Information Form. Applications for SSA may be made in parallel with the main application for ethical review (once the main REC has validated the application), or following issue of a favourable ethical opinion. Approval for each site will be issued to you by the main REC following SSA.

1. Name of the research site:

Cardiff School of Engineering

Principal Investigator for the study at this site:

Title: Dr   Forename/Initials: Catherine   Surname: Holt

Post: Senior Lecturer in Biomechanics
Work Address: Cardiff School of Engineering
                    Cardiff University
                    Queen's Buildings, The Parade
Postcode: CF24 3AA

PART B: Section 8 – Declarations

Declaration by Chief Investigator

1. The information in this form is accurate to the best of my knowledge and belief and I take full responsibility for it.

2. I undertake to abide by the ethical principles underlying the Declaration of Helsinki and good practice guidelines on the proper conduct of research.

3. If the research is approved I undertake to adhere to the study protocol, the terms of the full application of which the main REC has given a favourable opinion and any conditions set out by the main REC in giving its favourable opinion.

4. I undertake to seek an ethical opinion from the main REC before implementing substantial amendments to the protocol or to the terms of the full application of which the main REC has given a favourable opinion.

5. I undertake to submit annual progress reports setting out the progress of the research.

6. I am aware of my responsibility to be up to date and comply with the requirements of the law and relevant guidelines relating to security and confidentiality of patient or other personal data, including the need to register when necessary with the appropriate Data Protection Officer.

7. I understand that research records/data may be subject to inspection for audit purposes if required in future.

8. I understand that personal data about me as a researcher in this application will be held by the relevant RECs and their operational managers and that this will be managed according to the principles established in the Data Protection Act.

9. I understand that the information contained in this application, any supporting documentation and all correspondence with NHS Research Ethics Committees or their operational managers relating to the application:

    – Will be held by the main REC until at least 3 years after the end of the study.

    – May be disclosed to the operational managers or the appointing body for the REC in order to check that the application has been processed correctly or to investigate any complaint.

    – May be seen by auditors appointed by the National Research Ethics Service to undertake accreditation of the REC.

    – Will be subject to the provisions of the Freedom of Information Acts and may be disclosed in response to requests made under the Acts except where statutory exemptions apply.

10. I understand that information relating to this research, including the contact details on this application, may be held on national research information systems, and that this will be managed according to the principles established in the Data Protection Act 1998.

11. I understand that the lay summary of this study will be published on the website of the National Research Ethics Service (NRES) as it appears in this application. Publication will take place no earlier than 3 months after issue of the ethics committee's final opinion or the withdrawal of the application.

Optional – please tick as appropriate:

☑ I would be content for members of other RECs to have access to the information in the application in confidence for training purposes. All personal identifiers and references to sponsors, funders and research units would be removed.

Signature: ....

Print Name: Catherine Holt

Date: 15/05/2008 (dd/mm/yyyy)

Declaration by the sponsor's representative

If there is more than one sponsor, this declaration should be signed on behalf of the co-sponsors by a representative of the sponsor nominated to take the lead for the REC application.

I confirm that:

1. This research proposal has been discussed with the Chief Investigator and agreement in principle to sponsor the research is in place.

2. An appropriate process of scientific critique has demonstrated that this research proposal is worthwhile and of high scientific quality.*

3. Any necessary indemnity or insurance arrangements, as described in question A35, will be in place before this research starts.

4. Arrangements will be in place before the study starts for the research team to access resources and support to deliver the research as proposed.

5. Arrangements to allocate responsibilities for the management, monitoring and reporting of the research will be in place before the research starts.

6. The duties of sponsors set out in the NHS Research Governance Framework for Health and Social Care will be undertaken in relation to this research.**

7. I understand that the lay summary of this study will be published on the website of the National Research Ethics Service (NRES) as it appears in this application. Publication will take place no earlier than 3 months after issue of the ethics committee's final opinion or the withdrawal of the application.

* Not applicable to student research (except doctoral research).
** Not applicable to research outside the scope of the Research Governance Framework.

Signature: ....

Print Name:

Post:

Organisation:

Date: 15/05/2008 (dd/mm/yyyy)

Site–Specific Information Form

Does this application relate to a research site for which the NHS (or HPSS in Northern Ireland) is responsible or to a non–NHS research site?

- ○ NHS site
- ◉ Non–NHS site

This question must be completed before proceeding. The filter will customise the form, disabling questions which are not relevant to this application.

In which country is the research site located?

- ○ England
- ◉ Wales
- ○ Scotland
- ○ Northern Ireland

The data in this box is populated from Part A:

Short title and version number:
Shoulder Trauma Study v1.01

Name of NHS Research Ethics Committee to which application for ethical review is being made:
South East Wales

Project reference number from above REC:

Name of NHS REC responsible for SSA:
South East Wales

SSA reference (for REC office use only)

1. Title of the research *(populated from A1)*

Full title:	Assessment of shoulder function in healthy and pathological subjects using three dimensional motion analysis techniques.
Key words:	Shoulder, motion analysis, three dimensional

2. Name of Chief Investigator *(populated from A2)*

Title:	Forename/Initials:	Surname:
Dr.	Catherine	Holt

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3. Name of organisation acting as lead sponsor for the study *(populated from A59)*

     Cardiff University

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4. Research reference numbers if known *(populated from A65)*

Applicant's/organisation's own reference number, e.g. R&D: SPON525–08

Sponsor's/protocol number: SPON525–08

Funder's reference number: N/A

International Standard Randomized Controlled Trial Number (ISRCTN):   N/A

ClinicalTrials.gov Identifier (NCT number):   N/A

Project website: N/A

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5. Give the name of the trial site

Human Motion Analysis Lab, Cardiff School of Engineering, Cardiff University
If trial procedures are to be conducted at any other location, specify the location/department and describe the activity that will take place.
Patients will be recruited from outpatient clinics at the Dept. of Trauma and Orthopaedics Cardiff and Vale NHS Trust

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9. Give the name of the Site Management Organisation. *This is defined as the company or other legal entity responsible for the management of the research site.*

     Cardiff University

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10. Give details of the person with overall responsibility for the management and monitoring of the research at this site.

     Title: Forename/Initials: Surname:
     Dr   Catherine   Holt

Work Address: Cardiff School of Engineering

               Cardiff University   Telephone: 00 44 (0)29 2087 4533

               Queen's Buildings, The Parade   Fax: 00 44 (0)29 2087 4939

Postcode: CF24 3AA   Mobile:

E–mail: holt@cardiff.ac.uk

---

11. Who is the local Principal Investigator (PI) for this trial at this site?

     Title: Forename/Initials: Surname:
     Dr   Catherine   Holt

Post: Senior Lecturer in Biomechanics, Royal Academy of Engineering/Leverhulme Trust Senior Research Fellow

Qualifications: BEng PhD CEng FIMechE

Organisation: Cardiff University

Work Address: Cardiff School of Engineering

               Cardiff University   Telephone: 00 44 (0)29 2087 4533

               Queen's Buildings, The Parade   Fax: 00 44 (0)29 2087 4939

Postcode:	CF24 3AA		Mobile:
E–mail:	holt@cf.ac.uk		

Please provide a copy of the c.v. for the PI.

13. Give details of other members of the research team responsible to the Principal Investigator at this site:

1. Research Member

	Title:	Forename/Initials:	Surname:
	Mr.	Nicholas A.	Ferran

Employing organisation:	Cardiff & Vale NHS Trust
Post:	Trauma research Fellow
Qualifications:	MBBS, MRCSEd.
Role in research team:	doctor

2. Research Member

	Title:	Forename/Initials:	Surname:
	Mr.	Barry J.	Lovern

Employing organisation:	Cardiff University
Post:	PhD Candidate
Qualifications:	BEng (Honours) Biomedical Engineering
Role in research team:	other: Engineer

3. Research Member

	Title:	Forename/Initials:	Surname:
	Ms.	Lindsay A.	Stroud

Employing organisation:	Cardiff University
Post:	PhD Candidate
Qualifications:	BEng (Honours) Medical Engineering
Role in research team:	other: Engineer

4. Research Member

	Title:	Forename/Initials:	Surname:
	Mr	Richard O.N.	Evans

Employing organisation:	Cardiff & Vale NHS Trust
Post:	Consultant Orthopaedic Surgeon
Qualifications:	FRCS (Tr. & Orth.)
Role in research team:	doctor

15. Does the Principal Investigator or any other member of the site research team have any direct personal involvement (e.g. financial, share–holding, personal relationship etc) in the organisation sponsoring or funding the research that may give rise to a possible conflict of interest?

○ Yes   ◉ No

If Yes, give further details:

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16. What is the proposed local start and end date for the research at this site?

Start date: 01/07/2008 *(dd/mm/yyyy)*
Duration (Months):   60
End date: 30/06/2013 *(dd/mm/yyyy)*

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17. Summary of the research *(populated from A10–1)*

Purpose of Planned Research:

The purpose of the planned research is to gather kinematic and kinetic data of the shoulder complex from patients with shoulder pathologies or trauma pre–treatment and post–treatment.
This data will be compared with data collected from healthy volunteers' shoulders with the intent of analyzing the differences so as to establish a non–invasive diagnostic tool.
The prognosis of different treatment methods will also be assessed.

Methodology of Planned Research:

Subjects will be assessed in the Human Motion Analysis Laboratory, Cardiff School of Engineering a maximum of four times at intervals of 6 weeks, 3 months, 6 months and 12 months post injury/treatment, in the Cardiff School of Engineering Human Motion Analysis Laboratory. The sessions will last a maximum of three hours, including taking of consent, explanation of laboratory etc.
With some pathology subgroups, two sessions each of two hours may suffice.

Patient selection:

– Patients presenting to Cardiff & Vale NHS Trust with shoulder pathology such as shortened mid–shaft clavicle fractures and first time shoulder dislocators.
– As per usual patients will be clinically and radiographically assessed, and will be assessed, scored, and treated by shoulder physiotherapists.
– Patients will give consent for contact by Cardiff University PhD students

Consent Process:
Potential patients will be selected by Mr. Nicholas Ferran and Mr. Richard Evans during clinics at Cardiff & Vale NHS Trust. They will give verbal consent to be contacted by Cardiff University PhD students Barry Lovern or Lindsay Stroud, who will provide the patients with further information and an information pack. Willing patients will then be recruited to the trial. Upon arrival at the Motion Analysis Laboratory, patients will have the entire protocol explained to them. It will be made clear that they are free to withdraw from the trial at any time and that their participation in the trial will not affect their relationship with the NHS in any way.
Once patients are satisfied and wish to participate in the trial, informed consent will be obtained.

Anonymization:
Once patients are enrolled in the trial, they will be assigned a reference number which will be used as their identifier throughout the trial and for purposes of data analysis. A master copy of patient contact information and relevant reference numbers will be encrypted and stored on password protected Cardiff University computers to allow future contact with patients.
Any written/printed files will be stored in locked filing cabinets.

Data Collection:

Five patients from each subgroup (for e.g. midline clavicle shaft fracture conservative or operative, and first time dislocators) will be recruited for a pilot study.
Patients' range of motion for flexion–extension, abduction–adduction and internal–external rotation of the shoulder complex will be assessed.
Their abilities to perform activities of daily living (such as combing hair, taking hand to mouth and raising hand above head height) will also be assessed.
Joint strength will be assessed with the aid of a dynamometer.

Participants will be asked to remove their upper garments excluding bra in the case of females. The process will be conducted with utmost professionalism to maintain a comfortable environment for both parties. Female patients will be asked to wear a sports bra or other appropriate garment to the laboratory sessions.

During the session, participants will have reflective markers attached to bony landmarks of the arm and torso using double sided tape. This is to allow the calculation of segment and joint rotations using the recommended standards of the International Society of Biomechanics.

The reflective markers will be placed as follows:
• On the thorax: insicura jugularis and xiphoideus process on the sternum and the 7th cervical vertebra and 8th thoracic vertebra on the spine.
• On the clavicle: the sternoclavicular joint and the acromioclavicular joint.
• On the scapula: the acromion angle, the trigonum spinae, the inferior angle and the coroidal process.
• On the humerus: the medial epicondyle and the lateral epicondyle.
• On the forearm: the ulnar styloid and the radial styloid.

A marker cluster will also be placed on the upper arm using self–adhesive Coban tape.

The patients will then be instructed to perform the activities previously described.

The markers will then be removed and an electromagnetic tracking device in tandem with a scapula locator (a 3 pointed rigid device used to palpate the bony landmarks of the scapula) will be used to determine the orientation of one bone segment relative to another.

During this phase, the participants will be asked to use a supporting brace which minimises rotation of the forearm by holding the elbow flexed at 90º. The brace will be secured to the elbow using Velcro. Receivers will be mounted onto the participants using double sided tape and self adhesive tape at the following sites:
• Thorax receiver fixed to the sternum, between the incisura jugularis and the xiphoideus process
•   A second thorax receiver fixed to the 7th cervical vertebra
• Humerus receiver fixed to the supporting brace.
• Scapula receiver mounted on a three pin device which aids in the identification of the acromion angle, the trigonum spinae, and the inferior angle.

With the subject in a resting position, a stylus receiver will be used to identify the bony landmarks of the shoulder complex:
• On the thorax: incisura jugularis and xiphoideus process on the sternum and the 7th cervical vertebra and 8th thoracic vertebra on the spine.
• On the clavicle: the sternoclavicular joint and the acromioclavicular joint.
• On the scapula: the acromion angle, the trigonum spinae, the inferior angle and the coroidal process.
• On the humerus: the medial epicondyle and the lateral epicondyle.
• On the forearm: the ulnar styloid and the radial styloid.

The patients will then be instructed to perform full range of motion (within the confines of their injury/pathology and comfort level) for elevation in the negative 30 degree plane (behind the patient), elevation in the 0 degree plane (abduction), elevation in the scapular plane (approximately 30 degree), elevation in the 60 degree plane, elevation in the 90 degree plane (flexion) and when patients are able, elevation in a plane beyond 90 degrees.

Measurements of shoulder position will be taken at increments of 10–30 degrees with patients remaining still during this time. Adequate rest time will be provided when necessary.

Patients will be recorded using audiovisual cameras during the laboratory sessions. This is to allow re–assessment of results as a quality assurance measure.
Audiovisual files will be digitally stored on password protected Cardiff University computer drives. Patient faces will be digitally masked prior to saving files.

Based on the findings from the pilot study, the measurement protocol will be finalised and the statistical model validated.

Data Storage:
Soft copy data will be stored and encrypted on password protected drives in Cardiff University.
Printed data will be stored in locked filing cabinets in Cardiff University.

Data Analysis:
Body segment and joint coordinate systems will be established and joint and segment rotations calculated according to the recommendations of the International Society of Biomechanics.

When appropriate, parametric statistical analysis (t-test, ANOVA) will be performed. In other cases non-parametric analysis will be implemented.

The statistical analysis is necessarily exploratory and this is reflected in the study. We will be initially exploring the efficacy of applying motion analysis techniques to a number of traumas and pathologies to determine which may benefit from further study. This assessment will be made in terms of defining the usefulness of the functional analysis for a particular shoulder problem and the practical application of the measurement protocols to larger cohorts of patients. This will then include an assessment by the collaborating engineers, surgeons and physiotherapists as to the practical nature of continuing recruitment of patients for specific shoulder problems in terms of value of the assessment compared to existing assessments and possible correlations with qualitative outcome scores such as the Oxford Shoulder Score and the Oxford Shoulder Instability Score. Cohorts will be split into groups based on type of pathology (or healthy) and rehabilitation regime, i.e. surgically managed vs. conservatively managed. If a correlation of shoulder function is found within the various groups, then we will apply for an amendment to include more patients of that subgroup in the study in order to develop powerful statistical techniques for objective classification. A Dempster Shafer theory of evidence, linear discriminant analysis and artificial neural networking will be used to train a classifier to objectively categorise the various patient cohorts.

18. Details of clinical interventions *(populated from A12 where enabled)*

Additional Intervention	Average number per participant		Average time taken	Details of additional intervention or procedure, who will undertake it, and what training they have received.
	Routine Care	Research		

19. Details of non-clinical interventions *(populated from A13 where enabled)*

Additional Intervention	Average number per participant	Anticipated average time taken	Details of additional intervention or procedure, who will undertake it, and what training they have received.
Face to Face Interview	4	20 mins	Upon arriving at the Cardiff Motion Analysis Lab for the first time, PhD student Barry Lovern or Lindsay Stroud, will explain how the lab works and what will be happening during that session. Informed consent will then be obtained. (S)he will then ask for details of any previous injuries or problems

			with the upper limb or spine, aside from the condition which is currently being analysed and take a series of anthropometric measurements of the upper limb and record the patients height and weight. Participants will be asked to fill out the Oxford Shoulder Score.
Face to Face Interview	1	20 mins	Mr. Nicholas Ferran / Mr. Richard Evans will inform patients about the trial and obtain verbal consent for the patient to be contacted by either Mr. Barry Lovern or Ms. Lindsay Stroud.

20. Will any aspects of the research at this site be conducted in a different way to that described in Parts A and B or the study protocol?

◯ Yes ◉ No

If Yes, explain and give reasons.

21. How many research participants/samples is it expected will be recruited/obtained from this site?

All patients will be recruited from Cardiff & Vale NHS Trust. Initially 5 patients from each sub group will be recruited for validation of the 3D model and piloting statistics.

The statistical analysis is necessarily exploratory and this is reflected in the study. We will be initially exploring the efficacy of applying motion analysis techniques to a number of traumas and pathologies to determine which may benefit from further study. This assessment will be made in terms of defining the usefulness of the functional analysis for a particular shoulder problem and the practical application of the measurement protocols to larger cohorts of patients. This will then include an assessment by the collaborating engineers, surgeons and physiotherapists as to the practical nature of continuing recruitment of patients for specific shoulder problems in terms of value of the assessment compared to existing assessments and possible correlations with qualitative outcome scores such as the Oxford Shoulder Score and the Oxford Shoulder Instability Score. Cohorts will be split into groups based on type of pathology and rehabilitation regime, i.e. surgically managed vs. conservatively managed. If a correlation of shoulder function is found within the various groups, then we will apply for an amendment to include more patients of that subgroup in the study in order to develop powerful statistical techniques for objective classification.

22. Give details of how potential participants will be identified locally and who will be making the first approach to them to take part in the study?

Mr. Richard Evans and Mr. Nicholas Ferran will identify potential participants during clinical examination and will make the first approach.

23. Who will be responsible for obtaining informed consent at this site? What expertise and training do these persons have in obtaining consent for research purposes?

1 ☐	Dr Catherine Holt	
2 ☐	Mr. Nicholas A. Ferran	
3 ☑	Mr. Barry J. Lovern	Prior experience obtaining patient consent for Knee Motion analysis Trial. Fully aware of all aspects of the trial and relevant concerns participants may have on entering the trial.

Further more, a number of staff are trained as follows:
The school/directorate provides induction training for new/relocated staff and students
Managers and supervisors are trained in risk assessment

General Health and Safety Training is provided at all levels by the Schools /Directorates

First–Aiders are trained in First Aid in the Workplace and are available daily with notices and contact numbers placed in strategic positions around the buildings.

34. Give details of the arrangements for the management and monitoring of the research at this site.

In the case of Phase 1 trials in healthy volunteers, confirm that the unit's normal SOPs will be followed. Comment on any particular measures in place for this trial.

The PI will manage the research via regular fortnightly meetings with the other investigators to ensure the focus of the study is maintained and that all ethical issues are addressed and guidelines adhered to.   Day–to–day running of the trial will be controlled on the basis of continued availability of the PI to deal with unexpected occurrences and patient issues.

36. What arrangements will be made for insurance and/or indemnity to meet the potential legal liability of the Principal Investigator, the site management organisation and other members of the research team arising from harm to participants in the conduct of the research at this site?

Cardiff University has agreed to sponsor the project, subject to COREC approval. The reference number is SPON525–08
The University's standard insurance covers (Professional Indemnity and Public Liability) apply to this research and cover all University staff and students involved in the project.

Please enclose a copy of all relevant documents

Declarations

Declaration by Principal Investigator

1. The information in this form is accurate to the best of my knowledge and I take full responsibility for it.
2. I undertake to abide by the ethical principles underpinning the World Medical Association's Declaration of Helsinki and relevant good practice guidelines in the conduct of research.
3. If the research is approved, I undertake to adhere to the study protocol, the terms of the full application of which the main REC has given a favourable opinion and the terms of this application.
4. I am aware of my responsibility to be up to date and comply with the requirements of the law and relevant guidelines relating to the conduct of research, including legislation on human tissue and personal data.
5. I undertake to disclose any conflicts of interest that may arise during the course of this research, and take responsibility for ensuring that all staff involved in the research are aware of their responsibilities to disclose conflicts of interest.
6. I understand and agree that study files, records and data may be subject to inspection by the main REC or the SSA REC for audit purposes.
7. I understand that personal data about me as a researcher will be held by the relevant RECs and their operational managers and that this will be managed according to the principles established in the Data Protection Act 1998.
8. I understand that the information contained in this application, any supporting documentation and all correspondence with Research Ethics Committees or their operational managers relating to the application:

     ◆ Will be held by the REC system until at least 3 years after the end of the study.
     ◆ May be disclosed to the operational managers or the appointing body for the REC in order to check that the application has been processed correctly or to investigate any complaint.
     ◆ May be seen by auditors appointed by the National Research Ethics Service to undertake accreditation of the REC.
     ◆ Will be subject to the provisions of the Freedom of Information Acts and may be disclosed in response to requests made under the Acts except where statutory exemptions apply.

Signature of Principal Investigator: ....

Print Name: Catherine Holt
Date: 15/05/2008

Declaration on behalf of Site Management Organisation

I confirm that:

• The Principal Investigator has a contract with the SMO to conduct this research.
• All insurance and indemnity arrangements described above will be in place before the study starts at the site.
• The arrangements described above for management and monitoring of the research will be implemented.

Signature: ....

Print Name:
Date: 15/05/2008

Appendix E: Publications arising from this thesis

The following is a list of publications arising directly or indirectly from this thesis:

Journal articles:

1. Lovern B., Stroud L.A., Evans R.O., Evans S.L., and Holt C.A., (2009), Dynamic tracking of the scapula using skin mounted markers, Proc. IMechE, Part H: J. Engineering in Medicine, 2009, 223(H7), 823-831. DOI: 10.1243/09544119JEIM554

2. B. Lovern, L.A. Stroud, R.O. Evans N.A. Ferran, S.L. Evans, , L. Jones, C.A. Holt, 2009, Motion Analysis of the glenohumeral joint during activities of daily living, accepted for publication in Computer Methods in Biomechanics and Biomedical Engineering

Conference Proceedings:

3. Stroud L.A., Lovern B., Evans R.O., Evans S.L., and Holt C.A. (2010), Estimating the glenohumeral joint centre of rotation: regression equations versus helical

axis. Proceedings of the 9th symposium of Computer Methods in Biomechanics and Biomedical Engineering ,

4. Stroud L.A., Lovern B., Evans S.L., and Holt C.A. (2010), Investigating the use of digital image correlation to quantify scapula function. Proceedings of the 9th symposium of Computer Methods in Biomechanics and Biomedical Engineering

5. B. Lovern, L.A. Stroud, C.A. Holt and S.L. Evans, (2009), Using digital image correlation to measure scapula movement during shoulder motion, Proceedings of the 22 nd Congress of the International Society of Biomechancs

6. Stroud L.A., Lovern B., Ferran N., Evans R., Evans S.L. and Holt C.A., (2009), Measuring glenohumeral joint translations using motion analysis techniques, Proceedings of the 22nd Congress of the International Society of Biomechancs

7. B. Lovern, L.A. Stroud, J. Mahmud, S.P. Marsden, A. Kontaxis, G. R. Johnson, R.O. Evans, C.A. Holt and S.L. Evans, (2008) Using digital image correlation to measure scapula movement during shoulder motion, Proceedings of the '10th Meeting of the technical group on '3D Analysis of Human Movement' of the International Society of Biomechanics

8. B. Lovern, L.A. Stroud, N.A. Ferran, S.L. Evans, R.O. Evans and C.A. Holt, (2008), Motion analysis of the glenohumeral joint during activities of daily living, Proceedings of the '10th Meeting of the technical group on '3D Analysis of Human Movement' of the International Society of Biomechanics

9. Stroud LA, Lovern B, Jones L, Evans R, Evans SL, and Holt C, (2008), In vivo non-invasive measurements of scapula kinematics, Proceedings of the '10th

Meeting of the technical group on '3D Analysis of Human Movement' of the International Society of Biomechanics,

10. Lovern B., Evans R., Jones L, Evans S., Stroud L., Holt C., (2008), Use of passive markers vs. electromagnetic tracker and scapula locator in kinematic analysis of the shoulder complex. Proceedings of the 7th meeting of the International Shoulder Group, July 2008

11. Lovern B., Evans R., Jones L, Evans S., Stroud L., Holt C., (2008) Functional assessment of the shoulder complex using 3D motion analysis techniques. Proceedings of the 16th congress of the European Society of Biomechanics, July 2008

12. B. Lovern, L.A. Stroud, R.O. Evans N.A. Ferran, S.L. Evans, , L. Jones, C.A. Holt, 2008, 3d motion analysis of the glenohumeral joint: a comparison of maximal vs. functional range of motion, Proceedings of the British Elbow and Shoulder Society, June 2008

13. Lovern B., Evans R., Jones L, Evans S., Stroud L., Holt C., (2008) Error Evaluation of Skin-marker Movements in Motion Analysis of the Shoulder Complex, Proceedings of Institution of Mechanical Engineers, Engineering the Upper Limb Patient Specific Surgical Planning and Implementation, April 23-24 2008

14. Lovern B., Evans R., Jones L, Evans S., Stroud L., Holt C., (2008) Dynamic vs. Static Measurements in Motion Analysis of the Shoulder Complex, Proceedings of Institution of Mechanical Engineers, Engineering the Upper Limb Patient Specific Surgical Planning and Implementation, April 23-24 2008

15. Lovern B., Evans R., Jones L, Evans S., Stroud L., Holt C., (2008) In vivo measurements of the shoulder complex for use in musculoskeletal modelling. Extended proceedings of the 8th symposium of Computer Methods in Biomechanics and Biomedical Engineering, February 2008

16. Stroud, L; Lovern, B; Evans, R; Jones, L ; Evans, SL and Holt, C. (2008) Measuring scapula orientation during arm elevation. Extended proceedings of the 8th symposium of Computer Methods in Biomechanics and Biomedical Engineering, February 2008

17. Lovern B., Holt C., Evans S., Jones L., Stroud L., (2007) Error evaluation of skin-marker movements in motion analysis of the shoulder complex, Gait and Posture, Volume 26, Supplement 1, Proceedings of the 16th annual meeting of the European Society of Movement Analysis in Adults & Children, September 27-29 2007, ISSN 0966-6362 pg. S54

Dynamic tracking of the scapula using skin-mounted markers

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Abstract: The shoulder complex is prone to numerous pathologies and instabilities due to its large range of motion. The extent of injury is assessed through a series of observations and physical examinations. It is hypothesized that objective kinematic analysis of the shoulder could yield useful functional insights to aid clinical practice. Non-invasive motion analysis techniques to monitor shoulder function have been developed using passive markers; however, accurate measurement of scapula kinematics is problematic because of overlying tissue. The scapula locator is the accepted standard by which alternative non-invasive techniques of scapula tracking are validated. In this study, the viability of using skin-mounted markers to measure dynamic scapula movement is determined. Complete kinematic descriptions of ten healthy shoulders were obtained. Elevations of the glenohumeral joint were similar with both techniques, indicating that the skin marker method is suitable for gathering functional glenohumeral data. The main differences of note are seen at the scapulothoracic articulation where the skin marker method underestimated lateral rotation by more than 50° at maximum elevation. However, the correlation between the two approaches is greater than 0.7, suggesting that it may be possible to derive linear regression models to predict dynamic scapulothoracic lateral rotation accurately using skin-mounted scapula markers.

Keywords: shoulder, scapula, skin artefact, passive markers

1 INTRODUCTION

The shoulder complex consists of four articulations: the sternoclavicular (SC) joint; the acromioclavicular (AC) joint; the glenohumeral (GH) joint; and the scapulothoracic (ST) articulation. These four articulations act simultaneously to provide a greater range of motion (ROM) than any of the individual articulations and than any other joint complex in the human body. As a result of this extended ROM, the shoulder complex is inherently unstable and prone to a large variety of pathologies and injuries. Shoulder pathologies are diagnosed and monitored through a series of questionnaires, observations, and physical examinations, which combine to provide an overall score of functionality. There are more than 20 different clinical scores used to assess shoulder functionality [1]. These include the Oxford Shoulder Score [2, 3] (and the Oxford Shoulder Instability Score [4]), the Constant–Murley Score [5], and the American Shoulder and Elbow Surgeons Shoulder Score Index [6]. This method of assessment is problematic as there is no globally adopted standard, the correlations between different scores are low to moderate, and the assessments of function between different scores are not equivalent [1]. It is hypothesized that objective kinematic analysis of the shoulder complex could yield useful functional insights that may complement clinical practice pre and post-treatment.

The scapulothoracic articulation is responsible for approximately one third of the shoulder complex's full ROM [7]. Altered scapula kinematics can also be

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indicative of certain pathology types, e.g. increased lateral rotation, or 'winging' of the scapula in subjects with recurrent GH dislocations and abnormal scapulohumeral rhythm in patients with adhesive capsulities (frozen shoulder) [8]. Accurate *in-vivo* non-invasive measurement of the kinematics of the scapula is problematic because of the presence of overlying skin. Pronk [9] used a single-point locator attached to a three-dimensional spatial linkage instrument to determine the three-dimensional position of the acromial angle, the root of the scapular spine, and the inferior angle, and thus infer the orientation and position of the scapula. The method was found to be accurate but too time consuming, as the landmarks needed to be identified independently at each static increment of humeral elevation. Johnson *et al.* [10] expanded on this method by making the assumption that the scapula is a rigid body. They developed a three pointed palpator to determine the locations of the three landmarks simultaneously. The scapula locator has been applied since to numerous other studies [8, 11–13] and it has now become the 'gold standard' by which other non-invasive methods of scapula tracking are assessed and calibrated [14]. One limiting factor of the scapula locator is that it can only be used to take measurements of scapula orientation during static elevations. Dynamic scapulohumeral rhythm must then be inferred through linear regression equations for the arm-reachable workspace [15, 16]. Collecting the data necessary to establish the scapulohumeral rhythm for the arm-reachable workspace can be time consuming and, with patient groups where pain and fatigue are major factors, may not always be practical. The current study uses non-invasive opto-electronic motion analysis techniques to monitor shoulder function [17, 18]. Retro-reflective markers are attached to the bony landmarks of the four articulating segments of the shoulder complex. The trajectories of the markers

are tracked by eight Qualisys Pro-Reflex MCU 1000 cameras [19] with a sampling frequency of 60 Hz. Anatomical coordinate systems are generated and joint and segment rotations calculated according to the International Society of Biomechanics (ISB) recommendations [20]. In this study the viability of using skin-mounted markers to measure the dynamic movement of the scapula directly is assessed.

2 MATERIALS AND METHODS

2.1 Experimental protocols

Ten subjects (six males and four females of mean age 27.5 ± 5.1 years) with no previous history of shoulder pathology or instability were recruited for the study. Ethical approval for the study was granted by the Cardiff University Research Committee Ethics Panel and informed consent was obtained from each subject prior to the study. Retro-reflective markers were attached to the bony landmarks of the thorax, clavicle, scapula, humerus, and forearm of each subject's right arm as recommended by the ISB [20] (Fig. 1) (Table 1). The centre of GH rotation was estimated by linear regression [21] to provide a third
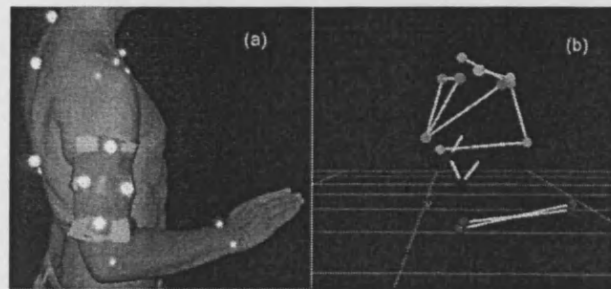

Fig. 1   (a) Subject posing in the neutral position wearing the upper-limb marker set with humerus marker cluster. (b) Qualisys Track Manager (QTM) software view of the subject

Table 1   Anatomical landmarks proposed by the ISB

Thorax	C7	Spinous process of the seventh cervical vertebra
	T8	Spinous process of the eighth thoracic vertebra
	IJ	Deepest point of Incisura Jugularis
	PX	Processus Xiphoideus, most caudal point on the sternum
Clavicle	SC	Most ventral point on the SC joint
	AC	Most dorsal point on the AC joint
Scapula	TS	Trigonium Spinae, the midpoint of the triangular surface on the medial border of the scapula in line with the scapular spine
	AI	Angulus Inferior, most caudal point of the scapula
	AA	Angulus Acromialis, most laterodorsal point of the scapula
	PC	Most ventral point of processus coracoideus
Humerus	GH	GH rotation centre (estimated)
	EL	Most caudal point on the lateral epicondyle
	EM	Most caudal point on the medial epicondyle
Forearm	RS	Most caudal–lateral point on the radial styloid
	US	Most caudal–medial point on the ulnar styloid

landmark to generate the humerus anatomical co-ordinate system (ACS). The humerus ACS was then related to a technical coordinate system (TCS) consisting of four markers (Fig. 1). Subjects performed incremental arm elevations in the coronal and sagittal planes. All elevations were performed with the arm straight and hand pronated.

A neutral-position anatomical calibration measurement was captured for 1 s at the start of each trial with the elbow flexed to 90° and the hand pronated (Fig. 1). An external reference frame fitted with retro-reflective markers was used to guide arm elevation in the different anatomical planes and to assist in post-experimental data acquisition (Fig. 2). Subjects performed each elevation in increments of 30° of the external frame. Static measurements were taken at each increment using a scapula locator with markers attached to represent each of the three scapula bony landmarks (Fig. 3(a)). Individual skin-mounted markers were then attached to each of the scapula bony landmarks (Fig. 3(b)) with the subject in a neutral-position measurement (Fig. 1(a)). Elevations in the coronal and sagittal planes were then repeated dynamically using skin-mounted markers.
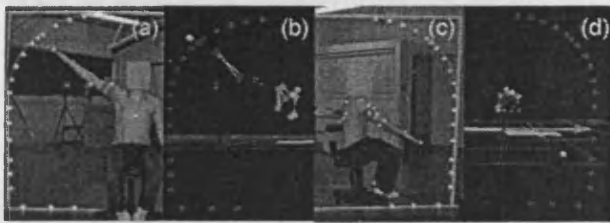
Fig. 2 Elevation of the arm by the subject using the frame for guidance: (a) coronal plane elevation in the real view; (b) coronal plane elevation in the QTM view; (c) sagittal plane elevation in the real view; (d) sagittal plane elevation in the QTM view
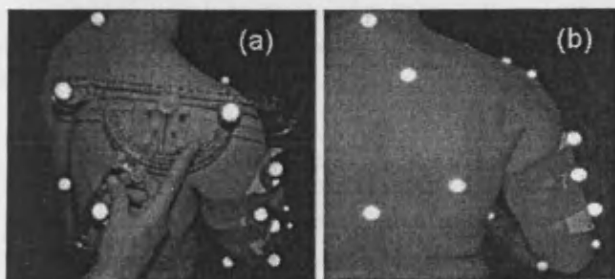
Fig. 3 (a) Scapula locator with markers attached used to measure the spatial orientation of the scapula; (b) skin markers used to identify the bony landmarks of the scapula

2.2 Data Processing

The static data collected with the scapula locator was used in a similar manner to previous studies [15, 16] to generate multiple linear regression models which predict scapula orientation during dynamic movements based on the position of the humerus relative to the thorax. Joint rotations for the AC joint, the GH joint, and the ST articulation were evaluated at each value of humerothoracic elevation, to allow comparison with the data collected dynamically using the skin-mounted scapula markers. Polynomial fits of order two to seven were fitted to the data sets generated by the ten subjects. The order of the polynomial fits were chosen to maximize the coefficient of determination values R^2 in each case, which indicate the proportion of variability in each data set that is accounted for by its associated model. The order of the polynomial fits and the R^2 values can be found in Table 2. Paired sample t tests ($p = 0.05$) were used to compare the rotations measured with each method during coronal and sagittal plane elevation, with the exception of plane of elevation and axial rotation of the GH joint, which were compared using the Wilcoxon signed-rank test, as their difference variables were not normally distributed.

3 RESULTS

Complete kinematic descriptions of the shoulder complex were obtained for the ten shoulders during elevations in the coronal and sagittal planes. To maintain consistency, all rotations are plotted against elevation of the humerus relative to the thorax. Polynomials were fitted to the data sets generated by the ten subjects (Table 2), similar to previous studies [8, 11]. A full set of rotations for the thorax relative to the global coordinate system (GCS), the SC joint, the AC joint, the GH joint, and the ST articulation are shown for coronal plane elevation (Fig. 4) and sagittal plane elevation (Fig. 5). Solid curves represent the dynamic rotations measured directly with the skin-mounted markers. Dashed curves represent the predicted rotations using multiple linear regression models based on static measurements with the scapula locator.

For the thorax relative to the GCS and for the SC joint, only the data collected during the skin-mounted marker trial are shown, as these rotations are unaltered by the different methods of measuring scapula orientation. It is not possible to measure axial rotation of the SC joint as only two landmarks

Table 2 R^2 values for the polynomial fits to the angles describing the rotations of the thorax relative to the GCS, the SC joint, the AC joint, the GH joint, and the ST articulation during humeral elevation in the coronal and sagittals plane for ten subjects as measured with the scapula locator and scapula-mounted skin markers. The values in parentheses represent the order of the polynomial used (see also Figs 4 and 5)

System Measurement method	Angle describing the rotation R^2					
	Abduction			Flexion		
Thorax relative to GCS	Flexion–extension	Lateral flexion	Axial rotation	Flexion–extension	Lateral flexion	Axial rotation
Skin markers	0.0671 (4)	0.9515 (5)	0.7271 (4)	0.9672 (2)	0.4372 (4)	0.751 (2)
SC joint	Retraction	Elevation	Axial rotation	Retraction	Elevation	Axial rotation
Skin markers	0.969 (2)	0.9346 (5)	N/A	0.9152 (5)	0.9533 (2)	N/A
AC joint	Protraction	Lateral rotation	Anterior–posterior tilt	Protraction	Lateral rotation	Anterior–posterior tilt
Scapula locator	0.8898 (5)	0.9983 (5)	0.9361 (2)	0.9435 (5)	0.9961 (5)	0.9762 (4)
Skin markers	0.9658 (3)	0.9521 (4)	0.9663 (3)	0.7202 (4)	0.9579 (5)	0.9595 (2)
GH joint	Plane of elevation	Elevation	External rotation	Plane of elevation	Elevation	External rotation
Scapula locator	0.8898 (5)	0.9976 (7)	0.9957 (5)	0.9558 (3)	0.9989 (7)	0.8937 (3)
Skin markers	0.2676 (6)	0.9877 (5)	0.7964 (5)	0.1342 (5)	0.9741 (4)	0.6974 (4)
ST articulation	Protraction	Lateral rotation	Anterior–posterior tilt	Protraction	Lateral rotation	Anterior–posterior tilt
Scapula locator	0.9467 (5)	0.9967 (5)	N/A*	0.8619 (3)	0.9946 (4)	0.8672 (7)
Skin markers	0.7521 (5)	0.9434 (4)	0.9474 (2)	0.7291 (3)	0.9686 (3)	0.9236 (2)

*N/A, not available.

on the clavicle can be palpated. For anterior tilt of the ST articulation during coronal plane elevation, only the skin marker data are presented, as it was not possible to generate a significant regression model using the scapula locator data.

The coefficient of determination values R^2 for each polynomial fit are shown in Table 2 to indicate the proportion of variability in each data set that is accounted for by its associated polynomial fit. Correlation values for each rotation as measured by the two different methods are given in Table 3. The measured ROMs and kinematic waveforms appeared to be comparable in many cases; however, the paired sample t tests and Wilcoxon signed-rank tests found that there was a statistically significant difference between measurements with the scapula locator and the skin-mounted markers for every rotation during both elevations. The salient features to note when comparing the rotations measured, using the scapula locator and the skin-mounted markers, are as follows.

For the AC joint:

1. For coronal plane elevation, an offset of 60° was observed for protraction. For sagittal plane elevation, the kinematic waveforms for protraction as measured with each method were different. The skin marker method measured a ROM of 10°, while the scapula locator measured a ROM of 60°.

2. During coronal and sagittal plane elevations, the measured lateral rotation began to deviate after arm elevation of 20°. The skin markers underestimated the rotation by over 50° as full arm elevation was reached.

3. Anterior–posterior tilt during coronal plane elevation displayed an initial offset of approximately 7°, which increased to 16° at full arm elevation. This resulted in underestimation of the ROM by the skin-marker method. During sagittal plane elevation, anterior–posterior tilt ROM was underestimated by the skin marker method from an arm elevation of 20° upwards, reaching a maximum difference of just over 60° at full arm elevation.

For the GH joint:

1. The main discrepancy when measuring the plane of elevation of the GH joint during elevation in the coronal and sagittal planes was caused by gimbal lock. This caused an offset greater than 40° for coronal plane elevation. During sagittal plane elevation the skin marker method showed an erratic kinematic profile with maximum offsets of approximately 60°.

2. Elevation profiles and ROMs in the coronal plane displayed an offset of approximately 30° throughout the majority of the movement. During sagittal plane elevation the arm elevation had an offset of approximately 10° up to 70°, after which the two waveforms began to diverge. By maximum arm elevation, the skin marker method underestimated elevation by approximately 35°.
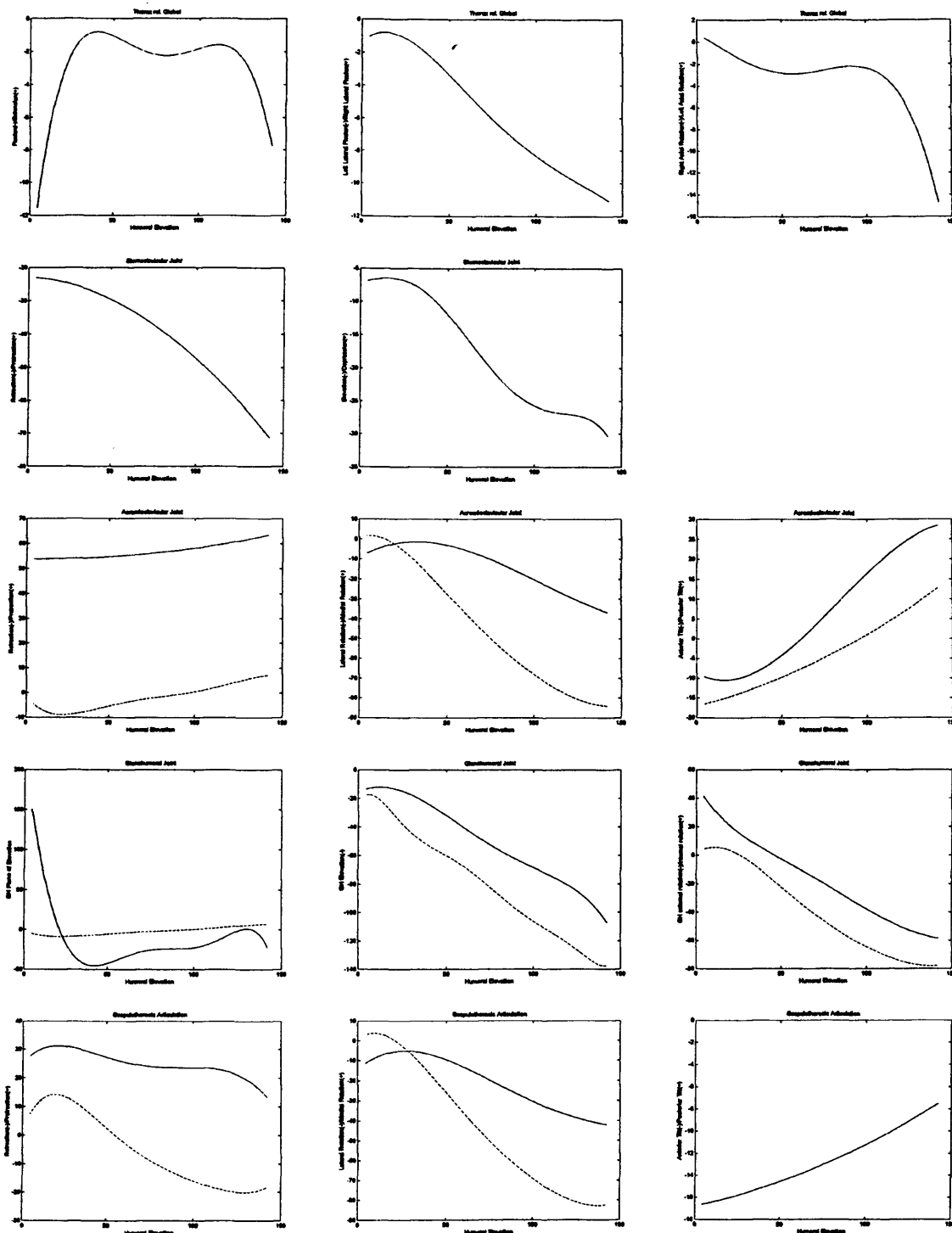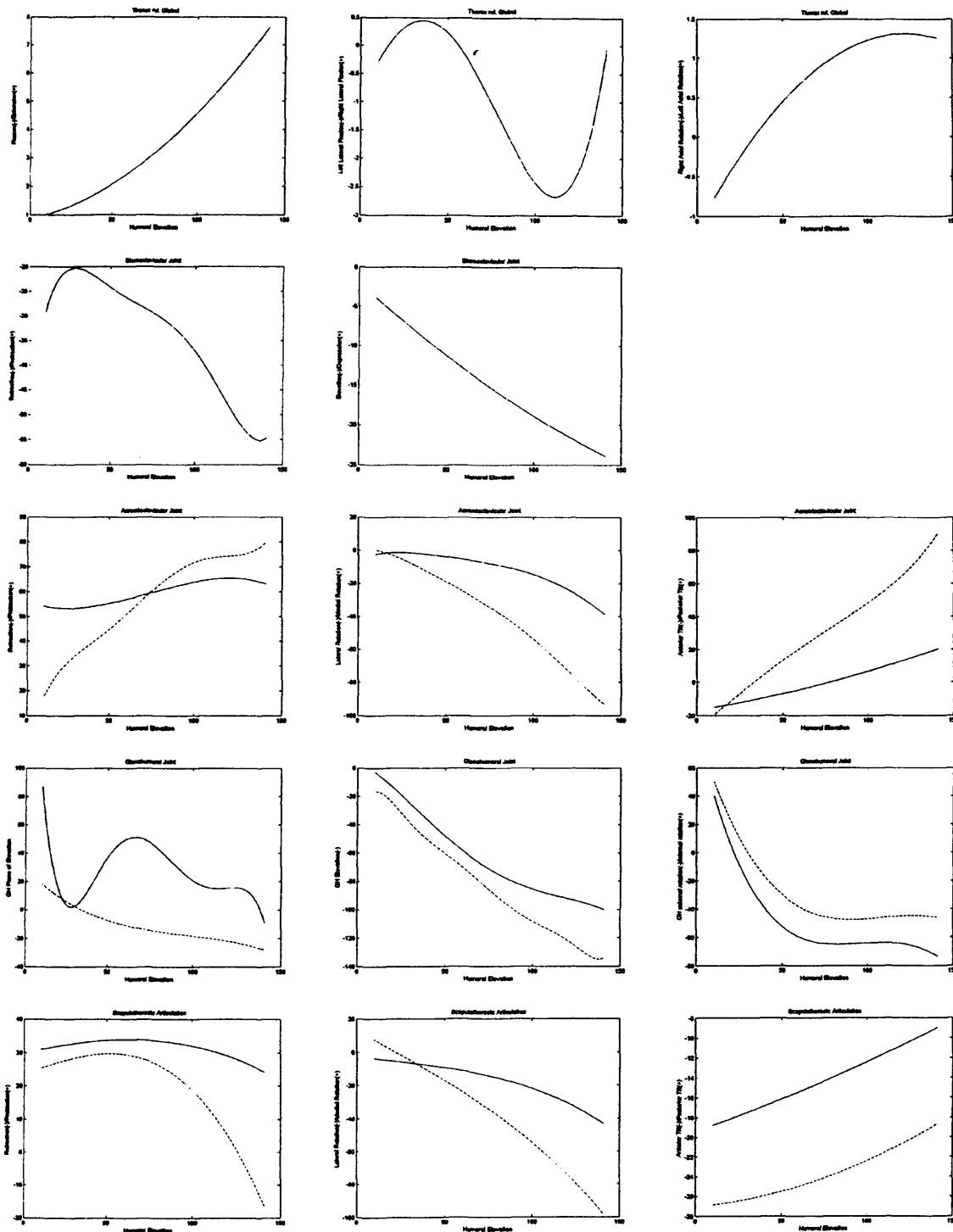
Fig. 4 Polynomial fits to the angles describing the rotations of the thorax relative to the GCS: the SC joint, the AC joint, the GH joint, and the ST articulation from a data set of ten healthy shoulders during sagittal plane elevation. Subjects have the elbow extended and the hand pronated. Solid lines: dynamic measurements with skin-mounted scapula markers. Dashed lines: dynamic motion profiles estimated through multiple linear regression based on static measurements taken with the scapula locator. All rotations measured in degrees

Fig. 5 Polynomial fits to the angles describing the rotations of the thorax relative to the GCS: the SC joint, the AC joint, the GH joint, and the ST articulation from a data set of ten healthy shoulders during coronal plane elevation. Subjects have the elbow extended and the hand pronated. Solid lines: dynamic measurements with skin-mounted scapula markers. Dashed lines: dynamic motion profiles estimated through multiple linear regression based on static measurements taken with the scapula locator. All rotations measured in degrees

Table 3 Pearson (or Spearman*) correlation values between the angles describing the rotations of the AC joint, the GH joint, and the ST articulation with the scapula locator (and regression equations) and dynamically with the skin-mounted markers during humeral elevation in the coronal plane and sagittal plane

System Correlation	Angle describing the rotation Pearson (or Spearman*) correlation value					
	Abduction			Flexion		
AC Joint	Protraction	Lateral rotation	Anterior–posterior tilt	Protraction	Lateral rotation	Anterior–posterior tilt
Correlation	0.463	0.624	0.776	0.471	0.745	0.905
GH Joint	Elevation plane	Elevation	External rotation	Elevation plane	Elevation	External rotation
Correlation	0.416*	0.923	0.693*	0.071*	0.955	0.82*
ST articulation	Protraction	Lateral rotation	Anterior–posterior tilt	Protraction	Lateral rotation	Anterior–posterior tilt
Correlation	0.164	0.726	N/A	0.367	0.777	0.56

3. When measuring axial rotation, an offset of 25° is observed for coronal plane elevation. During sagittal plane elevation there was an initial offset of 10°, which gradually increased to 20° by full arm elevation.

For the ST articulation:

1. There was an offset of 5° between the two methods when measuring protraction during sagittal plane elevation, up to an arm elevation of approximately 75°. For higher elevations the two kinematic profiles deviate, causing the skin marker method to underestimate the ROM by approximately 40° by full arm elevation. During coronal plane elevation, there was an initial offset of 17° which gradually increased to 25° at full arm elevation.

2. Lateral rotation measured by the skin markers produced different motion profiles during both coronal and sagittal plane elevation. In both cases the measured ROMs were underestimated by the skin marker method by more than 50°.

3. It was not possible to compare anterior tilt during coronal plane elevation as a significant regression model could not be generated from the scapula locator data. During sagittal plane elevation, both methods measured similar ROMs, with a 10° offset.

4 DISCUSSION

The scapula locator is regarded as the optimum method for tracking the movement of the scapula non-invasively [14]. This study objectively explores the motion profiles of the shoulder complex using both the gold standard (the scapula locator), and a simplified option of placing markers directly over the scapula bony landmarks. The aim of this was to determine whether skin markers could be used

to track dynamic movement of the scapula directly, and thus to reduce experimental times considerably. Complete kinematic descriptions of the shoulder were obtained for the ten subjects using both methods of scapula tracking. The recorded motion patterns and ROMs are comparable with those reported in the literature [8, 11] with the exception of the AC joint, particularly lateral rotation, which was between ten and 15 times larger for both movements. As it is only possible to palpate two bony landmarks on the clavicle, it is not possible to measure axial rotation of the clavicle directly. The previous studies estimated clavicle axial rotation by minimizing the rotations at the AC joint. This is feasible because the longitudinal axis of the clavicle is almost perpendicular to the scapular plane, meaning that axial rotation of the clavicle and lateral rotation of the scapula in the scapular plane are equivalent [22]. As the current study does not estimate clavicle axial rotation, the lateral rotations of the AC joint in the scapular plane are approximately equal to the sum of clavicle axial rotation and AC joint lateral rotation as measured in the previous studies. By applying a clavicle axial rotation of 60°, it is possible to reduce AC joint rotations to less than 10° [9].

In clinical practice, accurate measurement of the lateral rotation of the ST articulation is important as it can be indicative of certain pathology types [8]. The results indicate that the skin marker method is unsuitable for assessing ST lateral rotation. However, there is a correlation of 0.726 and 0.787 for coronal and sagittal plane elevation respectively between the two methods when measuring ST lateral rotation (Table 3). This would suggest that it is possible to derive further multiple linear regression models to predict ST lateral rotation accurately with the skin marker methods.

The simplified scapula marker set was found to be particularly useful for assessing GH elevation (Table 3). However, measurements of the GH plane of

elevation with the skin marker method were hampered by gimbal lock. Gimbal lock occurs when two of the three rotational axes of the GH joint are aligned with their pivot axes in a single plane. When this occurs, it is no longer possible to represent the orientation of the GH joint. This is likely to occur at low and high humeral elevations. Owing to gimbal lock, there is an offset of 50° between the two methods during coronal plane elevation, and the R^2 values of the polynomial fits are low.

The study is further limited as the volunteers were primarily young and slim. The use of skin markers to track the movement of the scapula would be less feasible with an obese population. Alternative methods of dynamic scapula tracking are thus being developed. A TCS placed on the acromion plateau of the scapula has been found to be reliable when tracking dynamic movement of the scapula up to elevations of 120° [23] but it is recommended to calibrate it statically against the scapula locator at the start of each trial [14].

In conclusion, this study has shown that, while there are differences in the observed rotations of the shoulder complex when measured with skin-mounted markers in place of a scapula locator, these differences are well defined in most cases, meaning that, with careful consideration, the skin-marker method may be used for measuring three-dimensional shoulder positions quickly and dynamically.

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Motion analysis of the glenohumeral joint during activities of daily living

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The shoulder complex has a larger range of motion (ROM) than any other joint complex in the human body, leaving it prone to numerous injuries. Objective kinematic analysis could yield useful functional insights that may assist clinical practice. Non-invasive optoelectronic motion analysis techniques have been used to assess the shoulders of five healthy subjects performing ROM tasks and 10 functional tasks of daily living. The four most demanding tasks – touching the side and back of the head, brushing the opposite side of the head, lifting an object to shoulder height and lifting an object to head height, required 78%, 60%, 61% and 71%, respectively, of the glenohumeral elevation necessary for full abduction in the scapular plane for the 10 shoulders. This has implications for clinical practice where maximum arm elevation is commonly used to determine a patient's ability to return to work and other everyday activities.

Keywords: shoulder; activities of daily living; range of motion; glenohumeral

1.   Introduction

The shoulder complex consists of four articulations: the sternoclavicular joint, the acromioclavicular joint, the glenohumeral joint; and the scapulothoracic articulation which act synchronously to provide a larger range of motion (ROM) than any of the individual articulations alone and than any other joint complex in the human body. This extended ROM leaves the shoulder susceptible to numerous pathologies, injuries and instabilities such as impingement, rotator cuff tears, acromioclavicular dislocation and glenohumeral dislocation/subluxation. Orthopaedic surgeons use a series of questionnaires, observations and physical examinations to determine the extent of the injury and provide an overall score of functionality. This method of assessment is problematic as there are over 20 different upper limb clinical scores in use with no globally adopted standard. Many of the scores contain redundant information (Kirkley et al. 2003; Placzek et al. 2004b) and are not equivalent in their assessment of functionality (Placzek et al. 2004b). Among the more commonly used scores are the constant score (Constant and Murley 1987) and the American shoulder and elbow surgeons shoulder score index (ASES) (Richards et al. 1994). The correlation between the constant and ASES scores with a sample group of 70 patients were 0.495, with a coefficient of determination of 0.245, meaning that one scale explains less than 25% of the variance in the other, rendering cross-scale comparisons meaningless (Placzek et al. 2004b). Age is also a confounding variable, particularly when applying the

constant score (Placzek et al. 2004b). When assessing the functionality of the upper limb, the disability of the arm, shoulder and hand (DASH) questionnaire (Hudak et al. 1996) is often used. This is a self-administered questionnaire designed to measure physical function and symptoms of several musculoskeletal disorders of the upper limb. DASH has been found to be a reliable and valid instrument for assessing shoulder disorders (Fayad et al. 2008) but has been criticised for redundancy in its questions and for not including interviews with patients with the conditions of interest during the item generation phase (Kirkley et al. 2003), as physician interpretation of disability consistently differs from patient perception (Haworth et al. 1981; Lieberman et al. 1996; Dowrick et al. 2006).

Soft tissue involvement and the range of possible pathologies make accurate diagnosis and prognosis through clinical consultations alone difficult. Ultrasound or magnetic resonance imaging (MRI) scans are often necessary for confirmation, e.g. to determine the size and extent of rotator cuff tears. This can prove costly and increase waiting times by three months (ultrasound) or up to nine months (MRI) in the UK.

It is believed that objective kinematic analysis of the shoulder complex could yield useful insights into its functionality that may assist clinical practice by providing new and more effective assessments that can be implemented easily in the clinical setting.

As it is not practical to assess every patient reporting to shoulder clinic in a motion lab, the aim of this study was

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Table 1. Activities of daily living (Murray and Johnson 2004).

Reach to opposite axilla	Drink from mug
Reach to opposite side of neck	Answer telephone
Reach to side and back of head	Brush opposite side of head
Eat with hand to mouth	Lift block (20 N) to shoulder height
Eat with spoon	Lift block (20 N) to head height

to extract a single or small number of objective measures which can be used in an everyday clinical setting without the need for specialised equipment. This study serves as a proof of concept by focusing exclusively on the required elevation of the glenohumeral joint in healthy subjects during maximum arm elevation and activities of daily living (ADL).

The standardised tasks of the Newcastle shoulder Group (Table 1; Murray and Johnson 2004) were chosen after consultation with an upper limb orthopaedic consultant as they cover a general range of daily activities necessary for independent living which are considered relevant to the majority of subjects. The activities are related to personal hygiene, feeding and handling of everyday objects. The data collected can also be used as inputs for future collaboration with the Newcastle shoulder musculoskeletal model (Charlton and Johnson 2006).

Following from lower limb function where the hip, knee and ankle have a substantially larger normal physiological ROM than that required during gait (Gerhardt and Rippstein 1990), it is further hypothesised by the authors that common upper limb ADL can be performed without the capacity for full physiological ROM of the glenohumeral joint.

2. Materials and methods

2.1 Experimental protocols

Five right-arm dominant subjects (M:F, 2:3; mean age 23 ± 1 year) with no previous history of pathology or instability in either shoulder were assessed for full ROM and 10 functional tasks of daily living (Table 1; Murray and Johnson 2004) for each arm. All subjects were instructed to perform the tasks at a speed and manner with which they felt comfortable. Each shoulder was assessed unilaterally with retro-reflective markers attached to the bony landmarks of the four articulating segments of the shoulder complex (including the scapula, see Lovern et al. (2009) for full description of marker positioning). Eight Qualisys Pro-Reflex MCU 1000 cameras[1] with a sampling rate of 60 Hz were used to track the marker trajectories. To provide a cyclical nature to the tasks, each task began and finished in the 'neutral position'. The neutral position is defined as the arm by the side, elbow flexed to 90° and hand pronated (Figure 1). Abduction and scapular plane abduction were performed unilaterally with the hand supinated. Forward flexion was performed unilaterally with the hand pronated.

Ethical approval for the study was granted by the University Research Committee Ethics Panel and informed consent was obtained from each subject prior to the study.

2.2 Data processing

Anatomical coordinate systems were generated for each subject, and joint and segment rotations were calculated according to the recommendations of the International Society of Biomechanics (Wu et al. 2005). The centre of glenohumeral rotation was calculated using linear
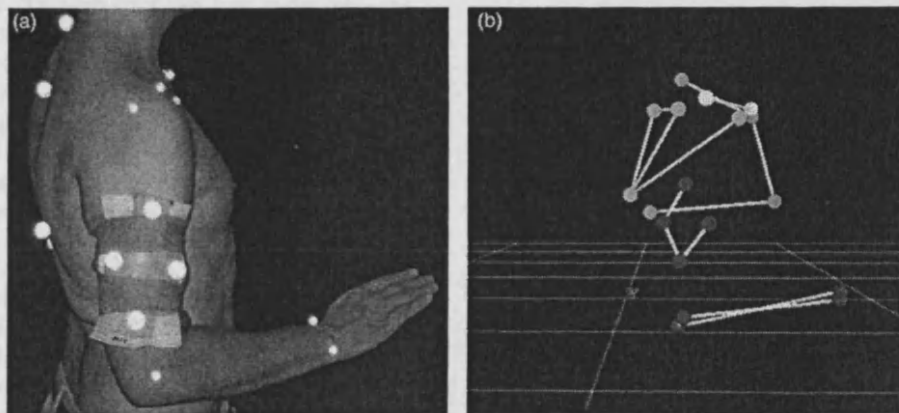

Figure 1. (a) Subject in neutral position fitted with upper limb marker set used to analyse the kinematics of the shoulder complex. (b) Qualisys view of subject.

regression equations (Meskers et al. 1998). The anatomical coordinate system of the humerus was related to a technical coordinate system (TCS) on the lateral humerus which was used to track dynamic humerus movements.

Paired sample t-tests ($p = .05$) were used to compare the level of glenohumeral elevation necessary to perform each task with the left and right shoulders, with the exception of elevation in the frontal plane. A Wilcoxon signed-rank test was instead used, as the difference variable was not normally distributed. The same tests were also used to compare the level of glenohumeral elevation necessary to perform full elevation in the scapular plane and to perform each task.

The difference variable for each task was assessed for normality based on the values of the mean, median, skew and kurtosis. Normality was accepted if the mean was approximately equal to the median, and if the skew and kurtosis were between -1 and $+1$. In cases where the skew and kurtosis were between -3 and -1 or between $+1$ and $+3$, then normality was accepted with caution.

3. Results

Complete kinematic descriptions of the shoulder were obtained for the 10 shoulders during abduction, scapular plane abduction, flexion and the 10 tasks of daily living. The glenohumeral elevation required to perform each of the tasks with the right arm, the left arm and the mean of both arms is presented in Table 2.

The four most demanding tasks were touching the side and back of the head, brushing the opposite side of the head, lifting an object to shoulder height and lifting an object to head height, as can be seen in Figure 2. To perform these four tasks with the right arm required 74%, 58%, 58% and 70%, respectively, of the glenohumeral elevation required for full elevation in the scapular plane. To perform these four tasks with the left arm required 83%, 62%, 64% and 72% respectively of the glenohumeral elevation required for full elevation in the scapular plane.

The mean glenohumeral elevation required to perform each task with the left and right arms was compared using paired sample t-tests on the normally distributed data and the Wilcoxon signed-rank test on the non-normal data. The tests revealed that only one of the tasks, touching the side and back of the head (right arm, 72.59 ± 8.77 and left arm, 82.11 ± 8.48; $p = .001$), showed a statistically significant difference (Table 2) between left and right shoulders. They also found a significant difference in the glenohumeral elevation required for full scapular abduction and to touch the side and back of the head (the task that required the largest elevation) for both the left and right ($p = .05$) shoulders.

Table 2. Glenohumeral elevation (°) required to perform a series of ROM tasks and ADL with the left and right arms ($n = 5$) and the left and right arms combined ($n = 10$).

Task	Arm	Mean $\pm$ SD (°)
Abduction	Right	94.92 $\pm$ 6.17
	Left	98.65 $\pm$ 4.84
	Combined	96.79 $\pm$ 5.59
Scapular abduction	Right	98.82 $\pm$ 6.38
	Left	98.84 $\pm$ 3.65
	Combined	98.83 $\pm$ 4.9
Flexion	Right	97.2 $\pm$ 5.75
	Left	99.36 $\pm$ 5.42
	Combined	98.28 $\pm$ 5.39
Reach opposite axilla	Right	32.36 $\pm$ 10.61
	Left	35.81 $\pm$ 5.54
	Combined	34.08 $\pm$ 8.18
Reach opposite side of neck	Right	50.39 $\pm$ 8.54
	Left	53.63 $\pm$ 5.84
	Combined	52.01 $\pm$ 7.1
Touch side and back of head	Right	72.59 $\pm$ 8.77
	Left	82.11 $\pm$ 8.48
	Combined	77.35 $\pm$ 9.56
Eat with hand to mouth	Right	34.13 $\pm$ 8.32
	Left	36.89 $\pm$ 10
	Combined	35.51 $\pm$ 8.79
Eat with spoon	Right	39.57 $\pm$ 7.13
	Left	45.94 $\pm$ 6.95
	Combined	42.75 $\pm$ 7.44
Drink from mug	Right	32.47 $\pm$ 4.99
	Left	33.57 $\pm$ 12.36
	Combined	33.02 $\pm$ 8.9
Answer telephone	Right	37.36 $\pm$ 10.22
	Left	36.62 $\pm$ 4.6
	Combined	36.99 $\pm$ 7.48
Brush opposite side of head	Right	57.3 $\pm$ 12.29
	Left	60.86 $\pm$ 5.27
	Combined	59.08 $\pm$ 9.11
Lift block to shoulder height	Right	56.98 $\pm$ 12.51
	Left	63.09 $\pm$ 5.29
	Combined	60.04 $\pm$ 9.61
Lift block to head height	Right	68.83 $\pm$ 9.84
	Left	70.93 $\pm$ 7.54
	Combined	69.78 $\pm$ 8.35

4. Discussion

This study objectively explores the required elevation of the glenohumeral joint in healthy subjects during maximum arm elevation and ADL. The results show that to perform the most demanding task, touching the side and back of the head, 83% of maximum glenohumeral elevation is required in the left arm and 73% is required in the right arm. Analysis of this sort may prove useful to clinicians by providing information on the function of the healthy shoulder, providing a baseline when assessing patients both pre- and post-surgery. This also has implications for litigation cases and insurance settlements as a patient's ability to perform maximum elevation is commonly assessed as an indicator of their ability to return

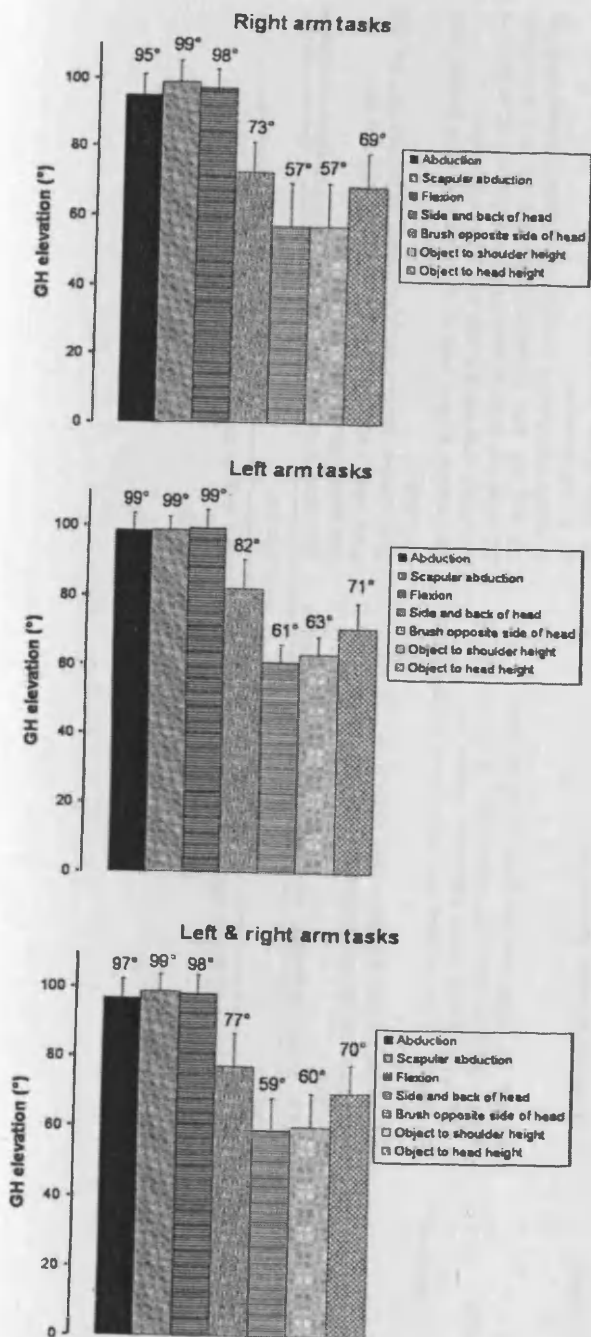4   B. Lovern et al.

Figure 2. Average glenohumeral elevation required by five subjects to perform abduction, scapular abduction, flexion, touching the side and back of the head, brushing the opposite side of the head, lift a 20 N object to shoulder height and lift a 20 N object to head height. (a) Right arm ($n = 5$), (b) left arm ($n = 5$) and (c) average of both arms ($n = 10$).

to physical activity. These results show that this is not necessarily representative of a patient's ability to perform everyday functional tasks and that more objective assessments may be beneficial. These findings are similar to studies of the lower limb which have shown that the functional ROM required of the hip, knee and ankle during walking and sitting is substantially lower than the normal values obtainable in healthy subjects (Gerhardt and Rippstein 1990). The results also indicate that arm dominance may possibly affect a subject's resulting kinematic waveforms when performing particular tasks. This may affect clinical scores which do not take into account a patient's dominant side (Placzek et al. 2004a).

Kinematic assessment of the upper limb and inter-study comparisons are difficult when compared to gait analysis due to the large range of path-dependant motions of the articulations and the numerous unstandardised tasks measured (Hill et al. 2007). Kinematic modelling of the upper limb requires *in vivo* data on the most frequently performed tasks. Unlike gait analysis, this requires careful selection of the activities believed to be most common and relevant (Murray and Johnson 2004). This can be very subjective as what is deemed important to one individual is of no significance to another, based on factors such as age, occupation, level of physical/sporting activity and even the ergonomic factors of an individual household or work-place. This level of subjectivity is reflected in the wide range of activities assessed in various studies (Safaee-Rad et al. 1990; Yang et al. 2002; Murray and Johnson 2004; Ohta et al. 2004; Magermans et al. 2005; Carey et al. 2008; van Andel et al. 2008).

The second difficulty encountered during kinematic assessment of the upper limb is accurate measurement of the movement of the scapula. The 'gold standard' for measurement of the kinematics of the scapula is the scapula locator (Johnson et al. 1993). The main limitation of the scapula locator is that it can only be used to take static measurements of scapula orientation. Dynamic scapulohumeral rhythm must then be inferred through linear regression models. Previous studies have found that the scapulohumeral rhythm of healthy subjects is predictable (Barnett et al. 1999; de Groot and Brand 2001), but this assumption cannot be made with patient cohorts. The scapulohumeral rhythm for each patient must be determined independently by measuring the scapula orientation for different levels and planes of arm elevation. This can be very time consuming, and where pain and fatigue are major concerns, may not always be practical. A previous study by Lovern et al. (2009) has assessed the viability of using markers placed directly on the scapula bony landmarks to measure dynamic scapula rotations directly, and thus reduce the measurement time consider-ably. The study concluded that for arm elevations close to flexion (as most of the ADL in this study are), the use of skin markers was a good approximation to the results obtained with a scapula locator, particularly up to 80° of arm elevation. A summary of the study's results is shown in Table 3.

Table 3. Summary of the findings of a previous paper (Lovern et al. 2009) which compares the usage of skin-mounted scapula markers with a scapula locator.

Articulation	Rotation	Abduction	Flexion
Acromioclavicular joint	Protraction	Similar ROM measured with both methods. 60° offset throughout	Skin marker method displayed different kinematic waveforms and underestimated ROM by 50°
	Lateral rotation	Skin marker method underestimated full ROM by 50°	Skin marker method underestimated full ROM by 50°
	Ant./post.	Skin marker method underestimated ROM by 9°	Skin marker method underestimated ROM by 60° for full elevation
Glenohumeral joint	Plane of elevation	Skin marker method seemed to be more prone to gimbal lock, as a result displaying erratic kinematic waveforms	Skin marker method seemed to be more prone to gimbal lock, as a result displaying erratic kinematic waveforms
	Elevation	Slightly different kinematic waveforms up to 20° of arm elevation. 30° offset from this point to full elevation	10° offset but with the same ROM measurement up to between 70° and 80° arm elevation. After this the two waveforms diverged, with the skin marker method underestimated ROM by 25° by full elevation
	Axial rotation	20° offset throughout of movement	10° offset at rest. Waveforms eventually diverge to an offset of 20–25°, with the skin marker method overestimated the rotation
Sternoclavicular articulation	Protraction	Offset of 17° at rest, eventually increasing to 25°. Skin marker method underestimated ROM by 8°	5° offset up to 75° of arm elevation. Skin marker method underestimated ROM by 40° by full arm elevation
	Lateral	The two methods give different kinematic waveforms, with the skin marker method underestimated the ROM by 50°	The two methods give different kinematic waveforms, with the skin marker method underestimated the ROM by 50°
	Ant./post.	No comparison available	8–10° offset throughout the movement

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A previous study by Magermans et al. (2005) used a six degrees-of-freedom electromagnetic tracking device to obtain 3D descriptions of the ROM and ADL of the shoulder and elbow. Due to the inherent difficulties in dynamic tracking of the scapula, the measurements were taken in an incremental quasi-static mode. This allowed for high accuracy in the measured joint rotations, but is very time consuming and not truly representative of the manner in which ADL are performed in everyday situations. This study found that during scapular plane abduction and forward flexion, arm elevation was brought about by approximately 80° glenohumeral elevation, compared to approximately 99° in this study. Conversely, this study recorded lower levels of glenohumeral elevation during each of the comparable ADL (touching the opposite axilla, eating with a spoon and combing the hair).

A more recent study by van Andel et al. (2008) used an active LED-marker motion capture system with three cameras to assess 10 healthy subjects. The protocol consisted of four ADL and six ROM tasks. The dynamic movement of the scapula was tracked using an acromion marker cluster, which has been found to be reliable for arm elevations up to 120° (Karduna et al. 2001; Meskers et al. 2007), but it is recommended not to exceed arm elevations of 100° (van Andel et al. 2009). Of the four ADL tasks assessed, three of them are directly comparable with ADL assessed in this study: hand to contra lateral shoulder, hand to mouth (drinking) and combing the hair. All humerus-related results are reported relative to the thorax, which make direct comparisons with this study difficult. Notably in this study, these tasks were among the least challenging performed by the subjects. The aim of the study was to develop a standardisation protocol for 3D motion capture of the upper extremity for clinical application which would form the basis for the development of an upper extremity analysis report, the upper limb equivalent of the gait analysis report.

The above studies by Magermans et al. and van Andel et al. aimed to develop upper limb motion analysis as a clinical tool for everyday use, to assist with diagnosis and prognosis. This study differed as it wished to use the knowledge learned from motion capture to complement current clinical assessments, where motion capture facilities may not be readily available.

This study is limited as it does not report elbow angles during the ADL. Elbow flexion alone is a strong indicator of a patient's ability to perform a particular ADL (Magermans et al. 2005). It is further limited by the use of skin markers on the scapula. It has been shown that this method of scapula tracking underestimates lateral rotation of the scapulothoracic articulation by approximately 50° when compared with a scapula locator (Lovern et al. 2009). Thus, compensatory motions of the acromioclavicular joint and the scapulothoracic articulation could not be accurately reported. In some settings, however, both

research (Cutti et al. 2005) and clinical (Garofalo et al. 2009), it may be useful to assess motion of the arm only, without considering the motions of the clavicle and scapula.

This study only tells a partial story, but the findings warrant further investigations to determine what are the key ROM and ADL tasks which need to be assessed to differentiate healthy shoulder cohorts from pathological cohorts.

Future studies will focus on more accurate representation of dynamic scapular movement, particularly during ADL. Alternative methods of calculating the glenohumeral rotation centre are also being considered. The instantaneous helical axis (IHA) method (Woltring 1990) has been found to be more accurate and suitable for testing pathologies, where the relationship between the scapula and the humerus has been altered (Stokdijk et al. 2000) and is the recommended method of the International Shoulder Group[2]. The SCoRE method (Ehrig et al. 2006) is also being considered as it has been found to give similar results to the IHA method *in vivo* but with a smaller error range and it is not affected by movements with slow velocities (Monnet et al. 2007). The TCS which is used to track dynamic movements of the humerus is currently being studied. The current TCS consists of a four-marker cluster (Figure 1) which is unsuitable for measuring axial rotation not only due to soft tissue artefacts (Cutti et al. 2005) but also due to the rigid shape of the TCS which causes the triceps muscle to impede its movement with the humerus during rotation. It is believed that a TCS derived from markers placed on the deltoid insertion, the insertion of the brachioradialis and the biceps belly will provide a more accurate representation of axial rotation and allow compensatory techniques for soft tissue artefacts to be implemented.

In conclusion, it has been shown that there is a substantial excess capacity of the glenohumeral joint that is not used during the majority of daily activities. Loss of this excess ROM should not affect an individual's ability to perform a range of everyday tasks.

Notes

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USING DIGITAL IMAGE CORRELATION TO MEASURE SCAPULA MOVEMENT DURING SHOULDER MOTION

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INTRODUCTION

Non-invasive motion analysis techniques to monitor shoulder function have been developed using passive retro-reflective markers. Accurate measurement of the kinematics of the scapula is problematic due to the presence of overlying skin. In this study Digital Image Correlation (D.I.C.), a non-contact method of providing three-dimensional shape and deformation of a surface area, has been used to track the movement of an applied surface pattern on the scapula during arm elevation.

METHODS

Five male subjects with no previous history of shoulder pathology were assessed during elevation. Speckled face paint was applied to the area of interest (Fig. 1). Subjects were instructed to raise their arms in the frontal plane at a self determined speed. Multiple images of the speckled area were taken simultaneously by the two cameras of the stereo-system during elevation. Each subject was then fitted with retro-reflective markers and the measurements repeated statically at increments of 20°, using a scapula locator to measure scapula orientation. An external reference frame was used to guide arm elevation in each case.

RESULTS

The shape, displacement and full-field strain of the region of interest were determined for each subject. The x and y axes are fitted by a least squares plane fit to an initial reference image. The z axis is perpendicular to the x-y plane pointing outwards. The initial positions of the three scapula bony landmarks, the acromial angle (AA), the root of the scapular spine (TS) and the inferior angle (AI) were identified at the rest position. The displacements of each of these points was tracked during arm elevation as shown for one subject in Fig. 2. The displacements of the three bony landmarks in three axes indicate that the scapula is laterally rotating, tilting anteriorly and protracting during arm elevation, similar to rotations measured using the optical method.

Figure 1: Speckled Pattern on the scapula

Figure 2: X-displacement (diamonds), Y-displacement (squares) and Z-displacement (triangles) of the skin over the AA (a), TS (b) and AI (c) during arm elevation. The profiles indicate protraction, lateral rotation and anterior tilting of the scapula

CONCLUSIONS

D.I.C. is potentially a very quick and accurate method of measuring scapula skin artefacts during motion analysis of the shoulder complex. The expected scapula motion profiles based on the skin movement can be compared with the motion profiles measured using a passive marker system to determine the level of inaccuracy caused by skin movements. The method could be further used to define volumetric muscle changes associated with arm elevation.

SPEAKER INFORMATION

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Using digital image correlation to measure scapula movement during shoulder motion

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Abstract—Accurate measurement of scapula kinematics is problematic due to overlying soft tissue. Digital Image Correlation (D.I.C.) is being used to track the movement of an applied surface pattern on the scapula during arm elevation. An exploratory study on two healthy shoulders shows that D.I.C. is potentially a very fast and accurate means of measuring skin movement over the scapula. Further work includes merging the D.I.C. protocol with the protocols already in place using passive markers and electromagnetic sensors to assess shoulder motion.

Keywords-scapula motion; skin artefacts; digital image correlation

1. INTRODUCTION

Non-invasive motion analysis techniques to monitor shoulder function have been developed by members of the U.K. Shoulder Biomechanics Group in Cardiff University, Newcastle University and Imperial College London. A combination of passive retro-reflective markers (Fig. 1(a)) and electromagnetic tracking sensors (Fig. 1(b)) are attached to bony landmarks of the trunk and upper limb. Joint rotations are calculated according to the recommendations of the International Society of Biomechanics [1].

Accurate measurement of the kinematics of the shoulder complex, particularly the kinematic profiles of the scapula, is problematic due to overlying soft tissue. Cardiff University has recently developed a new structural performance laboratory which is equipped with a digital image correlation (D.I.C.) system. D.I.C. is a non-contact method of providing full-field, three-dimensional shape and deformation of a surface area by tracking the change in grey value pattern.
The system consists of a two-camera stereo system which captures simultaneous images of the same surface area (Fig. 3). In this exploratory study it is proposed to use D.I.C. to track the movement of an applied surface pattern on the scapula during arm elevation to determine the level of inaccuracy caused by artifacts due to movement of the scapula under the skin that occurs during motion analysis of the shoulder complex.
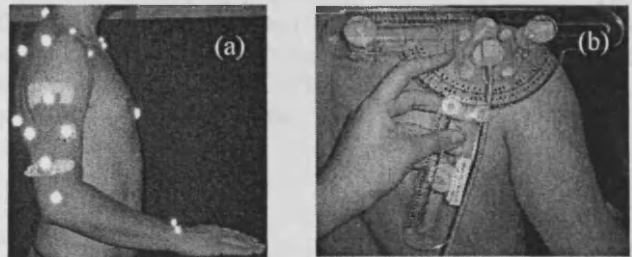
Figure 1. (a) Subject wearing passive markers as per I.S.B. recommendations (b). Scapula locator with electromagnetic sensor used to track scapula motion

2. METHODS

Two healthy right dominant shoulders were assessed during elevation in the frontal and sagittal planes and for internal/external rotation. Speckled face paint was applied to the area of interest by various means such as a sponge or a toothbrush (Fig. 2). Multiple images of the speckled area were taken simultaneously by the two cameras of the stereo-system during the various arm motions at a speed which was appropriate for image capture; approximately 7°/s of humeral elevation. The area of interest was manually selected and the correlation analysis was run using Vic-3D (Correlated Solutions) [2].
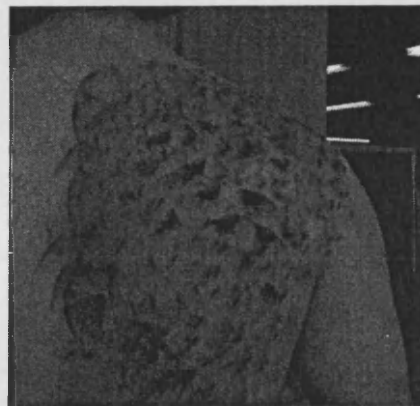
Figure 2. Speckled paint applied to surface area of overlying skin on scapula

3. RESULTS

The shape, displacement and full-field strain of the region of interest were determined. The x and y axes are fitted by a least squares plane fit to an initial reference image. The z axis is perpendicular to the x-y plane pointing outwards. The z-displacement contours for abduction are shown embedded over the scapula in Fig. 3. Fig. 4 shows the z-displacement profiles for each of the bony landmarks. The profiles indicate that the scapula is retracting during arm elevation.
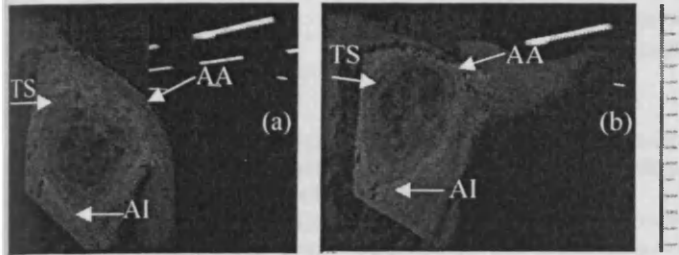
Figure 3. Z - contours for (a) 0° abduction, (b) 90° abduction. The three bony landmarks of the posterior scapula are shown; inferior angle (AI); root of the scapula spine (TS); and acromial angle (AA)
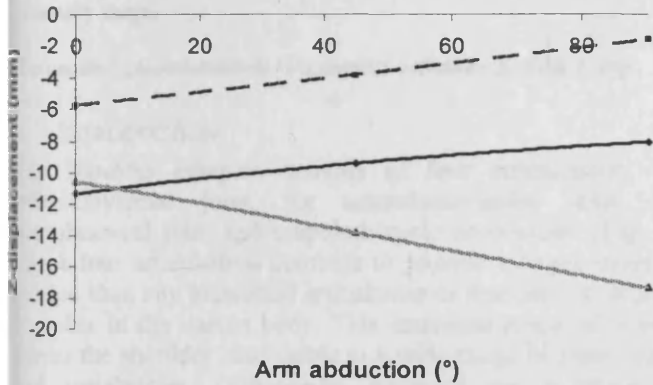
Arm abduction (°)

Figure 4. Z-contours of the posterior scapula bony landmarks during abduction. Solid line: Inferior Angle; Dashed Line: Root of the spine; Shaded Line: Acromial Angle. The contour paths of indicative of lateral rotation of the scapula during arm elevation

4. DISCUSSION

This exploratory study on two subjects concludes that D.I.C. is potentially a very quick and accurate method to assess scapula skin artefacts. The next stage of development is to implement the D.I.C. protocol in tandem with the standardized methods of assessing shoulder function which use passive optical markers and electromagnetic tracking sensors. With a larger sample cohort, and a representative protocol, the expected scapula motion profiles based on the skin movement will be compared with the motion profiles measured using a passive marker system (Qualisys Pro-Reflex, MCU 1000) [4] and an electromagnetic tracking system (Polhemus Liberty) [5] in Cardiff University to determine the level of inaccuracy caused by skin movements, with a possible view to analysis of pathological shoulders. This study lays the foundation for a marker-less method of measuring scapula motion, however soft tissue interference from muscle underlying the skin must also be explored to determine their effects and the method could be further used to define volumetric muscle changes associated with arm elevation.

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Motion analysis of the glenohumeral joint during activities of daily living

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Abstract— Passive marker based motion analysis has been used to assess glenohumeral function in five healthy subjects according to the recommendations of the International Society of Biomechanics. Glenohumeral elevation for arm elevation of 180° (maximum elevation) has been compared to the glenohumeral elevation required to perform a set of everyday tasks. To perform the most demanding task, placing an object at head height, 79% of maximum glenohumeral elevation is required. This has implications for clinical practice, as maximum elevation is commonly assessed in clinic as an indicator of a patient's recovery stage.

Keywords-; glenohumeral; kinematics; activities of daily living

1. INTRODUCTION

The shoulder complex consists of four articulations, the sternoclavicular joint, the acromioclavicular joint, the glenohumeral joint and scapulothoracic articulation (Fig. 1). These four articulations combine to provide a larger range of motion than any individual articulation or than any other joint complex in the human body. This increased range of motion leaves the shoulder susceptible to a wide range of pathologies and instabilities. Orthopaedic surgeons use a range of observations and physical examinations to diagnose shoulder ailments. This can be far from straightforward as it is largely dependant on their prior experience and training. It is hypothesised that more accurate clinical diagnosis and prognosis could be possible through further understanding of the kinematics of the shoulder complex. Non-invasive motion analysis techniques to monitor shoulder function have been developed at Cardiff University [1]. They have been used to compare the maximum range of glenohumeral motion with the functional range of glenohumeral motion required to perform a set of everyday tasks.
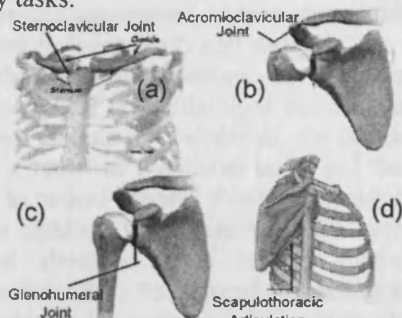
Figure 1. The four articulations of the shoulder complex: (a) sternoclavicular joint, (b) acromioclavicular joint, (c) glenohumeral joint and (d) scapulothoracic articulation. Adapted from [2] and [3].

2. METHODS

Five healthy subjects, 10 healthy shoulders, (M:F 2:3 mean age 23 ± 1 year) were tested. Fourteen retro-reflective markers were attached to bony landmarks of the trunk and upper limb, with a four-marker cluster placed on the humerus (Fig 2). Eight Qualisys Pro-Reflex cameras [4] with a sampling rate of 60Hz were used to track the markers. Joint rotations were calculated according to the recommendations of the International Society of Biomechanics [5]. Each shoulder was assessed separately for full range of motion (ROM) and 10 functional tasks of daily living (with and without loading) (Table 1) [6]. Comparisons were made between glenohumeral elevation for arm elevation to 180° (maximum elevation) and the glenohumeral elevation required to perform the functional tasks and also between dominant and non-dominant shoulders.

3. RESULTS

Complete kinematic descriptions of the shoulder were obtained for the ten subjects. The full range of glenohumeral motion was 96 ± 4.8°. 79% of max ROM was used in touching the back of the head. 59% of max ROM was used in combing the opposite side of the head. 71% of max ROM was used in lifting a weight (20N) above head height (Fig. 3). No significant differences in ROMs were observed between dominant and non dominant shoulders.
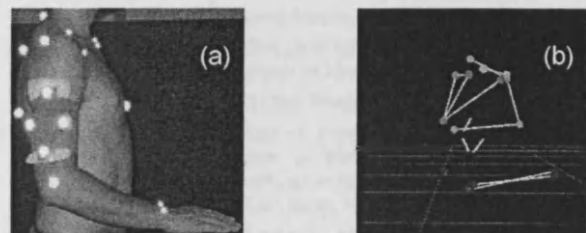
Figure 2. (a) Marker set-up used to analyse the kinematics of the shoulder complx. (b) Qualisys view of markers

Reach to opposite axilla	Drink from mug
Reach to opposite side of neck	Answer telephone
Reach to side and back of head	Brush opposite side of head
Eat with hand to mouth	Lift block to shoulder height
Eat with spoon	Lift block to head height

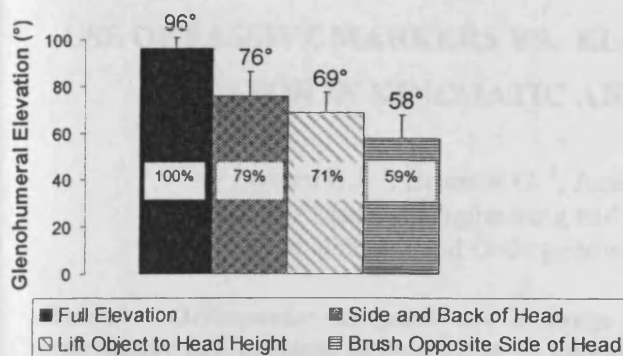Table I.   Activities of daily living, adapted from Murray & Johnson [6]

Figure 3. Glenohumeral elevation required to raise the arm to 180° and to perform the three most demanding activities of daily living; touching the side and back of the head; lifting an object to head height; and brushing the opposite side of the head.

4. DISCUSSION

A quantitative assessment of glenohumeral motion is reported. This study objectively explores the motion profiles of the shoulder complex for maximum arm elevation and during activities of daily living. These results have implications for clinical practice and occupational health where max range of motion is commonly assessed as an indicator of a patient's ability to return to physical activity. The results show that this is not necessarily representative of a patient's ability to perform everyday functional tasks. Accurate measurement of shoulder motion is difficult due to the presence of overlying tissue, particularly on the scapula. The current study uses skin mounted markers to identify the bony landmarks of the scapula which is known to introduce errors [7]. Regression equations have been developed to track the spatial orientation of the clavicle [8] and the scapula [9] for a given level of arm elevation. These equations are only valid for arm elevations up to 90° and have been found to be unsuitable for patient cohorts due to the change in scapulohumeral rhythm resulting from the injury or pathology. Current validation studies aim to quantify the scapula skin artefacts associated with arm elevation in different planes [10-12] to provide an alternative to the use of regression equations. Future studies on healthy subjects will incorporate these findings as well as the regression equations. For further confirmation, a technical marker frame may be placed on the acromion of the scapula. This method has previously been used to assess dynamic shoulder movements up to elevations of 120° [13]. This addition would also be suitable for studies of pathological shoulders. Furthermore, objective kinematic assessment of the upper limb is difficult when compared to lower limb gait analysis due to the large range of path dependant motions of the joints and the numerous non-cyclical unstandardised tasks measured. Areas for development include the validation and standardisation of a representative range of functional tasks and the application of these tasks to patient cohorts. Principal component analysis can be used to highlight the salient variables between healthy shoulders and shoulders with various pathologies. An objective classifier can be trained to recognise different shoulder pathologies by analysing the salient variables. In a similar method to that employed by Jones et al. [14] to monitor osteoarthritic knee function, the Dempster Shafer theory of evidence [15,16] can be used to develop a visual

output which allows for the representation of uncertainty in the prediction (Fig.4). The technique described serves as a basis for a diagnostic tool with practical applications including prediction of outcome for surgical intervention and functional analysis of joint prosthesis design.

Figure 4. Classification of shoulder pathologies using the Dempster-Shafer theory of evidence. A combination of a patients functional variables produces a point on the simplex plot. Sections 1 and 2 are dominant classifications, "healthy" and "pathological" respectively, sections 3 and 4 are non-dominant classifications of "healthy" and "pathological" subjects. The closer a point is to the base-line, the more uncertain the diagnosis.

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USE OF PASSIVE MARKERS VS. ELECTROMAGNETIC TRACKER AND SCAPULA LOCATOR IN KINEMATIC ANALYSIS OF THE SHOULDER COMPLEX

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Abstract – Orthopaedic surgeons use a range of observations and physical examinations to diagnose shoulder pathologies. This can be far from straightforward as it is largely dependant on their prior experience and training. It is hypothesised that more accurate clinical diagnosis and prognosis could be possible through further understanding of the kinematics of the shoulder complex. Non-invasive motion analysis techniques to monitor shoulder function have been developed at Cardiff University. Results are similar to those reported in the literature. The technique serves as a basis for the development of a non-invasive diagnostic tool with practical applications including prediction of outcome for surgical intervention and functional analysis of joint prosthesis design. It is currently being validated for 10 subjects against the more conventional scapula locator and electromagnetic sensors technique for intended use on pathological subjects.

1. INTRODUCTION

The shoulder complex consists of four segments; the thorax; the clavicle; the scapula; and the humerus. These combine to form four articulations; the sternoclavicular joint; the acromioclavicular joint; the glenohumeral joint and the scapulothoracic articulation. These four articulations provide a larger range of motion (ROM) than any individual articulation and than any other joint complex in the human body. As a result of this extended ROM, the shoulder complex is susceptible to a wide range of pathologies, injuries and instabilities. Currently, a series of observations and physical examinations are used to determine the cause and extent of a patient's discomfort. This can often be inconclusive as it is based on the individual surgeons experience and training, while many pathologies exhibit similar symptoms but require different treatment modes. A scan is often necessary for confirmation, increasing the waiting period for treatment by three months (ultrasound) or up to one year (magnetic resonance imaging). It is believed that clinical diagnosis and prognosis could benefit from further understanding of the kinematics of the shoulder complex.

The Cardiff University Human Motion Analysis Lab is equipped with 8 Qualisys ProReflex cameras (MCU1000) [1] with a sample frequency of 60Hz. A protocol has been developed [2] to determine

joint and body segment coordinate systems and calculate joint rotations (distal bone relative to the proximal articulating bone) and segment rotations (any bone relative to the thorax) in accordance with the recommended standards of the International Society of Biomechanics (ISB) [3]. The upper limb and trunk are fitted with retro-reflective markers (figure 1). The trajectories of the markers allow the formation of anatomical coordinate systems for each bone.

Fig. 1 (a) Marker-set used and (b) qualisys view

A scapula locator and Polhemus Liberty [4] electromagnetic tracking system have recently been acquired. They are commonly used together to determine the orientation of the scapula at different arm elevations [5]. The passive marker system is currently being validated against this system with the intention of applying a combined method to a study of pathological subjects.

2. MATERIAL AND METHODS

Subjects were fitted with retro-reflective markers to establish body segment and joint coordinate systems as per International Society of Biomechanics recommendations [3]. Static measurements at 10° increments of elevation in the coronal and sagittal planes were recorded. A frame fitted with retro-reflective markers was used to guide arm elevation (figure 2). A series of dynamic measurements were also taken.
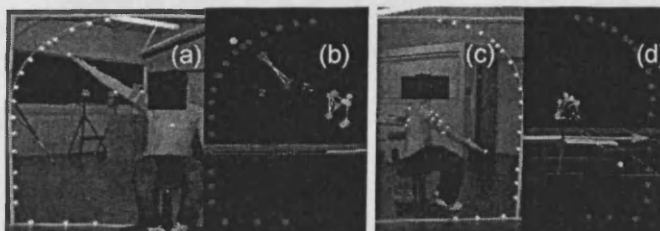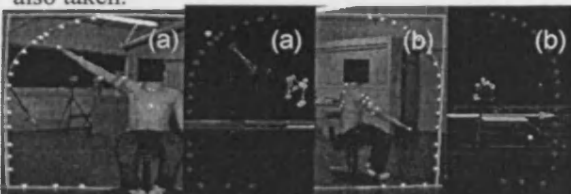

Fig. 2 : Subject elevates arm using frame for guidance; (a), (b) abduction, (c), (d) flexion

A scapula locator and Polhemus electromagnetic tracking sensor system (figure 3) was later used to take static measurements of arm elevation in the coronal, scapular, 60° and sagittal planes.

Fig. 3 Scapula locator and electromagnetic sensor

The protocol is being tested on 10 subjects with no history of shoulder pathology or instability.

3. RESULTS

Complete kinematic descriptions of the shoulder have been obtained using the passive marker system. Motion patterns and ROM's are similar to those reported in the literature [6], [7] with the exception of the AC joint ROM which was up to 7 times larger. It is hypothesised that this may be due to the use of skin markers based on the findings of de Groot [8]. Rotations at the scapulothoracic articulation are shown for five subjects (M:F 4:1 mean age 26.8 ± 5 years) (figure 4).
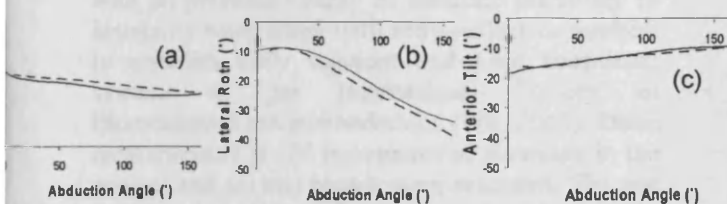
Fig. 4 Fifth order polynomial fits to the angles describing the orientations of the scapula relative to the thorax during abduction for five subjects; (a) protraction; (b) anterior tilt; (c) lateral rotation. Solid lines: static measurements. Dashed lines: dynamic measurements.

The same set of rotations are shown for a one subject pilot study comparing recorded motion profiles using passive markers and the electromagnetic system in figure 5.
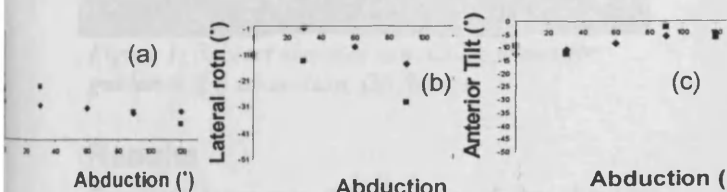
Fig. 5 Passive marker vs. electromagnetic for one subject; (a) protraction; (b) anterior tilt; (c) lateral rotation. Diamonds passive marker, squares electromagnetic system

4. DISCUSSION AND CONCLUSIONS

Results indicate that using passive markers is a viable method of gathering in vivo kinematic data. This method has the advantage of being able to assess dynamic movements. Comparing static and dynamic measurements aids in the further understanding of the biomechanics of the shoulder complex. During dynamic abduction, the motion profiles and ROM's were similar to the static values with occasional divergence either at low or high elevations. During dynamic flexion large differences were observed for protraction of the scapulothoracic articulation. Further testing is required to determine at what elevations these differences occur and to develop a viable hypothesis as to their cause. This will consequently lead to assessments of the validity of data used in musculoskeletal models of the upper limb and the viability of dynamic motion models used, for example, in tasks of daily living. The scapula locator is a tried and trusted method of analysing shoulder position. A pilot test showed reasonable agreement with the in-house method but further pre-validation trials may be necessary. It is planned to apply a combination of the two methods to studies of pathological subjects in the future. By analysing the kinematic waveforms it is hoped to establish differences between the healthy cohort and pathological cohort to aid in diagnosis and prognosis for different treatment types.

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6. ACKNOWLEDGEMENTS

FUNCTIONAL ASSESSMENT OF THE SHOULDER COMPLEX USING 3D MOTION ANALYSIS TECHNIQUES

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Introduction

Orthopaedic surgeons use a range of observations and physical examinations to diagnose shoulder pathologies. This can be far from straightforward as it is largely dependant on their prior experience and training. It is hypothesised that more accurate clinical diagnosis and prognosis could be possible through further understanding of the kinematics of the shoulder. Non-invasive motion analysis techniques to monitor shoulder function have been developed at Cardiff University. The technique serves as a basis for a diagnostic tool with practical applications including prediction of outcome for surgical intervention and functional analysis of joint prosthesis design.

Methods

Five subjects (M:F 4:1 mean age 26.8 ± 5 years) with no previous history of shoulder pathology or instability were fitted with retro-reflective markers to establish body segment and joint coordinate systems as per International Society of Biomechanics recommendations (Wu, 2005). Static measurements at 10° increments of elevation in the coronal and sagittal planes were recorded. The test was repeated with marker positions on the scapula manually adjusted as necessary at each increment to account for errors caused by movement of the scapula under the skin. A frame fitted with retro-reflective markers was used to guide arm elevation (figure 1). A series of dynamic measurements were also taken.

Figure 1: Subject elevates arm using frame for guidance; (a) abduction, (b) flexion

Results

Complete kinematic descriptions of the shoulder were obtained for the five subjects. Motion patterns and ranges of movement (ROM) are similar to those reported in the literature (Meskers 1998), (van der Helm 1995) with the exception of

the AC joint ROM which was up to 7 times larger. It is hypothesised that this may be due to the use of skin markers based on the findings of de Groot (1997).
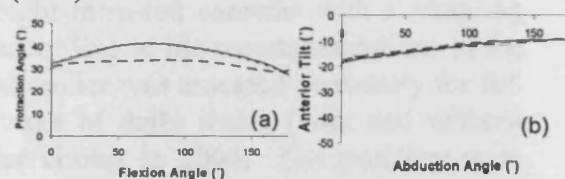
Figure 2: Motion profiles for the scapulothoracic articulation. Solid lines: Static. Small dashes: Static Adjusted. Large dashes: Dynamic.
(a) protraction during flexion, (b) anterior tilt during abduction

Discussion

Quantifying the errors caused by skin-marker discrepancies in motion analysis of the shoulder complex allows the validity of motion models generated to be determined. There is minimal difference between the static and static adjusted rotation values (<2°). This is less than the errors of 2° associated with palpation and the errors associated with noise and inter subject difference (33% and 55% respectively) (de Groot, 1997). Comparing static and dynamic measurements aids in the further understanding of the biomechanics of the shoulder complex. This consequently leads to assessments of the validity of dynamic motion models used, for example, in tasks of daily living. During dynamic abduction, the motion profiles and ROM's were similar to the static values with occasional divergence either at low or high elevations. During flexion large differences were observed for protraction of the scapulothoracic articulation (figure 2a). Smaller differences were seen during anterior tilt of the acromioclavicular joint and scapulothoracic articulation. Further testing is required to determine at what elevations these differences occur and to develop a viable hypothesis as to their cause.

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Van der Helm et al.,1995 J. BiomechEng;177:27-40
de Groot Clinical Biomech 12, 7/8, pgs. 461-472

3D MOTION ANALYSIS OF THE GLENOHUMERAL JOINT: A COMPARISON OF MAXIMAL VS. FUNCTIONAL RANGE OF MOTION

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Three-dimensional motion analysis techniques were used to compare the maximum range of glenohumeral motion with the functional range of glenohumeral motion required to perform everyday activities.

In-house ethical approval was obtained for the study. Five healthy subjects, 10 healthy shoulders, (M:F 2:3 mean age 23 ± 1 year) were recruited. Eighteen retro-reflective markers were attached to bony landmarks of the trunk and upper limb. The trajectories of the markers were tracked by eight infra-red cameras with a sampling rate of 60Hz. Joint rotations were calculated according to the recommendations of the International Society of Biomechanics. Each shoulder was assessed separately for full range of motion (ROM) and 10 functional tasks of daily living (with and without loading) designed by the Newcastle Shoulder Group in 2004. Comparisons were made between the full ROM and functional ROM and also between dominant and non-dominant shoulders.

The full range of glenohumeral motion was 96 ± 4.8°. Seventy-nine percent of max ROM was used in touching the back of the head. Fifty-nine percent of max ROM was used in combing the opposite side of the head. Seventy one percent of max ROM was used in lifting a weight (20N) above head height. No significant differences in ROMs were observed between dominant and non dominant shoulders.

A quantitative assessment of glenohumeral motion is reported. While maximum ROM is commonly assessed, this is not representative of a patient's ability to perform everyday functional tasks. This study objectively explores the motion profiles of the shoulder complex and highlights some of the potential benefits to everyday clinical practice. Further areas for development include the validation and standardisation of a representative range of functional tasks and the application of these techniques to patient cohorts.

Dynamic vs. static measurements in motion analysis of the shoulder complex

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1. INTRODUCTION

Musculoskeletal models are traditionally used for the analysis and visualisation of muscle bone dynamics. They have previously proved useful for examining the knee and hip in areas such as; implant design; diagnostics; surgery prognosis; functional classification; and analysis of various pathologies. More recently musculoskeletal modelling techniques have been applied to the upper limb, for example the Newcastle Shoulder Model[1], which predicts joint contact angles and forces in healthy and pathological shoulders. Input data is acquired from cadavers and in vivo kinematics. In vivo kinematic data of the shoulder complex is commonly gathered by taking a series of static measurements of arm elevation at different increments and in different planes of elevation. Regression equations are then developed to predict the scapulohumeral and scapulothoracic rhythms in different positions in the given workspace[2, 3]. These rhythms, developed from static measurements, are then inferred to dynamic motion models which are used to examine functional tasks of everyday living, and also as input data for musculoskeletal models. This method has the advantage of avoiding the effects of skin artefacts on the scapula during dynamic arm movements. The aim of this study is to determine if static measurements of shoulder kinematics are appropriate for inference to dynamic movements.

2. EXPERIMENTAL PROTOCOLS

The Cardiff Human Motion Analysis Laboratory is equipped with 8 Qualisys Pro-Reflex cameras[4] with a sampling frequency of 60Hz. Fourteen passive retro-reflective markers were attached to bony landmarks of the arm and torso and a marker cluster was placed on the upper arm (Figure 1). Body segment and joint coordinate systems were established and joint and segment rotations calculated as per recommended I.S.B. standards[5].
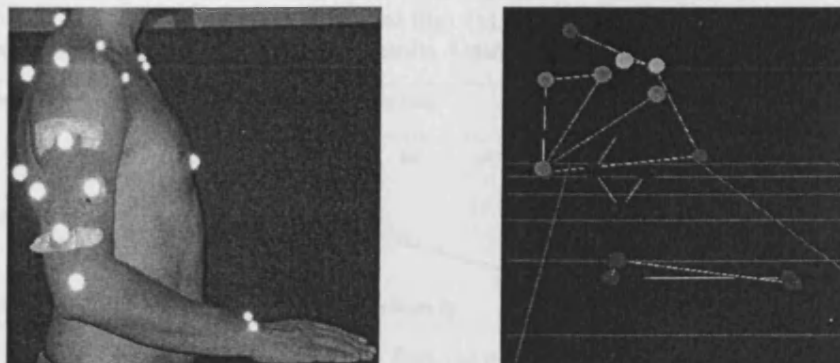
Figure 1: Marker set-up to model shoulder complex as per I.S.B. recommendations

Two external reference frames were constructed. The first guides arm elevation in different planes (Fig 2), the second guides arm orientation during internal/external rotation (Fig 3). Retro-reflective markers were attached to the frame at 10° increments. Subjects were instructed to point to each of the markers in turn and static measurements were taken for abduction, flexion and internal/external rotation at each increment. The motions were then repeated dynamically. The protocol was performed on five healthy right dominant shoulders (M:F 4:1mean age 26.8 ± 5 years) with no previous history of shoulder pathology or instability.
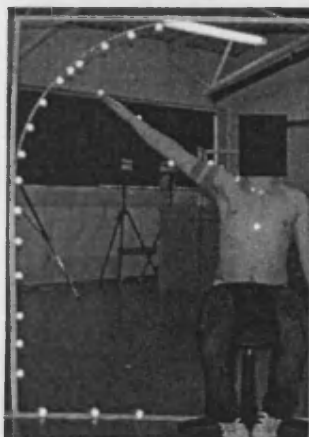
Figure 2: External reference frame to guide
arm elevation in different planes
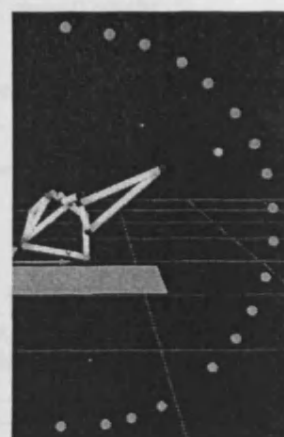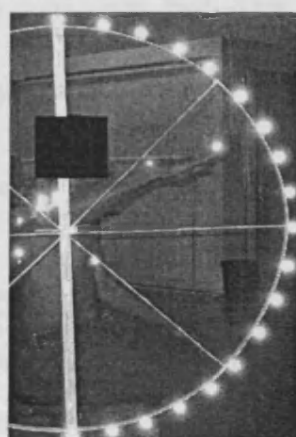
Figure 3: External reference frame to guide arm
orientation for internal/external rotation

3. RESULTS

Complete kinematic descriptions of the shoulder were obtained for the 5 subjects. Results are presented in the figures below for abduction (Fig. 4), flexion (Fig. 5) and internal/external rotation (Fig. 6) of the glenohumeral (GH) joint and for abduction (Fig. 7), flexion (Fig. 8) and internal/external rotation (Fig. 9) of the scapulothoracic (ST) articulation.
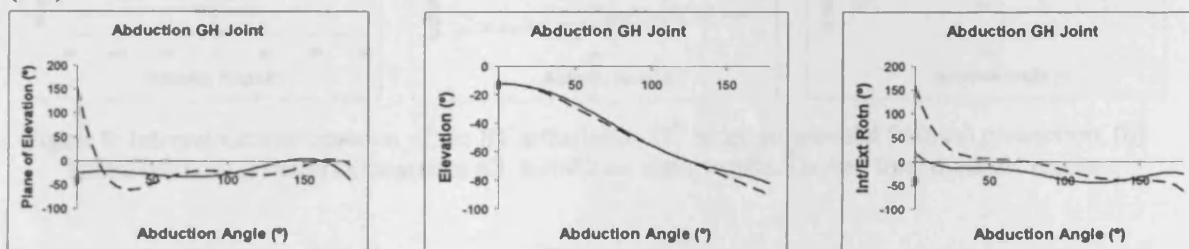
Figure 4: Abduction of the GH joint (5th order polynomial fits). (a) plane of elevation, (b) elevation, (c) internal/external rotation. Solid line: static results. Dashed line: dynamic results
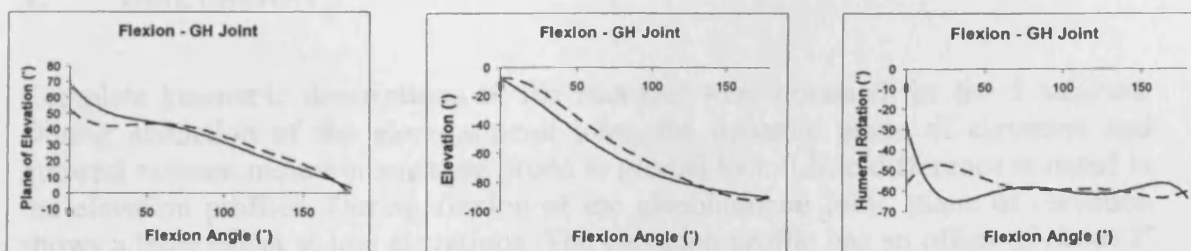
Figure 5: Flexion of the GH joint (5th order polynomial fits). (a) plane of elevation, (b) elevation, (c) internal/external rotation. Solid line: static results. Dashed line: dynamic results
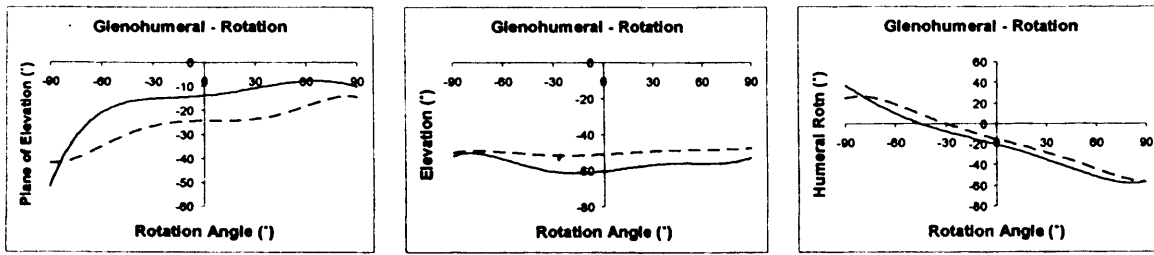
Figure 6: Internal/external rotation of the GH joint (5ᵗʰ order polynomial fits). (a) plane of elevation, (b) elevation, (c) internal/external rotation. Solid line: static results. Dashed line: dynamic results
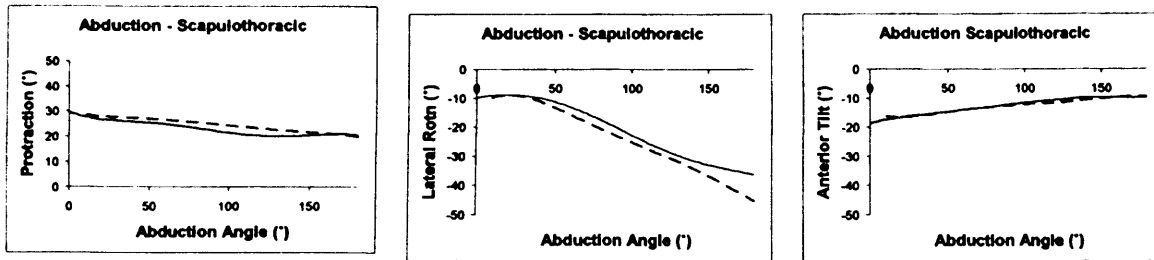
Figure 7: Abduction of the ST articulation (5ᵗʰ order polynomial fits). (a) protraction, (b) lateral rotation, (c) anterior/posterior tilt. Solid line: static results. Dashed line: dynamic results
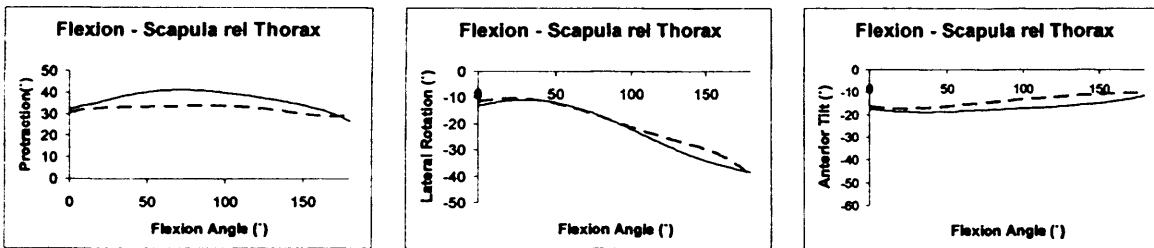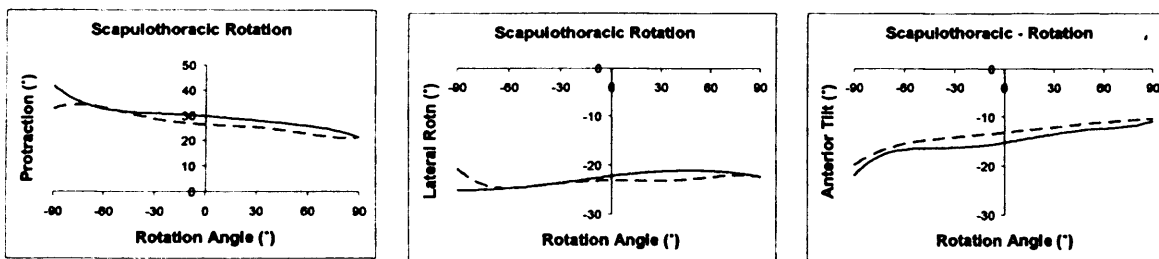

Figure 8: Flexion of the ST articulation (5ᵗʰ order polynomial fits). (a) protraction, (b) lateral rotation, (c) anterior/posterior tilt. Solid line: static results. Dashed line: dynamic results

Figure 9: Internal/external rotation of the ST articulation (5ᵗʰ order polynomial fits). (a) protraction, (b) lateral rotation, (c) anterior/posterior tilt. Solid line: static results. Dashed line: dynamic results

4. DISCUSSION

Complete kinematic descriptions of the shoulder were obtained for the 5 subjects. During abduction of the glenohumeral joint, the dynamic plane of elevation and humeral rotation measurements are prone to gimbal lock. Little difference is noted in the elevation profiles. During flexion of the glenohumeral joint, plane of elevation shows a large offset at low elevations. The elevation profile has an offset of about 7° throughout. Axial rotation of the humerus shows a variation in the motion profiles at low elevations and the static measurements are prone to gimbal lock.

Large differences are seen in the motion profiles of the scapulothoracic articulation during flexion, particularly when looking at protraction of the scapula. During abduction of the scapulothoracic articulation, a more linear profile of lateral scapular winging is noted. Internal/external rotation motion profiles of the scapulothoracic articulation show offsets of between $10'$ and $14°$ for anterior tilt. This may be due to the start-stop nature of the static measurements.

These results indicate that further testing is advisory to develop a viable hypothesis as to why these variations occur and at what arm elevations. Early presumptions include; use of stabilising muscles during static measurements; inertia/momentum effects during dynamic movements; and fatigue setting in during the static trial. The full protocol is to be performed on 10-15 healthy subjects. A separate trial is currently underway which uses a scapula locator[6] and electromagnetic tracking system to take static measurements of the scapula orientation at different arm elevations. The results of this trial will provide further static for comparison with the dynamic results.

Comparing static and dynamic measurements aids in the further understanding of the biomechanics of the shoulder complex. This consequently leads to assessments of the validity of dynamic motion models used, for example, in tasks of daily living or in recreating strength and ROM tests seen in clinic or as input data for upper limb musculoskeletal models. A study on activities of daily living and range of motion is currently being performed on healthy subjects on dominant and non-dominant shoulders. If appropriate, findings from the current study will be inferred to this study. It is then intended to perform this protocol on patient subgroups, ethical approval pending.

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6.   ACKNOWLEDGEMENTS

Error evaluation of skin-marker movements in motion analysis of the shoulder complex

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SYNOPSIS

Orthopaedic surgeons use a range of observations and physical examinations to asses shoulder pathologies. Diagnosis can often be inconclusive resulting in the need for a scan, increasing waiting times considerably. It is believed that surgeons could benefit from further understanding of the kinematics of the shoulder complex to aid in understanding the aetiology of shoulder disorders for clinical evaluation and rehabilitation purposes. Non-invasive motion analysis techniques have been developed at Cardiff University to monitor shoulder function. Passive skin-mounted markers are used to identify bony landmarks of the shoulder complex and form joint coordinate systems. However the technique is subject to inaccuracies due to movement of the scapula under the skin during arm elevation. This study aims to quantify these errors so that they can be accounted for in future studies of functional tasks of the upper limb.

1. INTRODUCTION

The shoulder complex consists of four articulations; the sternoclavicular joint; the acromioclavicular joint; the glenohumeral joint; and the scapulothoracic articulation. These four articulations combine to provide a larger range of movement than any individual articulation and than any other joint complex in the human body. This leaves the shoulder complex susceptible to a wide range of pathologies and instabilities including; tears of the rotator cuff; acromioclavicular joint dislocation; and glenohumeral instability. Currently orthopaedic surgeons use a range of observations and physical examinations to assess the extent of a patient's shoulder pathology. This assessment can be subjective and is based on the individual surgeons training and experience with similar cases. Many pathologies exhibit similar symptoms but require very different treatments. As a result, a scan is often necessary to confirm diagnosis. This results in a minimum waiting time of three months for an ultrasound and nine months for an MRI. Even with correct diagnosis, it is difficult to predict how well a patient will recover and with many pathologies debate still exists as to the best treatment mode. Non-invasive motion analysis techniques to monitor shoulder function have been developed in Cardiff School of Engineering, Cardiff University. Passive skin markers are used to identify bony landmarks and generate joint coordinate systems according to the recommendations of the International Society of Biomechanics (I.S.B.)[1]. The technique serves as a basis for the development of a sophisticated diagnostic tool with practical applications including: prediction of outcome for surgical intervention; comparison of outcomes for surgical treatment compared to conservative treatment; functional analysis of joint prosthesis

design; monitoring of joint degeneration; and post-operative monitoring. However the accuracy of the measurements is prone to errors caused by skin artefacts on the scapula. This study aims to quantify these errors.

2.   EXPERIMENTAL PROTOCOLS

The Cardiff Human Motion Analysis Laboratory is equipped with 8 Qualisys Pro-Reflex cameras[2] with a sampling frequency of 60Hz. Fourteen passive retro-reflective markers were attached to bony landmarks of the arm and torso and a marker cluster was placed on the upper arm (Figure 1). Body segment and joint coordinate systems were established and joint and segment rotations calculated as per recommended I.S.B. standards[1].
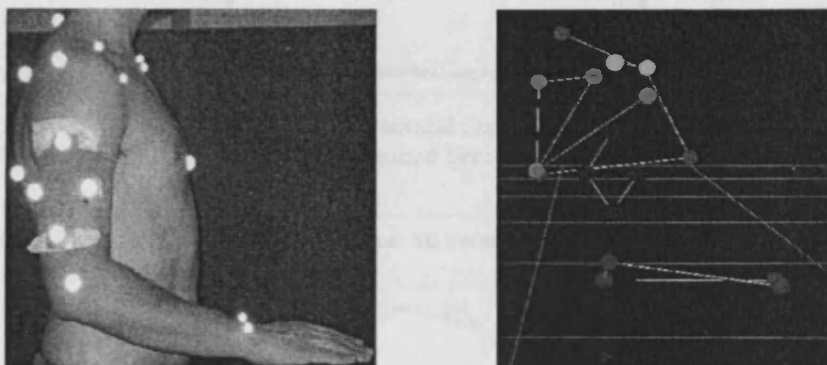
Figure 1: Marker set-up to model shoulder complex as per I.S.B. recommendations

An external reference frame was constructed to guide arm elevation in different planes (Fig 2). Retro-reflective markers were attached to the frame at 10° increments. Subjects were instructed to point to each of the markers in turn and static measurements were taken for abduction and flexion at each increment. The test was repeated with marker positions on the scapula manually adjusted as necessary at each increment to account for errors caused by movement of the scapula under the skin. The protocol was performed on five healthy right dominant shoulders (M:F 4:1mean age 26.8 ± 5 years) with no previous history of shoulder pathology or instability.
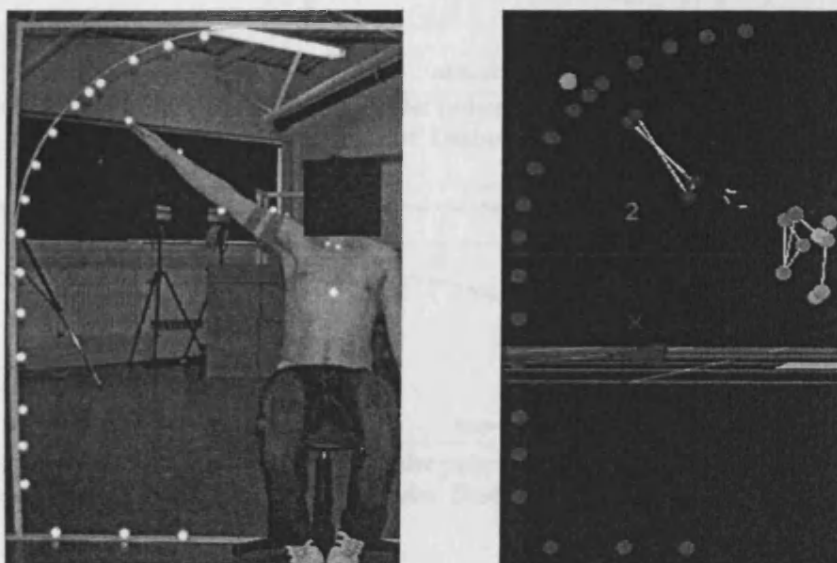
Figure 2: External reference frame to guide arm elevation in different planes

3.   RESULTS

Complete kinematic descriptions of the shoulder were obtained for the 5 subjects. Results are presented below for abduction and flexion of the acromioclavicular (AC) joint and the scapulothoracic (ST) articulation. Figure 3 is abduction of the AC joint, Figure 4 is flexion of the AC joint, Figure 5 is abduction of the ST articulation, and Figure 6 is flexion of the ST articulation.
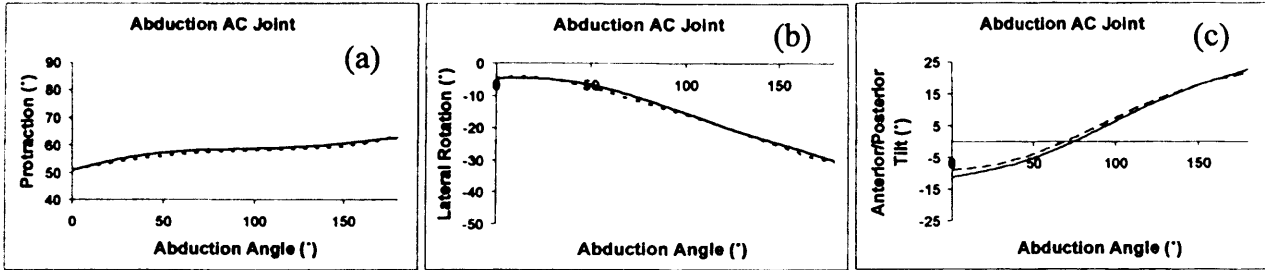

Figure 3: Abduction of the AC joint (5^{th} order polynomial fits). (a) protraction, (b) lateral rotation, (c) anterior/posterior tilt. Solid line: static results. Dashed line: results with adjusted scapula markers
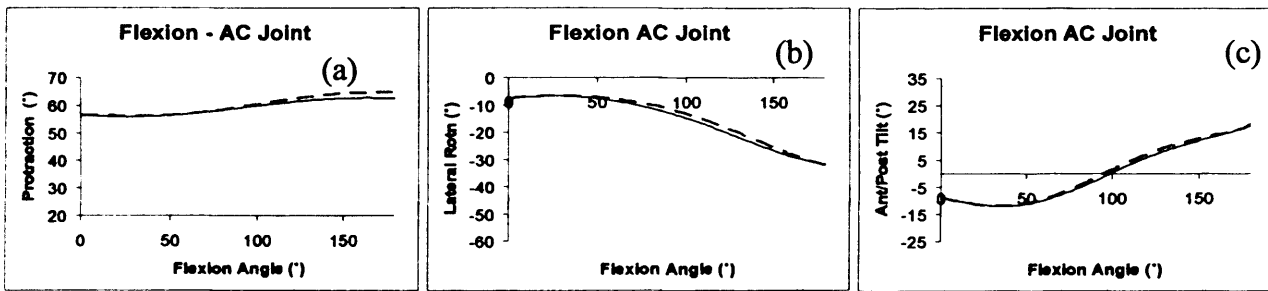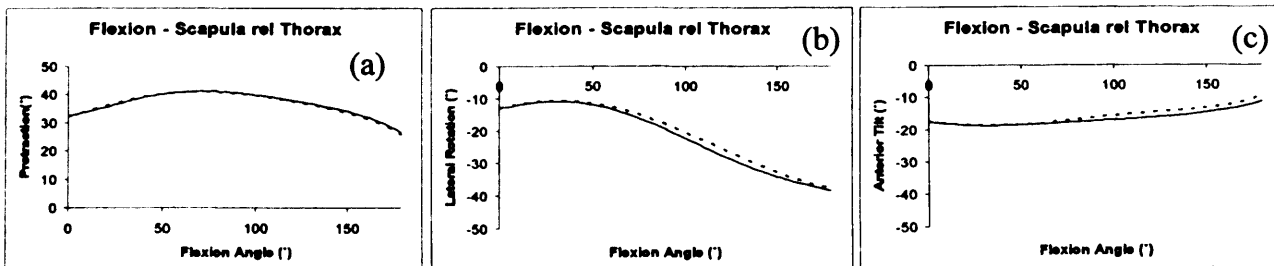

Figure 4: Flexion of the AC joint (5^{th} order polynomial fits). (a) protraction, (b) lateral rotation, (c) anterior/posterior tilt. Solid line: static results. Dashed line: results with adjusted scapula markers
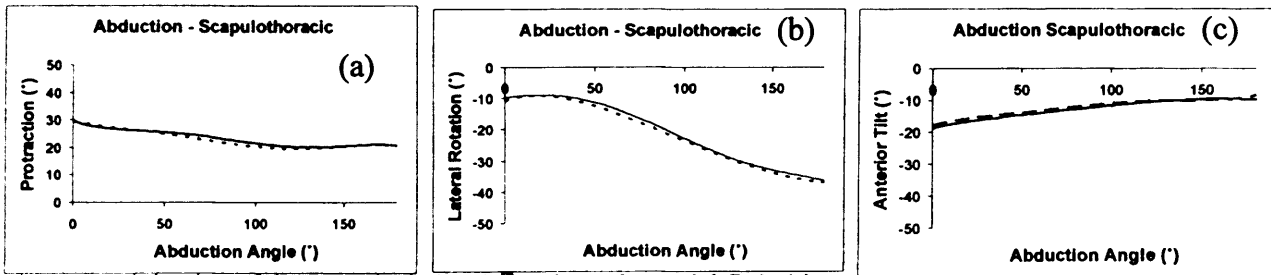
Figure 5: Abduction of the ST articulation (5^{th} order polynomial fits). (a) protraction, (b) lateral rotation, (c) anterior/posterior tilt. Solid line: static results. Dashed line: results with adjusted scapula markers

Figure 6: Flexion of the ST articulation (5^{th} order polynomial fits). (a) protraction, (b) lateral rotation, (c) anterior/posterior tilt. Solid line: static results. Dashed line: results with adjusted scapula markers

4.   DISCUSSION

Rotations at the acromioclavicular joint and for the scapula relative to the thorax were compared during abduction and flexion to establish the errors associated with scapular movement under the skin. In all cases the errors associated with skin artefacts of the scapula are less than 2°. A study by DeGroot[3] has shown errors of palpation alone to be 2°. The same study also found the inter-subject difference to be 55%. When other errors such as the use of skin-markers, noise in the cameras and the accuracy of the tracking software are factored in, the errors associated with skin-artefacts appear to be of little significance.

However it is still recommended to carry out further testing on a larger sample number to confirm these findings. As such, the full protocol will be performed on a total of 10-15 healthy subjects.

A separate trial is currently underway which uses a scapula locator[4] and electromagnetic tracking system to take static measurements of the scapula orientation at different arm elevations. The results of this trial will provide further data on the motion profiles of the scapula.

For further analysis, digital image correlation will be used to track the movement of an applied surface pattern on the scapula during arm elevation in different planes. The expected scapula motion profiles based on the skin movement will be compared with the recorded scapula motion profiles using the passive marker system and the electromagnetic tracking system.

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6.   ACKNOWLEDGEMENTS

IN VIVO MEASUREMENTS OF THE SHOULDER COMPLEX FOR USE IN MUSCULOSKELETAL MODELLING

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1. ABSTRACT

Musculoskeletal models of the shoulder use cadaver data and in vivo kinematic data to predict muscle and joint forces during different movements. A method developed by Cardiff University to acquire in vivo kinematic data was recently investigated for application to musculoskeletal modelling of the upper limb. Ten subjects with no previous history of shoulder pathology or instability were fitted with retro-reflective markers to establish body segment and joint coordinate systems as per International Society of Biomechanics recommendations. Static and dynamic measurements were recorded in the coronal and sagittal planes. Motion patterns and ranges of motion were found to be in accordance with published studies. This indicates that the methods developed serve as a reliable means of gathering accurate in vivo kinematic data for both healthy volunteers and patients with shoulder trauma for use in upper limb musculoskeletal modelling.

2. INTRODUCTION

The shoulder complex consists of four articulations; the sternoclavicular joint (SC); the acromioclavicular joint (AC); the glenohumeral joint (GH); and the scapulothoracic articulation (ST) (Fig. 1). These four articulations combine to provide a greater range of motion (ROM) than any individual articulation and than any other joint complex in the human body. As a result the shoulder complex is prone to a wide range of pathologies and instabilities. Orthopaedic surgeons use a range of physical observations and examinations to determine the level and extent of a patient's pathology. This can be very subjective as it is based on the individual surgeons training and experience of similar cases. Furthermore, many pathologies exhibit similar symptoms but require different treatment modes. As a result a scan is often necessary to confirm diagnosis, increasing waiting times by at least three months (ultrasound) or up to one year (MRI). Even with a correct diagnosis, it is still difficult to determine a patients prognosis and much debate exists regarding the optimum treatment mode for many pathologies. It is hypothesised that clinical practice may benefit from further understanding of the kinematics of the shoulder complex through musculoskeletal modelling of the upper limb.
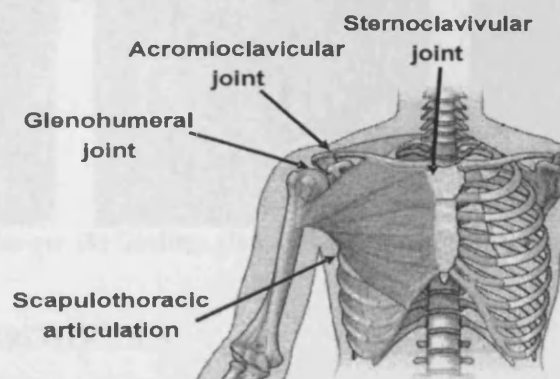

Figure 1: Anatomy of the shoulder complex.[1]

1. Institute of Medical Engineering and Medical Physics, Cardiff School of Engineering, Cardiff University, UK.
2. Dept. Trauma and Orthopaedics, University Hospital of Wales, Cardiff, UK.
3. UK Shoulder Biomechanics Group. www.uksbg.org

Musculoskeletal models allow for the analysis and visualisation of muscle-bone dynamics and have proved useful in studying the knee and hip in areas such as diagnostics, surgery prognosis, implant design, analysis of various pathologies and functional classification[2] (Fig 2a). More recently these techniques have been applied to the upper limb such as the Newcastle Shoulder Musculoskeletal Model (NSMM)[3] (Fig 2b). The NSMM predicts joint contact forces and angles in healthy and pathological shoulders. Input data for the model is acquired from cadaveric data and in vivo kinematic studies. As such, accurate kinematic models of the upper limb are required.
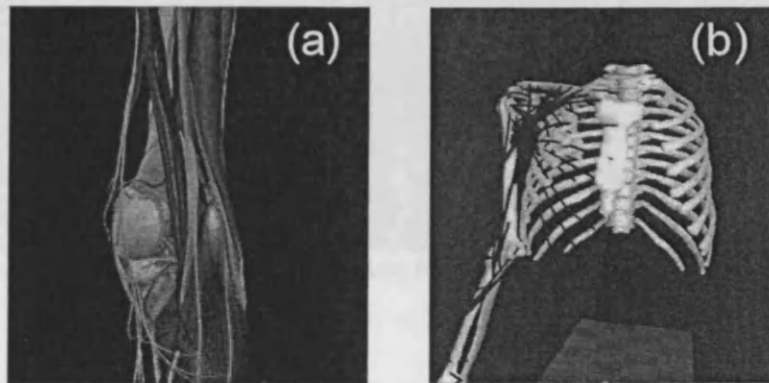
Figure 2: (a) Musculoskeletal model of the lower limb[4]
(b) Newcastle Shoulder Musculoskeletal Model of the upper limb[5]

The Cardiff Human Motion Analysis Laboratory is equipped with 8 Qualisys Pro-Reflex MCU 1000[6] cameras with a sampling frequency of 60Hz. Passive retro reflective markers are used to identify bony landmarks on the thorax, clavicle, scapula (skin mounted markers) and humerus (Fig 3) with body segment and joint coordinate systems established according to the recommendations of the ISB[7]. The anatomical coordinate system of the humerus is established at the rest position using the medial and lateral epicondyles and the centre of glenohumeral rotation, which is estimated by regression equations[8]. The anatomical coordinate system is then related to a technical reference system in the form of a marker cluster (Fig 3a).

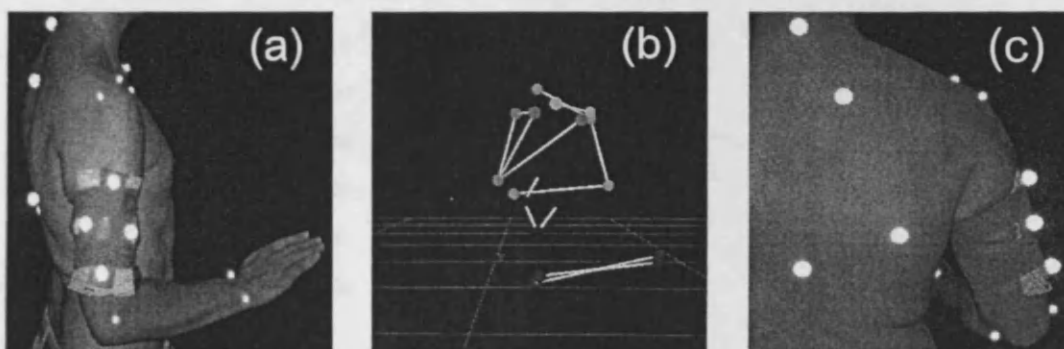Figure 3: (a) Shoulder marker-set (b) Qualisys view of the shoulder (c) Skin markers on the scapula

3. EXPERIMENTAL PROTOCOLS

Ten subjects (M:F 6:4mean age 27.5 ± 5.1 years) with no previous history of shoulder pathology or instability were asked to perform incremental arm elevations in the coronal and sagittal planes. The first five subjects performed the elevations at 10° increments. The second five subjects performed elevations at increments of 30° as good correlation

has been found between elevations of 10° and 30° in the development of scapulohumeral regression equations[9]. In all cases, the motions were repeated dynamically. An external reference frame fitted with markers was used to guide arm elevation in the different planes and assist in post experimental data acquisition (Fig. 4).
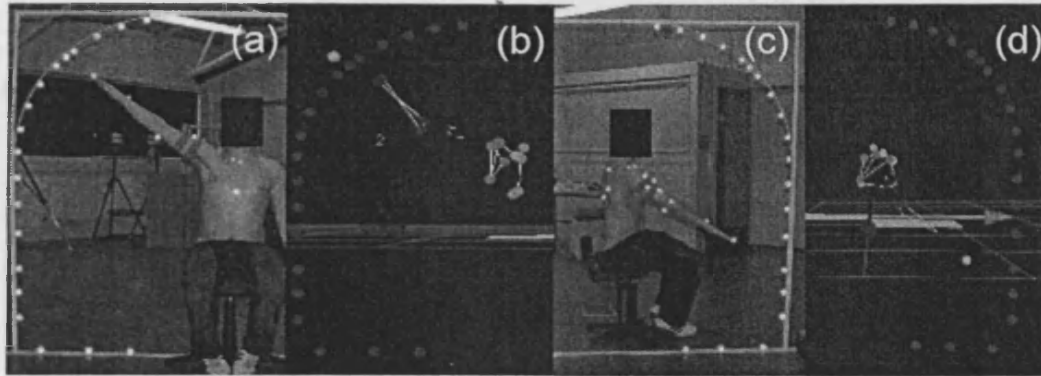

Figure. 4: Subject elevates arm using frame for guidance; (a), (b) abduction, (c), (d) flexion

4. RESULTS

For the first five subjects, incremental elevations of 10° were measured. To maintain consistency throughout the study, only those elevations which occur at 30° increments are reported. Motion patterns and ranges of motion (ROM's) are similar to those reported in the literature[10,11]. The only exception was ROM's recorded at the AC joint, which were up to 7 times larger than those reported in the literature. It is hypothesised that this may be due to the use of skin markers[12].
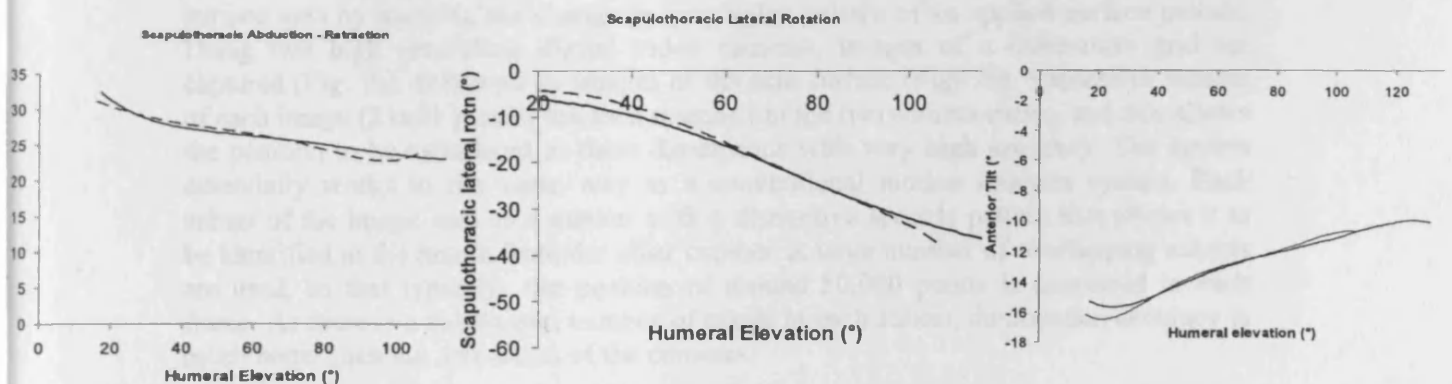

Figure. 5: 5th order polynomial fits to the kinematic waveforms for the scapulothoracic articulation during arm abduction. (a) retraction of the scapula, (b) lateral rotation of the scapula, (c) anterior tilt of the scapula. Solid line: dynamic elevation,, dashed line static elevations
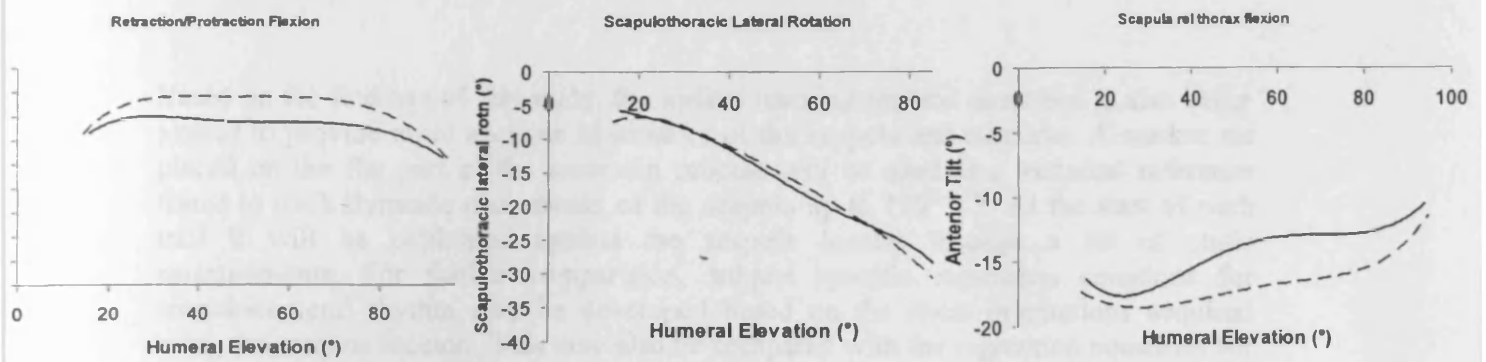
Figure. 6: 5th order polynomial fits to the kinematic waveforms for the scapulothoracic articulation during arm flexion. (a) retraction of the scapula, (b) lateral rotation of the scapula, (c) anterior tilt of the scapula. Solid line: dynamic elevation,, dashed line static elevations

5. DISCUSSION

The differences between static and dyamic measurements during abduction are minor. During flexion small offsets are noted during retraction and anterior tilt of the scapula. However, throughout this study skin mounted markers were used to identify the bony landmarks of the scapula. In a separate study undertaken by the same authors[13] comparing the use of skin markers on the scapula with a scapula locator (a three pointed rigid device used to palpate the scapula and track its movement[14]), the skin marker method was found to underestimate scapula lateral rotation by 5° in flexion and 6° in abduction, similar to other published findings[15]. Provided the errors associated with skin artefacts can be accounted for, and if the offset between static and dynamic measurements is predictable with a larger sample group, then it may be possible to use skin mounted scapula markers to assess dynamic movements with an appropriate level of confidence. To further this hypothesis, Digital Image Correlation (D.I.C.) is being used to measure skin movement over the scapula during arm elevation[16]. D.I.C. is a non-contact method of providing full-field, three-dimensional shape and deformation of a surface area by tracking the change in grey value pattern of an applied surface pattern. Using two high resolution digital video cameras, images of a calibration grid are captured (Fig. 7a), followed by images of the skin surface (Fig. 7b). Successive subsets of each image (21x21 pixels) are then matched in the two camera views, and this allows the position to be calculated in three dimensions with very high accuracy. The system essentially works in the same way as a conventional motion analysis system. Each subset of the image acts as a marker with a distinctive speckle pattern that allows it to be identified in the image from the other camera. A large number of overlapping subsets are used, so that typically the position of around 50,000 points is measured in each frame. As there is a substantial number of pixels in each subset, the location accuracy is much better than the resolution of the cameras.
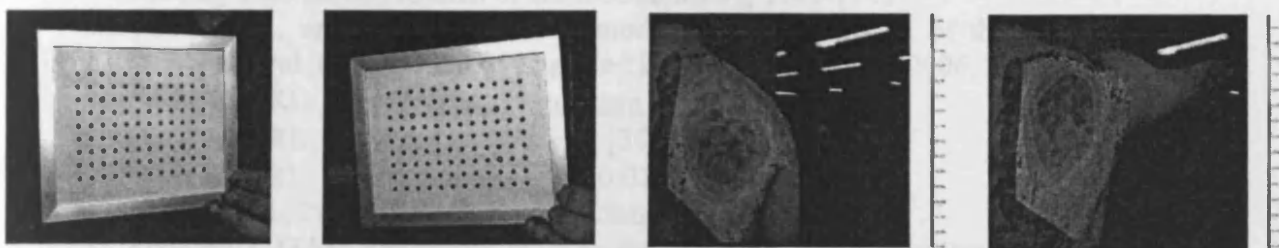

Figure 7: (a), (b) Calibration frame as viewed by two cameras. (c) Deformation of skin over scapula in plane perpendicular to scapula at 0° elevation. (d) Deformation of skin over scapula in plane perpendicular to scapula at 90° abduction.

Based on the findings of this study, the optical tracking method described is also being altered to provide more accurate kinematics of the scapula and humerus. A marker set placed on the flat part of the acromion process will be used as a technical reference frame to track dynamic movements of the scapula up to 120°[17, 18]. At the start of each trial it will be calibrated against the scapula locator through a set of static measurements. For further comparision, subject specific regression equations for scapulohumeral rhythm may be developed based on the static orientations acquired using the scapula locator. This may also be compared with the regression equations for healthy scapulas[9] used in the NSMM. The anatomical coordinate system of the humerus is generated using the medial epicondyle, lateral epicondyle and centre of glenohumeral rotation which is estimated by regression[8]. Future studies will estimate the centre of rotation with the instantaneous helical axis method[19] as it has been found to be more accurate and suitable for testing pathologies where the relationship between the scapula and the humerus has been altered[20]. The technical coordinate system which is used to track dynamic movements of the humrerus is also being altered. The current coordinate system consists of a four-marker cluster as shown in Fig. 3a. The new technical frame will be generated from markers placed on the insertion of the deltoid, the biceps belly and the insertion of the brachioradialis. It is believed that this will provide a better representation of axial rotation of the humerus.

To date all testing has been on healthy subjects. Ethical approval has just been granted to commence testing of hospital referred patients. Early studies on patient cohorts will focus on the prediction of recurrent glenohumeral dislocators from first time dislocator groups and the long term effects of conservatively treated and operatively managed mid-shaft clavicle fractures.

6. CONCLUSION

The method described in this study is a promising first step towards a reliable method of gathering accurate in vivo kinematic data from both healthy volunteers and referred patients for use in musculoskeletal modelling. With further modifications, this developmental model will lead to a definitive kinematic model of the upper limb.

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8. ACKNOWLEDGEMENTS

MEASURING SCAPULA ORIENTATION DURING ARM ELEVATION

L. Stroud[1], B. Lovern[1], R. Evans[2], L. Jones[1], S.L. Evans[1] and C. Holt[1]

1. ABSTRACT

Scapular motion presents a challenge to quantifying shoulder complex function in vivo as a significant amount of movement occurs under the skin. A palpator with retro-reflective markers attached to it and skin fixed marker systems were set up in the Motion Analysis Lab in Cardiff University to assess scapula motion in five healthy subjects with no previous history of shoulder pathology or instability. Subjects performed dynamic and static unilateral right hand side humerus elevation in the frontal and sagittal planes. International Society of Biomechanics recommendations were followed for marker placement and the reporting of motion. Scapula lateral rotation was underestimated by 6° in abduction and 5° in flexion when measured with the static skin fixed marker system compared to static palpator. Collection of accurate kinematic data is necessary for validation of musculoskeletal models used to analyse motion of the upper extremity. The palpator with retro-reflective markers attached to it measures scapula range of motion more accurately compared to skin fixed markers on the scapula as it follows the motion of the segment under the overlying skin.

2. INTRODUCTION

The shoulder complex has the largest range of motion in the human body. Its motion is accomplished through the coordinated interactions of 4 articulations: the glenohumeral joint, acromioclavicular joint, sternoclavicular joint and scapulothoracic articulation.

To analyse the motion of the human upper extremity, shoulder complex models have been developed, such as the Newcastle Shoulder Model (Fig 1), where biomechanical properties of bone segments, joints and muscle lines of action are included. Validating these musculoskeletal models requires accurate in-vivo kinematic data. Skin markers placed on specific landmarks on the arm and torso are used to quantify motion but the associated errors are introduced due to relative motion of the skin and the underlying bone. As a result, Johnson et al[1] developed a 3 pointed palpator which uses electromagnetic sensors and facilitates the identification of the scapula bony landmarks (acromial angle (AA), inferior angle (AI) and trigonum spinae (TS)) for any arm elevation; thus providing a more accurate measurement tool.

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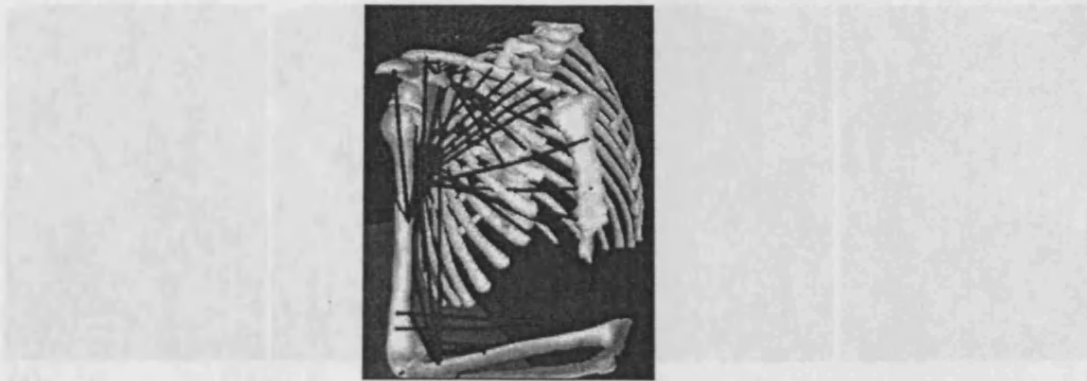2 Dept. Trauma and Orthopaedics, University Hospital of Wales, Cardiff, UK.

Fig 1. Newcastle Shoulder Model[1]

Motion analysis techniques have been developed at Cardiff University to assess shoulder function[3]. The aim of this study is to introduce the use of the 3 pointed palpator with retro-reflective markers attached to it to establish a locator coordinate system and quantify scapular motion.

3. MATERIALS AND METHOD

An eight camera Qualisys ProReflex MCU array (Qualisys, Sweden) was established to provide optimum tracking conditions, i.e., to define the 3D locations of markers attached to the subject whilst they perform specified arm movements.

Five healthy subjects (M:F 4:1 mean age 26.8 ± 5 years), with no previous history of shoulder pathology or instability, were included in the study. Retro-reflective markers were attached to bony landmarks on the arm and torso with a marker cluster placed on the upper arm (Fig 2). International Society of Biomechanics recommendations for the upper extremity[4] were followed for the reporting of motion.
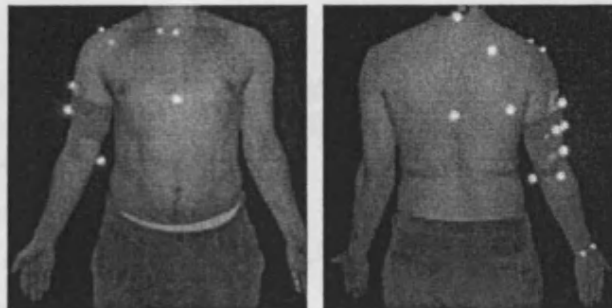

Fig 2. Marker Placement according to ISB recommendations

The subjects performed full range of motion (ROM) for flexion and abduction in a seated upright position (Fig 3). A frame was used to standardise arm elevations at 10° intervals.
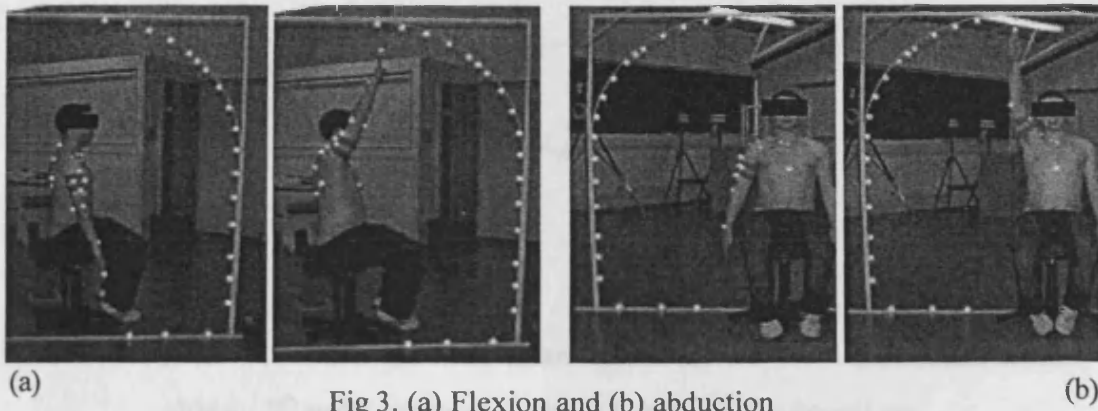
(a)   Fig 3. (a) Flexion and (b) abduction   (b)

Three approaches were used to record and quantify motion:
1) Dynamic measurement
2) Static measurement without marker adjustment
3) Static scapula locator (SL) measurement where the palpator was adjusted on the scapula for each arm elevation (Fig 4).

Fig 4. Palpator with retro-reflective markers

4. RESULTS

Complete kinematic descriptions of the right scapula were obtained for the 5 subjects. The mean values of the ROM of scapula lateral rotation during flexion and abduction are given in Fig 5 and 6 respectively.
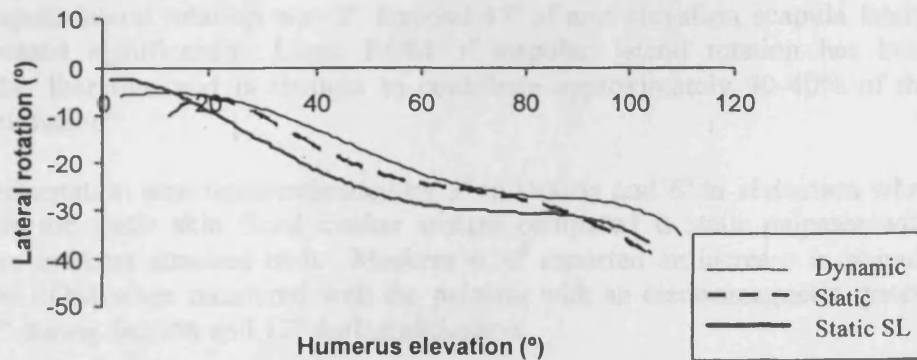

Fig 5: 5th order polynomial fits to Cardan angles describing scapula lateral rotation during flexion
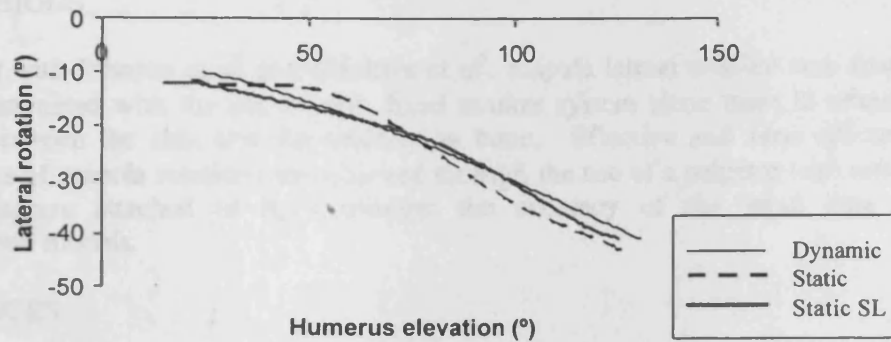
Fig 6: 5th order polynomial fits to Cardan angles describing
scapula lateral rotation during abduction

Patterns of motion are similar to those reported in the literature although the ROMs are less than those obtained by different research groups[5,6].

5. DISCUSSION

As full arm elevation is performed, the scapula retracts, tilts posterior and experiences lateral rotation. The rotations around each axis are illustrated in Fig 7. Lateral rotation is thought to contribute the most to arm elevation as the ROM is greatest for this rotation, therefore it was chosen for discussion.
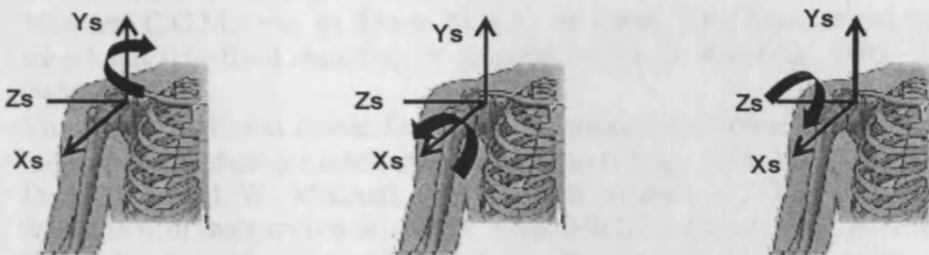

Fig 7. Illustration of scapula rotations (adapted from Wu et al[4] and Drake et al[7])

During the first 50° of arm elevation during flexion, the scapula rotated between 1 and 2° laterally; as the arm was elevated beyond 50°, scapular lateral rotation increased considerably (Fig 5). Similarly during abduction (Fig 6), between 0° and 45° of arm elevation, scapula lateral rotation was 2°. Beyond 45° of arm elevation, scapula lateral rotation increased significantly. Large ROM of scapular lateral rotation has been reported in the literature and is thought to contribute approximately 30-40% of the overall arm elevation[8].

Scapula lateral rotation was underestimated by 5° in flexion and 6° in abduction when measured with the static skin fixed marker system compared to static palpator with retro-reflective markers attached to it. Meskers et al[6] reported an increase in scapula lateral rotation ROM when measured with the palpator with an electromagnetic system of less than 7° during flexion and 13° during abduction.

6. CONCLUSIONS

In agreement with Johnson et al[1] and Meskers et al[5], scapula lateral rotation was found to be underestimated with the use of skin fixed marker system since there is relative movement between the skin and the underlying bone. Effective and time efficient measurements of scapula rotations are achieved through the use of a palpator with retro-reflective markers attached to it, improving the accuracy of the input data to musculoskeletal models.

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ERROR EVALUATION OF SKIN-MARKER MOVEMENTS IN MOTION ANALYSIS OF THE SHOULDER COMPLEX

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SUMMARY
A protocol has been established which aims to evaluate the errors caused by movements of the scapula under the skin during passive retro-reflective skin-marker based motion analysis of the shoulder complex. Preliminary results indicate that movement of the scapula under the skin has little effect on the joint and segment rotation calculations in healthy subjects.

CONCLUSIONS
As there is little change in the calculated joint angles, the validity of the motion models generated using this technique is not decreased notably. Further testing is required to confirm this.

INTRODUCTION
Motion analysis techniques to assess shoulder function have previously been developed [1] in the Human Motion Analysis Laboratory, School of Engineering, Cardiff University. Retro-reflective markers are attached to bony landmarks on the arm and torso on one side of the body and a marker cluster is placed on the upper arm. Body segment and joint coordinate systems are established and joint and segment rotations are calculated according to the recommendations of the International Society of Biomechanics (ISB) [2]. This measurement method is subject to inaccuracies caused by the movement of the scapula under the skin (particularly the inferior angle) during humeral elevation.

PATIENTS/MATERIALS AND METHODS
In order to quantify the errors associated with scapular movements under the skin, two experimental aids have been constructed. The first guides shoulder position in different planes of elevation and the second guides shoulder position during internal/external rotation. Retro-reflective markers are attached to each of the aids at 10° increments. Subjects are instructed to point to each of the markers in turn. At each increment, static measurements are taken for forward flexion, backward extension, abduction and internal/external rotation. The test is then repeated with marker positions on the scapula manually adjusted as necessary at each increment to account for errors caused by movement of the scapula under the skin. A scapula locator is also being implemented into the optical motion capture system used at Cardiff University to provide a further control measurement. A scapula locator is a three-pointed rigid body used to measure spatial orientation of the scapula [3]. Static measurements are again taken at each increment using the scapula locator to palpate the three bony landmarks of the scapula. Finally, for further comparison dynamic measurements are taken. The protocol is being tested on five subjects with no previous history of shoulder pathology or instability.

RESULTS
Complete kinematic descriptions of the shoulder have been obtained for two subjects. Joint and segment rotations were compared for each measurement protocol to establish the errors associated with scapular movement under the skin. Rotation profiles are in accordance with the literature [4], but with a larger range (up to 40°) for medial/lateral and anterior/posterior acromioclavicular joint rotation. Errors associated with movement of the scapula under the skin are largest (approx 7°) at 160° of humerus abduction.

DISCUSSION
Quantifying the errors caused by skin-marker discrepancies in motion analysis of the shoulder complex allows the validity of motion models generated to be determined. This study will serve as a validation study for future trials.

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