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DEPARTMENT OF SPORT AND EXERCISE SCIENCES

The Pathomechanics of Shoulder Injuries in Cricket Bowlers

by

Kathleen Anne Shorter

Thesis for the Doctor of Philosophy

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ABSTRACT

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Injury surveillance research has established that over 20 % of cricket injuries are related to the upper limb (Leary & White, 2000; Ranson & Gregory, 2008; Stretch, 2003), with bowlers associated altered rotational joint range of motion (Aginsky *et al.*, 2004, Bell-Jenje & Gray, 2005 and Stuelcken *et al.* 2008). As the applicability of such observations is limited, the aim of this thesis was to provide researchers with a greater understanding of the pathomechanics of shoulder injuries afflicting cricket bowlers though quantifying associated musculoskeletal adaptations and subsequently through the development and validation of a bowling specific kinematic model, establish the influence these may impart on bowling technique. The use of diagnostic ultrasound within the first experimental study in a cohort of bowlers without a history of shoulder injury, established a high prevalence of supraspinatus (45 %) and subscapularis (50 %) tendon pathology, providing insight into common musculotendinous pathology and adaptations that are indicative of the future potential of injury. Data presented within the second study aimed to first, quantify the kinematics of the shoulder during the bowling delivery in relation to humerothoracic motion and, second, the influence of rotation sequence to described humerothoracic motion was investigated. Findings established that whilst the bowling delivery was associated with large variability, future research must acknowledge the contribution of the scapula to shoulder motion. As such, due to the complexity of quantifying shoulder motion during cricket bowling, the following three experimental studies evaluated and developed the CSBT shoulder model through modifying current methods. The mCAST method in conjunction with an acromion cluster, was established to not only reduce resultant RMSE associated with scapula landmarks by up to 0.016 m, but also increase the repeatability and robustness of reconstructing GHJ location using the SCoRE method. The emphasis of the final experimental study was to apply the CSBT shoulder model to establish the contribution of individual rotator cuff muscles to shoulder joint stability and, to identify phases of the bowling delivery which increases the risk of injury. This case study established that during the bowling delivery the shoulder experiences large multi-planar forces placing demand on musculature, in particular supraspinatus and subscapularis to stabilise the joint. These findings in conjunction with those of the first experimental study, not only identify structures at risk of injury but also establish that for the effective formulation of injury prevention strategies the bowling delivery must be investigated in its entirety.

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Declaration of authorship

I, Kathleen Anne Shorter declare that the thesis entitled The Pathomechanics of Shoulder Injuries in Cricket Bowlers, and the work presented in the thesis are both my own and have been generated by me as the result of my own original research. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University;
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- Where I have consulted the published work of others, this is always clearly attributed;
- Where I have quoted from others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- None of this work has been published before submission.

Signed: KShorter

Date: 12/12/2011

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Finally, I would like to acknowledge the patient support of my family and friends both in Australia and the United Kingdom who have endured my frustrations and unique work hours.

Definitions and abbreviations used

Angulus Acromialis (AA): The prominent angle at the junction of the posterior and lateral borders of the acromion.

Anisotrophy: The property of being directionally dependant. In relation to diagnostic ultrasound anisotrophy results in the different echogenicity of tissues when the angle of the transducer is changed.

Acromioclaviculare joint (AC): The junction between the acromion and the distal end of the clavicle.

Anatomical coordinate system (ACS): A three dimensional coordinate system defined by the underlying anatomical landmarks of a segment.

AGT Distance: The distance between the infero-lateral edge of the acromion to the apex of the greater tuberosity of the humerus.

Angulus Inferior (AI): The acute angle formed by the junction of the medial and lateral borders of the scapula.

Anterior superior iliac spine (ASIS): The bony prominence on the anterior, superior aspect of the iliac crest of the pelvis.

Back foot contact (BFC): The moment during the bowling stride when the foot ipsilateral to the bowling arm (referred to as the back foot) contacts the ground.

Ball release (BR): The moment during the bowling stride when the bowler releases the ball.

Coracoacromial ligament (CA): A ligament between the coracoid process and the acromion.

Calibrated anatomical systems technique (CAST): The method proposed by Cappozzo, Catani, Della Croce & Leardini (1995) to minimise soft tissue artefact during kinematic analysis. Anatomical landmarks are defined statically in relations to a dynamic marker cluster, positioned in an area least affected by soft tissue artefact to enable reconstruction of anatomical landmarks during the dynamic movement of interest.

Centre of rotation (CoR): Centre of rotation of two adjacent segments.

Distraction: In relation to the shoulder joint, distraction commonly refers to a force exerted on the joint that results in the head of the humerus being pulled away from the glenoid cavity.

Echogenicity: Refers to the ability to bounce an echo off an object.

Elbow joint centre (EJC): The point of articulation between the distal humerus and the proximal head of the radius that is often defined as the midpoint between surface markers on the medial and lateral epicondyles.

Follow through (FT): The period during the bowling stride following ball release when the bowling arm continues to circumduct.

Front foot contact (FFC): The moment during the bowling stride when the foot contralateral to the bowling arm (referred to as the front foot) contacts the ground.

Functional joint centre (FJC): A mathematically derived centre of rotation about two joint centres.

Glenohumeral joint centre (GJC): The centre of rotation about the head of the humerus and glenoid cavity of the scapula often estimated by either regression or functional methods.

Gimbal lock (GL): The loss of one degree of freedom occurring due to singularity between coordinate systems when calculating Euler/Cardan angle sequences.

Googly: A type of delivery associated with a wrist spinner where at the moment of release the back of the hand faces the batsman enabling the bowler to impart clockwise spin on the ball.

Helical axis (HA): The helical axis or screw axis of a segment is a parameter that describes its simultaneous rotation and translation, and as such is often used to describe joint motion.

Hypoechoic: In utrasound, refers to an abnormal decrease in echoes due to a pathologic change in tissue density.

Intraclass correlation coefficient (ICC): A statistical measurement quantifying the strength and direction of resemblance between two or more variables.

Kinematics: The branch of biomechanics which studies the motion of a body without reference to the forces causing the motion.

Kinetics: The branch of biomechanics which studies the internal and external forces acting on a body resulting in motion.

Lateral epicondyle (LE): A small bony prominence on the lateral aspect of the distal portion of the humerus.

Legbreak: A type of delivery associated with a wrist spinner where the bowler releases the ball with the palm of their hand facing the batsman imparting anticlockwise spin on the ball.

Local coordinate system (LCS): A three dimensional coordinate system used to describe the position and orientation of a segment in relation to either other segments or the global coordinate system.

Long head of the biceps (LHB): The head of the biceps brachii that originates from supraglenoid fossa.

Magnetic resonance imaging (MRI): A medical imaging technique utilising nuclear magnetic resonance to visualise detailed internal structures of the body.

Maximal voluntary contraction (MVC): The peak force produced by a muscle as it contracts, often obtained through an isometric contraction against resistance.

Mean: A measure of central tendency, the average of a set of numbers.

Medial epicondyle (ME): A small bony prominence on the medial aspect of the distal portion of the humerus.

Modified CAST protocol (mCAST): A method proposed in chapter 5 for the reconstruction of scapula anatomical landmarks through the incorporation of a series of static calibration positions to aid in minimising error associated with the ability of an acromion cluster to reconstruct scapula landmarks.

Pre-delivery stride (PDS): The penultimate stride preceding the bowling stride.

Reliability: Within statistics, referring to the repeatability of a measure

Root mean square error (RMSE): A statistical measure of the difference between estimated and observed values to provide and indication of precision.

Sampling Frequency: The amount of data samples recorded per second; usually in hertz (Hz).

Shoulder joint centre (SJC): Synonymous with the glenohumeral joint centre and often viewed simplistically as the centre of rotation about the head of the humerus and the torso.

Soft tissue artefact (STA): The relative displacement between surface markers and underlying bone mainly attributed to the interposition of soft tissue structures.

Standard deviation: A measure of the spread of distribution about the mean.

Surface electromyography (sEMG): Is a method utilising non-invasive, surface electrodes to record the electrical activity produced by skeletal muscles.

Symmetrical centre of rotation estimation (SCoRE): A mathematical method proposed by Ehrig *et al.* (2006) to functionally estimate the centre of rotation about two articulating joint segments.

Technical coordinate system (TCS): A three dimensional coordinate system defined by surface markers lacking any anatomical relationship to the defining segment.

Trigonum Spinae Scapulae (TS): The junction at which the spine of the scapula meets the medial border.

Variability: Within statistics referring to the agreement between the value of a measurement and its true value.

Chapter 1

Introduction

Growing demands placed on cricketers have resulted in cricket playing nations placing increased emphasis on the identification and prevention of injuries, as characterised through the formalisation of injury definitions (Orchard *et al.*, 2005). Injury surveillance research has reported that over 20 % of injuries are related to the upper limb (Leary & White, 2000; Ranson & Gregory, 2008; Stretch, 2003), with a higher prevalence of shoulder tendon injuries associated with spin bowlers (1.1 %) compared to seam bowlers (0.9 %) (Orchard, James, Alcott, Carter & Farhart, 2002). Regardless of the sport under investigation, formulation of successful injury prevention measures is dependent on not only identifying the injury, but also gaining a comprehensive understanding of the mechanisms underlying the injury (Bahr & Krosshaug, 2005; Brooks & Fuller, 2006; Finch, 2006; Krosshaug, Andersen, Olsen, Myklebust & Bahr, 2005; Van Mechelen, Hlobil & Kemper, 1992). This thesis investigates the pathomechanics of shoulder injuries in cricket bowlers through the application of investigative techniques to first, quantify musculotendinous adaptations, and second, to establish the affect these impart on bowling technique.

The shoulder joint complex

The large degree of motion available at the shoulder occurs due to the unique interaction of multiple structures resulting in articulations about the glenohumeral joint, the sternoclavicular joint, the acromioclavicular joint and the scapulothoracic joint (Allen, 2008). For the purpose of this thesis, the shoulder joint will be generalised in relation to the glenohumeral joint (Figure 1.1) due to the biomechanically complex nature of this joint. Poor inherent joint stability as a consequence of the congruence between the articulating surfaces of the humeral head and glenoid, require surrounding musculature, primarily the rotator cuff group (Table 1.1) to provide dynamic joint stability (Lugo, Kung & Ma, 2008). Overhead sporting movements, particularly the throwing motion (Meister, 2000) are often associated with mechanical dysfunction of the rotator cuff, due to the stresses and strains placed on the musculature to meet the functional demands of the movement, whilst also maintaining the dynamic stability of the joint (Blevins, 1997; Meister, 2000).

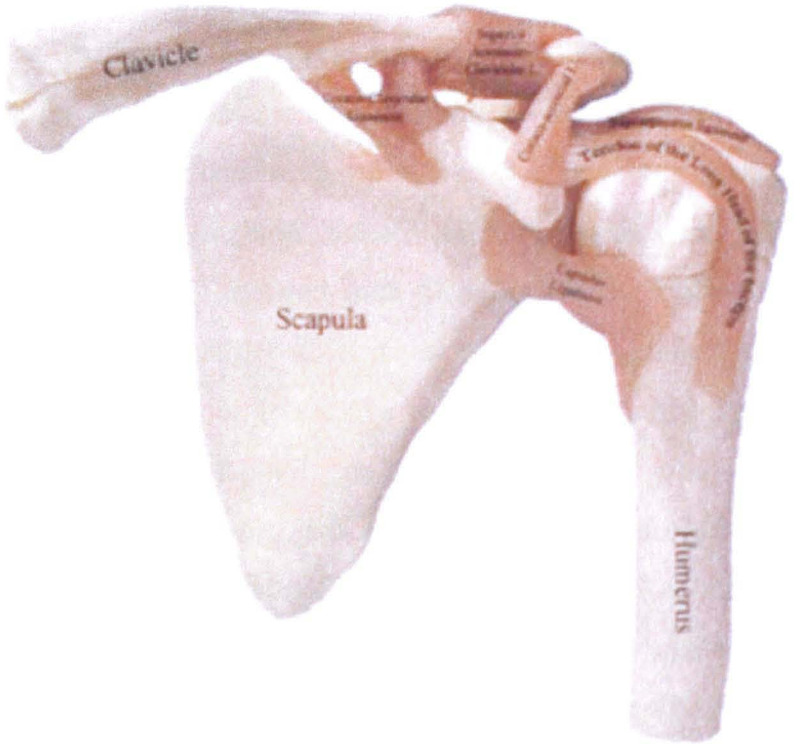


Figure 1.1 Glenohumeral joint

Table 1.1 Associated actions of the rotator cuff musculature

Rotator cuff muscle	Action
Supraspinatus	Initialises humeral abduction to 90 ° and assists in stabilising humeral head
Infraspinatus	External rotator of the humerus. Resists posterior and superior translation.
Teres minor	Adductor and external rotator of the humerus. Resists posterior and superior translation.
Subscapularis	Adductor and internal rotator of the humerus. Resists anterior and inferior translation.

The cricket bowling movement

The bowling movement (Figure 1.2) is recognised as a whole body motion, which culminates in the bowling arm contributing up to 50 % of resultant ball velocity through rapid circumduction of the arm (Elliott, Foster & Gray, 1986). Cricket bowlers can be generally classified as either spin or seam bowlers dependant on the bowler's reliance to impart either spin or speed on the ball to deceive the batsman (Woolmer, Noakes & Moffett, 2008). Seam bowlers rely on the generation of velocity achieved prior to ball release through efficient energy transfer that commences during the high paced run-up and culminates with rapid circumduction of the arm. The generated ball velocity achieved at release can be used to further classify seam bowlers as either slow-medium (18 - 27 $m.s^{-1}$), fast-medium (27 - 36 $m.s^{-1}$), fast (36 - 40.5 $m.s^{-1}$) or express (> 40.5 $m.s^{-1}$) (Abernethy, 1981 cited in Bartlett, Stockill, Elliott & Burnett, 1986). In comparison, spin bowlers are typified by a short, sedate run-up, with the objective of their technique being not to delivery the ball with force but rather to propel the ball so that it rotates rapidly (Woolmer *et al.,* 2008). The action utilised by the spin bowler to impart spin on the ball serves to classify them as either finger or wrist spinners (Woolmer *et al.,* 2008).

To date, description of the arm throughout the bowling movement has only been qualitatively described from largely a coaching perspective (Woolmer *et al.,* 2008) and has received relatively little attention within scientific literature (Chin, Elliott & Alderson, 2009). Myers & O'Brien (2001) describes the bowling arm as moving from being flexed and internally rotated, to circumducting through extension, abduction and external rotation, to thrusting flexion and internal rotation. Unlike the throwing motion, the bowler's body follows through in the same direction as the bowling arm, leading researchers to anecdotally believe that bowling is rarely the primary cause of shoulder injuries, but rather the repetitive nature of the movement can contribute to the causation of shoulder pain through creating weakness of the rotator cuff and shoulder instability (Myers & O'Brien, 2001).

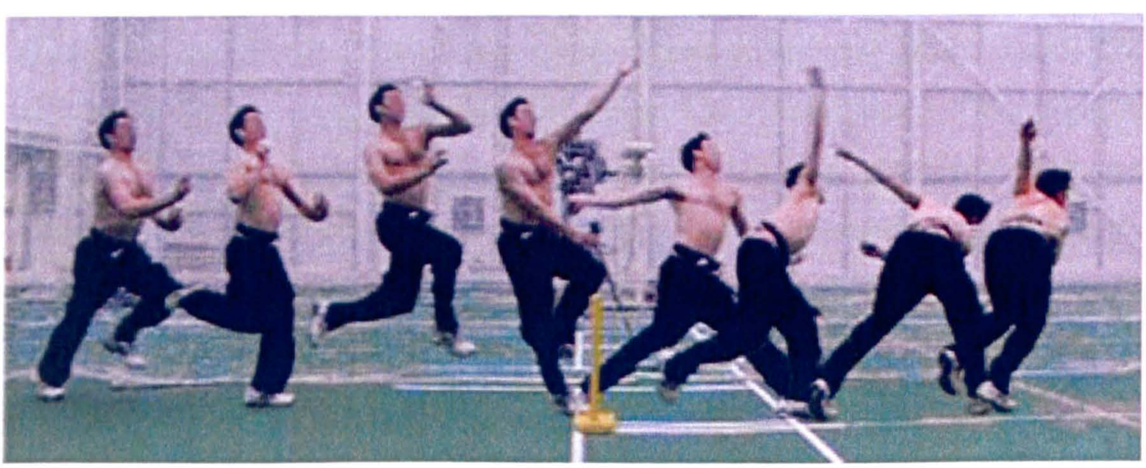


Figure 1.2 Cricket bowling motion from the gather to follow through

Nature and commonality of bowling related shoulder injuries

The identification of shoulder injuries amongst cricketers has been monitored since the 1990s using injury surveillance methods (Leary & White, 2000; Mansingh, Harper, Headley, King-Mowatt & Mansingh, 2006; Orchard *et al.*, 2002; Orchard, James & Portus, 2006; Stretch, 2003). Through adopting the model of Van Mechelen (Van Mechelen *et al.*, 1992), research has indicated that the incidence of upper limb injuries afflicting cricketers is over 20 % (Leary & White, 2000; Ranson & Gregory, 2008; Stretch, 2003), with Orchard *et al.* (2002) observing 6 % were associated with tendons of the shoulder joint complex. Amongst researchers (Aginsky, Lategan & Stretch, 2004; Bell-Jenje & Gray, 2005; Giles & Musa, 2008; Ranson & Gregory, 2008; Stuelcken, Ginn & Sinclair, 2008), there is growing consensus that injury surveillance definitions fail to identify the true incidence of shoulder injuries amongst cricketers, with no research to date undertaken to identify the long term influence of injuries as studies have only focused on elite, playing cohorts. Ranson & Gregory (2008) identified injured bowlers would often continue to bowl, modifying their technique through speed (45 %) and spin (15 %) or avoid particular deliveries (30 %), however such alterations in playing behaviour are not recognised by formal injury definitions.

Research by Aginsky *et al.* (2004), Bell-Jenje & Gray (2005), Giles & Musa (2008) and Stuelcken *et al.* (2008) has undertaken clinical assessments incorporating shoulder joint range of motion and joint strength to aid in identifying factors that may predispose bowlers to shoulder injuries. Similar to other overhead sports (Bak & Magnusson, 1997; Baltaci, Johnson & Kohl, 2001; Ellenbecker, Roetert, Bailie, Davies & Brown, 2002; Kibler, Chandler, Livingston & Roetert, 1996), Aginsky *et al.* (2004), Bell-Jenje & Gray (2005), Giles & Musa (2008) and Stuelcken *et al.* (2008) have all associated bowlers with demonstrating increased external rotation and limited internal shoulder rotation, however this has been reported in both bowlers with and without a history of shoulder pain and is typically observed as non-significant variations. Aginsky *et al.* (2004) established that bowlers with shoulder injuries were associated with significantly ($p < 0.009$) higher concentric internal torque at 180 $^{\circ}.s^{-1}$ which due to the lack of prior investigative research could only be anecdotally ascribed as compromising the dynamic stability of the shoulder (Myers & O'Brien, 2001).

The current lack of understanding in relating the nature of shoulder injuries afflicting cricket bowlers, impairs the formulation of injury prevention strategies. The first aim of this thesis is to utilise diagnostic ultrasound, incorporating quantitative measurements of associated musculotendinous structures, combined with a joint range of motion assessment to gain greater understanding of the nature and commonality of shoulder injuries. Findings would aid researchers in associating observed shoulder joint adaptations, as quantified through changes in joint dynamics to the aetiology of bowling related shoulder injuries caused by musculotendinous adaptations which could vary dependent on factors such as age, playing history and bowling style.

Kinematic model for cricket bowling

Whilst the bowling arm makes a significant contribution towards ball release speed (Chin *et al.,* 2009; Elliott *et al.,* 1986), to date, the focus of upper body kinematic analysis of the bowling movement has largely focused on factors relating to the legality of the bowling action through elbow joint kinematics (Aginsky & Noakes, 2010; Elliott, Alderson & Denver, 2007; Ferdinands & Kersting, 2007; Lloyd, Alderson & Elliott, 2000; Montazerian, Shaheen, Eftaxiopoulou & Bull, 2008; Roca, Elliott, Alderson & Foster, 2006). The surface marker model recommended by the International Cricket Council (ICC, 2009) makes it difficult for researchers to accurately describe shoulder motion during the bowling delivery, with Chin *et al.* (2009) acknowledging that observed measures within their study were not reflective of the motion observed. Without an accurate understanding of the position of the shoulder throughout the bowling motion it is difficult to gain an appreciation of the forces applied and how these may act to destabilise the shoulder joint, potentially leading to injury.

The complexity of the shoulder joint complex, makes it difficult to establish the position and orientation of the shoulder during dynamic movements such as cricket bowling. The accuracy of any kinematic model and its resultant calculations are dependent on the underlying validity of the techniques used to define the segments of interest, resulting in the International Society of Biomechanics (ISB) publishing recommendations for the definition of upper limb segment position and orientation (Wu *et al.,* 2005). Unlike other body segments, the translation of both the scapula and glenohumeral joint centre impair the validity of any kinematic analysis due to the dependence on these landmarks to define local coordinate systems (Ludewig, Hassett, Laprade, Camargo & Braman, 2010; Monnet, Desailly, Begon, Vallée & Lacouture, 2007). Whilst several kinematic models have been proposed for the shoulder (Dickerson, Chaffin & Hughes, 2007; Holzbaur, Murray & Delp, 2005; Kontaxis, Cutti, Johnson & Veeger, 2009), to date these have largely been applied within a controlled environment where movement patterns can be constrained (Gatti, Dickerson, Chadwick, Mell & Hughes, 2007; Gatti *et al.*, 2008; Grieve & Dickerson, 2008; Langenderfer, Carpenter, Johnson, An & Hughes, 2006).

Inherent difficulties in accurately reconstructing skeletal movement, particularly the scapula (Karduna, McClure, Michener & Sennett, 2001; Meskers, Vermeulen, de Groot, van Der Helm & Rozing, 1998b; van Andel, Wolterbeek, Doorenbosch, Veeger & Harlaar, 2008) and glenohumeral joint centre (Campbell, Alderson, Lloyd & Elliott, 2009; Meskers, van der Helm, Rozendaal & Rozing, 1998a; Monnet *et al.*, 2007; Roosen, Pain & Begon, 2009), have seen a multitude of techniques proposed. The appropriateness of such methods for dynamic, sporting movements can only be inferred. The second aim of this thesis is to evaluate the suitability of current methods used clinically to establish shoulder motion during cricket bowling and subsequently develop these further to design and validate a kinematic model specific to the demands of cricket bowling.

Contribution of the rotator cuff to shoulder stability during cricket bowling

The successful formulation of injury prevention measures requires a comprehensive understanding of the intrinsic factors that contribute to the causation of injury (Bahr & Krosshaug, 2005; Brooks & Fuller, 2006; Finch, 2006; Krosshaug *et al.*, 2005; Van Mechelen *et al.*, 1992). Similar to other overhead sports (Bak & Magnusson, 1997; Baltaci *et al.*, 2001; Ellenbecker *et al.*, 2002; Kibler *et al.*, 1996), cricket is perceived to result in biological adaptations as currently characterised by changes in shoulder joint dynamics (Aginsky *et al.*, 2004). Whilst lower limb and trunk injuries within cricket (Burnett, Barrett, Marshall, Elliott & Day, 1998; Elliott, 2000; Portus, Mason, Elliott, Pfitzner & Done, 2004; Ranson, Burnett, King, Patel & O'Sullivan, 2008) have received attention by researchers trying to identify phases of the movement and techniques which place the bowler at an increased risk of injury, to date no research has been undertaken regarding bowling related upper limb injuries.

Due to the structure of the shoulder joint, the rotator cuff plays an integral role in stabilising the joint, of which the contribution of each individual muscle can vary depending on the position of the arm (Favre, Jacob & Gerber, 2009). Defining the mechanical stability of individual muscles has gained increasing attention by researchers both *in vitro* (Hughes, Niebur, Liu & An, 1998; Klein Breteler, Spoor & Van der Helm, 1999) and *in vivo* (Gatti *et al.*, 2007; Graichen, Englmeier, Reiser & Eckstein, 2001; Juul-Kristensen *et al.*, 2000), all of which typically define muscular moment arms dependent on the origin-insertion method (Favre *et al.*, 2009). Such information can then be utilised by mathematical models (Dickerson *et al.*, 2007; Holzbaur *et al.*, 2005; Van der Helm, 1994) utilising representative population data for the simulation of movement patterns. Potvin & Brown (2005) proposed a simplified method for quantifying individual muscle contributions to joint stability requiring the origin and insertion coordinates of the muscle relative to the joint of interest and, the associated muscle force and stiffness. Subsequently this technique has been applied to the spine, hip and knee (Derouin & Potvin, 1990; Potvin & Derouin, 2005; Potvin & Brown, 2005), demonstrating its versatility as it can be applied to any two or three dimensional biomechanical analysis on an individual basis to gain a greater understanding of the pathomechanics of injury (Potvin & Brown, 2005).

As shoulder tendon injuries have been identified by Orchard *et al.* (2002) as accounting for 6 % of bowling injuries, there is a need to establish the contribution of the surrounding shoulder musculature, particularly the rotator cuff to joint stability. Through applying the method of Potvin & Brown (2005), the contribution of each rotator cuff muscle to dynamic shoulder joint stability can be quantified using an ecologically valid technique on an individual basis. Therefore, the final aims of this thesis are to apply the approach of Potvin & Brown (2005) to first, establish the role of each individual rotator cuff muscle to overall shoulder joint stability, and second, apply this method to identify phases of the bowling action which place the shoulder at an increased risk of injury.

Summary

Formulation of successful injury prevention strategies is a multistage process as proposed by Van Mechelen (Van Mechelen *et al.*, 1992). Whilst it is important to establish the incidence of injuries using surveillance techniques, researchers also need to gain a comprehensive understanding of the aetiological factors that contribute to the causation of injury. The aim of this thesis is to apply biomechanical techniques to provide researchers with knowledge to implement prevention strategies through first, providing a greater understanding of the nature and commonality of shoulder injuries afflicting cricket bowlers and second, to establish phases of the movement which place the bowler at an increased risk of injury.

Chapter 2

Nature and commonality of shoulder injuries within cricket bowlers

Introduction

The successful formulation of injury prevention strategies is reliant on a comprehensive injury profile which not only identifies the incidence and prevalence of injuries but also the associated intrinsic and extrinsic risk factors (Bahr & Krosshaug, 2005; Finch, 2006). Whilst the major cricket playing nations have undertaken injury surveillance studies since the 1980s (Hoy, 1987; Leary & White, 2000; Mansingh *et al.,* 2006; Orchard *et al.,* 2002; Orchard *et al.,* 2006; Stretch, 2003), the conclusions drawn in regards to bowling related shoulder injuries are limited. Subsequent research (Aginsky *et al.,* 2004; Bell-Jenje & Gray, 2005; Giles & Musa, 2008; Ranson & Gregory, 2008; Stuelcken *et al.,* 2008) through investigating changes in shoulder joint dynamics, specifically in relation to joint range of movement, has lead to a growing consensus amongst medical support staff that current injury definitions used by cricket governing bodies leads to an underestimation of the true incidence of shoulder injuries. To aid in gaining greater understanding of the nature and commonality of shoulder injuries affecting bowlers, the aim of this investigation was to utilise diagnostic ultrasound to provide insight into musculotendinous adaptations to the shoulder associated with bowling that may result in functionally destabilising the joint, whether the bowler is deemed to be injured or not under the current injury classification system.

Cricket injury surveillance research

The growing popularity of cricket combined with increasing demands placed on elite players, has seen an intensification by the main cricket playing nations of Australia, England, South Africa and the West Indies to identify common injury patterns and to implement appropriate preventative measures (Orchard *et al.*, 2005; Stretch, 2001).

Cricket injury surveillance research has adopted the model proposed by Van Mechelen *et al.* (1992), whereby evidence based measures to prevent injuries forms what is referred to as a 'sequence of prevention' composed of four stages (Orchard *et al.*, 2005). The first stage aims to identify and establish the extent of the sports injury problem. The second stage utilises the knowledge gained from the first stage to investigate and identify the the aetiology and mechanism of injuries. These initial stages help to formulate the third stage of introducing preventative measures whereby the last stage assesses the effectiveness of the preventative measures. Whilst other injury prevention models have been proposed (Finch, 2006; Meeuwisse, 1994), to date, most injury prevention research, particularly that adopting the Van Mechelen model (Van Mechelen *et al.*, 1992), fails to progress past the second stage due to both methodological limitations and a lack of consensus on injury definitions (Finch, 2006; Krosshaug & Verhagen, 2009).

The first published cricket injury surveillance study was conducted in the 1980s by Hoy (1987) on elite Australian cricketers. Subsequently, most major cricket playing nations have independently conducted surveillance studies since the 1990s (England: Leary & White, 2000; West Indies: Mansingh *et al.*, 2006; Australia: Orchard *et al.*, 2002; Orchard *et al.*, 2006; South Africa: Stretch, 2003), culminating in a published consensus statement regarding definitions and methods to calculate injury rates in cricket (Orchard *et al.*, 2005). Orchard *et al.* (2005) defines an injury as: any injury or medical condition that either a.) prevents a player from being fully available for selection for a major match or, b.) during a major match causes a player to be unable to bat, bowl, or keep wicket when required by either the rules or the team's captain. In addition, injury rates are reported in relation to injury incidence and injury prevalence. Injury incidence analyses the number of new (or new plus recurrent) injuries over a given time period and, injury prevalence considers the average number of squad players unavailable for selection through injury or illness for each match, expressed as a percentage of the total squad members (Orchard *et al.*, 2005).

Shoulder injury incidence and prevalence data collected from cricket injury surveillance studies published since 2000 is presented in Table 2.1, where variations in findings between studies may be a reflection of differing study cohorts and injury definitions (Orchard *et al.,* 2005).

Table 2.1 Reported shoulder injury incidence and prevalence data since 2000

Author	Surveillance cohort	Study Duration	Shoulder Injury Incidence	Shoulder Injury Prevalence
Gregory *et al.* (2002)	113 young cricket bowlers (mean age 14.9 ± 2.5 years) from three English county cricket centres of excellence	6 months, composed of 3 months preseason and the first 3 months of the 1998 season	14 shoulder injuries Fast bowler incidence: 0.007 Spin bowler incidence: 0.055	Not reported
Leary and White (2000)	54 English first XI county cricketers	Between 1985 and 1995	Upper limb 29.4%, of which 7.1% associated with the shoulder.	Not reported
Mansingh *et al.* (2006)	West Indies National team and first class domestic teams	Between June 2003 to December 2004	Shoulder injury: 0.02	Not reported
Orchard *et al.* (2002)	Australian male cricketers at state and national levels	Between 1995-1996 and 2000-2001 seasons	Shoulder tendon injuries related to bowling: 6%	Shoulder tendon injury prevalence: Fast bowler: 0.9%, Spin bowler: 1.1%
Orchard *et al.* (2006)	Australian male cricketers at state and national levels	Ten years	For all playing positions mean seasonal shoulder injury incidence 1.1	For all playing positions mean seasonal shoulder injury prevalence 0.75
Ranson and Gregory (2008)	158 English first XI county cricketers	2005 county season	23% experienced shoulder injuries	1.7%
Stretch (2003)	11 provincial and national South African teams	Three seasons	Glenohumural joint: 21.7%	not reported

Orchard *et al.* (2002) presented a profile of injuries occurring within Australian cricket at the elite level between the seasons 1995/1996 to 2000/2001. In regards to the shoulder in bowlers, tendon injuries were found to have an incidence of 6 %, with a higher prevalence amongst spin bowlers (1.1 %) compared to seam bowlers (0.9 %). Orchard *et al.* (2002) concluded by recommending that shoulder tendon injuries, such as tendonitis, which Leary & White (2000) associated with 45.7 % of shoulder injuries; along with side strains, hamstring and groin injuries in bowlers required further investigation, which was also identified in subsequent work (Orchard *et al.,* 2006).

Gregory, Batt & Wallace (2002) investigated one hundred and thirteen young English county cricketers, of which forty two participants were spin bowlers. Using telephone interviews over a six month period, injuries were self-reported and categorised using a four point scale. A grade 1 injury was associated with pain following bowling, grade 2 with pain during bowling, grade 3 with pain impairing bowling performance and grade 4 associated with pain preventing bowling. Of the 95 cricket injuries reported, 44 were attributed to bowling. Ten percent of fast bowlers and 16.7 % of spin bowlers developed shoulder injuries however no fast bowler directly ascribed their injury to bowling whilst all five bowlers with a grade 3 or 4 injury attributed their injury to bowling (Gregory *et al.,* 2002). The authors speculated that the higher incidence of shoulder injuries afflicting spin bowlers occurring during circumduction of the arm, whereby internal rotation may predispose bowlers to impingement and injury.

Ranson & Gregory (2008) investigated the impact of shoulder injuries on professional cricketers during the 2005 England and Wales county cricket season establishing that the incidence and prevalence of shoulder injuries was greater than that reported within injury surveillance data. Two questionnaires were administered during the season, with the last questionnaire occurring towards the end of the season in September. Shoulder injury definitions differed from the general injury definitions proposed by Orchard *et al.* (2005). A shoulder injury was defined as any shoulder pain, weakness or instability that caused the player to miss cricket matches or training during the season. In addition, players were also considered to be injured if they did not miss matches or training but experienced shoulder pain, weakness or instability that compromised cricket performance or training or impacted on daily living. Chronic injuries were defined as those that had an onset of more than 6 months prior to the beginning of the season. Recurrent shoulder injuries were defined as a shoulder injury during the season, with the cricketer also experiencing a similar, separate problem in their affected shoulder during any of the previous 3 years. Twenty three percent of players experienced shoulder injury, 83 % of which were new, 17 % chronic and 31 % recurrent (Ranson & Gregory, 2008). Six percent of spin bowlers and 15 % of fast bowlers experienced shoulder injuries. Of the twenty bowlers whom played whilst experiencing shoulder injuries, 30 % never experienced shoulder pain when bowling, 30 % rarely experienced shoulder pain when bowling and 15 % always had pain on bowling. Fifty percent of those injured reduced the number of balls bowled in training whilst 35 % reduced the number of overs bowled during matches as a consequence of shoulder injury. Speed and spin was affected in 45 % and 15 % of bowlers respectively and 30 % avoided particular deliveries. Ranson & Gregory (2008) acknowledged that as information utilised in the study was provided from the perspective of cricketers; findings may have been influenced by recall bias and inflated by having to exclude participants who only returned one questionnaire and therefore may not have experienced any shoulder injuries during the season. The modified injury definitions used within this study are the first investigating shoulder injury incidence that attempt to acknowledge cricketers who are still able to play whilst being injured, thereby potentially resulting in long term degenerative and overuse injuries, atypical of shoulder injuries identified in annual injury reports.

In comparison to many other sporting codes, the formalised injury surveillance definitions of Orchard *et al.* (2005) exemplifies the effort of the main cricket playing nations to identify and prevent common injuries afflicting cricketers. Whilst injury surveillance research, in agreement with (Finch, 2006; Krosshaug & Verhagen, 2009) can aid in identifying the incidence and prevalence of injuries afflicting cricket bowlers, the practical application of these findings is limited as such research fails to report fully the nature and mechanism of injury. As such, whilst a bowler may be reported as experiencing a shoulder injury, injury surveillance data is unable to establish in detail the anatomical structures involved or if the onset of injury was experienced whilst bowling, batting or fielding. Therefore, for the effective formulation of injury prevention strategies, cricket research must progress from injury surveillance reporting to instead place greater emphasis on understanding the pathomechanics of shoulder injuries through utilising other investigative methods.

Factors associated with shoulder injuries afflicting cricket bowlers

In agreement with Ranson & Gregory (2008) there is growing support amongst medical staff affiliated with cricket teams that the sole use of injury surveillance data to quantify shoulder injuries within cricket is inappropriate (Aginsky *et al.,* 2004; Bell-Jenje & Gray, 2005). Bell-Jenje & Gray (2005) monitored ninety six elite South African cricketers over a five year period incorporating postural, biomechanical and physiotherapy assessments. Assessments established cricketers demonstrated weak scapular stabilisers and limited internal rotation in participants with and without a prior history of shoulder injury. During the 5 year period, 24 % of injuries were related to the shoulder, of which 80 % collectively afflicted bowlers and all rounders. In addition to weak scapular stabilisers identified by Bell-Jenje & Gray (2005), cricket bowlers, similar to other throwing sports have been associated with demonstrating an altered joint range of motion compared to their non bowling shoulder (Aginsky *et al.,* 2004; Bell-Jenje & Gray, 2005; Stuelcken *et al.,* 2008).

Aginsky *et al.* (2004), Bell-Jenje & Gray (2005), Giles & Musa (2008) and Stuelcken *et al.* (2008) have all associated bowlers with demonstrating increased external rotation and limited internal shoulder rotation, however this has been reported in both bowlers with and without a history of shoulder pain and is typically observed as non-significant variations. Research investigating changes in joint range of motion has been utilised within other sporting movements to aid in understanding how restricted joint range of motion may lead to alterations in movement technique which may either result in injury or impair performance (Bak & Magnusson, 1997; Baltaci, Johnson & Kohl III, 2001; Ellenbecker *et al.*, 2002; Kibler, Chandler, Livingston & Roetert, 1996). There is conjecture within shoulder research as to the significance of changes in shoulder rotation, and if it is a decrease in total joint range of motion rather than an alteration in the ratio between internal and external rotation that contributes to the causation of shoulder injuries (Meister, 2000). The use of joint range of motion assessment, whilst acknowledged as a valuable method for monitoring of athletes, fails to provide an indication of osseous, musculoskeletal and soft tissue adaptations that occur; as to date neither the quality of movement and end point feel are reported (Clarkson, 2000).

Aginsky *et al.* (2004) reported provincial bowlers displayed a non-significant alteration in joint range of motion (internal rotation: injured = 84.00 ± 10.77 °, uninjured = 89.75 ± 17.26 °, $p = 0.361$; external rotation: injured = 116.22 ± 10.26 °, uninjured = 116.83 ± 7.91 °, $p = 0.884$). Whilst Aginsky *et al.* (2004) could not establish differences in joint range of motion between bowlers with and without shoulder injury, bowlers with shoulder injuries were associated with significantly ($p < 0.009$) higher concentric internal torque at 180 $°.s^{-1}$ (injured: 65.20 ± 10.03 $Nm.kg^{-1}$; uninjured: 45.91 ± 10.26 $Nm.kg^{-1}$). The findings of Aginsky *et al.* (2004) are in agreement with Myers & O'Brien (2001) in attributing weak external rotator strength as compromising the stability of the shoulder particularly during the deceleration phase of the bowling action. Further research is required to establish the link between altered joint dynamics as typified by range of motion and relative strength, to the underlying adaptive mechanisms to aid in researchers gaining a more comprehensive understanding of factors which contribute to cricket bowling shoulder injuries.

Isolated reports of shoulder injuries afflicting cricket bowlers

Whilst cricket injury surveillance fails to identify the specific presentation of shoulder injuries afflicting cricket bowlers, there are numerous studies, which, whilst unable to conclusively ascribe the bowling movement as the primary causative factor of shoulder injuries provide an indication of injury mechanisms.

Myers & O'Brien (2001) attributed the repetitive bowling motion as placing strain on the rotator cuff which may lead to weakness and increased translational movement of the humeral head resulting in labral tears and superior labral anterior lesions. This is supported by the findings of Bell-Jenje & Gray (2005) who established within elite South African cricketers the majority of shoulder injuries presented as either primary or secondary impingement. In addition, isolated case reports on shoulder injuries afflicting cricket bowlers have been reported.

Drescher *et al.* (2004) reported a case of a 12 year old male presenting with little league shoulder syndrome, an injury associated with baseball pitchers and characterised by proximal humeral epiphysiolysis. The mechanism of this injury is associated with the whip like activity of the arm during throwing, pitching and bowling activities placing repetitive traction strain on the shoulder, particularly the epiphysiolysis in younger, skeletally immature athletes. de Villiers, Pritchard, De Beer & Koning (2008) presented a case study of a 21 year old professional fast bowler presenting with a scapular stress fracture affecting his bowling arm. In common with other injury reports, de Villiers *et al.* (2008) speculated that the causation of this injury in relation to the cricket bowler may be associated with bowling workload, as the repetitive nature of the action which would place unusual stresses on the scapula. Varied presentations of shoulder injuries afflicting bowlers of different ages would suggest that research is required to establish the influence of factors such as playing experience, bowling style and skeletal maturity have on the nature and commonality of shoulder injuries afflicting cricket bowlers.

Diagnostic imaging to aid in understanding the aetiology of cricket injuries

Whilst the use of diagnostic imaging has yet to be incorporated to aid in establishing the nature and commonality of shoulder injuries afflicting cricket bowlers, it has previously been utilised by researchers investigating trunk and lower limb bowling injuries (Engstrom *et al.,* 1999; Hides *et al.,* 2008; Humphries & Jamison, 2004; Ranson, Kerslake, Burnett, Batt & Abdi, 2005; Ranson & Gregory, 2008). Humphries & Jamison (2004) utilised both clinical and magnetic resonance imaging (MRI) data to investigate bowling side strains to gain a greater understanding of the musculoskeletal structures involved and to aid in identifying phases of the bowling action which would place these structures under increased strain. Hides *et al.* (2008) successfully utilised MRI to provide an insight into trunk muscle size and function in elite cricketers and how it contributes to low back pain. Hides *et al.* (2008) established muscle asymmetry was present in all bowlers as a consequence of the nature of the asymmetrical bowling action, with bowlers with lower back pain demonstrating the greatest asymmetry of the quadratus lumborum muscle. Findings from these investigations aid in providing researchers with a link between cricket injury surveillance data and the kinematics of associated cricket movements through establishing adaptive soft tissue and musculoskeletal changes which occur as a result of the demands of the sport and, which may contribute to the causation of injuries.

Use of diagnostic ultrasound to identify adaptive changes to the shoulder joint

Whilst diagnostic ultrasound has traditionally been used to supplement clinical assessment through qualitatively assessing the shoulder joint and associated structures, there is a growing trend to incorporate quantitative measures. Research to date has investigated the use of measurements such as tendon size to aid in the diagnosis of pathology such as subacromial impingement (Cholewinski, Kusz, Wojciechowski, Cielinski & Zoladz, 2008) and, to identify adaptive changes associated with specific movements within sporting (Brasseur *et al.,* 2004) and musical environments (Wilkinson & Grimmer, 2000; Wilkinson & Grimmer, 2001).

Shoulder joint injuries, particularly those affecting shoulder joint stability are commonly associated with musculotendinous structures such as the rotator cuff and coracoacromial ligament (Lewis, 2009a, Lewis, 2009b). The majority of rotator cuff tears are associated with progressive attrition and degeneration over time (Rockwood, 2009), in particular, tendon thinning is seen as a precursor for full and partial thickness tears (Leotta & Martin, 2000). Changes in musculotendinous structures over time can be attributed to factors such as the composition of surrounding osseous structures impinging soft tissue structures, combined with repetitive stresses and strains placed on the rotator cuff leading to soft tissue adaptations which can act to destabilise the shoulder joint. Whilst MRI imaging is acknowledged to be the current gold standard in diagnostic imaging for quantitative measurements the associated expense and accessibility has resulted in ultrasound been acknowledged as an acceptable alternative (Juul-Kristensen *et al.,* 2000). The successful incorporation of ultrasound whilst providing a non-invasive method to monitor athletes' shoulders would need to be undertaken with caution as, ultrasound is not only operator dependant but also prone to errors associated with 2D imaging as the position and orientation of the probe will alter the visual appearance of structures under investigation (Leotta & Martin, 2000). However, information which could be collected using this modality would provide professionals with a greater understanding of musculotendinous adaptations associated with movements such as cricket bowling that occur over time.

Cholewinski *et al.* (2008) conducted an investigation to evaluate the usefulness of ultrasound measurements in the diagnosis of subacromial impingement syndrome in the shoulder in fifty seven participants displaying unilateral symptoms of impingement syndrome compared to a control group of thirty six participants with no history of shoulder pain. Ultrasound measures included assessment of rotator cuff integrity, measurements of rotator cuff thickness and the distance between the infero-lateral edge of the acromion to the apex of the greater tuberosity of the humerus (AGT distance). Cholewinski *et al.* (2008) established differences in rotator cuff thickness of more than 1.1 mm and a difference in AGT distance of more than 2.1 mm between shoulders with and without symptoms of impingement syndrome. Results from Cholewinski *et al.* (2008) suggest that quantitative ultrasound measurements may be used to establish dysfunction of the rotator cuff.

Brasseur *et al.* (2004) investigated one hundred and fifty competitive, veteran tennis players aged between thirty five to seventy seven years of age to correlate sonographic abnormalities of the rotator cuff with clinical findings. Ultrasonographic assessment was conducted by three trained radiologists assessing the muscles, periarticular bursae and rotator cuff tendons of both shoulders. Rotator cuff assessment included tendon measurement, tendon thickness and the presence of calcification. Ultrasound abnormalities found in the dominant shoulder were compared to those observed in the non dominant shoulder and findings further analysed in regards to players with and without a history of shoulder pain. Brasseur *et al.* (2004) established that tears to the long head of the biceps (LHB) tendon were only observed in the dominant shoulder, with significantly more ($p < 0.001$) supraspinatus tears (both partial and complete) observed in 43 dominant compared to 16 non dominant shoulders. In addition, subscapularis calcifications were observed in 23 dominant shoulders compared to only 12 non dominant shoulders ($p < 0.05$). Non significant variations in both LHB and rotator cuff thickness were observed between dominant and non dominant shoulders, with no significant relationship associated between tendon thickness and history of shoulder pain. Brasseur *et al.* (2004) concluded that whilst asymptomatic morphological changes were observed in both LHB and rotator cuff tendons, it would be impossible to associate the aetiology of these changes with tennis specific movements particularly for the age group investigated and, that such changes do not prevent players in participating in competitive level tennis.

Wilkinson & Grimmer (2001) conducted an investigation using 15 elite orchestral violists and violinists to assess the effectiveness of ultrasound to substantiate changes in muscle after workload and its recovery over time. The LHB, the supraspinatus tendon, the trapezius muscle and rhomboid muscle were measured using a previously validated protocol (Wilkinson & Grimmer, 2000). Findings from this investigation established significant changes in the LHB and trapezius indicating that ultrasound is an effective modality for demonstrating changes in muscle over time, however, as no normative data has been collected, limited conclusions regarding occupational demands and stresses in relation to specific activities can be drawn (Wilkinson & Grimmer, 2001).

Reliability and reproducibility of quantitative ultrasound measurements

The use of quantitative ultrasound measurements to aid in investigating and establishing shoulder injuries is yet to be fully accepted with a growing number of publications investigating the reliability and repeatability of associated methods (Collinger, Gagnon, Jacobson, Impink & Boninger, 2009; Nielsen, Jensen, Darvann, Jorgensen & Bakke, 2000). Quantitative measurements, like any assessment utilising ultrasound is acknowledged to be both operator dependant and prone to limitations associated with the quality of equipment (Leotta & Martin, 2000; Read & Perko, 1998). To aid in the acceptance of quantitative ultrasound measurements, researchers such as Brushøj *et al.* (2006), Collinger *et al.* (2009), Nielsen *et al.* (2000) and Nielsen, Jensen, Darvann, Jørgensen & Bakke (2006) have conducted investigations aimed to establish the reliability and repeatability of quantitative measurements to assess their feasibility for integration into future assessment protocols.

Collinger *et al.* (2009) undertook an investigation to quantify the reliability and measurement error of quantitative ultrasound imaging protocols for the LHB and supraspinatus tendons using generalizability theory. Findings from this study, established that quantitative ultrasound measurements exhibited moderate intrarater reliability ($\Phi > 0.50$) but poor interrater reliability ($0.26 < \Phi > 0.82$) which is in agreement with earlier research by Brushøj *et al.* (2006) investigating the reproducibility of ultrasound and MRI measurements associated with the lower limb. Both Brushøj *et al.* (2006) and Collinger *et al.* (2009) recommended that due to poor repeatability and reliability, investigations utilising quantitative ultrasound measurements must address these issues through incorporating a set protocol aimed to minimise measurement error that is conducted by a sole, experienced operator.

Study aim

Research to date (Gregory *et al.,* 2002; Orchard *et al.,* 2002; Orchard *et al.,* 2006), has identified a need for further cricket research to investigate shoulder injuries, particularly tendon injuries associated with bowlers due to the underestimation of the true occurrence of injuries by current cricket injury surveillance studies. Similar to other overhead sports, cricket bowlers are associated with an altered joint range of motion which is attributed to destabilising the joint (Aginsky *et al.,* 2004; Myers & O'Brien, 2001). Whilst case reports (Drescher *et al.,* 2004; de Villiers *et al.,* 2008), indicate that the nature of shoulder injuries may vary dependant on factors such as skeletal maturity and playing experience, no research to date has attempted to quantify musculotendinous adaptations observed in the bowling shoulder.

The aim of this investigation was to utilise an diagnostic ultrasound assessment incorporating both qualitative and quantitative measures to establish musculotendinous adaptations associated with the bowling shoulder to provide insight into the nature and commonality of shoulder injuries afflicting cricket bowlers. Through focussing on a cohort of county bowlers yet to experience a shoulder injury according to current injury definitions (Orchard *et al.,* 2005), it was hypothesised that in accordance with researchers (Aginsky *et al.,* 2004; Bell-Jenje & Gray, 2005; Giles & Musa, 2008; Ranson & Gregory, 2008; Stuelcken *et al.,* 2008), the incidence of shoulder pathology would be greater than that reported by injury surveillance studies and, the presentation of pathology would increase with playing experience which whilst yet to prevent the player from bowling would compromise the integrity of the joint.

Method

Participants

After gaining university ethical approval, a cohort of twenty participants (age: 21.50 ± 4.85 years, mass: 79.25 ± 8.03 kg and height: 1.83 ± 0.07 m) from Hampshire and Sussex County Cricket Clubs were recruited and provided informed consent. For any participant under the age of 18, consent was provided by club officials acting on behalf of the player's parent or guardian. In agreement with the research design of Brasseur *et al.* (2004) investigating shoulder injuries in tennis players, participants acted as their own control and were divided into two subgroups (academy:- n: 9, age: 17.45 ± 1.81 years, mass: 74.56 ± 4.45 kg and height: 1.80 ± 0.06 m and elite:- n: 11, age: 24.82 ± 4.12 years, mass: 83.09 ± 8.41 kg and height: 1.84 ± 0.08 m) to enable the influence of playing experience to be investigated. Academy bowlers were defined as players contracted to their respective club as an academy player and yet to play for the first XI in an official match. Elite players were defined as being currently contracted to their respective county club and having been selected to bowl in an official first XI match during the previous season. Inclusion for participation in this study required that all bowlers had no documented history of shoulder injury affecting either their bowling or non bowling arm by their respective club according to the injury definitions of Orchard *et al.* (2005).

Equipment

All ultrasound assessments were undertaken by an experienced radiologist using a Sonosite Micromaxx machine (Sonosite, Hitchin, UK) with onscreen distance callipers to enable quantitative measurements to be recorded. Scanning was performed using a electronic high frequency, linear, broadband (10-5 MHz) transducer with a 9 cm scan depth.

Testing procedure

Data collection was performed during the 2010 and 2011 pre-seasons, a period previous injury surveillance research associated with the highest injury incidence (Leary & White, 2000). All data obtained from the ultrasound assessment for both bowling and non bowling shoulders were collated using CSBT DataCompiler (Shorter, 2010, unpublished program) (Figure 2.1)(Appendix D), a custom LabVIEW™ program (National Instruments, Austin, USA) for later analysis.

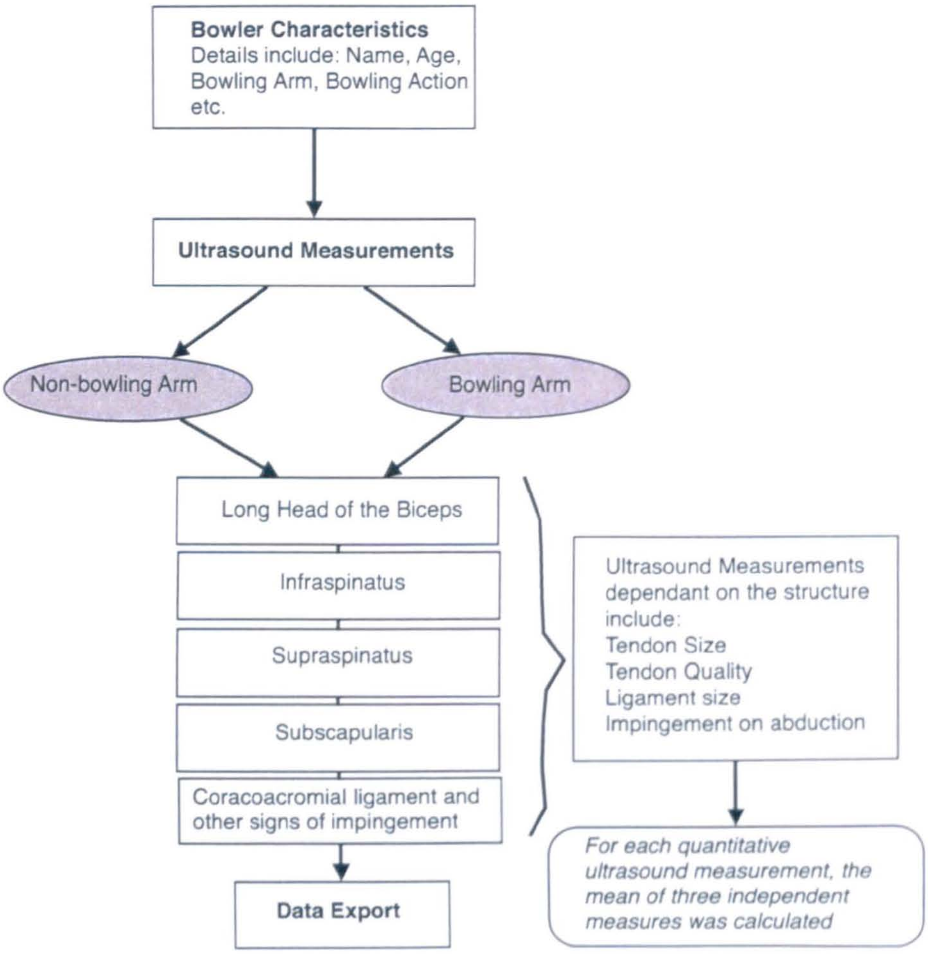


Figure 2.1 CSBT DataCompiler (Shorter, 2010, unpublished program) explanatory program flow diagram

Diagnostic ultrasound assessment

For both bowling and non bowling shoulders, diagnostic ultrasound was conducted by one experienced radiologist as previous research by Collinger *et al.* (2009) advocated the use of a sole operator due to the influence this imparts on the reliability of quantitative ultrasound measurements. The following protocol was used to establish shoulder joint integrity through incorporating both visual qualitative assessment and quantitative measurements of the main soft tissue structures.

Long head of the biceps tendon

LHB was assessed with the patient in a seated position. The humerus was positioned parallel to the long axis of the torso with the forearm in a supinated position (Figure 2.2). Using a modified protocol from Wilkinson & Grimmer (2001) and in agreement with Brasseur *et al.* (2004), LHB tendon measurement was standardised to correspond with the proximal aspect of the intertubercular groove at the point of maximal thickness measured in the transverse plane. Three measurements were collected with the ultrasound probe repositioned following each measure, and the mean of the measurements used for subsequent analysis. Evaluation of LHB tendon quality was assessed in using a modified clinical scale (Table 2.2) adapted from Cholewinksi *et al.* (2008).

Figure 2.2 Participant position for LHB measurement

Table 2.2 Definition of tendon quality adapted from Cholewinski *et al.* (2008)

Scale	Definition
0 - normal	Normal tendon contour and echogenicity with no discontinuity
1 - tendinopathy	Abnormal, non-homogenous echogenicity,which may be associated with diffuse inflammation or degenerative changes and no discontinuities to the tendon surface
2 - partial tear	Area of discontinuity to the tendon resulting in loss to the tendon shape or hypoechoic area
3 - full tear	Hypoechoic zone extending through the entire thickness of the tendon

Rotator cuff tendons

Subscapularis, supraspinatus and infraspinatus were used to quantify rotator cuff integrity through assessing both tendon size and tendon quality using the four point scale (refer to Table 2.2). Similar to LHB tendon size measurement, for each rotator cuff tendon, the mean of three independent measurements was obtained for subsequent analysis. As previous research (Collinger *et al.,* 2009; Wilkinson & Grimmer, 2000) has highlighted that the reliability of quantitative ultrasound measurements is dependant on a set pre-established protocol. Pilot testing was undertaken to determine positions which would minimise the affect of anisotrophy and, enable the most repeatable tendon measurements to be taken. For subscapularis, the humerus was externally rotated with the forearm in a supinated position (Figure 2.3a) to enable tendon size measurement to be taken at the footprint of the tendon overlying the lesser tubercle within the sagittal oblique view. Supraspinatus was measured with the humerus posteriorly displaced through shoulder extension with the forearm supinated (Figure 2.3b) Whilst supraspinatus pathology was assessed within the coronal oblique view, measurement of tendon thickness was obtained within the sagittal oblique view overlying the greater tubercle. To assess both infraspinatus pathology and tendon thickness, the participant was positioned with their arm internally rotated across their body (Figure 2.3c). Infraspinatus tendon thickness was measured within the sagittal oblique view at the inferior aspect of the greater tubercle.

Figure 2.3 Participant position for measurement of a. subscapularis, b. supraspinatus and c. Infraspinatus tendons

Subacromial impingement

Subacromial shoulder impingement was assessed in regard to the size of the coracoacromial ligament and also on either the presence or absence of bulging of supraspinatus at the coracoacromial arch, or, distension of the subacromial bursa on passive abduction of the arm. The coracoacromial ligament was measured with the humerus posteriorly displaced, as per the position used to assess supraspinatus. The probe was placed on the acromion and rotated to find the coracoid process with coracoacromial ligament thickness defined by the maximum depth of the ligament, with the mean of three independent measurements used for subsequent analysis.

Statistical analysis

To investigate the influence of playing experience on musculotendinous adaptations, data analysis was undertaken for both the entire study cohort and, for each subgroup of bowler (academy and elite). Statistical analysis was undertaken using SPSS version 16 for windows (SPSS inc., Chicago, USA) with the alpha level set at $p \leq 0.05$. As variables for statistical analysis included data which were either continuous or ordinal in nature, both parametric and non-parametric statistical tests were conducted respectively. Quantitative ultrasound measurements such as measurements of tendon and ligament size, were expressed as means (± SD), with measurements for the bowling shoulder compared using paired t-tests to those obtained for the non bowling shoulder. For each tendon, non-parametric Wilcoxon signed-rank tests were undertaken to establish if the incidence of pathology, as defined through tendon quality and the presence of impingement, was greater within the bowling shoulder compared to the non bowling shoulder.

Results and Discussion

The study cohort investigated in this study was composed of 11 elite and 9 academy bowlers. Due to the lack of spin bowlers (n=3) within the cohort no comparison in relation to playing style in regard to shoulder injuries could be made. In agreement with the study hypothesis the incidence of tendon pathology was found to be greater with increased playing experience. Whilst both groups of bowlers were observed to exhibit pathology affecting both their bowling (elite: 90.9 %, academy: 44.4 %) and non bowling shoulders (elite: 54.5 %, academy: 22.2 %), the incidence associated with elite players was far greater. Whilst this study is unable to solely attribute this to playing experience or indeed if bowling is the causative factor, it does provide an indication that injury prevention measures must start before players begin to play at higher levels of the game as by this stage many bowlers will already exhibit some form of shoulder tendon pathology.

In agreement with Aginsky *et al.* (2004), Bell-Jenje & Gray (2005), Giles & Musa (2008), Ranson & Gregory (2008) and Stuelcken *et al.* (2008), the incidence of shoulder pathology afflicting the LHB, infraspinatus, supraspinatus and subscapularis (Table 2.3) was greater than that reported within previous injury surveillance research. Seventy percent of bowlers investigated, all of whom had no prior history of shoulder injury according to injury definitions, were found to have shoulder pathology affecting their bowling shoulder, and 40% were found to have pathology associated with their non bowling shoulder. Whilst injury surveillance research often fails to distinguish between player positions when reporting the incidence of shoulder injuries, the incidence of tendon pathology associated with the bowling shoulder is far greater than that reported within cricketers by Leary & White (2000) (7.1%) and Orchard *et al.* (2002) (6%) using standard injury definitions, and still almost three times that reported by Ranson & Gregory (2008) (23%) using modified definitions.

Whilst the incidence of tendon pathology associated with the bowling shoulder reported within this study is alarming given inclusion required participants to have no prior documented history of shoulder injury, these findings are a direct reflection of the modality used to establish the presence of pathology which has not been utilised in previous shoulder related cricket research. Prior research investigating shoulder injuries in cricketers has been reliant on the presence of pain to establish injury, whereas the diagnosis of shoulder pathology using ultrasound is subjective due to being reliant on the interpretation of the radiologist. The reliance on ultrasound to diagnose the presence of of tendon pathology within this study and the increased incidence of pathology observed, given it was noted in both bowling and non bowling shoulders, may be attributed to pain-free pathology which is yet to impact the player whether it be during cricket related or daily living activities. Regardless of this, these findings do provide insight into common musculotendinous pathology and adaptations, that are experienced in the bowling shoulder which are indicative of the future potential of injury and may aid researchers in gaining greater understanding of the pathomechanics of bowling related shoulder injuries.

Table 2.3 Incidence of tendon pathology in observed in both the bowling and non bowling shoulder (numbers in parentheses are percentages)

	Academy		First XI		Total	
	Bowling Arm	Non Bowling Arm	Bowling Arm	Non Bowling Arm	Bowling Arm	Non Bowling Arm
Long head of the biceps						
Normal	9 (100)	9 (100)	11 (100)	11 (100)	20 (100)	20 (100)
Tendinopathy	0	0	0	0	0	0
Partial tear	0	0	0	0	0	0
Full tear	0	0	0	0	0	0
Supraspinatus						
Normal	7 (77.8)	8 (88.9)	4 (36.4)	7 (63.6)	11 (55)	15 (75)
Tendinopathy	2 (22.2)	1 (11.1)	4 (36.4)	3 (27.3)	6 (30)	4 (20)
Partial tear	0	0	3 (27.3)	1 (9.1)	3 (15)	1 (5)
Full tear	0	0	0	0	0	0
Infraspinatus						
Normal	9 (100)	9 (100	11 (100)	10 (90.9)	20 (100)	19 (95)
Tendinopathy	0	0	0	1 (9.1)	0	1 (5)
Partial tear	0	0	0	0	0	0
Full tear	0	0	0	0	0	0
Subscapularis						
Normal	6 (66.7)	9 (100)	4 (36.4)	7 (63.6)	10 (50)	16 (80)
Tendinopathy	3 (33.3)	0	6 (54.5)	4 (36.4)	9 (45)	4 (20)
Partial tear	0	0	1 (9.1)	0	1 (5)	0
Full tear	0	0	0	0	0	0
Impingement						
Absent	8 (88.9)	8 (88.9)	4 (36.4)	10 (90.9)	12 (60)	18 (90)
Present	1 (11.1)	1 (11.1)	7 (63.6)	1 (9.1)	8 (40)	2 (10)

Musculotendinous adaptations and pathology

Similar to the findings of Brasseur *et al.* (2004), largely non-significant variations were observed in relation to the difference in quantitative ultrasound measurements between the bowling and non bowling shoulders (Table 2.4). Only the LHB tendon in academy players was observed to be significantly ($t_{(8)}$ = -3.598 , p = 0.007) thinner in the bowling shoulder compared to the non bowling shoulder by 0.81 mm. Whilst thinning of tendons, particularly of the rotator cuff of more than 1.1 mm (Cholewinski *et al.*, 2008), is acknowledged by clinicians to be a pre-cursor to tendon pathology, particularly partial and full thickness tears (Leotta & Martin, 2000; Rockwood, 2009), in agreement with both Brasseur *et al.* (2004) and

Wilkinson & Grimmer (2001), as no normative data has been previously collected it is impossible to establish if observed variation in tendon thickness is related to the demands of bowling or, is due to natural variation that could be influenced by factors such as age, hand dominance and daily living activities. Future research needs to incorporate other diagnostic imaging modalities to quantify changes in musculoskeletal properties of the rotator cuff such as muscle stiffness which may provide a more comprehensive understanding of any alterations in musculotendinous properties which may occur as a result of the demands of bowling.

Table 2.4 Maximum (mean ± SD) musculotendinous measures of structure thickness (mm) and the associated level of significance ($p \leq 0.05$)

Tendon	Bowling Arm	Non Bowling Arm	*p*
Long head of the biceps			
Academy (n=9)	3.64 ± 1.96	4.45 ± 2.21	0.007
First XI (n=11)	4.45 ± 1.30	4.35 ± 1.94	0.777
Total (n=20)	4.09 ± 1.64	4.39 ± 2.01	0.213
Supraspinatus			
Academy (n=9)	4.83 ± 0.59	4.90 ± 0.94	0.726
First XI (n=11)	5.88 ± 1.15	5.89 ± 1.10	0.983
Total (n=20)	5.41 ± 1.06	5.45 ± 1.13	0.868
Infraspinatus			
Academy (n=9)	3.85 ± 0.76	3.86 ± 0.91	0.968
First XI (n=11)	3.90 ± 0.86	4.07 ± 1.17	0.573
Total (n=20)	3.88 ± 0.80	3.98 ± 1.04	0.603
Subscapularis			
Academy (n=9)	4.11 ± 0.52	4.14 ± 0.97	0.933
First XI (n=11)	5.25 ± 1.08	5.68 ± 1.38	0.313
Total (n=20)	4.74 ± 1.04	4.99 ± 1.42	0.379
Coracoacromial ligament			
Academy (n=9)	1.20 ± 0.79	0.74 ± 0.32	0.083
First XI (n=11)	1.15 ± 0.53	1.00 ± 0.21	0.404
Total (n=20)	1.18 ± 0.65	0.89 ± 0.30	0.056

Supraspinatus, Infraspinatus and LHB

Whilst non-significant variation in tendon thickness was observed for both supraspinatus and infraspinatus, pathology was observed within both tendons. Tendinopathy to infraspinatus was only observed in the non bowling shoulder in one elite bowler however a greater incidence of pathology was observed to affect supraspinatus. Whilst no significant difference in the prevalence of supraspinatus pathology was observed in academy bowlers between shoulders ($z = -0.577$, $p = 0.564$), tendinopathy to the bowling shoulder was found in 22.2 % of bowlers compared to only 11.1 % for the non bowling shoulder. A greater incidence of shoulder pathology affecting supraspinatus was observed in elite bowlers with no significant difference observed in the prevalence of injury between shoulders ($z = -1.58$, $p = 0.129$). Whilst the incidence of tendinopathy was observed to be similar between shoulders (bowling shoulder: 36.4 %, non bowling shoulder: 27.3 %), a higher incidence of partial tears was found in the bowling shoulder (27.3 %) compared to the non bowling shoulder (9.1 %), which is greater than the incidence reported by Brasseur *et al.* (2004) within veteran tennis players. The observed pathology involving supraspinatus is typical of the presentation of rotator cuff tears associated with overhead sports due to anterior and superior shoulder instability (Anderson & Alford, 2010). During the deceleration phase of the throwing motion the rotator cuff muscles contract to both decelerate the arm and, dynamically stabilise the joint to prevent translation of the humeral head which can result in superficial under-surface tears to supraspinatus (Anderson & Alford, 2010; Cavallo & Speer, 1998; Halbrecht, Tirman, & Atkin, 1999; Lintner, Noonan, & Kibler, 2008). Findings from this investigation support the consensus of researchers (Aginsky *et al.*, 2004; Myers & O'Brien, 2001) who have associated the follow-through phase of the bowling delivery as increasing the risk of injury. However, as no associated pathology was observed to involve the LHB tendon, which contracts to aid in increasing shoulder stability in the presence of rotator cuff weakness (Andrews, Carson, & McLeod, 1985; Carpenter *et al.*, 2005; Hsu, Miller, & Curtis, 2008; Lintner *et al.*, 2008), forces exerted on the shoulder and the impact these impart on the shoulder musculature may be less than estimated compared to other overhead sports.

Subscapularis

Subscapularis was observed to have the highest incidence of pathology compared to the other shoulder tendons investigated. This is alarming and requires further investigation as subscapularis pathology in isolation is rarely reported within the literature affecting overhead sports given the high prevalence of injuries involving supraspinatus and infraspinatus (Anderson & Alford, 2010; Roger *et al.,* 1999). Whilst there was a significant difference in the prevalence of pathology between bowling and non bowling shoulders for the entire study cohort ($z = -2.111$, $p = 0.035$), no significant difference was observed within each playing group (elite: $z = -1.414$, $p = 0.157$; academy: $z = -1.732$, $p = 0.083$). Within the academy group, tendinopathy was observed in the bowling shoulder of three bowlers (33.3 %), constituting the highest incidence of tendon pathology observed within this group. Similarly the incidence of subscapularis pathology was high in elite bowlers and was observed to affect both the bowling and non bowling shoulder in elite bowlers. Tendinopathy was observed in 54.5 % of bowling shoulders and 36.4 % of non bowling shoulders, with a partial tear observed in the bowling shoulder of one bowler (9.1 %).

Further investigation is required to establish the role of subscapularis during the bowling delivery. Whilst supraspinatus, infraspinatus and the LHB would be at an increased risk of injury during the follow-through, it is unlikely that subscapularis would be strained at this stage of the bowling delivery due to its primary role as an internal rotator. Until comprehensive biomechanical analysis is undertaken it is the author's opinion that pathology to subscapularis, such as tendinopathy would occur during the early stages of the bowling delivery when the muscle is eccentrically loaded, which would be in agreement with Roger *et al.* (1999) who associated subscapularis tears to anterior joint overload. If this theory can be substantiated within future research as part of this thesis, this has important implications for both researchers and the cricket fraternity who to date have assumed the early stages of the delivery are inconsequential to both performance and injury causation in relation to the shoulder.

Findings from this investigation in relation to subscapularis aid to support the observed change in shoulder joint dynamics reported by Aginsky *et al.* (2004), Bell-Jenje & Gray (2005), Giles & Musa (2008) and Stuelcken *et al.* (2008). Whilst researchers particularly within baseball have attributed changes in internal and external rotation to largely osseous adaptations to the humeral head (Crockett *et al.*, 2002; Ellenbecker *et al.*, 2002), this study provides evidence for another causative factor which could result in decreased internal rotation at the shoulder. Glousman *et al.*(1988) and Kelly et *al.* (2005) associated changes in subscapularis muscle activity as determined through electromyography between participants with and without the presence of rotator cuff tears. The high prevalence of subscapularis tendinopathy observed within this cohort would suggest that such bowlers would also exhibit altered muscle activation which would result in both, decreased internal rotation range of motion and strength which has been observed previously in cricket research in relation to bowlers (Aginsky *et al.*, 2004; Bell-Jenje & Gray, 2005, Giles & Musa, 2008; Stuelcken *et al.*, 2008). As subscapularis is the sole rotator cuff muscle that acts as an internal rotator, dysfunction of this tendon functionally destabilises the joint affecting shoulder joint integrity as it results in superior translation of the humeral head with abduction (Lewis, 2009a; Lewis, 2009b). Buchberger (1999) investigated the prevalence of subscapularis dysfunction in baseballers reporting that subscapularis may be implicated in throwing related shoulder instability and that symptoms related to the posterior aspects of the rotator cuff such as supraspinatus may occur as as result of subscapularis weakness. Buchberger (1999) suggested that clinical assessment of subscapularis may assist in the early detection of shoulder dysfunction in the throwing athlete and as such could be used as a way to monitor cricket bowlers at an increased risk of developing shoulder pathology.

Impingement and the Coracoacromial ligament

Although no significant difference was observed within each subgroup, for the entire study cohort the difference in coracoacromial ligament thickness between shoulders (bowling shoulder: 1.18 ± 0.65 mm, non bowling shoulder: 0.89 ± 0.30 mm) was observed to approach significance ($p = 0.056$). It has been acknowledged within research (Anderson & Alford, 2010; Cholewinski *et al.*, 2008) that thickening of the coracoacromial ligament leads to subacromial impingement due to restricting the subacromial space. Impingement due to thickening of the coracoacromial ligament is more commonly associated with the older overhead athlete (Anderson & Alford, 2010) which was observed within this study cohort. Whilst impingement was observed to affect academy players (bowling shoulder: 11.1 %, non bowling shoulder 11.1 %), no significant difference was observed between shoulders ($z = 0.00$, $p = 1.00$). In contrast, a greater incidence was observed within the typically older, elite players with a significant difference between the bowling (63.6 %) and non bowling shoulders (9.1 %) ($z = -2.499$, $p = 0.014$). The high incidence of impingement in relation to the bowling shoulder in elite players with no prior history of shoulder injury observed within this study is in agreement with Bell-Jenje & Gray (2005) who established within elite South African cricketers the majority of shoulder injuries over a five year period presented as either primary or secondary impingement.

Conclusion

The aim of this investigation was to utilise diagnostic ultrasound to establish musculotendinous adaptations associated with cricket bowling to provide insight into the nature and commonality of shoulder injuries afflicting cricket bowlers. Through investigating a cohort of twenty county bowlers yet to experience a shoulder injury according to current injury definitions (Orchard *et al.*, 2005), findings support the consensus that current definitions underestimate the true prevalence of shoulder injuries afflicting bowlers (Aginsky *et al.*, 2004; Bell-Jenje & Gray, 2005; Giles & Musa, 2008; Ranson & Gregory, 2008; Stuelcken *et al.*, 2008). Seventy percent of bowlers investigated were found to have shoulder pathology affecting their bowling shoulder and 40% were found to have pathology associated with their non bowling shoulder. This observed incidence is far greater than that previously reported (Leary & White (2000): 7.1%; Orchard *et al.* (2002): 6% and Ranson & Gregory (2008): 23%), however it is important to acknowledge that within this investigation, ultrasound is unable to attribute the causation injuries to bowling alone and as such shoulder pathology reported may have occurred as a consequence of batting, fielding or daily living activities.

The LHB tendon in academy bowlers was observed to demonstrate a significant difference ($p = 0.007$) between the bowling and non bowling shoulder. As all other tendons demonstrated non significant variations in thickness between shoulders, to gain a greater understanding of musculotendinous adaptations associated with bowling, future research needs to incorporate other diagnostic imaging modalities such as elastography to more comprehensively investigate changes in muscle properties such as muscle stiffness.

Findings from this investigation build on the current knowledge relating to shoulder injuries afflicting cricket bowlers. Supraspinatus pathology observed aids in substantiating the theories of Aginsky *et al.* (2004) and Myers & O'Brien (2001), that the follow-through is a period of the bowling delivery which would appear to place bowlers at an increased risk of injury. More importantly however, the high incidence of subscapularis tendinopathy, yet to be documented within cricket research, provides support to the observed change in shoulder joint dynamics reported by Aginsky *et al.* (2004), Bell-Jenje & Gray (2005), Giles & Musa (2008) and Stuelcken *et al.* (2008) and suggests that both researchers and coaches should place greater emphasis on the early phases of the bowling delivery due to the contribution subscapularis imparts on internal shoulder rotation.

The greater incidence of shoulder pathology reported within this investigation in comparison to previous research can be attributed to using ultrasound for the diagnosis of pathology. Whilst in comparison to injury surveillance research, ultrasound provides greater insight into common musculotendinous pathology and adaptations which are indicative of the future potential of injury, the limitations of diagnostic ultrasound must be acknowledged. Whilst ultrasound is a practically feasible diagnostic modality to monitor musculotendinous pathology and adaptations, due to being both operator dependant and prone to error due to the positioning of the probe, the incorporation of ultrasound within future research must be utilised using a set protocol whereby, if monitoring athletes over time test-re-test reliability of the method needs to be established.

Whilst findings from this investigation provide insight into the nature and commonality of shoulder injuries affecting cricket bowlers that has not previously been reported, further research is required. To aid in the prevention of injuries, researchers must not only establish the nature and commonality of injuries but also gain an understanding of the associated movement pattern. Further research quantifying the biomechanics of the bowling delivery is required substantiate observations established within this investigation and theorised in previous research (Aginsky *et al.,* 2004; Myers & O'Brien, 2001) that both the early phases of the delivery and the follow through place the bowler at an increased risk of shoulder injury.

Chapter 3

Shoulder kinematics during the bowling delivery

Introduction

Injury surveillance studies, whilst providing an integral part of any injury prevention study, can not elucidate the direct mechanisms of injury (Finch, 2006). To date researchers such as Gregory *et al.* (2002) and Aginsky *et al.* (2004), have only been able to anecdotally ascribe changes in glenohumeral internal rotation, particularly in spin bowlers, to increasing the susceptibility of bowlers to develop shoulder injuries during the later stages of the bowling motion. The incidence of supraspinatus and subscapularis tendon pathology established in chapter 2, substantiates that the follow-through would appear to place the bowler at an increased risk of injury, however, findings relating to subscapularis also suggests that the early phases of the bowling delivery may contribute to the pathomechanics of shoulder injuries. The direct applicability of such findings to date is limited until the biomechanics of the bowling movement is quantified, as such knowledge would aid in definitively identifying key stages of the bowling movement that would increase the risk of injury.

Literature review

Shoulder joint range of motion associated with cricket bowlers

Shoulder injury prevalence in cricket bowlers has been reported at 0.9 % for fast bowlers and 1.1 % for spin bowlers within injury surveillance research (Orchard *et al.*, 2002), with growing consensus that the limitations associated with this form of research result in an underestimation of the true injury occurrence (Aginsky *et al.*, 2004; Bell-Jenje & Gray, 2005; Giles & Musa, 2008; Ranson & Gregory, 2008; Stuelcken *et al.*, 2008). In keeping with the Van Mechelen model (Van Mechelen *et al.*, 1992), researchers have conducted studies aimed to address the second stage of the injury prevention model through attempting to identify the aetiology and mechanisms of shoulder injuries afflicting cricketers with conflicting findings (Aginsky *et al.*, 2004; Bell-Jenje & Gray, 2005; Giles & Musa, 2008; Stuelcken *et al.*, 2008).

Aginsky *et al.* (2004) investigated the relationship between shoulder flexibility as defined through joint range of motion and isokinetic strength as possible factors that may predispose provincial South African fast bowlers to shoulder injury. Twenty one bowlers, nine of whom had a prior history of shoulder injury were assessed using a Cybex Norm isokinetic dynamometer, with the shoulder abducted at 90 ° using speeds of 90 $°.s^{-1}$ and 180 $°.s^{-1}$. Whilst to the author's knowledge this is the first reported research utilising isokinetic dynamometers to establish shoulder torque strength within cricket bowlers, the reflectiveness of such speeds to those observed during the bowling motion is yet to be substantiated due to erroneous values reported for bowling arm velocity within the literature (Barlett *et al.,* 1996). In addition, shoulder flexibility was established using a Leighton Flexometer, with internal and external rotation assessed passively with the participant lying supine with their arm abducted at 90 °. Aginsky *et al.* (2004) established bowlers displayed non-significant alterations in joint range of motion with a significantly ($p < 0.009$) greater concentric internal torque at 180 $°.s^{-1}$ when weight normalised between bowlers with and without a history of shoulder injury (injured: 65.20 ± 10.03 $Nm.kg^{-1}$, uninjured: 45.91 ± 10.26 $Nm.kg^{-1}$). In contrast, weight normalised eccentric torque between bowlers with and without a history of shoulder injury, whilst similar at 180 $°.s^{-1}$ was observed to be non-significantly ($p < 0.069$) weaker at 90 $°.s^{-1}$ (injured: 44.11 ± 10.91 $Nm.kg^{-1}$, uninjured: 54.67 ± 13.31 $Nm.kg^{-1}$). Aginsky *et al.* (2004) anecdotally ascribed weak external rotator strength as functionally compromising the ability of the musculature to prevent humeral head migration during the follow through phase of the bowling delivery. Within this study cohort, bowlers with a front-on bowling technique (n=5) displayed a greater incidence of shoulder injury than both semi-open (n=2) and side-on (n=2) bowlers. Aginsky *et al.* (2004) associated a change in the rotation strength ratio related to the rotator cuff musculature combined with bowling technique as factors that may predispose bowlers to shoulder injuries.

Bell-Jenje & Gray (2005) conducted a study investigating ninety six elite South African cricketers, over a five year period to identify possible risk factors that may predispose elite cricketers to shoulder injuries. All participants underwent a comprehensive postural analysis and biomechanical assessment conducted by the investigator and three additional physiotherapists all trained with respect to the assessment procedure. During the study period, 24 % of injuries were related to the shoulder, of which 80% collectively afflicted both bowlers and all rounders. Of those afflicted by shoulder injuries (including non bowlers), 42 % had weak scapular stabilisers and 37 % demonstrated limited internal glenohumeral rotation prior to injury. In contrast with Aginsky *et al.* (2004), Giles & Musa (2008) and Stuelcken *et al.* (2008), internal glenohumeral rotation was assessed using the 'hand behind the back' test, whereby a difference of 3 cm between shoulders was viewed as a significant difference. Whilst this form of assessment is often used within clinical assessments, the validity of this method has been questioned due to demonstrating only a low to moderate correlation to active shoulder internal rotation (Ginn, Cohen & Herbert, 2006).

Giles & Musa (2008) conducted an investigation to determine if glenohumeral internal rotation and external rotation range of motion difference exists between the dominant and non-dominant shoulders of cricketers, and if different how this may relate to cricketers with and without a history of shoulder pain. One hundred and thirty three elite English male and female cricketers (mean age: 18.1 ± 5.5 years) underwent a questionnaire to ascertain arm dominance, playing position, cricket exposure, additional sporting activities and shoulder pain. Shoulder pain was defined by the authors as an ache, discomfort or pain that developed in the shoulder and/or upper arm which could radiate elsewhere (Giles & Musa, 2008). Passive internal and external glenohumeral joint rotation was measured using a goniometer with the participant lying supine with the shoulder abducted at 90 °. Aginsky *et al.* (2004) established that cricketers who regularly bowled displayed significantly less internal (mean difference: -7.9 °, $p < 0.001$) and greater external (mean difference: 8.6 °, $p < 0.001$) dominant to non-dominant glenohumeral rotation. However, as Giles & Musa (2008) also reported wicket keepers displayed similar changes in glenohumeral joint rotation it is difficult to determine if differences in joint range of motion occur directly due to the demands of bowling.

Stuelcken *et al.* (2008) investigated twenty six elite female fast bowlers, of whom twelve reported a history of shoulder pain. To determine the prevalence of shoulder pain and to compare shoulder joint range of motion and strength, bowlers were assessed using a self-administered questionnaire to determine demographic information, cricket experience and history of shoulder pain that was attributed or aggravated by bowling or throwing. In addition, bilateral active shoulder rotation was assessed with the participant supine with their arm abducted at 90 ° using a goniometer, and isokinetic testing of shoulder rotation strength was assessed at 90 $°.s^{-1}$ with the arm abducted to 45 °. In agreement with Bell-Jenje & Gray (2005) and Aginsky *et al.* (2004), Stuelcken *et al.* (2008) established bowlers with a history of shoulder pain, exhibited a significant ($p < 0.05$) difference in internal rotation at 90 degrees abduction between their bowling (42.8 ± 5.5 °) and non-bowling arms (49.4 ± 5.3 °). Unlike Aginsky *et al.* (2004), no significant differences were reported for bowlers with and without a history of shoulder pain in relation to joint torques, with only a significant association established between concentric internal rotation torque for the bowling shoulder and bowling experience ($r_s = 0.45$, $p = 0.020$).

Findings of Aginsky *et al.* (2004), Bell-Jenje & Gray (2005), Giles & Musa (2008) and Stuelcken *et al.* (2008), whilst inconclusive due to methodological differences, provide an insight into the potential influence changes in shoulder joint dynamics may contribute to the aetiology of shoulder injuries amongst cricket bowlers. Whilst conjecture exists over the true significance and implication of altered joint range of motion in regards to the pathogenesis of shoulder injuries (Meister, 2000), to date, no research has established the kinematics of the shoulder throughout the bowling delivery to aid researchers in identifying key phases of the bowling technique which places the bowler at an increased risk of injury.

Shoulder kinematics during the bowling delivery

The bowling motion (Figure 3.1) is typically described according phases which vary dependent on the focus of the analysis undertaken whether it be coaching (Woolmer *et al.*, 2008) or research based (Chin *et al.*, 2009; Hurrion, Dyson & Hale, 2000; Myers & O'Brien, 2001). Whilst the arm contributes greatly to resultant ball velocity, to date, the movement of the bowing arm throughout the bowling movement has only been qualitatively described within research (Chin *et al.*, 2009; Myers & O'Brien, 2001).

Figure 3.1 Cricket bowling motion from the gather to follow through

During the run up the position of the bowling arm is individualised to enable the bowler to efficiently gain momentum, culminating into the gather, whereby the bowler positions the bowling arm so that it is internally rotated and flexed at both the shoulder and elbow, with the ball held close to the chest (Myers & O'Brien, 2001; Woolmer *et al.*, 2008). During the pre-delivery stride, the bowling arm begins to uncoil through elbow extension and circumduction of the shoulder. Anticlockwise circumduction of the bowling shoulder continues through back foot contact, whereby as the arm begins to extend behind the body, the shoulder externally rotates (Myers & O'Brien, 2001). At front foot contact, the arm continues to circumduct in an extended position where it is often observed to be close to horizontal. At ball release, through circumduction of the bowling shoulder, the arm is extended close to the vertical, in a position to ensure maximum height of ball release (Chin *et al.*, 2009; Woolmer *et al.*, 2008). Immediately following ball release the arm continues to circumduct, with the bowling shoulder internally rotating and flexes to enable the arm to follow through to its final position close to the contra lateral hip (Myers & O'Brien, 2001; Woolmer *et al.*, 2008).

Although the velocity of the arm has been reported to contribute towards 50 % of ball release speed (Elliott, Foster & Gray, 1986), to date, minimal research has been published quantifying shoulder motion during the bowling delivery. Chin *et al.* (2009) investigated the kinematics of the off break and doosra deliveries in both elite and high performance bowlers. The success of both forms of delivery are dependant on the amount of spin the bowler is able to achieve through the flight of the ball in the air, resulting in the ball after it bounces either deviating from the off-side to leg (off-break) or, from leg-side to off (doosra) for the right-handed batsmen (Woolmer *et al.*, 2008).

Due to the incidence of shoulder injuries afflicting high profile spin bowlers, it is antidotally believed that spin bowlers are at a greater risk of shoulder injuries compared to seam bowlers due to the rotational torque placed on the shoulder in order to aid in imparting spin onto the ball (Gregory *et al.,* 2002). Movement of the shoulder was limited by Chin *et al.* (2009) to describing shoulder abduction at ball release (off break: elite: 123 °, high performance: 121.4 °; doosra: elite: 122.5 °, high performance: 122.7 °) as movement within the other planes were not felt to be accurate quantitative measures due to limitations of the marker set.

Description of shoulder motion

Description of shoulder kinematics during any movement is complicated by the large degrees of freedom available at the shoulder joint combined with difficulties of non-invasive techniques in accurately reconstructing skeletal movement (Lempereur, Brochard, Burdin & Remy-Neris, 2010a; Senk & Chèze, 2006). Whilst various methods for the description of three dimensional joint motion have been suggested (Ying & Kim, 2002), motion of the shoulder has consistently been reported using Euler/Cardan angles. Euler/Cardan angles, as advocated by Grood & Suntay (1983) require Cartesian coordinate systems to be defined for the proximal, fixed segment and, the moving, distal segment of the joint of interest. Therefore, joint position is defined by three ordered rotation angles about the coordinate system axes of either the fixed or moving segment which correspond to clinical descriptions of motion (Grood & Suntay, 1983; Ying & Kim, 2002). In accordance with ISB recommendations (Wu *et al.,* 2005), movement at the shoulder joint can be described in regards to scapular motion relative to the thorax, humeral motion relative to the scapular and humeral motion relative to the thorax. The choice of rotation sequence to define joint motion using Euler/Cardan rotation sequences as recommended by the ISB (Wu & Cavanagh, 1995; Wu *et al.,* 2002; Wu *et al.,* 2005), are susceptible to gimbal lock (GL) occurring due to singularity between coordinate axes when the second rotation approaches 0 or 180 ° for Euler sequences, and 90 or -90 ° for Cardan sequences (Senk & Chèze, 2006).

The choice of rotation sequence to define shoulder motion, particularly that involving the scapula has been the focus of numerous investigations within the clinical setting (Karduna, McClure & Michener, 2000; Senk & Chèze, 2006), with only Bonnefoy-

Mazure *et al.* (2010) investigating the influence of rotation sequence to describe shoulder motion during a sporting movement. Bonnefoy-Mazure *et al.* (2010) investigated shoulder kinematics during the tennis serve as defined through motion between the humerus and thorax (humerothoracic motion). Nine professional tennis players performed a minimum of five flat serves with the kinematics of the movement recorded using an optoelectric motion analysis system recording at 250 Hz. Whilst the ISB advises the use of the YXY Euler sequence to calculate such motion, Bonnefoy-Mazure *et al.* (2010) investigated three different rotation sequences (YXY, ZXY and XZY) to examine the occurrence of GL and angle amplitude coherence. Bonnefoy-Mazure *et al.* (2010) reported that during the tennis serve GL was observed to affect all serves for all players for both YXY and ZXY rotation sequences suggesting that the XZY Cardan sequence was most appropriate for this overhead, multi-planar movement.

Study aim

With the above in mind, the aims of this investigation were two-fold. First, to quantify the kinematics of the shoulder throughout the bowling delivery as described by humerothoracic motion, and second, to establish the influence rotation sequence imparts on the description of humerothoracic motion to identify the most appropriate sequence to use within bowling research. Findings from this investigation begin to quantify the kinematics of the shoulder during the bowling delivery to provide an indication of key phases during the movement that warrant further investigation within subsequent studies due to their associated injury potential.

Method

Participants

After gaining University of Chichester ethical approval, eight male bowlers from Hampshire County Cricket Club were recruited as participants. The mean ± SD age, height and mass of the participants were 20.38 ± 4.53 years, 1.82 ± 0.05 m and 78.88 ± 6.36 kg. Following an explanation of the experimental aims and procedures all participants provided informed consent. For any bowler under the age of 18, consent was provided by club officials on behalf of the bowler's guardian. Inclusion for participation in this study required that bowlers had no recent history of injury within three months prior to data collection and were deemed fit to bowl by the club physiotherapist.

Equipment

Data collection was conducted at the indoor school at Hampshire County Cricket Club, allowing bowlers to bowl using their normal run up onto a standard size, artificial wicket. To record the kinematics during the bowling action, six 100 Hz Basler cameras (Basler A602fc-2, Germany) synchronised with a MX Ultranet control unit (Vicon, Oxford, UK) were positioned around the bowling crease (Figure 3.2). A 25-point calibration frame (Peak Performance Technologies Inc., Colorado, USA) was positioned over the bowling crease to provide a calibrated volume of 2.22 m × 1.91 m × 1.58 m with a residual calibration error of 0.0051 m.

Figure 3.2 Experimental setup

To analyse skeletal movement, surface retroflective markers (12 mm diameter) (Table 3.1) were placed on bony landmarks on the thorax and humerus in accordance with ISB guidelines (Wu *et al.,* 2005), with additional markers used to enable bowling technique classification modified from Portus *et al.*(2004). For the purpose of this investigation joint centres were defined as the midpoint between the Angulus Acromialis (AA) and Acromioclaviculare (AC) for the shoulder joint centre, and medial (ME) and lateral (LE) humeral epicondyles for the elbow joint centre. To minimise soft tissue artefact (STA) and to maximise participant comfort during bowling, the calibrated anatomical systems technique (CAST) protocol (Cappozzo, Catani, Della Croce & Leardini, 1995) was utilised which required a static calibration to define anatomical landmarks in relation to the dynamic marker cluster, affixed onto semi-rigid plates where appropriate, for use during bowling trials (Figure 3.3).

Table 3.1 Surface retroflective markers to enable reconstruction of skeletal movement

Segment	Marker	Definition
Thorax (anatomical)	SN	Suprasternal notch
	XP	Xiphoid procress - most caudal point of the sternum
	C7	Spinous process of the C7 vertebra
	T8	Spinous process of the T8 vertebra
Humerus - non bowling (anatomical)	NBAA	Angulus acromialis of the non bowling arm
	NBAC	Acromioclaviculare of the non bowling arm
	NBSJC	Virtual marker halfway between NBAA and NBAC
Humerus - bowling (anatomical)	AA	Angulus acromialis of the bowling arm
	AC	Acromioclaviculare of the bowling arm
	ME	Most caudal point of the medial epicondyle
	LE	Most caudal point of the lateral epicondyle
	EJC	Virtual marker halfway between ME and LE
	BSJC	Virtual marker halfway between AA and AC
Pelvis (anatomical)	RASIS	Right anterior iliac crest
	LASIS	Left anterior iliac crest
Thorax (technical)	T1 (SN) T2 (XP) T3 (C7) T4 (T8)	Identical to the thorax anatomical coordinate system to enable reconstruction of both SJC during the bowling movement
Humerus - bowling (technical)	H1 H2 H3	Three non-linear markers affixed to a semi-rigid plate, positioned on the humerus to minimise the influence of soft tissue artefact and enable reconstruction of the humerus anatomical markers
Pelvis (technical)	P1 P2 P3	Three markers corresponding to the sacrum, right posterior iliac spine and left posterior iliac spine, to enable reconstruction of both RASIS and LASIS during the bowling movement due to excessive marker dropout

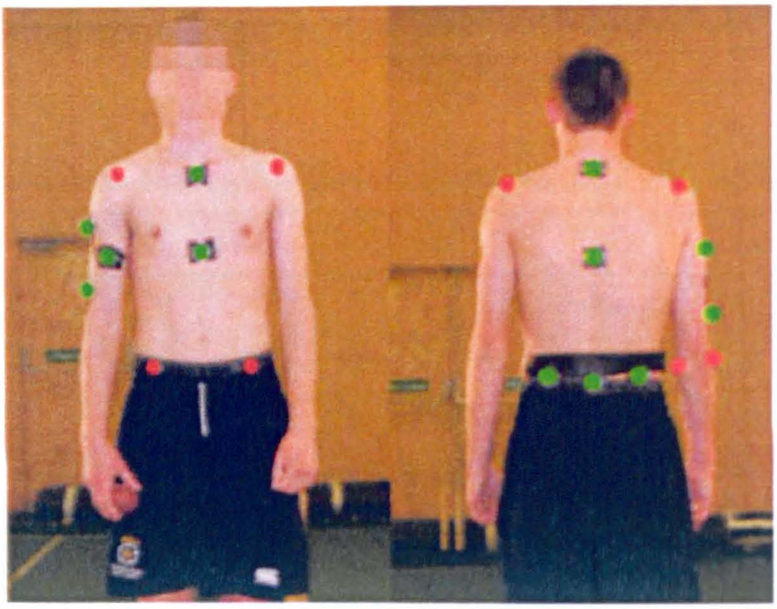


Figure 3.3 Bowling marker set incorporating static (red) and dynamic (green) markers

Testing procedure

Following an adequate warm up and habituation with the testing environment, participants were instructed to bowl an over (6 deliveries) at match pace. Due to experimental difficulties in ensuring markers remained attached to the participant throughout data collection, five deliveries with minimal marker drop out were selected for subsequent analysis. Delivery line and length were not controlled to provide an indication of the within and between bowler variability that can occur during match conditions. Every delivery was subjectively assessed by the bowler and coaching staff to ensure it was representative of the bowler's technique.

Data processing

Kinematic data were processed using a quintic spline filter (Woltring, 1986) with the degree of smoothing selecting using generalised cross-validation within Vicon Motus 9.2 software (Vicon, Los Angeles, USA). Data were then exported into a custom program CSBT Chucker (Shorter, 2010, unpublished program)(Figure 3.4)(Appendix E) created using LabVIEW™ 2009 (National Instruments, Austin, USA) for reconstruction of static anatomical landmarks during the bowling movement in accordance with the CAST protocol (Cappozzo *et al.,* 1995) and creation of segment anatomical coordinate systems (Table 3.2). The bowling delivery was temporally divided into four phases (Table 3.3) and subsequently normalised to account for variations between deliveries and bowlers.

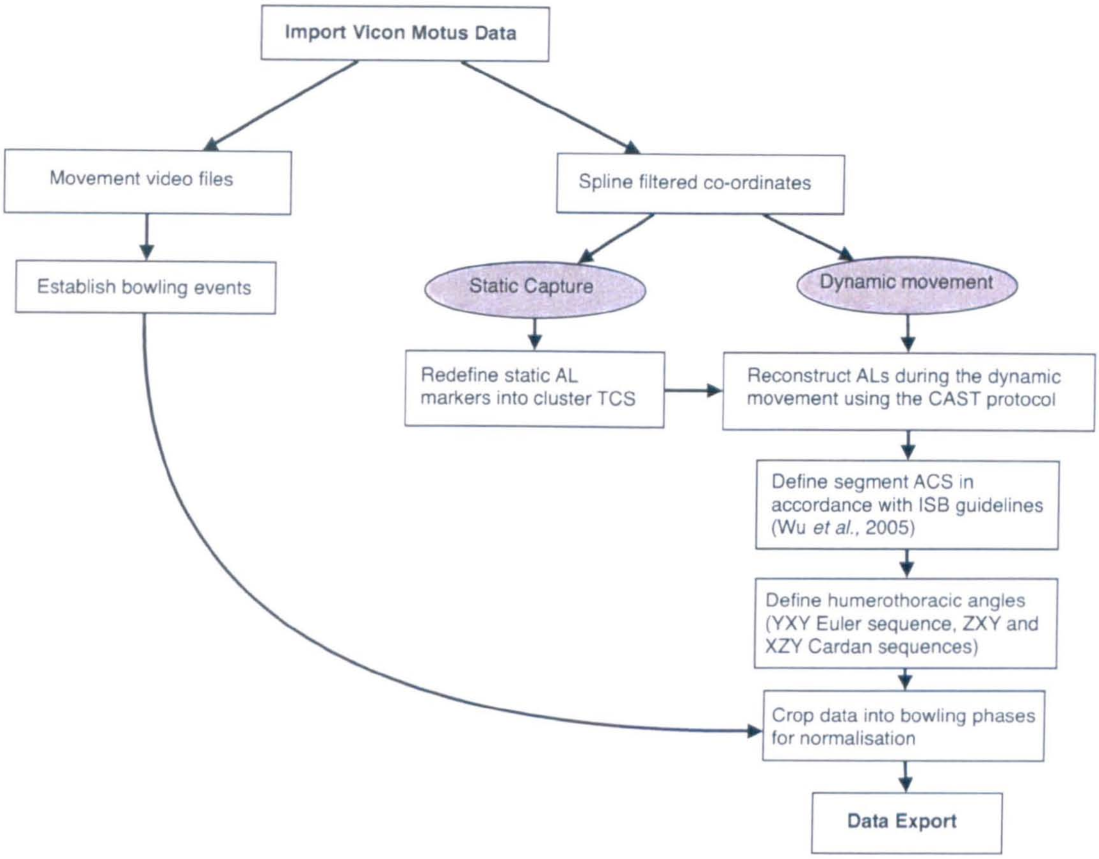


Figure 3.4 CSBT Chucker (Shorter, 2010, unpublished program) explanatory program flow diagram

Table 3.2 Segment anatomical coordinate systems (Wu *et al.*, 2005)

Coordinate system	Axis	Definition
Thorax	Y	Line connecting the midpoint between XP and T8, and the midpoint between SN and C7, pointing upward
	Z	The line perpendicular to the plane formed by the midpoint between XP and T8, SN and C7, pointing to the right
	X	The line perpendicular to the Z axis and Y axis, pointing forwards
Humerus	Y	Line connecting the SJC and EJC, pointing towards the SJC
	X	The line perpendicular to the plane formed by the SJC, ME and LE, pointing forward
	Z	The line perpendicular to the Y axis and X axis, pointing to the right

Table 3.3 Bowling delivery phases

Phase	Description
PDS to BFC	Commencement of arm rotation during the pre-delivery stride until back foot contact
BFC to FFC	Back foot contact until front foot contact
FFC to BR	Front foot contact until the instant of ball release
BR to FT	Ball release until the arm ceases to rotate during the follow through

To enable bowling classification for seam bowlers according to Portus *et al.* (2004) (Table 3.4), the horizontal axis of both the pelvis and shoulders were defined by unit vectors between the shoulder joint centres (shoulders) and ASISs (pelvis). The horizontal axis of the pelvis was modified to incorporate ASIS markers rather than the hip joint centres proposed by Portus *et al.* (2004) due to the error associated in accurately defining joint centres. Subsequent trunk angular data was solely used to classify bowling technique using the recognised protocol of Portus et al. (2004) whereby each unit vector was projected onto the transverse plane to calculate the shoulder angle at back foot contact (BFC), the hip-shoulder separation angle and maximum shoulder counter rotation occurring between BFC and front foot contact (FFC).

Table 3.4 Seam bowling technique classification adapted from Portus *et al.* (2004)

Action Type	Back foot contact shoulder angle	Hip-shoulder separation angle at back foot contact	Shoulder counter rotation
Front-on	>240 °	<30 °	<30 °
Semi-open	210 - 240 °	<30 °	<30 °
Side-on	<210 °	<30 °	<30 °
Mixed	NA	≥30 °	≥30 °

Shoulder position throughout the bowling movement was defined by humerothoracic motion using three different rotation sequences (YXY Euler sequence (Equation 3.1), ZXY (Equation 3.2) and XZY (Equation 3.3) Cardan sequences) used previously within shoulder research (Bonnefoy-Mazure *et al.*, 2010). Validation of the angular output from CSBT Chucker (Shorter, 2010, unpublished program) was undertaken using

Microsoft Excel 2007 (Microsoft, Richmond, USA) with an example dataset shown in Appendix F.

$$
\begin{aligned}
&YXY(\alpha,\beta,\gamma) \\
&\alpha = a\sin\left(\frac{y_p \bullet x_d}{\sin\beta}\right) && \textit{Where:} \\
&\beta = a\cos\left(y_p \bullet y_d\right) && \alpha = \textit{plane of elevation} \\
&\gamma = a\sin\left(\frac{x_p \bullet y_d}{\sin\beta}\right) && \beta = \textit{angle of elevation} \\
& && \gamma = \textit{axial rotation}
\end{aligned}
$$

Equation 3.1

$$
\begin{aligned}
&ZXY(\alpha,\beta,\gamma) \\
&\alpha = a\cos\left(\frac{y_p \bullet y_d}{\cos\beta}\right) && \textit{Where:} \\
&\beta = a\sin\left(y_p \bullet z_d\right) && \alpha = \textit{plane of elevation} \\
&\gamma = a\cos\left(\frac{z_p \bullet z_d}{\cos\beta}\right) && \beta = \textit{angle of elevation} \\
& && \gamma = \textit{axial rotation}
\end{aligned}
$$

Equation 3.2

$$
\begin{aligned}
&XZY(\alpha,\beta,\gamma) \\
&\alpha = a\cos\left(\frac{y_p \bullet y_d}{\cos\beta}\right) && \textit{Where:} \\
&\beta = -a\sin\left(y_p \bullet x_d\right) && \alpha = \textit{plane of elevation} \\
&\gamma = a\cos\left(\frac{x_p \bullet x_d}{\cos\beta}\right) && \beta = \textit{angle of elevation} \\
& && \gamma = \textit{axial rotation}
\end{aligned}
$$

Equation 3.3

Humerothoracic motion describes the position of the humerus (distal segment) relative to the thorax (proximal segment) through the plane of elevation (0° is abduction, 90° is forward flexion) (Figure 3.5), angle of elevation (Figure 3.6) and axial rotation (internal rotation (+) and external rotation (-)).

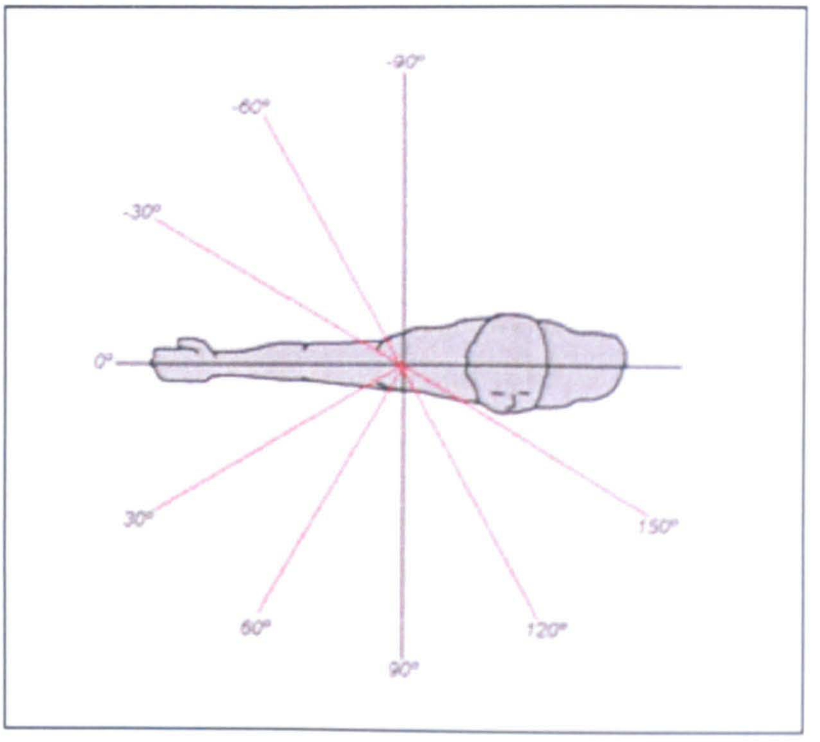


Figure 3.5 Humerothoracic motion: Plane of elevation

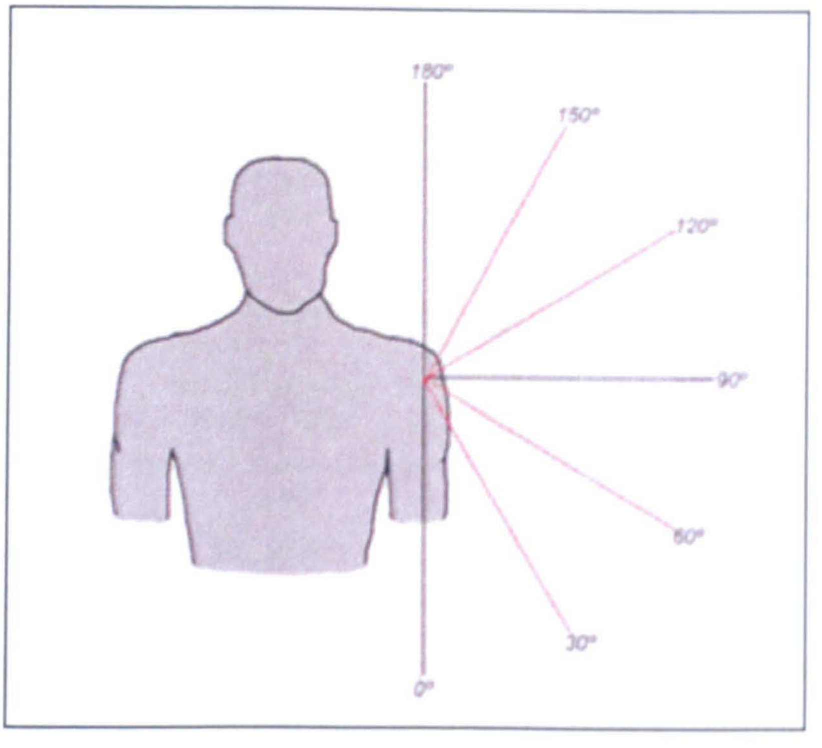


Figure 3.6 Humerothoracic motion: Angle of elevation

Each bowling delivery was assessed for the occurrence of GL for every rotation sequence, where it was described as being either present or absent. GL incidence in accordance with Senk & Chèze, (2006) was defined as the discontinuity of the curves alpha or gamma that coincide with those of beta close to 0 or 180 ° for Euler sequences, and 90 or -90 ° for Cardan sequences.

Statistical analysis

Analysis of data was undertaken at discrete 10 % time increments of the normalised bowling delivery. The mean ± SD angular position of the shoulder was calculated within Microsoft Excel 2007 (Microsoft, Richmond, USA) for both each individual bowler, and the group. RMSE was calculated to provide an indication of the magnitude of both within and between-bowler variation using the following formula (Equation 3.4) (Payton & Bartlett, 2008):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\Delta x_i)^2}{n}}$$

where:

Δx_i = *difference between measure and criterion*

n = *number of measurements*

Equation 3.4

Results and Discussion

Bowling technique classification

Bowlers analysed within this study cohort exhibited a range of bowling techniques (spin: n=3, seam: n= 5). Seam bowling classification in accordance with Portus *et al.* (2004), established that the seam bowling cohort included side-on (n=1), mixed (n=2) and semi-open (n=2) techniques. Whilst the mixed bowling technique is the most common bowling style observed, as supported by 31 of 42 bowlers investigated by Portus *et al.* (2004) bowling with this style, the variety of seam bowling techniques within this study cohort are reflective of the array of techniques evident within contracted county bowlers. Through analysing the findings in regard to each individual bowler and for the group as a whole, greater understanding of the position of the shoulder during the bowling delivery and, the differing demands bowling style may impart on the shoulder can be gained.

Rotation Sequence and Gimbal Lock

Within this group of bowlers, the occurrence of GL during the bowling movement was found to be individualised and affected all three rotation sequences (Table 3.5). An example of gimbal lock affecting the both the plane of elevation (α) and axial rotation

(γ) when the angle of elevation (β) approached 0 ° when using a YXY Euler sequence is shown in Figure 3.7.

Table 3.5 Gimbal lock incidence during the bowling delivery

Sequence	Bowler								
	1	2	3	4	5	6	7	8	TALLY
YXY	—	✓	—	—	✓	—	—	—	2
ZXY	—	—	—	✓	—	—	—	✓	2
XZY	—	✓	✓	✓	—	—	—	—	3

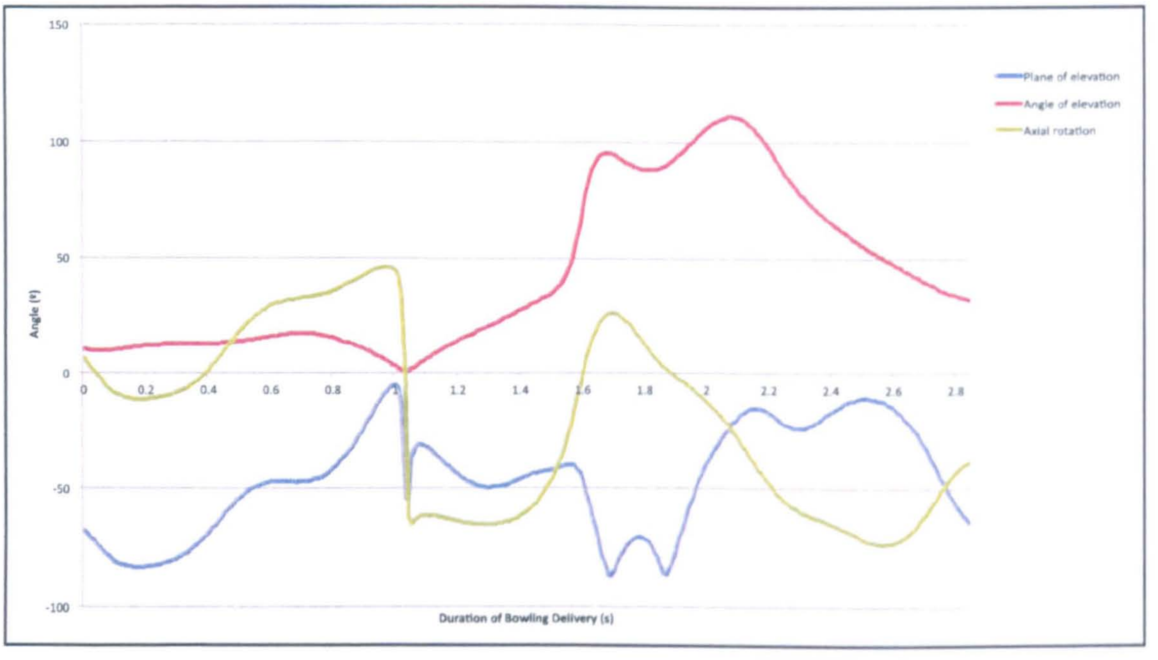


Figure 3.7 Representative example of GL occurrence affecting the YXY sequence

In contrast to the findings of Bonnefoy-Mazure *et al.* (2010) investigating the tennis serve, the XZY sequence (n=3) was found to have the highest incidence of GL whereas both the YXY and ZXY sequences only had 2 incidences each. Whilst both the tennis serve and bowling action are multi-planar movements associated with high degrees of arm elevation, these contrasting findings indicate subtle differences between the movement patterns. It could be hypothesised that the stationary position at the commencement of the tennis serve places greater demands on the upper limb to aid in increasing the height of release through increased humerothoracic elevation to aid in force generation. In comparison, during the bowling movement, the bowling arm has to overcome the moment of inertia as it circumducts in opposition to the path of the body, whereby a lower angle of elevation aids in conserving angular momentum to ensure ball velocity at release is not compromised. Results of this study combined with the findings of previous research investigating the influence of rotation sequences on joint motion (Bonnefoy-Mazure *et al.,* 2010; Senk & Chèze, 2006; Karduna *et al.,* 2000) highlight that the selection of a rotation sequence must be movement specific and may need to be chosen on an individual basis.

The findings of Bonnefoy-Mazure *et al.,* (2010) may have been influenced by the chosen methodology. Surface markers were used to reconstruct anatomical landmarks, with the shoulder joint centre defined using a regression method which was not detailed. As GL incidence for both the YXY and ZXY sequences affected all nine players investigated, some of the anomalies in joint angles observed may have been influenced by STA and noise occurring due to the velocity of the arm during the tennis serve combined with ball impact. This could be seen to be supported by the lower incidence of GL during the bowling delivery which incorporated the CAST protocol in an attempt to minimise the influence of STA on subsequent calculations.

Although the incidence of GL during the bowling delivery was the same for both the YXY and ZXY sequences, the use of the YXY sequence for the description of shoulder motion during the bowling delivery is deemed more appropriate. The incidence of GL is dependent on the second rotation, which for both these sequences relates to the angle of elevation. The benefit of using the YXY Euler sequence is that singularity would occur with the arm at 0 or 180 ° elevation which will rarely occur in relation to humerothoracic motion which rarely exceeds 120 °, particularly during cricket bowling.

Shoulder position during the bowling delivery

Representative examples of the position of the shoulder during the bowling delivery for a spin bowler and semi-open bowler are shown in Figure 3.8 and Figure 3.9 respectively. In addition to differences in shoulder position throughout the delivery, variations in the duration of bowling phases, supports the need for data normalisation within each phase prior to both within and between bowler analysis.

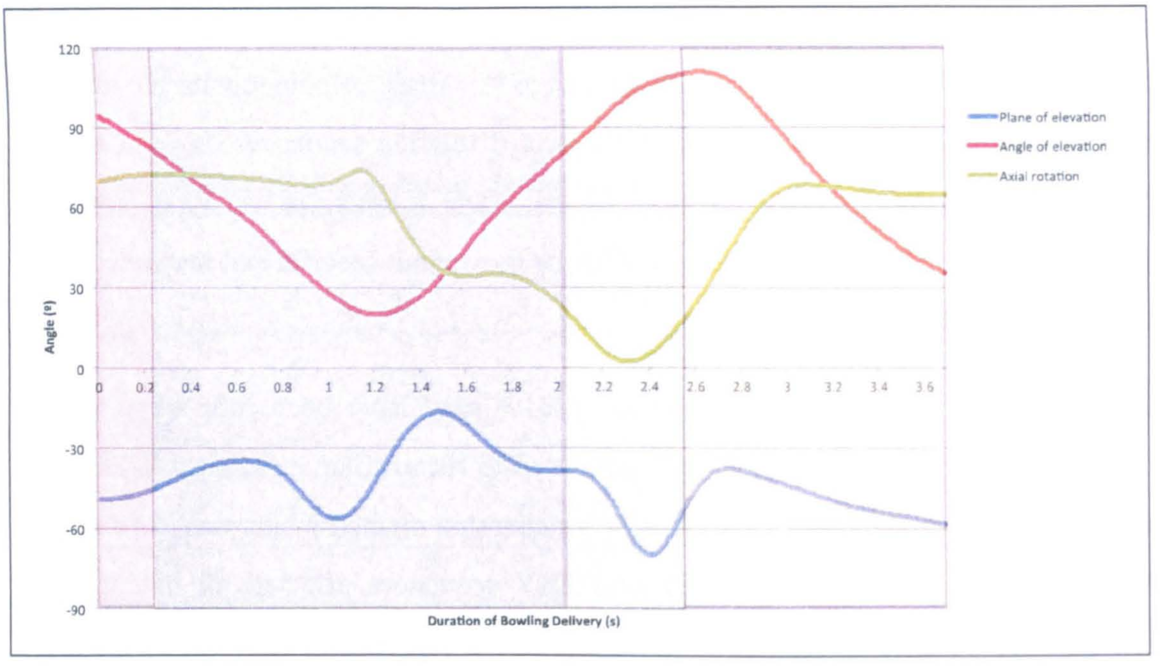


Figure 3.8 Representative example the shoulder position during the bowling delivery associated with a spin bowler. Bowling phases (PDS to BFC: pink, BFC to FFC: blue, FFC to BR: green, BR to FT: yellow) are shown.

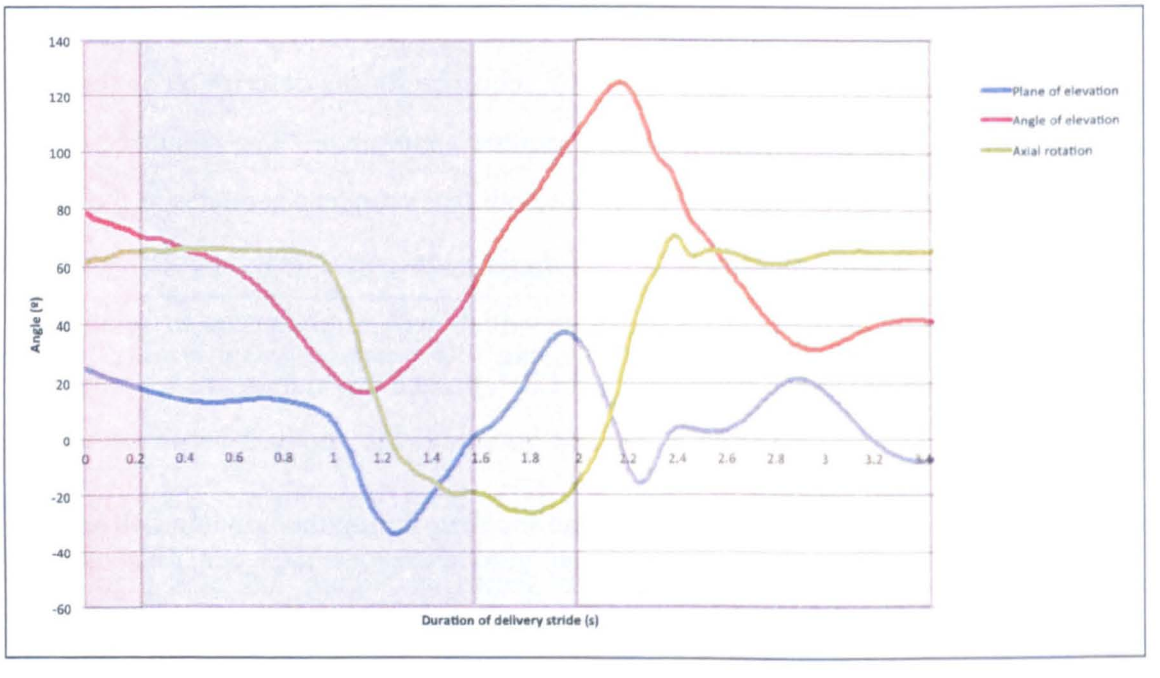


Figure 3.9 Representative example the shoulder position during the bowling delivery associated with a semi-open bowler. Bowling phases (PDS to BFC: pink, BFC to FFC: blue, FFC to BR: green, BR to FT: yellow) are shown.

The mean position of the shoulder during the bowling delivery following normalisation is shown in Figure 3.10 using the YXY Euler sequence, whereby any trials affected by

GL were excluded. Variations in shoulder position as defined by humerothoracic motion, were observed between bowlers, with further investigation required to establish if this may be related to factors such as bowling style and bowling experience.

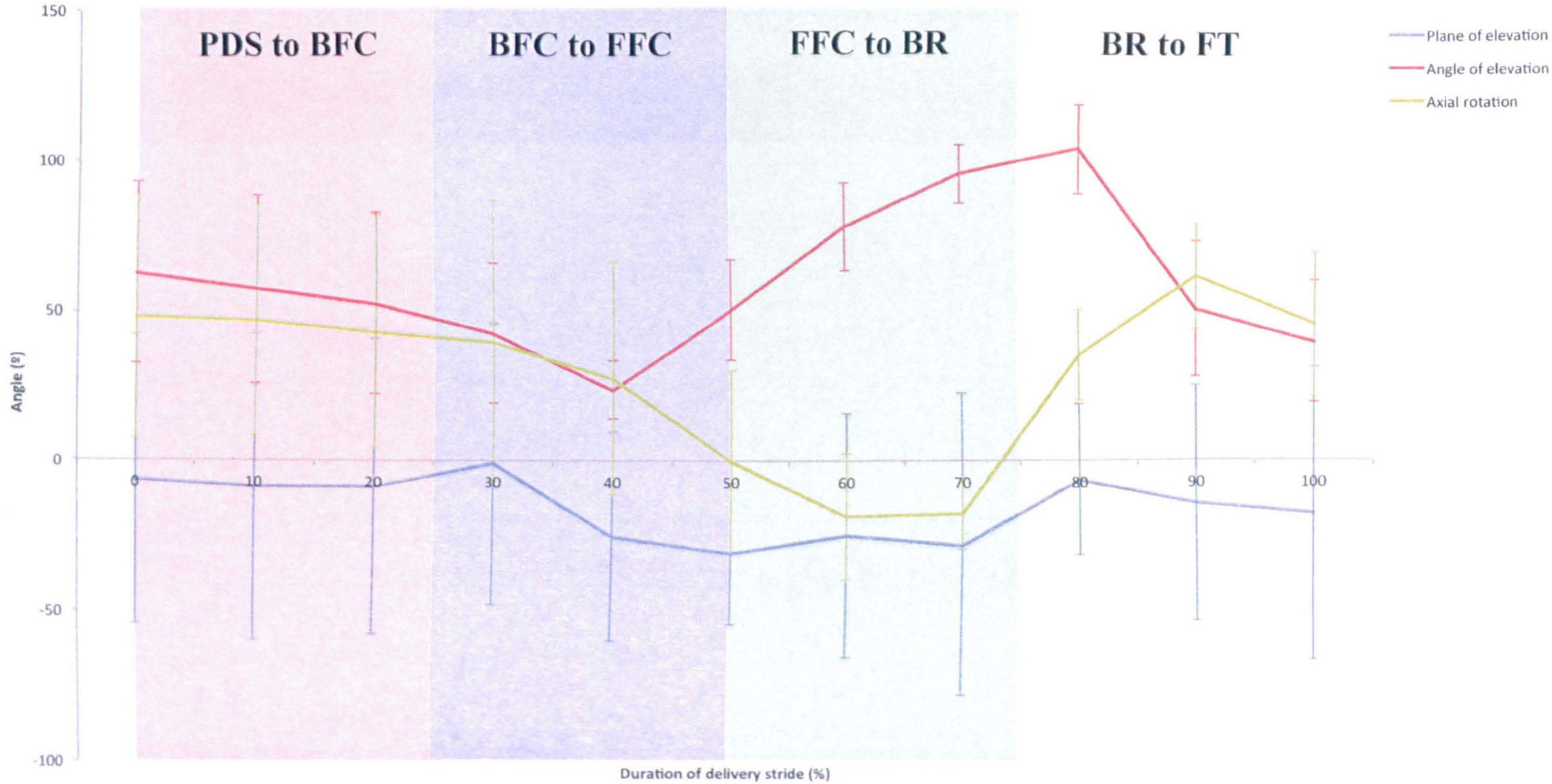


Figure 3.10 Mean humerothoracic motion during the delivery stride

Plane of elevation:

Throughout the bowling delivery the plane of elevation was found to be slightly extended behind the torso (Table 3.6), ranging from -1.11 ± 47.21 ° to -28.03 ± 50.40 °. Such joint positioning highlights that rather than relying on shoulder joint flexion/ extension as the arm circumducts, the bowler utilises upper body rotation to convert the momentum obtained during the run-up to increase ball release speed. Whilst further research incorporating inverse dynamics is required, it could be hypothesised that a lack of movement within this plane aids in stabilising the arm which would be imperative to assist in maintaining elbow position in keeping with the rules of the game, combined with increasing ball release speed.

Angle of elevation:

During the bowling delivery the arm maintains an abducted position (Table 3.7), ranging from 23.70 ± 9.80 ° during BFC to FFC to 103.01 ± 14.79 ° during BR to FT. Whilst maximum abduction coincided closely to ball release, this is less than previously reported by Chin *et al.* (2009) for a cohort of spin bowlers at ball release (off break: elite: 123.0 °, high performance: 121.4 °; doosra: elite: 122.5 °, high performance: 122.7 °). Differences in magnitude between this study and the work of Chin *et al.* (2009) may be reflective of the the manner in which shoulder abduction was defined which was not detailed. In addition the relatively low maximum angle of elevation may be reflective of differences in study cohorts where this investigation included 5 seam bowlers. Whilst not quantified, seam bowlers typically can be observed to utilise greater trunk lateral flexion, rather than relying on shoulder abduction to contribute to the height of ball release which may account for the lower mean angle of humerothoracic elevation. The trunk position, combined with the velocity of the arm during the bowling delivery may necessitate bowlers to adapt a lower level of humeral elevation to aid in stabilising the upper limb whilst conserving angular momentum.

Axial rotation:

Axial rotation observed during the delivery stride is shown in Table 3.8. For the majority of the delivery stride the bowler's arm maintains an internally rotated position, which becomes externally rotated around ball release, whereby during follow through it once again internally rotates. Internal rotation of the humerus, particularly during the early stages of the bowling delivery would place strain on subscapularis to aid in

3.6 Plane of elevation (mean ± SD) during the bowling delivery

ler	Duration of Bowling delivery (%)										
	PDS to BFC			BFC to FFC			FFC to BR		BR to FT		
	0	10	20	30	40	50	60	70	80	90	100
p	-49.73° ± 1.75°	-48.90° ± 2.10°	-47.07° ± 1.28°	-25.72° ± 8.44°	-38.93° ± 2.70°	-44.81° ± 12.16°	-52.24° ± 26.44°	-76.90° ± 9.03°	-39.05° ± 2.18°	-41.35° ± 18.44°	-51.94°
i	-52.92° ± 17.99°	-68.35° ± 19.35°	-63.08° ± 27.35°	-10.67° ± 47.49°	0.85° ± 26.01°	-51.06° ± 14.64°	-50.06° ± 27.61°	-74.14° ± 1.19°	-25.40° ± 4.04°	-23.38° ± 11.67°	-76.05°
ı	-25.91° ± 4.23°	-29.37° ± 2.20°	-36.52° ± 2.70°	-60.51° ± 11.53°	-66.25° ± 5.75°	-35.29° ± 22.45°	-56.47° ± 15.57°	-74.73° ± 6.89°	-28.68° ± 17.75°	-51.47° ± 12.02°	-53.76°
ı	76.01° ± 9.21°	74.33° ± 14.09°	76.07° ± 10.67°	55.89° ± 1.58°	-23.85° ± 5.69°	-50.45° ± 10.61°	-67.57° ± 4.27°	-56.33° ± 16.02°	0.46° ± 23.53°	-43.79° ± 12.36°	-38.95°
p	41.36° ± 15.75°	49.70° ± 12.61°	44.35° ± 6.24°	66.00° ± 9.00°	-59.15° ± 5.77°	6.27° ± 17.04°	36.58° ± 23.03°	51.92° ± 2.47°	16.6° ± 23.25°	0.93° ± 50.37°	23.57°
p	-5.08° ± 2.85°	-6.49° ± 7.23°	-10.37° ± 14.88°	11.23° ± 9.27°	29.13° ± 39.07°	-33.55° ± 7.62°	11.52° ± 14.93°	3.36° ± 5.00°	27.11° ± 1.89°	59.09° ± 2.90°	56.08°
o	25.11° ± 0.19°	21.23° ± 0.30°	17.61° ± 1.66°	11.08° ± 2.67°	1.53° ± 6.83°	-2.36° ± 4.65°	14.45° ± 11.07°	37.21° ± 4.78°	1.85° ± 14.58°	9.39° ± 10.86°	-1.78°
o	-59.38° ± 7.70°	-60.70° ± 10.35°	-48.53° ± 29.33°	-56.20° ± 4.51°	-44.93° ± 12.39°	-38.59° ± 11.28°	-36.30° ± 5.48°	-34.60° ± 2.71°	-2.43° ± 3.10°	-23.64° ± 11.33°	0.74°
UP	**-6.32° ± 48.17°**	**-8.57° ± 51.22°**	**-8.44° ± 49.54°**	**-1.11° ± 47.21°**	**-25.20° ± 35.08°**	**-31.23° ± 23.54°**	**-25.01° ± 40.76°**	**-28.03° ± 50.40°**	**-6.19° ± 25.05°**	**-14.28° ± 39.08°**	**-17.76°**

ıner, si – side on, m – mixed, so – semi open

3.7 Angle of elevation (mean ± SD) during the bowling delivery

vler	Duration of Bowling delivery (%)										
	PDS to BFC			BFC to FFC			FFC to BR		BR to FT		
	0	10	20	30	40	50	60	70	80	90	10
sp	97.73° ± 4.02°	93.26° ± 3.61°	88.03° ± 3.13°	63.86° ± 3.19°	18.48° ± 1.46°	78.66° ± 4.01°	101.91° ± 12.07°	106.16° ± 2.32°	108.83° ± 3.43°	60.78° ± 5.04°	31.93
si	23.53° ± 11.20°	17.48° ± 5.15°	12.30° ± 2.47°	10.38° ± 7.06°	12.14° ± 10.26°	28.85° ± 4.83°	71.76° ± 26.65°	99.70° ± 10.47°	106.14° ± 3.10°	57.90° ± 2.60°	57.17°
m	78.05° ± 7.36°	75.42° ± 6.81°	70.92° ± 6.56°	54.46° ± 10.85°	21.42° ± 1.87°	47.87° ± 6.73°	77.21° ± 4.51°	90.32° ± 1.44°	91.26° ± 2.90°	67.17° ± 4.46°	53.03°
m	16.39° ± 2.91°	11.93° ± 1.49°	14.32° ± 2.94°	21.71° ± 3.19°	30.35° ± 6.75°	69.18° ± 7.05°	84.90° ± 2.95°	84.27° ± 3.95°	130.14° ± 8.83°	79.88° ± 6.20°	51.85
sp	69.72° ± 3.11°	61.86° ± 2.14°	56.96° ± 0.50°	35.60° ± 4.11°	20.58° ± 2.51°	49.57° ± 1.93°	73.20° ± 2.70°	92.21° ± 2.54°	87.18° ± 17.79°	2.72° ± 0.94°	7.99
sp	93.68° ± 2.39°	88.91° ± 2.96°	82.17° ± 6.24°	69.58° ± 6.43°	41.80° ± 9.52°	38.14° ± 12.51°	73.02° ± 6.22°	106.73° ± 5.48°	92.97° ± 4.04°	45.16° ± 7.53°	20.15
so	80.40° ± 1.90°	78.45° ± 3.23°	75.21° ± 3.71°	65.41° ± 3.63°	22.48° ± 3.49°	48.39° ± 9.06°	75.35° ± 3.38°	95.74° ± 1.14°	109.00° ± 7.12°	44.05° ± 8.36°	44.55°
so	43.08° ± 5.63°	31.06° ± 4.27°	22.63° ± 8.51°	19.26° ± 6.15°	22.38° ± 3.55°	42.22° ± 5.26°	62.94° ± 3.50°	82.25° ± 3.33°	98.59° ± 6.14°	42.66° ± 1.53°	48.18
UP	**62.82° ± 30.26°**	**57.30° ± 31.29°**	**52.82° ± 30.46°**	**42.53° ± 23.15°**	**23.70° ± 9.80°**	**50.36° ± 16.61°**	**77.54° ± 14.33°**	**94.67° ± 9.64°**	**103.01° ± 14.79°**	**50.04° ± 22.44°**	**39.36°**

nner, si – side on, m – mixed, so – semi open

3.8 Axial rotation (mean ± SD) during the bowling delivery

ler	Duration of Bowling delivery (%)										
	PDS to BFC			BFC to FFC			FFC to BR		BR to FT		
	0	10	20	30	40	50	60	70	80	90	100
p	69.32° ± 0.94°	70.76° ± 0.98°	72.07° ± 0.57°	71.21° ± 0.58°	65.54° ± 1.81°	31.60° ± 6.77°	7.16° ± 6.47°	2.67° ± 0.15°	40.55° ± 4.18°	68.02° ± 0.79°	67.44°
i	39.50° ± 39.87°	30.06° ± 32.31°	1.61° ± 28.10°	-44.15° ± 17.62°	-13.15° ± 30.71°	46.88° ± 15.75°	10.37° ± 24.22°	-18.77° ± 5.70°	20.64° ± 1.63°	66.16° ± 6.26°	7.37° ±
n	63.47° ± 2.25°	61.04° ± 2.40°	56.41° ± 3.65°	41.93° ± 10.31°	24.87° ± 40.05°	3.08° ± 7.37°	-13.49° ± 5.11°	-10.33° ± 18.56°	28.85° ± 5.09°	55.22° ± 4.07°	28.92° ±
n	-48.72° ± 12.54°	-42.98° ± 19.15°	-37.29° ± 13.04°	-27.73° ± 5.00°	29.12° ± 32.76°	18.28° ± 13.46°	-14.67° ± 4.24°	-27.10° ± 10.73°	21.26° ± 12.33°	70.72° ± 10.26°	54.54° ±
p	67.62° ± 3.94°	68.68° ± 1.15°	67.48° ± 1.63°	63.20° ± 4.06°	-33.75° ± 5.78°	-38.95° ± 4.23°	-41.01° ± 6.55°	-29.34° ± 5.85°	29.47° ± 29.57°	41.22° ± 46.79°	36.22° ±
p	72.91° ± 3.30°	64.78° ± 12.86°	62.09° ± 17.30°	82.70° ± 2.77°	57.28° ± 27.33°	-32.30° ± 6.36°	-46.76° ± 3.14°	-16.56° ± 4.68°	52.08° ± 5.32°	54.53° ± 4.06°	46.46°
o	60.97° ± 2.18°	63.35° ± 1.83°	65.47° ± 1.01°	66.21° ± 0.35°	54.15° ± 7.05°	-20.10° ± 4.05°	-25.06° ± 1.59°	-20.50° ± 2.31°	45.04° ± 10.30°	68.59° ± 8.27°	66.22°
o	58.54° ± 1.90°	60.56° ± 4.75°	57.22° ± 3.47°	65.81° ± 3.73°	37.45° ± 10.82°	-11.28° ± 7.32°	-24.94° ± 4.44°	-20.71° ± 3.42°	40.98° ± 2.12°	61.57° ± 3.50°	54.22°
UP	**47.95° ± 40.54°**	**47.03° ± 38.65°**	**43.13° ± 39.09°**	**39.90° ± 46.65°**	**27.69° ± 38.90°**	**-0.35° ± 30.37°**	**-18.55° ± 21.12°**	**-17.58° ± 11.92°**	**34.86° ± 15.02°**	**60.75° ± 17.42°**	**45.17° ±**

ner, si – side on, m – mixed, so – semi open dynamically stabilising the shoulder joint in its internally rotated position, suggesting that the observed tendinopathy reported in chapter 2 may occur due to the repetitive overload of the musculature. Ranges of internal rotation for all bowlers throughout the bowling action were observed to be similar regardless of bowling technique. This finding would appear to contradict Gregory *et al.* (2002) who associated spin bowlers with adopting greater internal rotation predisposing them to increased risk of injury in comparison to seam bowlers. Whilst this study cohort had no prior history of shoulder injury, future research needs to investigate the influence of axial rotation on the aetiology of shoulder injuries amongst different bowling styles. It is this author's belief that it may not be the magnitude of internal rotation but rather the associated torque that predisposes spin bowlers to an increased risk of bowling related shoulder injuries compared to seam bowlers.

During BR to FT, the bowling arm reaches its maximal internally rotated position (60.75 ± 17.42 °), corresponding with the phase previous research (Aginsky *et al.*, 2004) has associated with the highest risk of shoulder injury. The internally rotated position established in this research highlights a phase in the movement where great stress would be placed on the shoulder where surrounding musculature would need to both stabilise the joint and decelerate the bowling arm. Research such as that by Aginsky *et al.* (2004) and Stuelcken *et al.* (2008) have associated bowlers with both weak external rotator strength and altered joint range of movement. The large magnitude of internal rotation would appear to contradict the findings of Stuelcken *et al.* (2008) who associated bowlers, like other overhead sportsmen with limited internal rotation. Internal rotation within this study was not limited to purely that around the glenohumeral joint but incorporated movement about both the glenohumeral and scapulothoracic joints. It is therefore feasible that although bowlers may have limited internal rotation at the glenohumeral joint, they can functionally adapt to this through increased scapulothoracic movement (anterior tilt and internal rotation) which aids in increasing internal rotation at the shoulder. Future research needs to establish the contribution of the scapula during the bowling motion as although increased scapulothoracic motion may aid the bowler in meeting the functional demands of the movement, it may act to destabilise the glenohumeral joint through altering the moment arms of the rotator cuff and other surrounding musculature.

Within and Between Bowler Variability

Within and between bowler variability was found to be large in magnitude throughout the bowling movement (Table 3.9, 3.10, 3.11). There are several factors that may contribute to the variability observed such as bowling style, bowling experience and experimental methodology which is apparent in the variability observed between bowlers. The unconstrained bowling action allowed during data collection may have influenced this given both line and length of delivery were not monitored.

Greatest variability for all angles, as defined by RMSE for the group was observed during the PDS to BFC phase (plane of elevation RMSE max: 80.64, angle of elevation RMSE max: 49.74 and axial rotation RMSE max: 73.85). Such large variation observed during this phase both within and between bowlers is reflective of the associated movement pattern. The gather which defines the beginning of the phase and its subsequent movement pattern, is acknowledged to be individualised and varies depending on the degree to which the bowler is trying to the hide the grip of the ball from the batter (Woolmer *et al.,* 2008). In contrast, minimum values for RMSE were found to occur during different phases of the bowling delivery. For both the angle of elevation (RMSE min: 14.04 at 70% of the bowling delivery) and axial rotation (RMSE min: 15.21 at 90% of the bowling delivery), the lowest variability was observed to closely occur either prior or after ball release (ball release at 75% of the bowling delivery). In contrast, the lowest variability associated with the plane of elevation (RMSE min: 32.98) was found to occur at 50% of the bowling delivery coinciding with front foot contact.

Variability observed within this study provides a strong indication of the flexibility bowlers have in altering their technique and the potential influence this may result in both being able to adapt to match demands, along with varying stresses placed on the shoulder in regards to injury. Future biomechanical analysis needs to appreciate the influence such variability may impart on research findings. In accordance with Salter, Sinclair & Portus (2007), it would appear within bowler analysis, combined with more stringent data collection protocols will aid in being able to generate more robust findings which can be then generalised to the bowling population as a whole.

Table 3.9 RMSE plane of elevation (°) during the bowling delivery

Bowler	Duration of Bowling delivery (%)										
	PDS to BFC			BFC to FFC			FFC to BR		BR to FT		
	0	10	20	30	40	50	60	70	80	90	100
1_{sp}	1.43	1.72	1.05	6.89	2.20	9.93	21.59	7.38	1.78	15.05	8.65
2_{si}	14.69	15.80	22.33	38.78	21.23	11.95	22.54	0.97	3.30	9.52	8.74
3_{m}	3.45	1.80	2.21	9.41	4.69	18.33	12.71	5.63	14.50	9.81	33.99
4_{m}	7.52	11.51	8.72	1.29	4.64	8.66	3.49	13.08	19.21	10.09	17.39
5_{sp}	12.86	10.30	5.10	7.35	4.71	13.92	18.80	2.02	18.98	41.13	42.18
6_{sp}	2.33	5.90	12.15	7.57	31.90	6.22	12.19	4.08	1.54	2.37	22.02
7_{so}	0.15	0.24	1.36	2.18	5.58	3.79	9.04	3.90	11.90	8.87	11.28
8_{so}	6.29	8.45	23.95	3.68	10.12	9.21	4.47	2.21	2.53	9.25	5.96
GROUP	**75.93**	**80.64**	**76.34**	**71.45**	**50.87**	**32.98**	**60.50**	**79.94**	**35.15**	**55.77**	**68.48**

sp – spinner, si – side on, m – mixed, so – semi open

Table 3.10 RMSE angle of elevation (°) during the bowling delivery

Bowler	Duration of Bowling delivery (%)										
	PDS to BFC			BFC to FFC			FFC to BR		BR to FT		
	0	10	20	30	40	50	60	70	80	90	100
1_{sp}	3.28	2.94	2.55	2.60	1.20	3.27	9.86	1.89	2.80	4.11	2.35
2_{si}	9.14	4.21	2.01	5.76	8.37	3.94	21.76	8.55	2.53	2.12	26.09
3_{m}	6.01	5.56	5.36	8.86	1.53	5.50	3.68	1.18	2.37	3.64	10.36
4_{m}	2.37	1.22	2.40	2.60	5.51	5.76	2.41	3.23	7.21	5.06	4.45
5_{sp}	2.54	1.75	0.41	3.36	2.05	1.58	2.20	2.07	14.53	0.77	2.58
6_{sp}	1.95	2.42	5.10	5.25	7.77	10.22	5.08	4.47	3.30	6.14	4.53
7_{so}	1.55	2.63	3.03	2.96	2.85	7.40	2.76	0.93	5.81	6.83	8.63
8_{so}	4.59	3.49	6.95	5.02	2.89	4.30	2.86	2.72	5.01	1.25	7.86
GROUP	**47.78**	**49.74**	**48.25**	**36.10**	**13.55**	**24.80**	**17.69**	**14.04**	**21.01**	**35.19**	**26.91**

sp – spinner, si – side on, m – mixed, so – semi open

Table 3.11 RMSE axial rotation (°) during the bowling delivery

Bowler	Duration of Bowling delivery (%)										
	PDS to BFC			BFC to FFC			FFC to BR		BR to FT		
	0	10	20	30	40	50	60	70	80	90	100
1_{sp}	0.77	0.80	0.47	0.47	1.48	5.53	5.28	0.12	3.41	0.65	2.01
2_{si}	32.55	26.38	22.94	14.39	25.08	12.86	19.77	4.66	1.33	5.11	28.48
3_{m}	1.84	1.96	2.98	8.42	32.70	6.02	4.17	15.16	4.16	3.32	20.00
4_{m}	10.24	15.64	10.65	4.08	26.75	10.99	3.46	8.76	10.06	8.38	12.15
5_{sp}	3.22	0.94	1.33	3.32	4.72	3.45	5.35	4.77	24.14	38.21	8.63
6_{sp}	2.70	10.50	14.13	2.26	22.32	5.19	2.56	3.82	4.35	3.31	7.30
7_{so}	1.78	1.50	0.82	0.29	5.76	3.31	1.30	1.88	8.41	6.76	5.90
8_{so}	1.55	3.87	2.83	3.05	8.83	5.97	3.62	2.79	1.73	2.86	5.81
GROUP	**61.66**	**58.83**	**60.15**	**73.85**	**53.41**	**47.01**	**31.20**	**15.41**	**17.53**	**15.21**	**31.00**

sp – spinner, si – side on, m – mixed, so – semi open

Conclusion

This body of work aids in quantifying shoulder kinematics during the bowling delivery as defined through humerothoracic motion. In contrast to the findings of Bonnefoy-Mazure *et al.* (2010) investigating the tennis serve, all rotation sequences investigated were found to be affected by GL. Shoulder abduction observed during the bowling delivery, as defined by the angle of humerothoracic elevation (23.70 ± 9.80 ° to 103.01 ± 14.79 °), suggests that the use of the ISB recommended YXY Euler sequence is appropriate as singularity only occurs if the angle were to approach 0 ° or 180 °.

Shoulder movement was found to be typical of the observed movement pattern, with large variability throughout indicating subsequent research investigating the bowling delivery should be undertaken using a within bowler design. Greatest variability was associated during the PDS to BFC phase (plane of elevation RMSE max: 80.64, angle of elevation RMSE max: 49.74 and axial rotation RMSE max: 73.85), reflective of the associated individualised technique (Woolmer *et al.,* 2008). Due to the dynamic nature of the bowling delivery, whereby variability could be influenced by factors such as bowling style and experience, to minimise the influence variability may impart on statistical findings, future research must ensure the experimental methodology is robust and controls for factors such as the line and length of the deliveries.

Through quantifying shoulder motion during the bowling delivery stride as defined by humerothoracic motion, findings from this investigation aid in providing researchers with a greater understanding of the demands on the shoulder during the bowling delivery. The shoulder was observed to maintain an internally rotated position throughout the bowling delivery, supporting the findings from chapter 2 relating to subscapularis tendon pathology, suggesting this may arise due to the repetitive demands on the musculature to dynamically stabilise the joint. As the maximum degree of internal rotation (60.75 ± 17.42 °), observed to occur during the follow through, contradicts the findings of Stuelcken *et al.* (2008), future research needs to quantify the contribution of scapular movement to establish the influence this imparts on both bowling performance and joint stability.

Chapter 4

Acromion cluster reliability under dynamic loading

Introduction

Cricket bowlers have been shown to be characterised by an altered range of shoulder motion through decreased internal rotation (Aginsky *et al.,* 2004; Bell-Jenje & Gray, 2005; Giles & Musa, 2008; Stuelcken *et al.,* 2008). However, a lack of quantitative kinematic analysis makes it difficult to establish the influence this imparts on bowling technique. Results from chapter 3 established that throughout different phases of the bowling movement, the bowling shoulder is in an internally rotated position (maximum internal rotation: 60.75 ± 17.42 °), the magnitude of which, is in contrast to the range of motion measured clinically (mean internal rotation: 43.5 ± 7.3 ° (Stuelcken *et al.,* 2008)). Such findings demonstrate the limited applicability of applying humerothoracic angles to describe shoulder position, due to it representing the resultant motion about both glenohumeral and scapulothoracic joints. Therefore, in order to gain a comprehensive understanding of shoulder position during dynamic sporting movements, research must aim to address the inherent difficulties associated in establishing scapula position and orientation (Lempereur *et al.,* 2010a), to enable motion about each joint to be accurately established.

Literature review

Scapula motion

Large degrees of freedom about the shoulder joint arise from the complex interaction of multiple structures including the humerus, clavicle, scapula and thorax (Lugo, Kung & Ma, 2008). During arm elevation, the scapula externally rotates, upwardly rotates and posteriorly tilts (Meyer *et al.,* 2008). As scapula motion, referred to as scapulothoracic motion (Figure 4.1), is crucial for normal shoulder mechanics, the scapula is a major determinant of shoulder joint function, particularly during sporting movements such as throwing where scapula dyskinesia can contribute to the causation of injuries such as shoulder impingement, instability and rotator cuff tears (Karduna *et al.,* 2001; Kibler *et* *al.*, 1996; Meyer *et al.*, 2008). As identified in chapter 3, during the bowling motion, the bowling shoulder undergoes large degrees of movement, particularly internal rotation during elevation of the arm in the final phases of the action. Previous research has established that the scapulothoracic joint, as it translates provides the shoulder joint with additional degrees of motion, whereby with increased arm elevation the contribution between scapulothoracic and glenohumeral motion are nearly identical (Illyés & Kiss, 2007; Lugo *et al.*, 2008). The translatory movement of the scapula combined with surrounding muscle and soft tissue structures, impart methodological difficulties in establishing scapula position and orientation during both controlled clinical and dynamic environments (Lempereur *et al.*, 2010a).

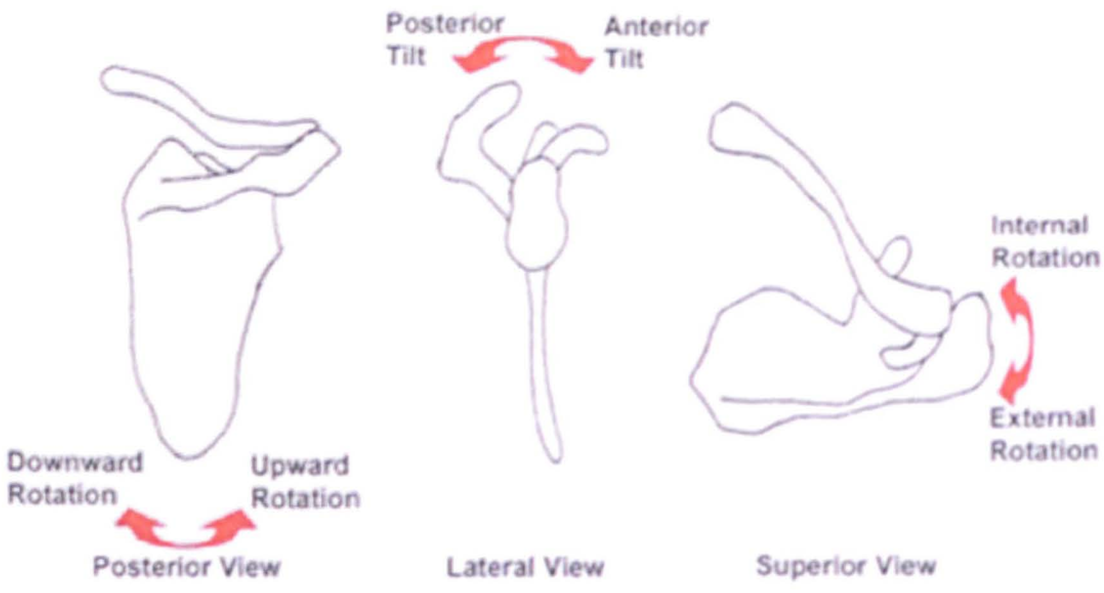


Figure 4.1 Scapula motion (adapted from Meyer *et al.* (2008))

Non-invasive methods to record scapula kinematics

Although motion of the scapula contributes to elevation of the arm, few studies have attempted to quantify scapula motion, as defined by scapulothoracic motion, during dynamic sporting movements (Bonnefoy-Mazure *et al.*, 2010). Whilst it is possible to estimate scapula motion indirectly through applying regression methods underpinned by scapulohumeral rhythm; the coordinated movement of the scapula and humerus (de Groot & Brand, 2001; McQuade & Smidt, 1998), there is conjecture surrounding the applicability of such methods to account for effects from various conditions such as dynamic movements, external resistance and shoulder pathology (McQuade & Smidt, 1998). Due to these limitations, researchers have investigated a myriad of alternative non-invasive methods to directly record scapula motion. As there is a lack of consensus regarding the most appropriate method, studies to date have been conducted within controlled, clinical settings whereby the appropriateness for dynamic movements can only be inferred.

In accordance with ISB recommendations (Wu *et al.*, 2005) a minimum of three anatomically defined landmarks are required to directly establish the three dimensional position and orientation of the scapula, of which the Angulus Acromialis (AA), Angulus Inferior (AI) and Trigonum Spinae Scapulae (TS) are commonly used, although early research has previously incorporated the Acromioclaviculare (AC) (Figure 4.2) (Ludewig, Hassett, Laprade, Camargo & Braman, 2010). The irregular shape of the scapula combined with overlying muscle and soft tissue mass, has seen numerous *in vivo* techniques such as surface markers (Brochard, Lempereur & Rémy-Néris, 2009; Matsui, Shimada & Andrew, 2006; Lovern, Stroud, Evans, Evans & Holt, 2009), electromagnetic sensors (Cutti, Giovanardi, Rocchi, Davalli & Sacchetti, 2008, Fayad *et al.*, 2008; Karduna *et al.*, 2001; Meskers, van de Sande & de Groot, 2007), a scapula locator (Meskers *et al.*, 1998b; van Andel *et al.*, 2009) and the acromion cluster (Salvia *et al.*, 2009; van Andel, van Hutten, Eversdijk, Veeger & Harlaar, 2009; van Andel *et al.*, 2008) proposed; all of which aim to accurately establish the position of these landmarks (Figure 4.3).

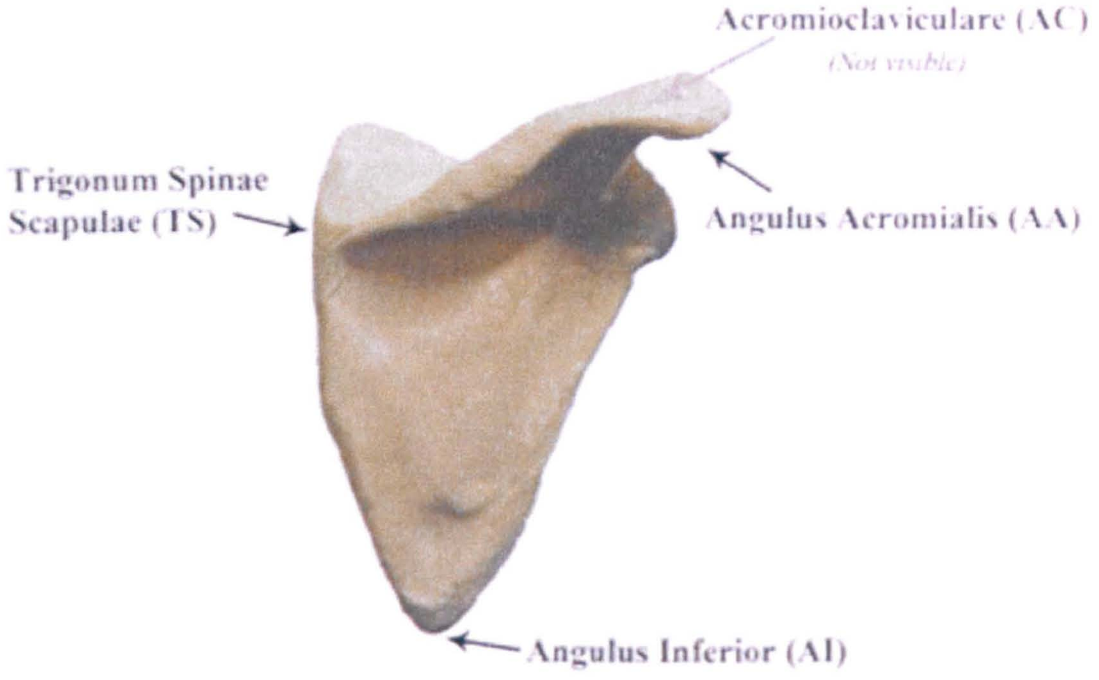


Figure 4.2 Scapula anatomical landmarks used within biomechanical analysis to define the position and orientation of the scapula

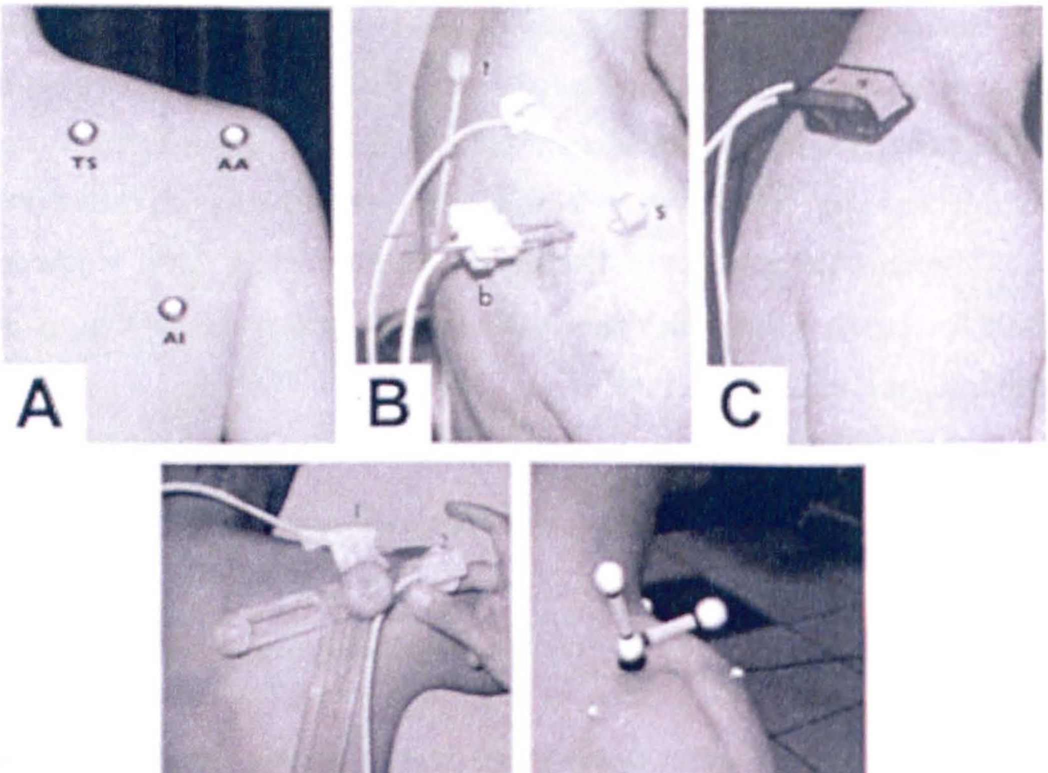


Figure 4.3 Methods to record scapula motion. A. Surface markers B. Bone pins (Karduna *et al.*, 2001) C. Electromagnetic sensor (Cutti *et al.*, 2008) D. Scapula locator (Meskers *et al.*, 2007) E. Acromion cluster (Brochard *et al.*, 2009)

Acromion cluster to record scapula kinematics

Within research utilising both stereophotogrammetric and optoelectric systems, the acromion cluster is increasingly being adopted as it allows for unconstrained recording of scapula motion whilst minimising the effect of soft tissue artefact (STA) (Brochard *et al.*, 2009; van Andel *et al.*, 2009). Used in conjunction with the calibrated anatomical systems technique (CAST) protocol (Cappozzo *et al.*, 1995), scapula anatomical landmarks, AA, AI and TS, individually referred to as p^M within equations 4.1 and 4.2, are first mathematically defined from the global coordinate system (G) into the acromion cluster technical coordinate system (AC^T) (Equation 4.1). As the acromion cluster is positioned in an area least affected by STA, following recording of the movement of interest, each anatomical landmark can then be reconstructed into the global coordinate system (Equation 4.2). To date, several studies (Brochard *et al.*, 2009; Karduna *et al.*, 2001; Meskers *et al.*, 2007; Salvia *et al.*, 2009; van Andel *et al.*, 2009; Warner, Chappell & Stokes, 2010) have aimed to establish the validity of this approach with inconclusive findings which may be related to methodological differences in incorporating this method and the standard used for comparison. Therefore, before the acromion cluster can be applied to establish scapula motion during cricket bowling, further validation, particularly under simulated, dynamic conditions is required.

$$ {}_{AC^T}p^M(st) = {}^{AC^T}_{G}T(st)^{-1}\,{}_{G}p^M(st) $$

Equation 4.1

$$ {}_{G}p^M(t) = {}^{AC^T}_{G}T(t)\,{}_{AC^T}p^M(st) $$

Equation 4.2

van Andel *et al.* (2009) assessed the validity of the acromion cluster method using simultaneous scapula locator recordings for comparison. The authors noted that whilst variability arising from changes within both the plane of movement and angle of elevation were apparent, the acromion cluster generally underestimated movements by no more than 6 degrees during both forward flexion and abduction of the humerus which was in agreement with the work of Meskers *et al.* (2007) but partly contradicted the findings of Karduna *et al.* (2001). Brochard *et al.* (2009) investigated if an acromion cluster could significantly improve the accuracy of establishing scapular motion compared to surface markers. Palpation was used to determine actual scapula position as it is deemed the gold standard for static measurement of scapula kinematics (de Groot, 1997). Findings from this study established that scapula orientation as described by the YXZ Euler rotation sequence was not significantly different between palpation and the acromion cluster, whereas surface markers both significantly overestimated upward/downward rotation and underestimated anterior/posterior tilt. Similar to van Andel *et al.* (2009), Brochard *et al.* (2009) associated the acromion cluster with errors of up to 10 degrees, which increased with arm elevation. This error was anecdotally attributed to deltoid muscle mass and contraction compromising the congruence between the cluster and the acromion, with researchers advising caution should be taken when using the acromion cluster for movements over 100 degrees elevation (Brochard *et al.*, 2009; Karduna *et al.*, 2001; van Andel *et al.*, 2009). Therefore, before the acromion cluster can be used to establish scapula motion during overhead movements, further investigation is required to gain a greater understanding of the underlying cause of acromion cluster error occurring with increasing arm elevation.

Influence of load on scapula kinematics

Previous research has investigated the influence of muscle activity and external load on scapular motion with contrasting findings. Ebaugh, McClure & Karduna (2005) investigated the influence of muscle activity on scapula position between active and passive arm elevation. Twenty participants, with no prior history of shoulder injury, underwent passive and active arm elevation within the scapula plane (40 ± 10 ° anterior to the frontal plane). Three dimensional kinematics were recorded at 40 Hz using electromagnetic sensors attached to the scapula, thorax and humerus. In addition surface electromyography of the upper and lower trapezius, serratus anterior, anterior and posterior deltoid and infraspinatus muscles was recorded at 1024 Hz. Arm elevation was recorded with the participant in a seated position, with movement of the elbow joint unconstrained. Passive arm elevation was obtained by the examiner elevating the participant's arm using a pulley system, where a passive movement was defined as one whereby the observed muscle activity was less than 20 % of the maximal voluntary isometric contraction value recorded. Ebaugh *et al.* (2005) observed similar patterns of scapula motion between both active and passive movements, with greater upward rotation at 90 ° ($t_{(16)} = 4.12$, $p < 0.001$), 120 ° ($t_{(16)} = 9.80$, $p < 0.001$) and maximum positions ($t_{(16)} = 3.75$, $p < 0.002$) with active arm elevation. From these findings, Ebaugh *et al.* (2005) reported that scapula motion differs between active and passive elevation, particularly in regards to upward scapula rotation where upper and lower trapezius and serratus anterior muscles contribute.

In contrast, de Groot, van Woensel & van der Helm (1999) when investigating the effect of arm loads on scapula position during arm abduction established that it is not the magnitude of load that alters scapula position but rather the direction that the force is applied in. Ten male participants were instructed to maintain seven symmetrical postures of arm abduction in the frontal plane, corresponding to increments of 30 ° elevation until maximum arm elevation of 180 °. Four different load conditions were applied to the wrists (0 kg, 0.9 kg, 1.9 kg and 2.9 kg) with measures incorporated to minimise the influence of fatigue during data collection. Subsequent data analysis incorporating repeated measures ANOVAs established that whilst scapula angles were significantly related ($p < 0.05$) to the angle of arm elevation, using linear regression no relationship existed between scapula angles and load. de Groot *et al.* (1999), theorised that as scapula orientation is determined by the equilibrium of forces acting on the segment, it is the direction of applied force rather than the magnitude, which will alter the equilibrium and thus affect scapula orientation. As de Groot *et al.* (1999) only investigated movement within the frontal plane and did not quantify any changes in muscle activity between loads, further research investigating other movement patterns would be required to substantiate this theory.

Study aim

As the use of the acromion cluster in conjunction with the CAST technique has to date, been largely researched using controlled, static conditions, the primary aim of this investigation was to establish the reliability of the acromion cluster for dynamic movements. Findings from chapter 3, through investigating humerothoracic motion, established that the cricket bowling delivery elicits multi-planar motion from the shoulder joint, which due to its dynamic nature elicits varying degrees of activity from surrounding musculature, particularly from the deltoid group (Shorter, Smith, Lauder and Khoury, 2010). As previous research (Brochard *et al.*, 2009; Karduna *et al.*, 2001; van Andel *et al.*, 2009) has attributed deltoid contraction with affecting the validity of the acromion cluster, this study aimed to investigate the influence that load may impart on acromion cluster reliability as observed through changes in anatomical landmark reconstruction and deltoid muscle activity during movement within both the frontal (abduction) and sagittal (forward flexion) planes. In addition to this, this study aimed to investigate if the application of a second static calibration used within the CAST protocol could aid in addressing the errors associated with the acromion cluster with increasing arm elevation over 100 degrees.

Method

Participants

After gaining university ethical approval, five male participants, with no recent history of shoulder pathology were recruited. The mean ± SD age, height and mass of the participants were 32.8 ± 6.4 years, 1.78 ± 0.05 m and 91.20 ± 20.70 kg. Following an explanation of the experimental aims and procedures all participants provided informed consent.

Equipment

Surface electromyography (sEMG) activity was recorded at 500 Hz using a radio telemetry system (MIE Medical Research Ltd, Leeds, UK) and synchronised to four Basler 100 Hz cameras recording kinematic data using a MX Ultranet control unit (Peak Performance Technologies Inc., Englewood, USA). A 17-point calibration frame (Peak Performance Technologies Inc., Colorado, USA) provided a calibrated volume of 1.26 m × 1.08 m × 0.90 m with a residual calibration error of 0.0023 m.

sEMG activity of the middle fibres of the deltoid were recorded using surface AgAgCl electrodes. Following skin preparation in accordance with Payton & Bartlett (2008), electrodes were placed on the lateral aspect of the upper arm 5 cm apart and 3 cm inferior to the acromion process (Cram, Kasman & Holtz, 1998).

To analyse skeletal movement, surface retroflective markers (12 mm diameter) were placed on bony landmarks of the thorax, scapula and humerus in accordance with ISB guidelines (Wu *et al.*, 2005) with an acromion cluster (retroflective marker diameter: 10 mm diameter) positioned on the posterior aspect of the acromion plateau (Table 4.1). For the purpose of this study both the glenohumeral and elbow joint centres were defined as being halfway between medial and lateral bony prominences. Anatomical coordinate systems (ACS) for both the thorax and humerus were defined in accordance with ISB guidelines (Table 4.2) (Wu *et al.*, 2005).

Table 4.1 Surface retroflective markers to enable reconstruction of skeletal movement

Segment	Marker	Definition
Thorax (anatomical)	SN	Suprasternal notch
	XP	Xiphoid process - most caudal point of the sternum
	C7	Spinous process of the C7 vertebra
	T8	Spinous process of the T8 vertebra
Humerus	AA	Angulus acromialis
	AC	Acromioclaviculare
	ME	Most caudal point of the medial epicondyle
	LE	Most caudal point of the lateral epicondyle
	EJC	Virtual marker halfway between ME and LE
	BSJC	Virtual marker halfway between AA and AC
Scapula (anatomical)	AA	Angulus acromialis
	AI	Angulus Inferior
	TS	Trigonum Spinae Scapulae
Thorax (technical)	T1, T2, T3, T4	Identical to the thorax anatomical coordinate system to enable reconstruction of both SJC during the dynamic movement
Humerus (technical)	H1, H2, H3	Three non-linear markers positioned to minimise the influence of soft tissue artefact and enable reconstruction of the humerus anatomical markers
Acromion Cluster (technical)	A1, A2, A3	Three orthogonal markers, on a rigid structure positioned on the acromion plateau to enable reconstruction during dynamic movement of scapula anatomical markers (AA, AI, TS)

Table 4.2 Segment anatomical coordinate systems (Wu *et al.*, 2005)

Coordinate system	Axis	Definition
Thorax	Y	Line connecting the midpoint between XP and T8, and the midpoint between SN and C7, pointing upward
	Z	The line perpendicular to the plane formed by the midpoint between XP and T8, SN and C7, pointing to the right
	X	The line perpendicular to the Z axis and Y axis, pointing forwards
Humerus	Y	Line connecting the SJC and EJC, pointing towards the SJC
	X	The line perpendicular to the plane formed by the SJC, ME and LE, pointing forward
	Z	The line perpendicular to the Y axis and X axis, pointing to the right

Scapula markers (AA, AI and TS) were defined statically in relation to the acromion cluster technical coordinate system using the CAST protocol to enable reconstruction during movement trials (refer to Equation 4.1) (Cappozzo *et al.*, 1995). To investigate the influence of the static calibration position on the acromion cluster, two positions were recorded (Figure 4.4). The first position (static 1), was recorded with the participant in the anatomical position, and the second position (static 2) was recorded with the participant's arm at 90 ° elevation. The second position was selected due to being a position where previous research (Karduna *et al.*, 2001; Meskers *et al.*, 2007; van Andel *et al.*, 2009), has established poor cluster validity attributed to an increase in soft tissue and muscle bulk around the cluster.

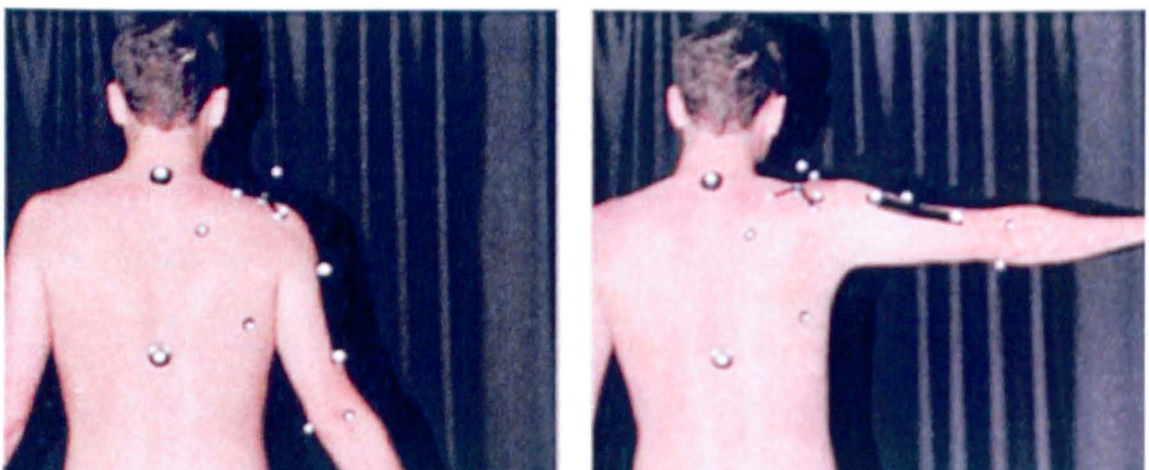


Figure 4.4 Static calibration positions in the anatomical position (static 1) and at 90° abduction (static 2)

Testing procedure

Following habituation with the testing environment, a maximal voluntary contraction (MVC) was recorded with the participant abducting their arm against manual resistance. Participants were instructed to perform three repetitions of arm elevation within both the frontal (abduction) and sagittal (forward flexion) planes for each load condition (no weight, 1.5 kg and 5.5 kg) throughout the full range of motion. Load conditions were selected in agreement with magnitudes previously used by de Groot *et al.* (1999), with the 5.5 kg load chosen to elicit a range of muscle activity reflective of the magnitude observed during the bowling movement (Shorter *et al.,* 2010). Movement velocity was controlled using a metronome set at 60 beats per minute.

Data processing

Kinematic data were processed using a quintic spline filter (Woltring, 1986) with the degree of smoothing selecting using generalised cross-validation and extrapolated to 500 Hz using Vicon Motus 9.2 software (Vicon, Los Angeles, USA). Data were then exported into CSBT DynACRel (Shorter, 2010, unpublished program)(Figure 4.5) (Appendix G), a custom program using LabVIEW™ 2009 (National Instruments, Austin, USA) to enable reconstruction of scapula anatomical landmarks in accordance with the CAST protocol using both the static 1 and static 2 positions (refer to Equation 4.1, 4.2).

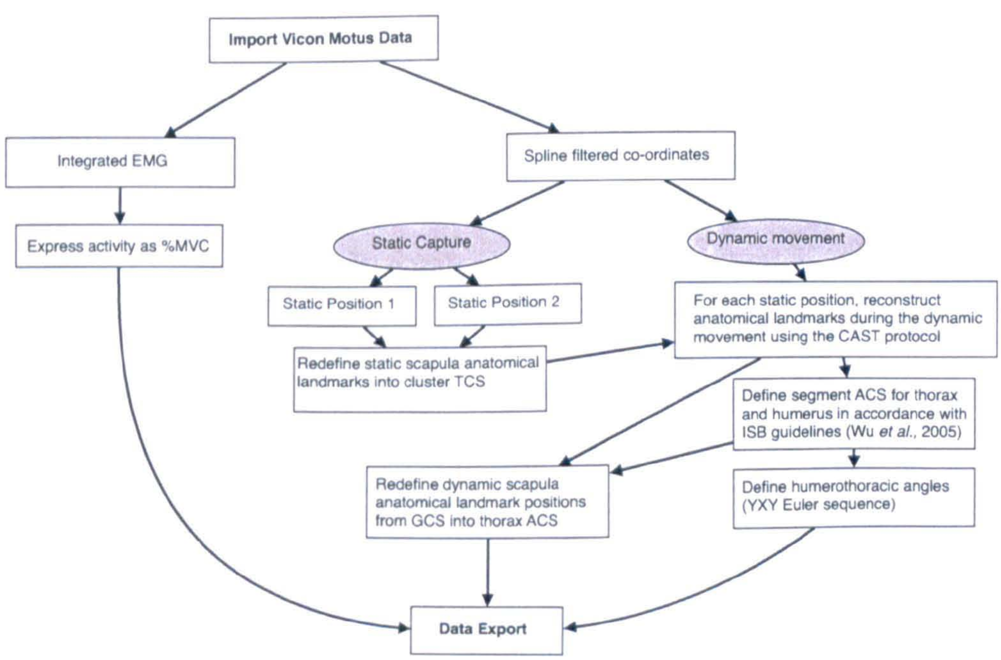


Figure 4.5 CSBT DynACRel (Shorter, 2010, unpublished program) explanatory program flow diagram

To account for the influence of the trunk on scapula position during the movement, each scapula anatomical landmark, AA, AI and TS, referred to individually as p^{M} in equation 4.3, once reconstructed from the acromion cluster technical coordinate system (AC^{T}) was redefined in relation to the thorax ACS (TH^{ACS}) (Equation 4.3).

$$
\begin{aligned}
{}_{AC^T}p^{M}(st) &= {}^{AC^T}_{G}T(st)^{-1}\,{}_{G}p^{M}(st)\\
{}_{G}p^{M}(t) &= {}^{AC^T}_{G}T(t)\,{}_{AC^T}p^{M}(st)\\
{}_{TH^{ACS}}p^{M}(t) &= {}^{TH^{ACS}}_{G}T(t)^{-1}\,{}_{G}p^{M}(t)
\end{aligned}
$$

Equation 4.3

The angle of arm elevation and plane of elevation were defined in relation to the humerothoracic angle using an YXY Euler sequence (Equation 4.4) (Wu *et al.*, 2005). For the purpose of this investigation each movement was analysed at discrete intervals of 40, 60, 80, 100 and 120 degrees (static 1) and 100 and 120 degrees (static 2) elevation during the positive displacement phase only. The plane of elevation corresponding with 0 ° for movement in the frontal plane, and 90 ° movement in the sagittal plane, was established in order to monitor the dynamic movement, ensuring that this was consistent across load conditions due to the changes this could impart on marker position.

$$YXY(\alpha,\beta,\gamma)$$

$$
\begin{aligned}
\alpha &= a\sin\left(\frac{y_p \bullet x_d}{\sin\beta}\right)\\
\beta &= a\cos\left(y_p \bullet y_d\right)\\
\gamma &= a\sin\left(\frac{x_p \bullet y_d}{\sin\beta}\right)
\end{aligned}
$$

Where:

α = *plane of elevation*

β = *angle of elevation*

γ = *axial rotation*

Equation 4.4

sEMG data was analysed using a linear envelope, incorporating a low pass Butterworth filter with a cut-off frequency of 6 Hz selected by residual analysis (Winter, 2009) and expressed as a percentage of the participant's MVC. To establish if the load conditions chosen elicited different magnitudes of deltoid muscle activity that could impair acromion cluster reliability, for each condition, muscle activity was normalised in relation to the angle of elevation, and the total contribution of muscle activity during the movement was subsequently defined by the area under the curve using the trapezoid rule.

Statistical analysis

Statistical analysis was undertaken using SPSS version 16 for windows (SPSS inc., Chicago, IL) with the alpha level set at $p \leq 0.05$. To establish if the amount of muscle activity differed between load conditions for each movement, a one-way repeated measures ANOVA with post-hoc paired t-tests incorporating Bonferroni adjustments was undertaken. After ensuring all data were normally distributed and met statistical assumptions, for each marker coordinate, at each angle of elevation, one-way repeated measures ANOVAs with post-hoc paired t-tests incorporating Bonferroni adjustments were used to investigate the interaction effect between load (repeated measure) and angle of elevation. To investigate the effect of static position on reconstructed anatomical coordinates, at each angle of elevation paired t-tests with Bonferroni adjustment (adjusted $p = 0.0167$) were performed between load conditions.

Movement within the frontal plane (abduction)

Muscle activity

Normalised average deltoid muscle activity observed during movement within the frontal plane for all participants in respect to the linear envelope sEMG is shown in Figure 4.6. Deltoid muscle activity throughout the movement, as defined by the area under the curve, was observed to significantly differ between load conditions ($F_{(1.197,16.759)} = 80.675$, $p < 0.001$, $1- \beta = 1$) with subsequent post hoc tests establishing significant differences between each load (no load and 1.5 kg: $t_{(14)} = -5.135$, $p < 0.001$, no load and 5.5 kg: $t_{(14)} = -9.460$, $p < 0.001$ and 1.5 kg and 5.5 kg: $t_{(14)} = -12.474$, $p < 0.001$). The significantly different deltoid muscle activity elicited between conditions (no load: 27.89 ± 11.40 %MVC.$^{o-1}$, 1.5 kg: 43.68 ± 14.85 %MVC.$^{o-1}$, 5.5 kg: 68.50 ± 19.83 %MVC.$^{o-1}$), supports the selection of these loads to investigate the influence deltoid muscle contraction may impart on acromion cluster reliability for movement within the frontal plane.

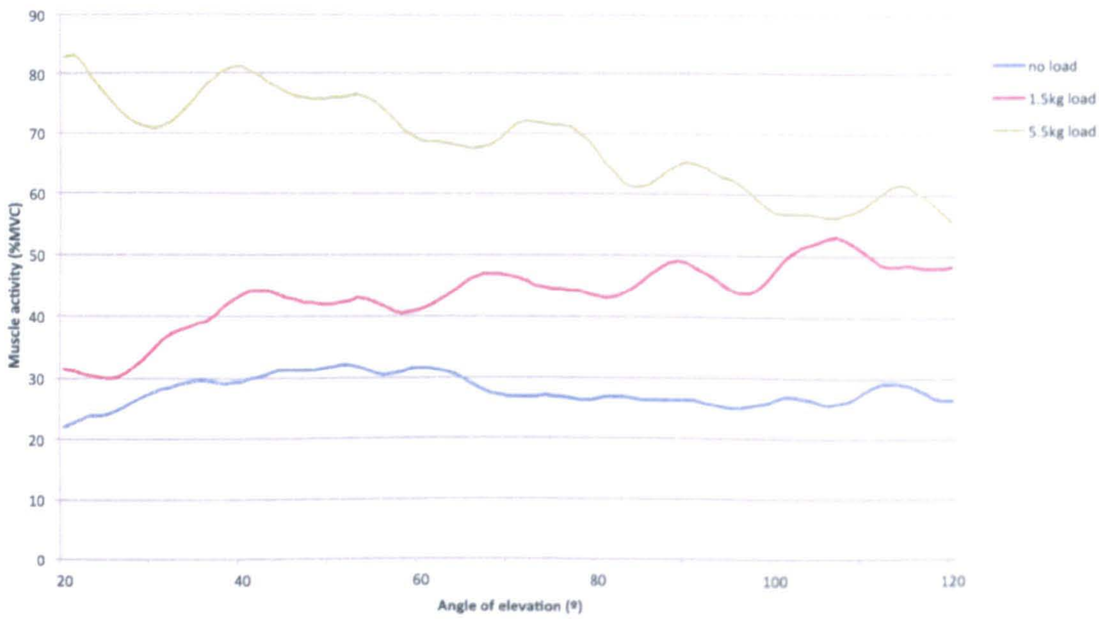


Figure 4.6 Normalised average deltoid muscle activity during movement within the frontal plane

Plane of elevation

Whilst participants were instructed to execute each movement solely within the plane of interest, the plane of elevation was observed to increase with increasing elevation for movement within the frontal plane. Non-significant ($p > 0.05$) changes within the plane of elevation (Figure 4.7), throughout all angles of elevation were observed between load conditions which may have contributed to variations in marker position for all scapular marker coordinates.

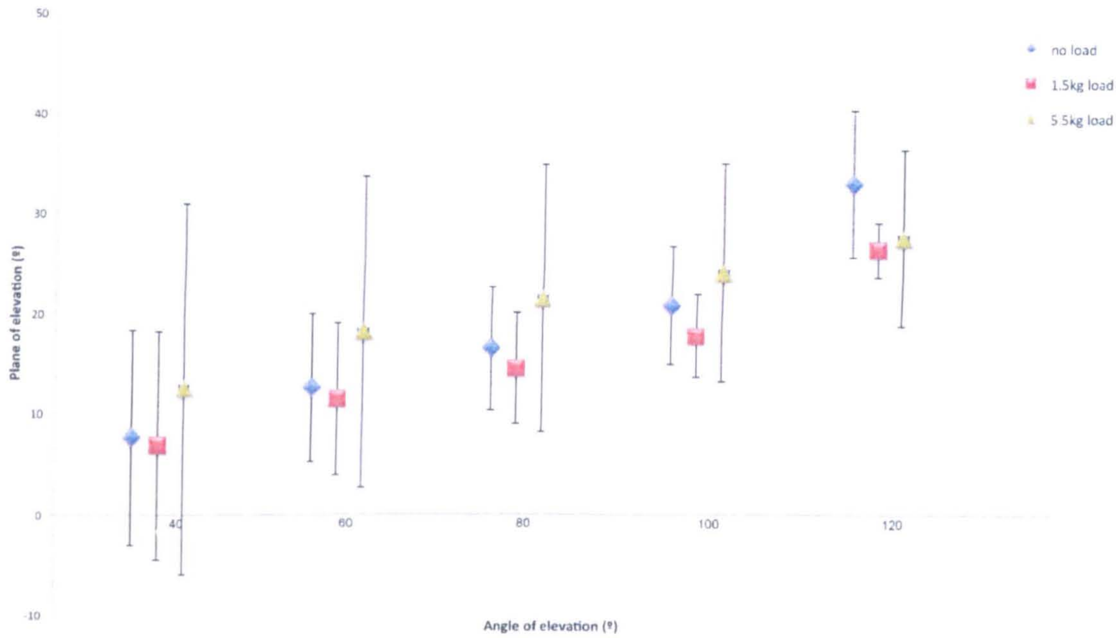


Figure 4.7 Plane of elevation during movement within the frontal plane

Influence of load on scapular marker coordinates

For each scapula marker, variations in coordinate position was observed between load conditions (Figure 4.8, 4.9, 4.10). Statistical analysis established that only the AAx, AAy and AIy coordinates were found to have significant interaction effects (Table 4.3).

Table 4.3 Significant interaction effects between load conditions for movement within the frontal plane

Marker	Static calibration position	Angle of elevation	Significance
AAx	Static 1	120	$F_{(2,8)} = 4.615$, $p = 0.046$, $1-\beta = 0.604$
	Static 2		$F_{(2,8)} = 5.751$, $p = 0.028$, $1-\beta = 0.704$
AAy	Static 1	40	$F_{(2,8)} = 17.854$, $p = 0.001$, $1-\beta = 0.994$
		60	$F_{(2,8)} = 13.535$, $p = 0.003$, $1-\beta = 0.973$
		80	$F_{(2,8)} = 7.798$, $p = 0.013$, $1-\beta = 0.823$
AIy	Static 1	40	$F_{(2,8)} = 6.001$, $p = 0.026$, $1-\beta = 0.723$
		60	$F_{(2,8)} = 5.492$, $p = 0.032$, $1-\beta = 0.683$
		80	$F_{(2,8)} = 7.809$, $p = 0.013$, $1-\beta = 0.833$

For both AAx and AIy coordinates subsequent post-hoc analysis failed to establish significant differences between load conditions. In contrast significant differences between load conditions were established for the AAy coordinate. At 40 °, a significant difference between no load and 1.5 kg ($t_{(4)} = 4.812$, $p = 0.009$, mean difference: 0.0088 m) and no load and 5.5 kg was observed ($t_{(4)} = 6.514$, $p = 0.003$, mean difference: 0.017 m). For both 60 and 80 ° elevation only a significant difference between no load and 5.5 kg was established (60 °: $t_{(4)} = 5.427$, $p = 0.006$, mean difference: 0.0146 m; 80 °: $t_{(4)} = 4.484$, $p = 0.011$, mean difference: 0.0093m).

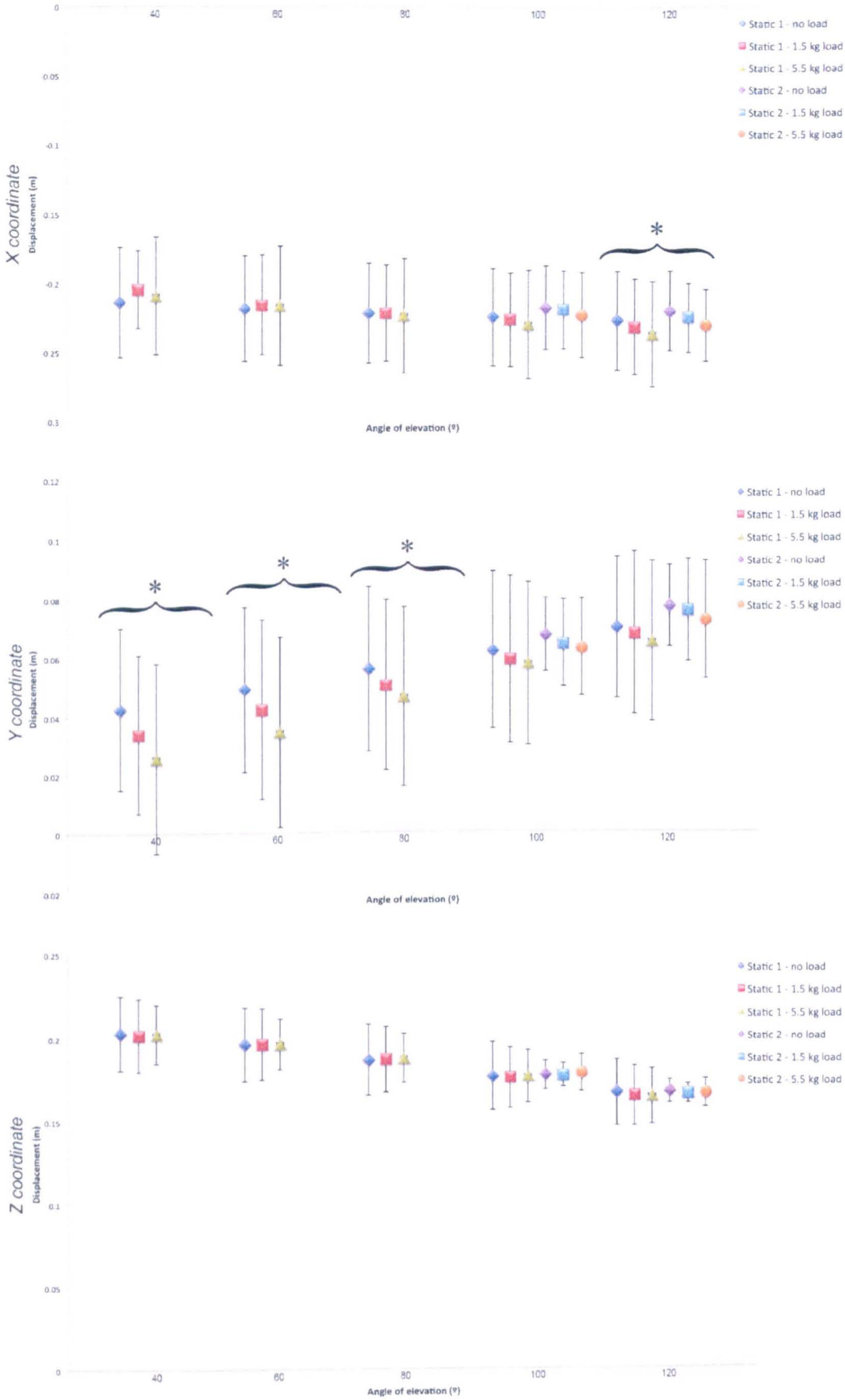


Figure 4.8 AA marker coordinate position during movement within the frontal plane (* denotes a significant difference between loads)

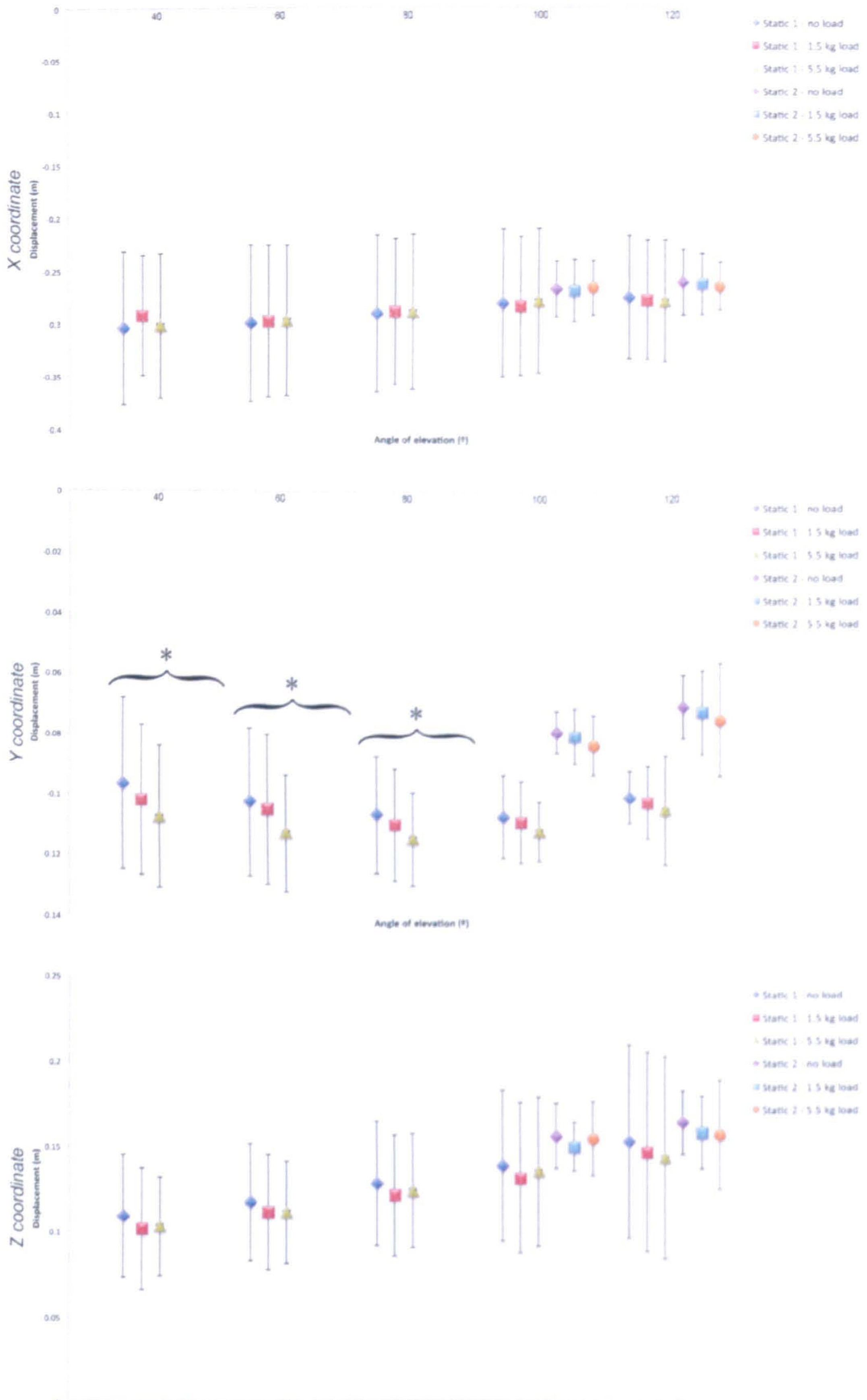


Figure 4.9 AI marker coordinate position during movement within the frontal plane (* denotes a significant difference between loads)

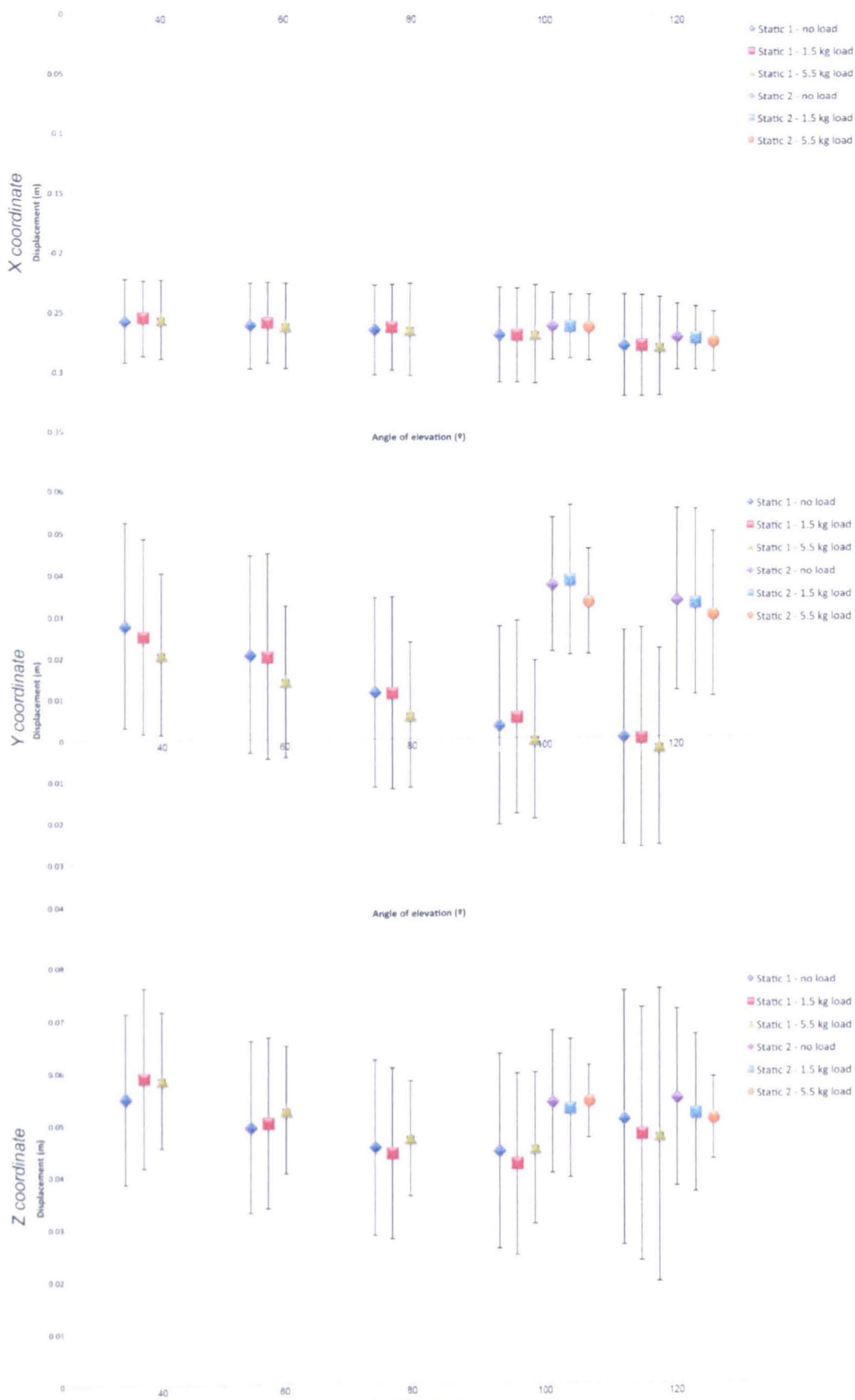


Figure 4.10 TS marker coordinate position during movement within the frontal plane (* denotes a significant difference between loads)

Movement within the sagittal plane (forward flexion)

Muscle activity

Figure 4.11 depicts the normalised average deltoid muscle activity observed during movement within the sagittal plane in respect to the linear envelope sEMG. Similar to movement within the frontal plane, deltoid muscle activity associated with movement within the sagittal plane was found to significantly differ between load conditions ($F_{(2,28)} = 114.064$, $p < 0.001$, $1-\beta = 1$), supporting the appropriateness of the selected loads in establishing the effect of deltoid muscle contraction on acromion cluster reliability. Muscle activity as described by the area under the curve using trapezoid rule (no load: 24.66 ± 9.59 %MVC.$^{o-1}$, 1.5 kg: 37.66 ± 16.48 %MVC.$^{o-1}$, 5.5 kg: 66.58 ± 21.57 %MVC.$^{o-1}$) was observed to differ between load conditions, with post hoc tests establishing significant differences between each load condition (no load and 1.5 kg: $t_{(14)} = -7.57$, $p > 0.001$, no load and 5.5 kg: $t_{(14)} = -34.62$, $p > 0.001$ and 1.5 kg and 5.5 kg: $t_{(14)} = -23.58$, $p > 0.001$).

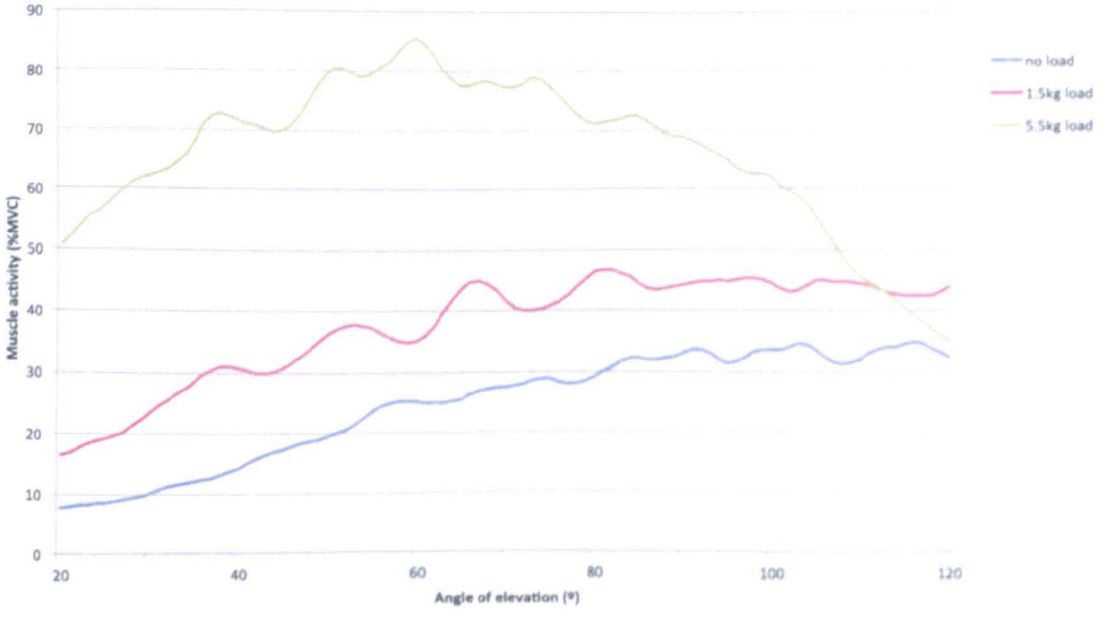


Figure 4.11 Normalised average deltoid muscle activity during movement within the sagittal plane

Plane of elevation

Similar to movement within the frontal plane, variations in marker position were observed for all scapular marker coordinates which may have been influenced by the plane of elevation. The plane of elevation (Figure 4.12), whilst fairly consistent between load conditions (mean plane of elevation: no load: 59.60 °, 1.5 kg: 58.97 ° and 5.5 kg: 53.45 °), was found to vary dependent on the angle of elevation.

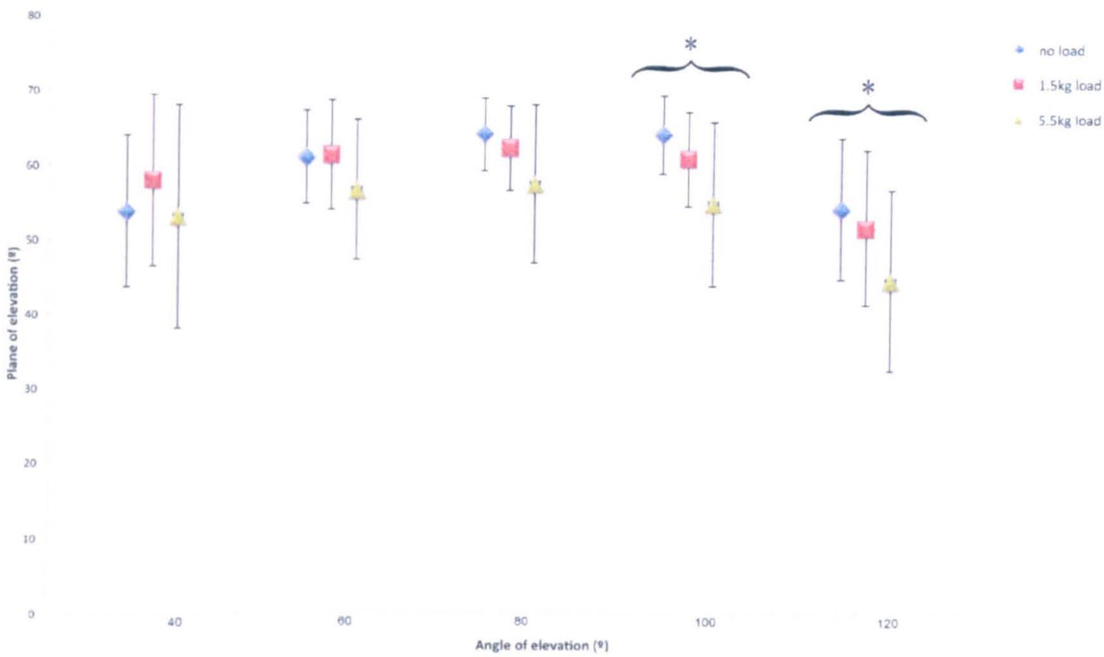


Figure 4.12 Plane of elevation during movement within the sagittal plane (* denotes a significant difference between loads)

A significant change within the plane of elevation between loads at both 100 ° and 120 ° elevation was observed. At 100 ° elevation ($F_{(2,8)} = 6.050$, $p = 0.025$, $1-\beta = 0.726$), post-hoc analysis failed to establish any significant difference between loads (no load and 5.5 kg: $t_{(4)} = 2.870$, $p = 0.045$, no load and 1.5 kg: $t_{(4)} = 2.780$, $p = 0.050$ and 1.5 kg and 5.5 kg: $t_{(4)} = 1.899$, $p = 0.130$). The plane of elevation was observed to differ significantly between load conditions at 120 ° elevation ($F_{(2,8)} = 7.531$, $p = 0.014$, $1-\beta = 0.819$), with a significant difference occurring between the no load and 5.5 kg conditions ($t_{(4)} = 4.221$, $p = 0.013$, mean difference: 9.60 °).

Influence of load on scapular marker coordinates

Movement within the sagittal plane was found to have greater affect on the reliability of the acromion cluster between load conditions for both static positions (Figure 4.13, 4.14, 4.15) with significant changes associated with AAx, AAy, AAz, AIy, TSy and TSz (Table 4.4).

Table 4.4 Significant interaction effects between load conditions for movement within the sagittal plane

Marker	Static calibration position	Angle of elevation	Significance
AAx	Static 1	40	$F_{(2,8)} = 5.370$, $p = 0.033$, $1-\beta = 0.673$
		120	$F_{(2,8)} = 4.933$, $p = 0.040$, $1-\beta = 0.634$
	Static 2	120	$F_{(2,8)} = 5.741$, $p = 0.029$, $1-\beta = 0.701$
AAy	Static 1	100	$F_{(2,8)} = 9.486$, $p = 0.008$, $1-\beta = 0.899$
	Static 2	100	$F_{(2,8)} = 8.490$, $p = 0.011$, $1-\beta = 0.864$
AAz	Static 1	80	$F_{(2,8)} = 8.173$, $p = 0.012$, $1-\beta = 0.850$
		100	$F_{(2,8)} = 8.983$, $p = 0.009$, $1-\beta = 0.882$
	Static 2	100	$F_{(2,8)} = 8.732$, $p = 0.010$, $1-\beta = 0.873$
AIy	Static 2	100	$F_{(2,8)} = 10.267$, $p = 0.006$, $1-\beta = 0.921$
TSy	Static 1	100	$F_{(2,8)} = 11.265$, $p = 0.005$, $1-\beta = 0.943$
	Static 2	100	$F_{(2,8)} = 14.219$, $p = 0.002$, $1-\beta = 0.979$
TSz	Static 1	40	$F_{(2,8)} = 6.595$, $p = 0.020$, $1-\beta = 0.764$
		120	$F_{(2,8)} = 4.914$, $p = 0.041$, $1-\beta = 0.632$

The AA marker was found to be the most affected by load conditions for movement within the sagittal plane with each coordinate associated with significant findings. The AAx coordinate position was found to be significantly different between load conditions at 40 ° elevation with a significant difference between no load and 5.5 kg ($t_{(4)} = -4.174$, $p = 0.014$, mean difference: 0.022 m). For both static positions a significant difference between load conditions was found at 120 ° elevation. A significant difference between 1.5 kg and 5.5 kg was associated with both the static 1 position ($t_{(4)} = 6.248$, $p = 0.003$, mean difference: 0.0068 m) and static 2 position ($t_{(4)} = 7.980$, $p = 0.001$, mean difference: 0.0074 m). For both static positions a significant difference in AAy coordinate position was established at 100 ° elevation between no load and 5.5 kg (static 1: $t_{(4)} = -7.853$, $p = 0.001$, mean difference: 0.1160 m; static 2: $t_{(4)} = -7.533$, $p = 0.003$, mean difference: 0.1113 m). The AAz coordinate was associated with a significant difference at 80 ° and 100 ° elevation, however subsequent post-hoc analysis failed to establish significant differences between loads, with no load and 5.5 kg ($t_{(4)} = 3.928$, $p = 0.017$, mean difference: 0.01060 m) at 80 ° approaching significance. The AIy coordinate was found to significantly differ between load conditions at 100 ° elevation for the static 2 position with a significant difference established between no load and 5.5 kg ($t_{(4)}$ = -7.732, p = 0.002), with a mean difference of 0.0118 m.

For both static positions, the TSy coordinate was found to significantly differ between load conditions at 100 ° elevation with subsequent post-hoc analysis establishing a significant difference between no load and 5.5 kg (static 1: $t_{(4)}$ =-7.588, p = 0.002, mean difference: 0.01127 m; static 2: $t_{(4)}$ =-9.231, p = 0.001, mean difference 0.01193 m). The TSz coordinate associated with static position 1 at both 40 ° and 120 ° elevation was found to significantly differ between load conditions. However, subsequent post-hoc analysis failed to support this with large variance observed at both angles of elevation (40 °: no load and 5.5 kg: $t_{(4)}$ = -2.705, p = 0.054, no load and 1.5 kg: $t_{(4)}$ = -3.305, p = 0.030 and 1.5 kg and 5.5 kg: $t_{(4)}$ = 0.468, p = 0.664; 120 °: no load and 5.5 kg: t(4) = 3.008, p = 0.040, no load and 1.5 kg: $t_{(4)}$ = 1.880, p = 0.133 and 1.5 kg and 5.5 kg: $t_{(4)}$ = 1.429, p = 0.226).

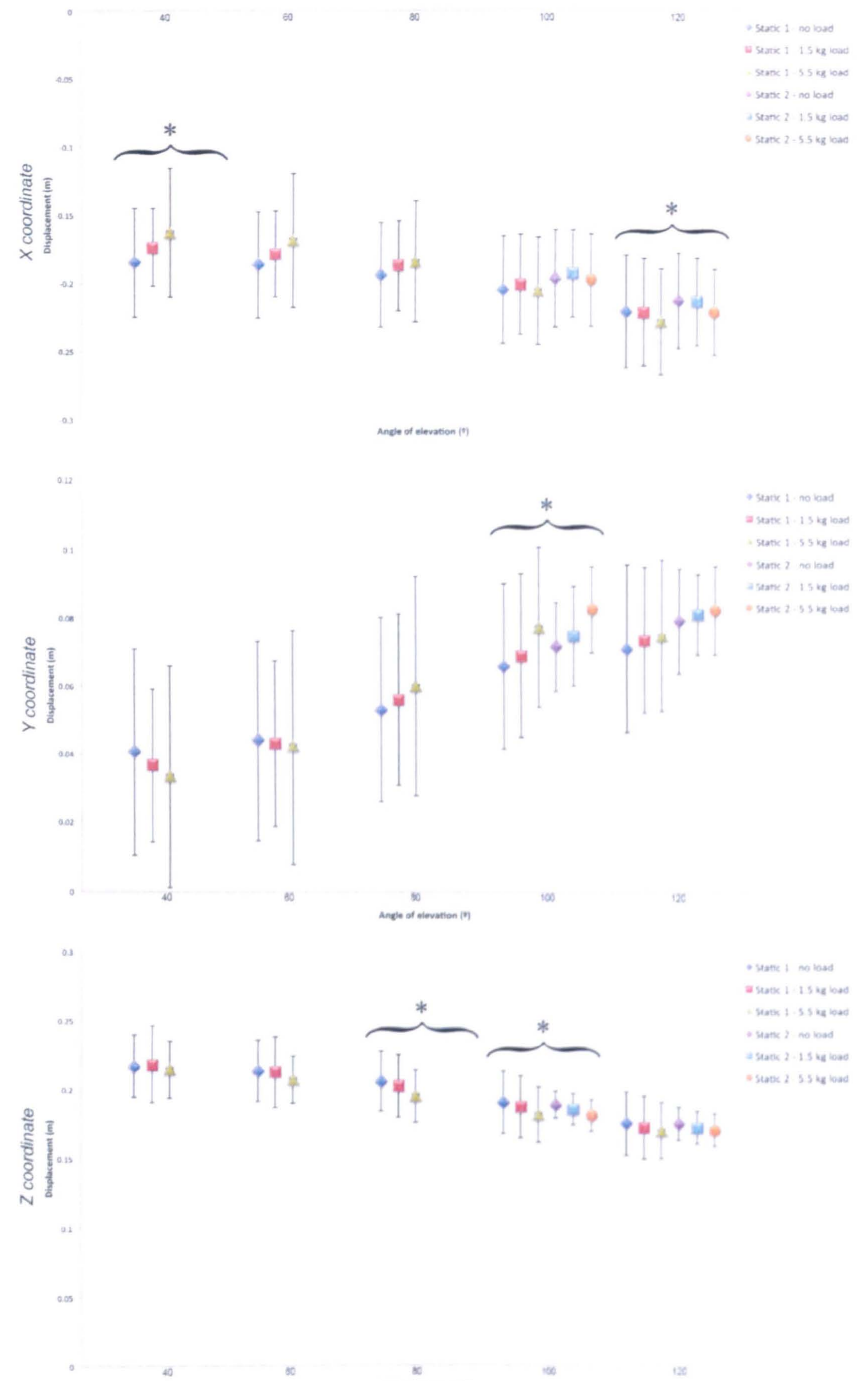


Figure 4.13 AA marker coordinate position during movement within the sagittal plane (* denotes a significant difference between loads)

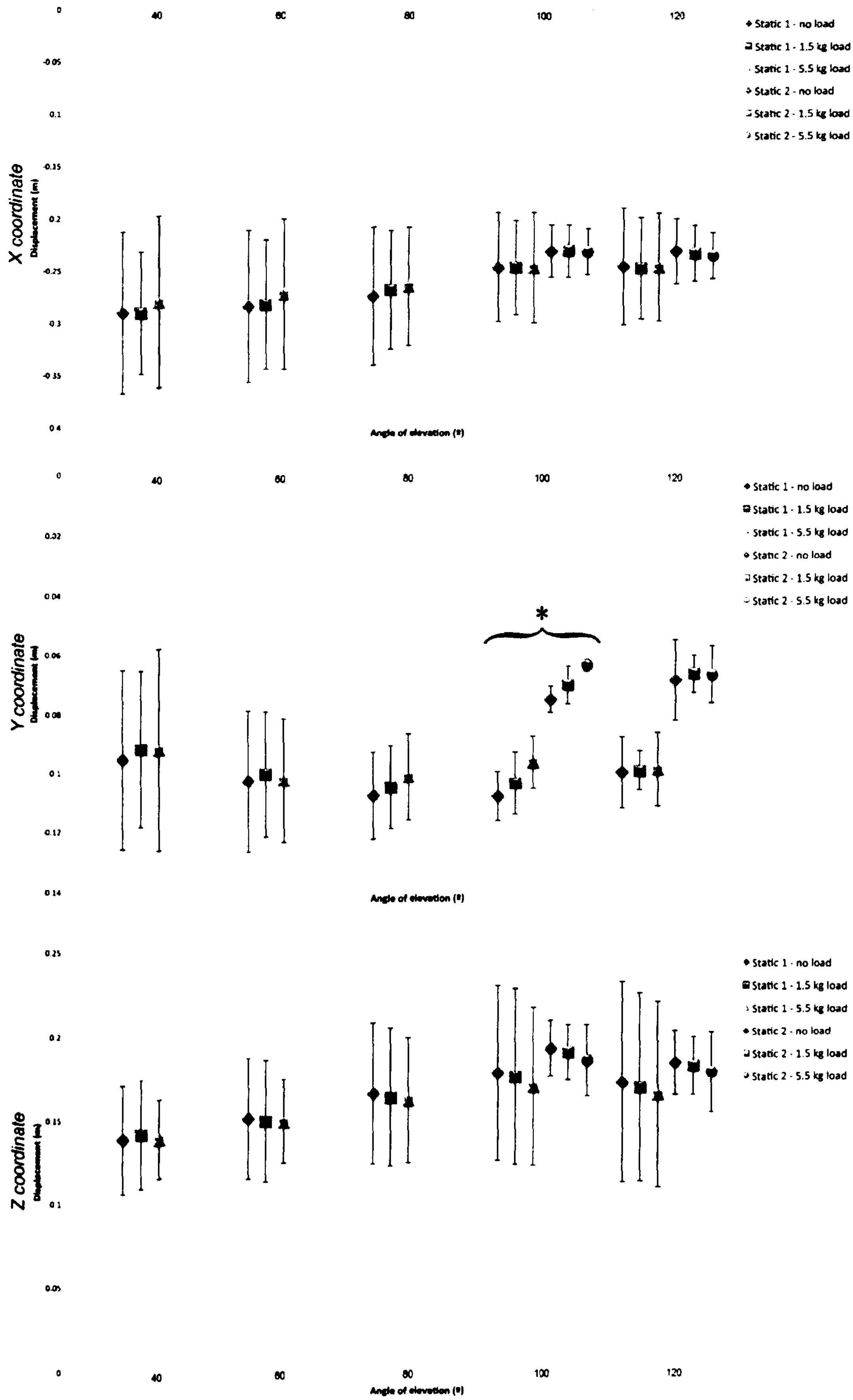


Figure 4.14 AI marker coordinate position during movement within the sagittal plane (* denotes a significant difference between loads)

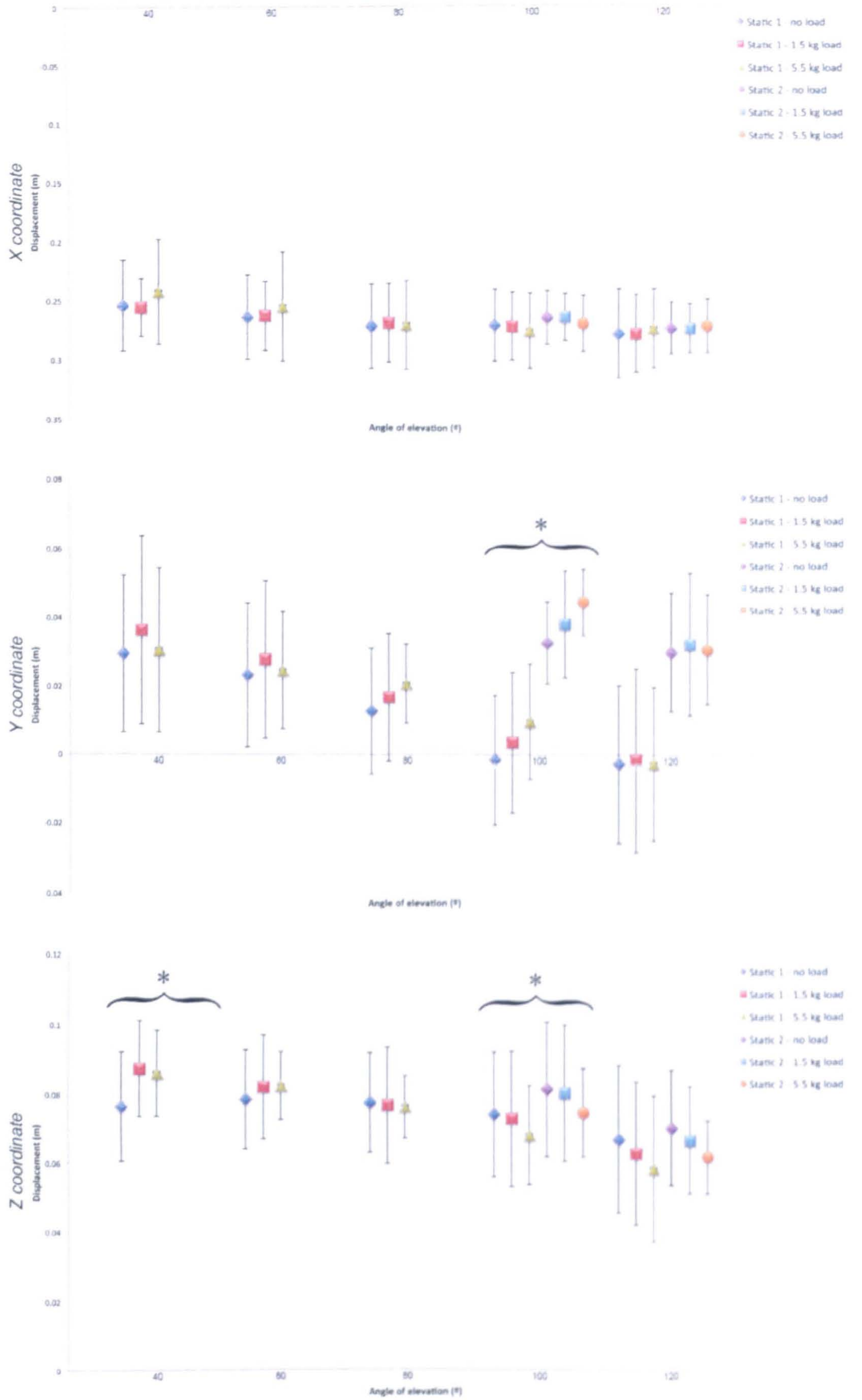


Figure 4.15 TS marker coordinate position during movement within the sagittal plane (* denotes a significant difference between loads)

Influence of static position

Whilst the influence of static position on the reliability of the acromion cluster was minimal at 100 ° and 120 ° elevation, differences in marker position dependent on the static calibration position used were observed for both movement patterns. Subsequent paired t-tests established that both AIy and TSy coordinates were sensitive to the static position used to form the basis of the marker reconstruction with significant findings reported in Table 4.5. Differences in AIy due to static position were found to vary between 0.0285 and 0.0334 m with similar differences observed with TSy (range: 0.0320 to 0.0350 m).

Table 4.5 Significant differences in marker coordinate position between static calibration positions

Marker	Plane	Angle of elevation	Load	Significance	Mean difference (m)
Aly	Frontal	100	No load	$t_{(4)} = -7.032$, $p=0.002$	0.0285
			1.5 kg	$t_{(4)} = -7.400$, $p=0.002$	0.0289
			5.5 kg	$t_{(4)} = -9.079$, $p=0.001$	0.0288
		120	No load	$t_{(4)} = -19.328$, $p<0.001$	0.0305
			1.5 kg	$t_{(4)} = -20.591$, $p<0.001$	0.0302
			5.5 kg	$t_{(4)} = -19.937$, $p<0.001$	0.0301
	Sagittal	100	No load	$t_{(4)} = -13.512$, $p<0.001$	0.0325
			1.5 kg	$t_{(4)} = -12.964$, $p<0.001$	0.0334
			5.5 kg	$t_{(4)} = -9.217$, $p=0.001$	0.0331
		120	No load	$t_{(4)} = -20.232$, $p<0.001$	0.0317
			1.5 kg	$t_{(4)} = -28.863$, $p<0.001$	0.0331
			5.5 kg	$t_{(4)} = -13.632$, $p<0.001$	0.0324
TSy	Frontal	100	No load	$t_{(4)} = -4.477$, $p=0.011$	0.0338
			1.5 kg	$t_{(4)} = -4.374$, $p=0.012$	0.0331
			5.5 kg	$t_{(4)} = -4.354$, $p=0.012$	0.0332
		120	No load	$t_{(4)} = -5.227$, $p=0.006$	0.0331
			1.5 kg	$t_{(4)} = -5.162$, $p=0.007$	0.0325
			5.5 kg	$t_{(4)} = -5.220$, $p=0.006$	0.0320
	Sagittal	100	No load	$t_{(4)} = -4.529$, $p=0.011$	0.0343
			1.5 kg	$t_{(4)} = -4.659$, $p=0.010$	0.0348
			5.5 kg	$t_{(4)} = -4.542$, $p=0.010$	0.0350
		120	No load	$t_{(4)} = -5.099$, $p=0.007$	0.0327
			1.5 kg	$t_{(4)} = -4.958$, $p=0.008$	0.0337
			5.5 kg	$t_{(4)} = -5.067$, $p=0.007$	0.0335

Discussion

The aim of this investigation was to establish the suitability of the acromion cluster for dynamic movements through determining the reliability of the cluster under different load conditions. Load conditions (no load, 1.5 kg and 5.5 kg) were found to elicit significantly different ($p<0.001$) deltoid muscle activity for movement within both the frontal and sagittal planes. As the muscle activity observed was similar to that associated with seam bowling (Shorter *et al.,* 2010), findings from this study not only assess the reliability of the acromion cluster under different load conditions, through investigating if deltoid muscle contraction affects acromion cluster validity but, also establishes the appropriateness of the acromion cluster for use during cricket bowling.

Whilst variations in marker position were observed between load conditions, findings from this study contradict the conclusions of previous research such as that by van Andel *et al.* (2009) and Brochard *et al.* (2009) who associated deltoid contraction as being the underlying contributor to STA affecting acromion cluster validity at higher angles of elevation. Marker position for movement within the frontal plane between load conditions was observed to have minimal influence at higher levels of elevation. These findings suggest that rather than deltoid muscle activity and therefore muscle contraction affecting acromion cluster validity at higher levels of elevation, it is more likely as a consequence of soft tissue and muscle bulk around the acromion cluster occurring irrespective of muscle activity and external load.

Movement within the frontal plane below 80 ° elevation (AAx, AAy and AIy) and movement within the sagittal plane (AAx, AAy, AAz, AIy (static position 2 only), TSy and TSz) were found to have issues relating to the reliability of the acromion cluster being able to reconstruct marker positions across load conditions. These findings would suggest that caution may need to be taken when using the acromion cluster during dynamic movements such as cricket bowling. It is important to acknowledge however, that changes in marker position between load conditions may not occur in relation to deltoid muscle contraction compromising the acromion cluster, but rather as a consequence of the experimental design. Whilst participants were instructed to execute each movement solely within the plane of interest, results indicate that significant changes in marker position may have occurred more as a consequence of variations within the plane of elevation. Non-significant variations in the plane of elevation were observed at lower angles of elevation during movement within the frontal plane, with significant changes between load conditions occurring above 100 degrees elevation during movement within the sagittal plane. Findings from this investigation are in agreement with de Groot *et al.* (1999) who reported that changes in scapula position occur not as a result of the magnitude of external load, but rather due to changes in the direction the load is applied which in this investigation was quantified through changes in the plane of elevation.

It is important to acknowledge the influence experimental design may have imparted on the statistical significance of findings within this investigation. The sample size of five participants used within this investigation was not dissimilar to previous acromion cluster research incorporating sample sizes ranging from two to thirteen participants (Brochard *et al.*, 2009; Karduna *et al.*, 2001; Meskers *et al.*, 2007; Salvia *et al.*, 2009; van Andel *et al.*, 2009; Warner *et al.*, 2010). Whilst statistical power related to repeated measures ANOVAs was largely acceptable ($1-\beta > 0.800$), power was observed to vary between variables ($1-\beta$ range: = 0.394 to 1.00), which was further compounded by large standard deviations impairing the ability of subsequent post hoc analysis to establish significant differences between load conditions. Similar to other research utilising small sample sizes, shoulder research must acknowledge the short failings of traditional statistical analysis. There is consensus amongst researchers that the validity and reliability of the acromion cluster should be assessed using methods such as ICC (Meskers *et al.*, 2007) and RMSE (Brochard *et al.*, 2009; Karduna *et al.*, 2001; Meskers *et al.*, 2007; Salvia *et al.*, 2009). Whilst such statistical methods are able to discern differences, particularly for small sample sizes, they are unable to differentiate between error and natural variability which would be expected between individuals (Bates, 1996). Statistical findings from this investigation support the need for future research investigating the shoulder, particularly investigations assessing the validity and reliability of methods, to adopt single subject analysis. Such analysis would not only increase statistical power when applied appropriately but would also provide a more appropriate and robust manner to account for influences such as body somatotype and abnormal shoulder function.

Significant differences in marker position for both AIy and TSy coordinates between static calibration positions, suggest that a multiple calibration method that is specific to the movement under investigation may aid in increasing the accuracy of the acromion cluster. Such differences dependent on the static calibration position used (AIy range: 0.0285 to 0.0334 m; TSy range: 0.0320 to 0.0350 m) would impair the accuracy of any kinematic analysis investigating movements incorporating large ranges of shoulder joint motion. Whilst unable to establish the validity of reconstructed scapula landmarks dependent on the static calibration position used, findings from this investigation would suggest that movements incorporating large ranges of shoulder motion may benefit from the application of a multiple calibration procedure to increase acromion cluster accuracy.

The multiple calibration method initially proposed by Cappello, Cappozzo, La Palombara, Lucchetti & Leardini (1997) in relation to lower limb limb kinematics, has yet to be applied to the upper limb but may be a feasible approach to improve acromion cluster accuracy for specific movement patterns such as cricket bowling. Mean differences observed in this study between static calibration positions, are in agreement with Matsui *et al.* (2006), who reported translatory discrepancies between an acromion marker and the underlying bony landmark of up to 0.039 ± 0.011m during full elevation. Whilst the application of the CAST protocol is theoretically sound for lower limb kinematics due to the constant relationship between the cluster and segment of interest, findings from this investigation and Matsui *et al.* (2006) indicate that this method is not directly applicable to reconstruct scapula motion. Unlike other body segments, the scapula translates during movement of the arm resulting in a variable relationship between the acromion cluster and scapula that is influenced by STA impairing the congruence between the segments. Therefore, errors associated with the validity of the acromion cluster by previous researchers (Brochard *et al.*, 2009; Karduna *et al.*, 2001; van Andel *et al.*, 2009), largely occur as a consequence of the application of the CAST protocol, as the initial static relationship is a poor reflection of the relationship between the acromion cluster and scapula at higher angles of elevation. Future research needs to investigate both the validity and reliability of multiple calibration method for the acromion cluster which is designed specific to the movement under investigation.

Conclusion

The aim of this chapter was to investigate the reliability of the acromion cluster under dynamic load conditions during movement within both the frontal and sagittal planes. Whilst largely non-significant variations were observed in marker position between load conditions, findings from this study aid in establishing issues pertaining to the reliability of the acromion cluster at higher levels of elevation are not due to deltoid muscle activity, contradicting the conclusions of van Andel *et al.* (2009) and Brochard *et al.* (2009). Findings from this investigation suggest that whilst caution needs to be taken, the acromion cluster is a suitable method for use during cricket bowling.

Significant differences in marker position for both AIy and TSy coordinates between static calibration positions was observed at 100 and 120 ° elevation for both movement patterns (AIy range: 0.0285 to 0.0334 m; TSy range: 0.0320 to 0.0350 m). This finding suggests that errors previously associated with the validity of the acromion cluster by researchers (Brochard *et al.*, 2009; Karduna *et al.*, 2001; van Andel *et al.*, 2009), largely occur as a consequence of the application of the CAST protocol, as the choice of static calibration position directly affects the position of the reconstructed scapula anatomical landmarks. As the application of a single calibration position, traditionally defined by researchers in relation to the anatomical position is a poor reflection of the position and orientation of the scapula at higher levels of elevation, findings from this investigation advocate the future application of multiple static calibrations. A multiple calibration method when used in conjunction with the CAST protocol, may aid in addressing the previously reported issues pertaining to acromion cluster reliability. Such an approach may enable researchers to progress from scapula kinematics under controlled, static conditions to investigating complex, multi-planar movements such as cricket bowling.

Chapter 5

Multiple Calibration Procedure for the Acromion Cluster

Introduction

Recording of scapula position and orientation is integral to accurate reconstruction of shoulder movement (Lempereur *et al.*, 2010a). Emphasis by researchers to date (Brochard *et al.*, 2009; Karduna *et al.*, 2001; Meskers *et al.*, 2007; Salvia *et al.*, 2009; van Andel *et al.*, 2009; Warner *et al.*, 2010) to investigate the validity and reliability of the acromion cluster within controlled, clinically settings limits the direct application of this method to dynamic movements such as cricket bowling. Findings from chapter 4 establish that issues pertaining to use of the acromion cluster with increasing arm elevation occur as a consequence of the application of the calibrated anatomical systems technique (CAST) protocol failing to account for the non constant relationship between the cluster and scapula. Whilst the acromion cluster, through minimising soft tissue artefact (STA) is currently the most appropriate non-invasive method to reconstruct scapula motion dynamically, further research is required to investigate methods to improve the validity of this method that is specific to the movement of interest, such as cricket bowling.

Literature review

Error associated with the acromion cluster establishing scapula orientation

Methods to enable the accurate reconstruction of scapula position and orientation have gained increasing interest within shoulder biomechanics research due to the inherent difficulties that face non-invasive techniques (Cutti & Veeger, 2009). Researchers have been evaluating the suitability of an acromion cluster in conjunction with the CAST protocol through comparing this method to current gold and silver standards of manual palpation and a scapula locator respectively (Table 5.1). The first study to propose and evaluate an acromion cluster was by Karduna *et al.* (2001) who compared an acromion sensor to an affixed bone pin sensor, with nine participants (eight free from shoulder pathology and one with a prior history of subacromial impingement syndrome) undertaking various movement patterns such as sagittal plane elevation and horizontal abduction. Results from this investigation, due to the use of bone pins are open to conjecture due to changes invasive pins may themselves impart on STA during shoulder movement. Karduna *et al.* (2001) established that in general scapula orientation derived from an acromion cluster was comparable to using bone pin sensors with an error of typically less than 10 °, however, that caution needed to be taken with movements over 120 degrees elevation.

Table 5.1 Research establishing acromion cluster error (RMSE) associated with scapula orientation

Study	Method	Angle Sequence	Movement	Retraction/ Protraction (°)	Anterior/ Posterior tilt (°)	Medial/ Lateral rotation (°)
Brochard *et al.* (2009)	Acromion cluster vs. palpation	YXZ	Sagittal plane elevation	6.15	1.45	4.44
Karduna *et al.* (2001)	Acromion sensor vs. Bone pin sensor	ZYX	Scapular plane elevation	9.40	6.60	6.30
			Sagittal plane elevation	11.40	8.60	5.90
			Horizontal abduction	10.00	7.30	4.80
			External rotation	6.20	3.70	4.40
Meskers *et al.* (2007)	Acromion sensor vs. scapula locator	YXZ	Pooled data from both elevation in the frontal and sagittal planes	3.88	1.00	6.47
van Andel *et al.* (2009)	Acromion cluster vs. scapula locator	YXZ	Frontal plane elevation at 120°	8.00	8.40	4.10
			Sagittal plane elevation at 120°	7.70	7.30	3.90
Warner *et al.* (2010)	Acromion cluster vs. scapula locator	Not detailed	Sagittal plane elevation (+ phase) at 122.5 ± 9.43°	-1.60 ±5.70	3.90 ± 8.10	2.20 ±5.00
			Sagittal plane elevation (- phase) 119.2 ± 12.2°	-1.60 ± 5.40	5.70 ± 8.00	1.40 ± 7.00

The susceptibility of the acromion cluster in imparting errors on scapula orientation with increasing elevation has been identified in subsequent research. Meskers *et al.*

(2007) assessed scapula orientation of eight participants using both an acromion sensor and scapula locator, referred to as a tripod. Findings from this study indicated poor repeatability of angles when the acromion sensor was repositioned (RMSE = 5 °) and a general underestimation of scapula rotation of 6.5 °, which could be lowered for the group using a correction factor derived from linear regression.

van Andel *et al.* (2009) assessed the validity of an acromion cluster compared to simultaneous scapula locator recordings from thirteen participants free from shoulder pathology. Only a significant difference was reported with external rotation during abduction (no values published), with larger variance in relation to the standard deviation observed with the acromion cluster. In general the acromion cluster was observed to underestimate scapula motion (maximum mean difference associated with humeral forward flexion and abduction of 6.8 ° or lower). The authors concluded that when using an acromion cluster both its placement and the plane of motion to be investigated need to be considered, advising the cluster should not be used for movements associated with humeral elevation greater than 100 ° (van Andel *et al.*, 2009).

Brochard *et al.* (2009) investigated the difference in surface scapula anatomical markers to the acromion cluster, using palpation as the gold standard to establish scapula position. In agreement with van Andel *et al.* (2009), the acromion cluster was associated with establishing scapula tilt well (RMSE= 1.45 °) but in contrast found the cluster underestimated upward/downward rotation (RMSE = 6.15 °) and associated the cluster with less error in relation to medial/lateral rotation. Brochard *et al.* (2009) established that whilst an acromion cluster can aid in minimising STA in comparison to surface markers, differences still exist between acromion cluster and palpation methods.

Warner *et al.* (2010) investigated the use of an acromion cluster for sagittal plane arm elevation during both raising (+ phase) and lowering (- phase) phases comparing scapulothoracic angles to those derived from a scapula locator in eleven participants. Warner *et al.* (2010) reported no significant differences ($p < 0.05$) for both internal and upward rotation, however a significant difference ($p = 0.03$, maximum mean difference: 5.7 ± 8.0 °) was established for posterior tilt between methods.

Methods to aid in minimising error associated with an acromion cluster establishing scapula orientation

To date there has been a reliance by researchers to evaluate the suitability of an acromion cluster based on its ability to establish scapulothoracic angles, with authors such as Karduna *et al.* (2001) and Meskers *et al.* (2007), trying to improve acromion cluster accuracy through applying correction factors. Karduna *et al.* (2001) applied a correction factor whereby upward rotation errors were modelled as a linear function based on the difference in position between the acromion sensor and the bone based sensor. This method assumed that the source of error was due to skin motion artefact caused by motion of the scapula (Karduna *et al.*, 2001). The application of the resultant correction factor for the eight healthy individuals was found to lower RMSE from 6.0 ° to 2.0 ° but applying the same correction factor to the unhealthy individual was found to increase RMSE to 5.7 °. Results from this study highlight that correction methods may be best applied on an individual basis regardless of the presence or absence of pathology.

Meskers *et al.* (2007) established similar results when trying to correct acromion sensor derived scapulothoracic angles using group pooled data. Stepwise linear regression was undertaken using variables including acromion sensor orientation, humeral elevation angle, plane of elevation and axial rotation. Findings of Meskers *et al.* (2007) once again established that whilst the application of group data could be used to lower RMSE, on an individual basis it was not possible to lower RMSE by means of a single method. The use of some of the variables chosen by Meskers *et al.* (2007) are questionable as Karduna *et al.* (2001) advocated the use of scapula specific variables only. Karduna *et al.* (2001) argued that the inclusion of humeral variables whilst decreasing error would result in a model assuming scapula motion is dependent on humerus position whilst not addressing underlying STA. Findings from both investigations would seemingly indicate that methods aiming to address errors established between skin and bone based methods should be undertaken on an individual basis, however this has yet to be investigated within the published literature.

Scapulothoracic angles in accordance with ISB guidelines (Wu *et al.*, 2005) are expressed using a YXZ Euler sequence between the scapula and thorax anatomical coordinate systems. As the scapula anatomical coordinate system is dependent on the accurate location of AA, AI and TS anatomical landmarks (Figure 5.1), errors in establishing the position of one of these landmarks would result errors affecting each of the scapulothoracic angles. Matsui *et al.* (2006) highlighted different translatory errors occur between each of the scapula anatomical landmarks of interest ranging from 0.0147 ± 0.0111 m for the AA with the arm positioned behind the back to up to 0.0868 ± 0.0281 m for TS with arm elevation when using surface markers, imparting differing errors onto each axis of the anatomical coordinate system. Therefore, the current application of correction methods to individual scapulothoracic angles fails to adequately acknowledge the differing magnitude of error affecting the reconstruction of each scapula landmark; hindering the ability to both accurately evaluate the ability of the acromion cluster to establish scapula orientation and, to identify underlying contributors to error.

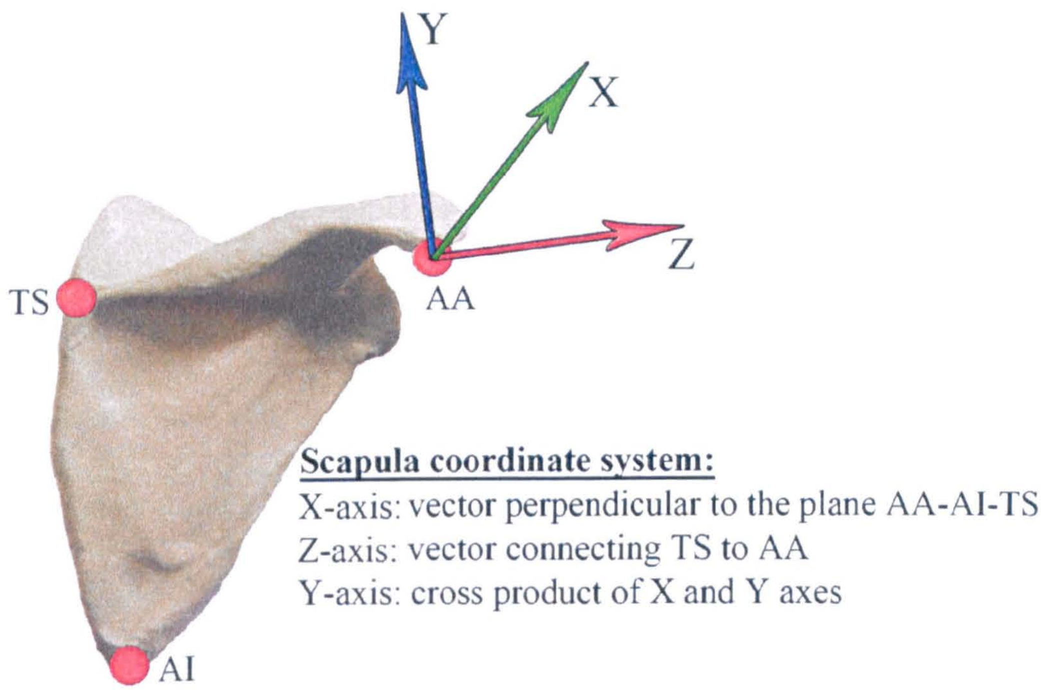


Figure 5.1 Scapula coordinate system using anatomical landmarks AA, AI and TS

Error associated with the acromion cluster establishing scapula position

The ability of an acromion cluster to establish scapula position has to date largely only been inferred based on scapulothoracic angles. Whilst the work of Karduna *et al.* (2001) focused on scapula orientation, Matsui *et al.* (2006) estimated from published findings that the error in translation of an acromion marker could be estimated at 0.015 m, which was less than Matsui *et al.* (2006) established using MRI for a surface acromion marker during full elevation of 0.0523 ± 0.0143 m. The only other study investigating the error associated with an acromion cluster in reconstructing scapula position was by Salvia *et al.* (2009). Salvia *et al.* (2009) investigated the use of both a calibrated pointer and a new method - A-Palp, a calibrated device attached to the finger of the palpator to aid accuracy through increasing tactile feedback, reporting inter-operator error in using a calibrated pointer ranging from 0.0029 ± 0.0006 m for AA to 0.0051 ± 0.0024 m for TS. Whilst both participants in this study were instructed to elevate their arm within the sagittal plane, during the movement there was no protocol incorporated to accurately establish the position of the scapula at any given time. Therefore, results from this investigation, rather than evaluating the use of an acromion cluster, present a convoluted manner to establish the palpation error associated with both a calibrated pointer and the A-Palp method in identifying scapula landmarks with the participant in the anatomical position.

Influence of STA on the application of the CAST method

The general underestimation of the acromion cluster, combined with increasing error associated with humeral elevation has been attributed to STA affecting the congruence between the acromion and cluster (Brochard *et al.*, 2009; Meskers *et al.*, 2007; van Andel *et al.*, 2009). As discussed in chapter 4, whilst STA affects the acromion cluster through soft tissue and muscle bulk affecting cluster congruence combined with translatory differences between skin and bone; to date there has been no attempt within published literature to both acknowledge and address the influence this imparts on the CAST method (Cappozzo *et al.*, 1995) in regards to the scapula.

The underlying assumptions of the CAST protocol is that first, there is a constant relationship between the anatomical landmarks defined statically in relation to the cluster, and second, that during the dynamic movement of interest this continues to remain true. Whilst researchers have established that the CAST method and variations of the method is suitable for the lower limb in reconstructing anatomical landmarks and decreasing the influence of STA (Cappozzo, Cappello, Della Croce & Pensalfini, 1997; Della Croce, Cappozzo & Kerrigan, 1999; Donati, Camomilla, Vannozzi & Cappozzo, 2007; Lu & O'connor, 1999); the unique structure and translatory movement of the scapula in relation to overlying soft tissue means the direct application of the CAST method is prone to error. An indication of the influence this may impart on resultant scapula position was shown in chapter 4, where different initial static calibration poses resulted in significant differences of between 0.025 to 0.035 m on subsequent anatomical landmark coordinates.

Cappello *et al.* (1997) proposed a method for the lower limb to further decrease the influence of STA through incorporating a multiple calibration procedure. This method involves defining anatomical landmarks at differing joint positions, to enable a combined configuration for estimating anatomical landmark position through the use of a least squares method based on singular value decomposition (Arun, Huang & Blostein, 1987). Cappello *et al.* (1997) validated this method using a cycling test incorporating static calibration positions at: 1. maximum hip and knee extension, and 2. maximum hip and knee flexion; reporting that the multiple calibration procedure appreciatively decreased RMSE associated with the greater trochanter from over 0.015 m to less than 0.010 m. This method was subsequently been modified by Cappello, Stagni, Fantozzi & Leardini (2005) to further decrease associated position and orientation RMSE using knee angle as a weighting factor, and has been applied to the scapula by Brochard, Lempereur and Remy-Neris (2011) using a system the authors referred to as DCAST. Brochard *et al.* (2011) through using a double calibration procedure defined by two static positions captured at the end ranges of elevation for movement within both the frontal and sagittal planes reported subsequent scapula reconstruction using angle of elevation as a weighting factor, could lower RMSE from 6 to 9.19 ° with a single calibration to 2.19 to 4.48 ° with a double calibration procedure. The findings of Brochard *et al.* (2011) support the use of multiple calibration methods in conjunction with the acromion cluster for reconstructing scapula landmarks, however as this method is only appropriate for single plane movements, the direct applicability of the DCAST system for complex multi-planar movements such as cricket bowling is inappropriate.

Study aim

The aim of this investigation was to develop and evaluate the suitability of an acromion cluster method for use within cricket bowling. As research to date assessing the acromion cluster has been typified by investigating shoulder movements in isolation, the direct application of these findings to cricket bowling is difficult. As established in chapter 3, the bowling motion is a multi-planar motion associated with humeral elevation of over 90 °, a position associated with increased error affecting the acromion cluster. Through utilising the technique of Cappello *et al.* (1997), this investigation aimed to validate a cricket bowling specific, multiple calibration procedure (mCAST) to assist in decreasing RMSE associated when an acromion cluster is used in conjunction with the CAST technique. It was hypothesised that the mCAST method would not only be associated with lower RMSE than the CAST technique, but would also be comparable to the RMSE associated with palpation error throughout a range of static positions observed during the cricket bowling movement.

Method

Participants

After gaining university ethical approval, six male bowlers from Hampshire County Club, with no recent history of shoulder pathology were recruited. The mean ± SD age, height and mass of the participants were 17.50 ± 1.52 years, 1.83 ± 0.03 m and 74.83 ± 4.49 kg. Following an explanation of the experimental aims and procedures all participants provided informed consent. For bowlers under 18 years of age consent was obtained from club officials on behalf of the bowler's guardians.

Equipment

Accelerometer system:

The application of the mCAST method requires the experimenter to accurately position the shoulder at different positions reflective of the movement of interest whilst the palpation of each scapula anatomical landmark is recorded by the motion analysis system. To provide the experimenter with the ability to accurately position the shoulder independent to the motion analysis system, a standalone accelerometer system was devised enabling real-time feedback on the position of the shoulder. To investigate the application of the mCAST method for cricket bowling, five shoulder positions reflective of the range of humerothoracic motion observed during the bowling delivery reported within chapter 3, were achieved using two, tri-axial accelerometers (ADXL335, Analog Devices, Norwood, USA) connected to a LilyPad Arduino 328 mainboard (Atmel, San Jose, USA) loaded with a custom program, CSBT BentAcc (Shorter, 2010, unpublished program) written using Arduino 0018 open source software at 50 Hz (Appendix H). As tri-axial accelerometers measure acceleration along three orthogonal axes, the orientation of the accelerometer can be defined in relation to the earth's gravity to produce pitch, roll and theta angles that bear no direct relationship to anatomical angles. Pitch refers to the angle between the horizontal and accelerometer x-axis, roll refers to the angle between the horizontal and accelerometer y axis and theta refers to the angle of the accelerometer z axis relative to gravity. To define the position of the humerus relative to the thorax, resultant pitch, roll and theta angles between the accelerometers were calculated. Five static positions were chosen to be reflective of the multi-planar shoulder position during the bowling delivery and were converted from anatomical (humerothoracic) angles during a calibration procedure conducted prior to data collection into pitch, roll and theta angles (Table 5.2). Each static position was reconstructed using a mechanical limb, with both accelerometers and retroflective markers positioned to replicate the thorax and humerus anatomical coordinate systems (Figure 5.2). The shoulder kinematic derived anatomical position of the mechanical limb was then established at 50 Hz using three Basler cameras (Basler A602fc-2, Germany) synchronised with a MX Ultranet control unit (Vicon, Oxford, UK) using a YXY Euler sequence, with simultaneous data collection of the accelerometer output recorded via CSBT Bent (Shorter, 2010, unpublished program) for one second.

Table 5.2 Bowling shoulder angular positions (anatomical and accelerometer based)

Position	Plane of elevation (°)	Angle of elevation (°)	Axial rotation (°)	Pitch (°)	Roll (°)	Theta (°)
A	-5	57	-45	-39	-58	-34
B	-29	34	-12	-12	-33	-30
C	-27	85	15	16	-81	-72
D	-3	99	-30	-29	-98	-57
E	-15	42	-51	-35	-43	-22

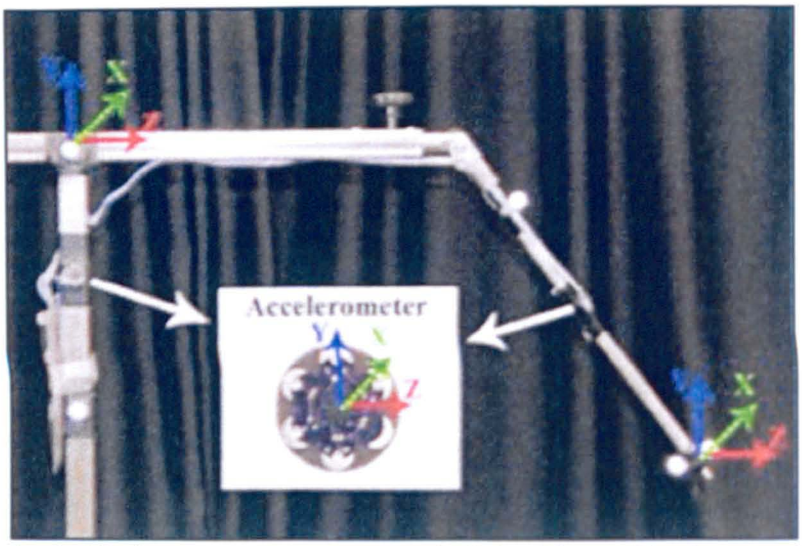


Figure 5.2 Mechanical limb setup to convert anatomical shoulder position into accelerometer pitch, roll and theta angles

During subsequent data collection, placement of each accelerometer was standardised between participants with the thorax accelerometer positioned on C7 and the humerus accelerometer positioned 15 cm inferior to the midpoint between the AA and AC anatomical landmarks; a position chosen due to minimal interference from muscle and STA. To monitor shoulder position during data collection, accelerometer output was transmitted wirelessly using two XBee 1mW Chip Antennas (Digi International Inc., Minnetonka, USA) and viewed within CSBT Bent (Shorter, 2010, unpublished program) (Appendix H), a custom LabVIEW™ program (National Instruments, Austin, USA) which could both graphically display and save the data.

Kinematic system:

Scapula kinematics of each participant were recorded at 50 Hz using three Basler cameras (Basler A602fc-2, Germany) synchronised with a MX Ultranet control unit (Vicon, Oxford, UK). A 16-point calibration frame (Peak Performance Technologies Inc., Colorado, USA) was positioned in the field of view to provide a calibrated volume of 1.26 m × 1.08 m × 0.90 m with a residual calibration error of 0.0027 m. To establish scapula position, each scapula anatomical landmark (AA, AI and TS) were palpated in accordance with ISB guidelines (Wu *et al.*, 2005) by an experienced physiotherapist using a calibrated pointer. Palpation was chosen to establish scapula position due to being the current gold standard for non-invasive methods (de Groot, 1997). To reconstruct scapula position in accordance with the acromion cluster and CAST protocol (Cappozzo *et al.*, 1995), an acromion cluster, composed of three orthogonal retroflective markers was positioned on the acromion plateau, medial to the origin of the posterior fibres of the deltoid.

Testing procedure

Following habituation of the testing environment, participants were requested to initially assume the anatomical position to enable the accelerometers to be offset (for further programming details refer to Appendix H). Each of the five static positions were recorded with the participant standing due to the influence body position may impart on both scapula position and movement. Participants were placed in the position of interest by the experimenter; where, if they were unable to match the angular position in each plane, participants were requested to move to the associated passive end range of movement. For each static position, scapula anatomical landmarks were palpated three times in order by the physiotherapist (Figure 5.3). Participants were requested to closely maintain shoulder position throughout palpation, with shoulder position monitored by the participant using the graphical output as a visual aid, whilst being simultaneously recorded through CSBT Bent (Shorter, 2010, unpublished program) for later referral.

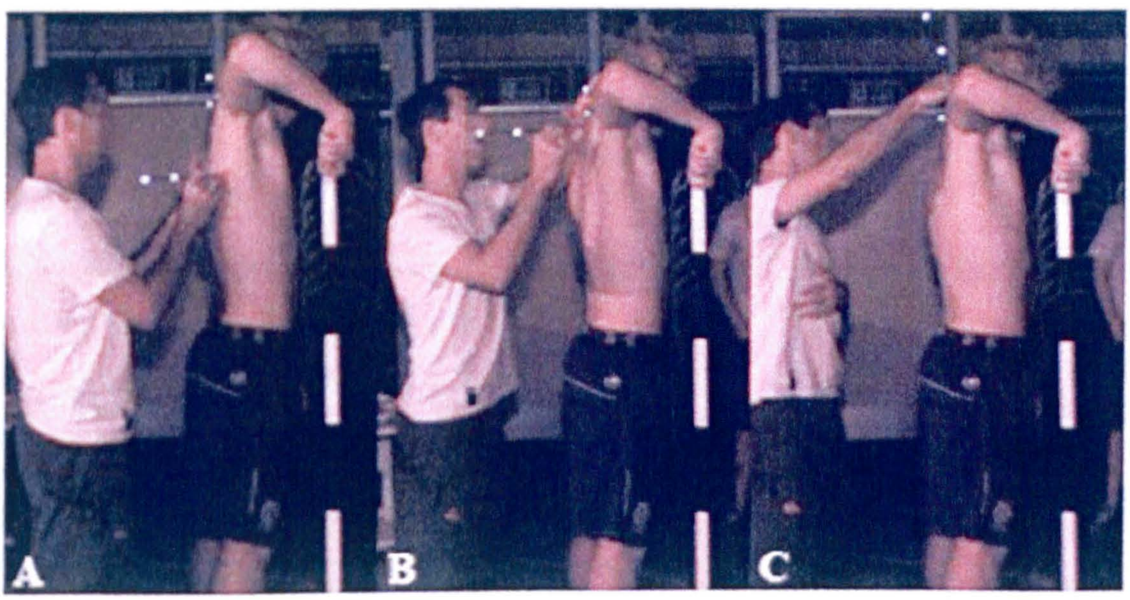


Figure 5.3 Palpation of (a) AI, (b) TS and (c) AA anatomical landmarks using a calibrated pointer

Data processing

Whilst accelerometer output highlighted that five participants were able to adequately maintain each static position during scapula landmark palpation (less than 5 ° variation in shoulder position), one participant was excluded from further analysis due to an inability to maintain each static position (greater than 10 ° variation in shoulder position).

All digitising was conducted within Vicon Motus 9.2 software (Vicon, Los Angeles, USA) by the experimenter (average digitisation RMSE error: 0.0026 m) with all subsequent processing and analysis performed within CSBT mCASTanalyser (Shorter, 2010, unpublished program) (Figure 5.4)(Appendix I).

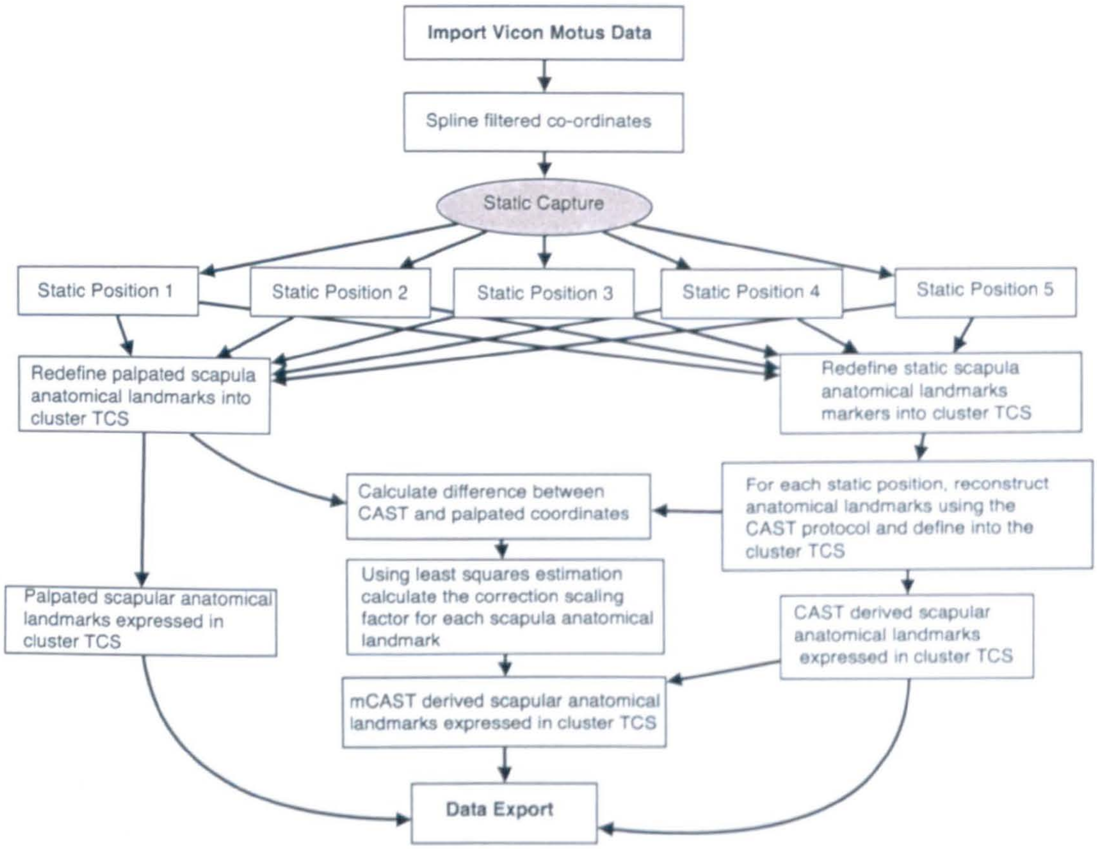


Figure 5.4 CSBT mCASTanalyser (Shorter, 2010, unpublished program) explanatory program flow diagram

For the three scapula anatomical landmarks during each static position, both the calibrated pointer and acromion cluster were digitised for one frame of interest to provide raw three-dimensional spatial co-ordinates for each marker, as the low recording sampling frequency and use of filters could impart error if multiple frames were analysed. Each scapula anatomical landmark (${}_{G}P^{AL}$) was reconstructed from the calibrated pointer (${}_{G}P^{p1}$ and ${}_{G}P^{p2}$) using the formula:

$${}_{G}P^{AL}(t) = {}_{G}P^{P1} + 2.47({}_{G}P^{P1} - {}_{G}P^{P2})$$

Equation 5.1

The cluster local coordinate system (cLCS) was calculated using the three orthogonal retroflective acromion cluster markers (${}_{G}P^{C1}$, ${}_{G}P^{C2}$ and ${}_{G}P^{C3}$) with axes defined as:

$$cLCS\ origin = {}_{G}P^{C2}$$
$$y-axis = \frac{({}_{G}p^{C1} - {}_{G}p^{C2})}{\left[{}_{G}p^{C1} - {}_{G}p^{C2}\right]}$$
$$z-axis = \frac{({}_{G}p^{C1} - {}_{G}p^{C2})}{\left[{}_{G}p^{C1} - {}_{G}p^{C2}\right]} \times \frac{({}_{G}p^{C3} - {}_{G}p^{C2})}{\left[{}_{G}p^{C3} - {}_{G}p^{C2}\right]}$$
$$x-axis = y-axis \times z-axis$$

Equation 5.2

Each palpated anatomical landmark was then redefined into the cLCS (Equation 5.3) to enable comparison between palpation and cluster methods (CAST and mCAST), whist also minimising the influence changes of body orientation between static positions would impart on marker position if expressed in relation to the global coordinate system.

$$_{cLCS}P^{AL} = {}_{cLCS}^{G}T^{-1}\,{}_{G}P^{AL}$$

Equation 5.3

To investigate the influence of static position on reconstructed anatomical landmarks, the first palpation of the three scapula landmarks in each of the five static positions were individually used to reconstruct scapula landmarks (P^{Re}) during the other positions in accordance with the CAST protocol outlined by Cappozzo *et al.* (1995) (Equation 5.4). In this manner, the static position showing the smallest overall difference compared to the associated manually palpated scapula landmarks (P^{AL}) was used to calculate scapula landmarks reconstructed through both the CAST protocol and the mCAST method, during subsequent palpations in each of the five static positions.

$$_{cLCS}P^{Re}(st) = {}^{cLCS}_{G}T(st)^{-1}\,{}_{G}P^{Re}(st)$$
$$_{G}P^{Re}(t) = {}^{cLCS}_{G}T(t)\,{}_{cLCS}P^{Re}(st)$$

Equation 5.4

Differences in palpated landmarks and those reconstructed from an acromion cluster using the CAST protocol have been reported (Brochard *et al.*, 2009). This difference (d), which may occur as a result of factors such as STA, human error and difficulty in accurately establishing true scapula position, can be described in the cLCS using the following equation, where d is a vector:

$$d = {}_{cLCS}P^{AL} - {}_{cLCS}P^{Re}$$

Equation 5.5

As the magnitude of d varies dependent on the shoulder position on an individual basis, the suitability of methods such as linear models (Karduna *et al.*, 2001; Meskers *et al.*, 2007), particularly linear regression as used to correct scapulothoracic angles by Meskers *et al.* (2007) are questionable as the independent relationship between each scapula landmark and the acromion cluster is not fully acknowledged. Therefore, the mCAST method adapts the multiple calibration method proposed by Cappello *et al.* (1997) utilising a least squares approach whereby the magnitude of d for each scapula landmark (as defined by Equation 5.5) can be established independently in relation to the orientation of the acromion cluster (${}^{cLCS}_{G}R$) at any given time:

$$d = {}^{cLCS}_{G}R\,{}_{cLCS}c$$ **Equation 5.6**

Incorporating Equation 5.5, Equation 5.6 can be expressed as:

$${}^{cLCS}_{G}R\,{}_{cLCS}c = {}_{cLCS}P^{AL} - {}_{cLCS}P^{Re}$$

Equation 5.7

Therefore using each of the five static positions, the following can be minimised to provide a correction factor (${}_{cLCS}c$):

$${}_{cLCS}c = ({}^{cLCS}_{G}R^{T}\,{}^{cLCS}_{G}R)^{-1}\,{}^{cLCS}_{G}R^{T}\left[{}_{cLCS}P^{AL} - {}_{cLCS}P^{Re}\right]$$

Equation 5.8

Whereby the mCAST method subsequently calculates each scapula landmark as:

$${}_{G}P^{Re}(t) = {}^{cLCS}_{G}T(t)\,{}_{cLCS}P^{Re}(st) + {}^{cLCS}_{G}R(t)\,{}_{cLCS}c$$

Equation 5.9

For the purpose of this investigation, each scapula landmark utilising the mCAST method was redefined in relation to the cLCS, in keeping with both the palpation and CAST methods.

Data analysis

Data analysis was conducted within Microsoft Excel (Microsoft Inc., Richmond, USA). Determination of the most suitable static position to define each scapula anatomical landmark for use with both the CAST and mCAST methods was undertaken through calculating RMSE. RMSE was defined in regard to the resultant difference when applied to all five static positions, between the known palpated landmarks and reconstructed landmarks using the CAST method, where the initial palpation of scapula landmarks at each of the five static positions was used.

To provide an indication of the systematic error associated with palpation, for each participant, resultant RMSE for each scapula anatomical landmark at each of the five static positions was calculated within the cLCS in respect to the 2nd and 3rd palpations in relation to the initial palpation. In this manner, the influence of STA differences affecting scapula landmarks and the acromion cluster between static positions through both skin to bone displacement discrepancies and soft tissue and muscle mass were minimised.

For each scapula anatomical landmark, quantification of the difference between palpation and the CAST and mCAST methods in establishing scapula position was defined in relation to RMSE. To determine the most suitable cluster method to apply to reconstruct scapula landmarks during cricket bowling, differences were analysed qualitatively both within and between participants due to a lack of statistical power to conduct quantitative statistical analysis.

Results and Discussion

Choice of static calibration position

Similar to the preliminary findings of chapter 4 relating to the choice of static calibration position for use within the CAST method, the selection of the initial static position was found to influence resultant RMSE for all scapula landmarks (Table 5.3). Of the three anatomical landmarks, AA was found to exhibit less sensitivity, with the initial position, A, displaying the smallest RMSE of 0.023 ± 0.006 m when applied to the other positions. The small RMSE associated with AA is in agreement with previous research by Matsui *et al.* (2006) who established that due to the landmark's proximity to the AC joint, this anatomical landmarks shows less sensitivity to shoulder position and STA making it appropriate for use with non-invasive methods. In contrast, RMSE associated with CAST technique reconstructing both the AI and TS was found to be dependent on joint position with the largest RMSE for AI (0.052 ± 0.010 m) and TS (0.051 ± 0.010 m) associated with the third static position C; where the humerus was both elevated and internally rotated in relation to the thorax. Such positioning of the arm upwardly rotates, anteriorly tilts and externally rotates the scapula, a position which researchers such as Karduna *et al.* (2001) and van Andel *et al.* (2009) associated with the acromion cluster overestimating scapula orientation due to poor congruence between the acromion and cluster. Therefore, the use of such a static position would be a poor reflection of scapula position as reconstructed using the CAST method if the movement of interest is one which places the the shoulder in other positions such as at lower angles of elevation. Based on these findings, the use of the first static position, A (plane of elevation: -5 °, angle of elevation: 57 ° and axial rotation: -45 °), was deemed most appropriate for the calibration of scapula anatomical landmarks for use with both CAST and mCAST methods when related to cricket bowling as it was associated with the smallest RMSE for both AA (0.023 ± 0.006 m) and AI (0.037 ± 0.015 m), and was only 0.001 m worse than the best position for TS (0.034 ± 0.012 m).

Table 5.3 Resultant RMSE associated with the definition of scapula landmarks for the CAST method

Static Position	Resultant RMSE (m)		
	AA	AI	TS
A	0.023 ±0.006*	0.037 ±0.015*	0.034 ±0.012
B	0.029 ±0.005	0.046 ±0.017	0.041 ±0.011
C	0.026 ±0.005	0.052 ±0.010	0.051 ±0.010
D	0.027 ±0.006	0.044 ±0.014	0.033 ±0.008*
E	0.024 ±0.004	0.041 ±0.016	0.035 ±0.007

* denotes smallest RMSE of all five static positions

Systematic error inherent with palpation

Table 5.4 provides an indication of the systematic error associated with palpation. It has to be acknowledged that whilst arm movement between palpations was minimised and found to be less than 5 °; this may have contributed to some of the variance observed. RMSE associated with AA was found to be fairly consistent across positions, with position A demonstrating the lowest resultant RMSE for both all positions and anatomical landmarks of 0.013 ± 0.003 m. Greater variation was observed for both AI and TS reflective of the difficulty of non-invasive methods to establish the position of the scapula. Greater RMSE associated with both AI and TS, particularly for static position C (AI: 0.043 ± 0.031 m, TS: 0.033 ± 0.015 m), can be attributed to the large translatorary movement, combined with both soft tissue and muscle bulk overlying these anatomical landmarks. This is supported by larger RMSE for these scapula landmarks being associated with both the X and Z coordinates; relating to anterior/ posterior and medial/lateral dimensions which would be associated with increased sensitivity to changes in scapula depth owing to both inconstancies in soft tissue depth and calibrated pointer depth varying with shoulder position.

Table 5.4 Scapula landmark palpation mean ± SD RMSE (m) at each static position

Scapula Landmark	Static Position	Three-dimensional spatial coordinate palpation RMSE (m)			
		X	Y	Z	R
AA	A	0.006 ± 0.001	0.004 ± 0.002	0.010 ± 0.005	0.013 ± 0.003
	B	0.006 ± 0.002	0.006 ± 0.002	0.017 ± 0.010	0.020 ± 0.009
	C	0.004 ± 0.003	0.007 ± 0.006	0.017 ± 0.010	0.020 ± 0.010
	D	0.010 ± 0.003	0.006 ± 0.003	0.013 ± 0.003	0.018 ± 0.002
	E	0.007 ± 0.002	0.008 ± 0.008	0.024 ± 0.016	0.027 ± 0.016
	TOTAL	**0.007 ± 0.004**	**0.006 ± 0.005**	**0.017 ± 0.011**	**0.020 ± 0.011**
AI	A	0.010 ± 0.009	0.006 ± 0.003	0.010 ± 0.004	0.017 ± 0.006
	B	0.009 ± 0.003	0.008 ± 0.002	0.013 ± 0.012	0.019 ± 0.010
	C	0.021 ± 0.016	0.024 ± 0.026	0.025 ± 0.016	0.043 ± 0.031
	D	0.012 ± 0.007	0.007 ± 0.003	0.011 ± 0.005	0.019 ± 0.006
	E	0.010 ± 0.003	0.007 ± 0.007	0.015 ± 0.007	0.020 ± 0.007
	TOTAL	**0.013 ± 0.010**	**0.011 ± 0.014**	**0.015 ± 0.012**	**0.025 ± 0.019**
TS	A	0.009 ± 0.004	0.005 ± 0.002	0.011 ± 0.002	0.015 ± 0.003
	B	0.012 ± 0.007	0.006 ± 0.002	0.016 ± 0.010	0.023 ± 0.008
	C	0.011 ± 0.008	0.012 ± 0.007	0.026 ± 0.016	0.033 ± 0.015
	D	0.006 ± 0.003	0.010 ± 0.003	0.014 ± 0.009	0.019 ± 0.008
	E	0.008 ± 0.003	0.007 ± 0.005	0.017 ± 0.014	0.022 ± 0.012
	TOTAL	**0.010 ± 0.005**	**0.008 ± 0.005**	**0.018 ± 0.013**	**0.023 ± 0.012**

The magnitude of RMSE associated with palpation in this investigation was larger than expected given the use of a sole, experienced palpator and the similar body somatotype of bowlers investigated. In regards to the accuracy of palpation for use of determining anatomical landmarks, results from this research are comparable to those reported by Della Croce *et al.* (1999) for anatomical landmarks of the pelvis and lower limb of up to 0.0248 m. In relation to previous scapula research such as that by Salvia *et al.* (2009) and de Groot (1997), palpation errors of less than 3 ° in relation to its contribution to scapula orientation have been reported. The direct comparison of findings from the work of de Groot (1997) to this investigation are questionable as de Groot (1997) applied rigid body morphology into their research protocol that would have aided in minimising palpation error. de Groot (1997) did however acknowledge that there are several sources of variance such as palpation error, motoric noise and inter-subject variability which affect the validity and reliability of palpation as a means to establish both scapula position and orientation. Whilst researchers currently use methods such as scapula locators and palpation to determine the suitability of alternative methods, there has to be an acknowledgement that current gold standard methods such as palpation are both subjective in nature and affected by systematic errors which may skew the evaluation of the suitability of other methods to determine scapula kinematics.

Evaluation of CAST and mCAST methods

Group RMSE associated with the CAST and mCAST methods are depicted in Table 5.5. Similar to palpation, smaller resultant RMSE was found to be associated with AA (CAST: 0.023 ± 0.006 m, mCAST: 0.023 ± 0.005 m), compared to both AI (CAST: 0.037 ± 0.015 m, mCAST: 0.032 ± 0.006 m) and TS landmarks (CAST: 0.034 ± 0.012 m, mCAST: 0.031 ± 0.004 m). This is in agreement with Matsui *et al.* (2006) who established that anatomical landmarks further away from the AC joint are more difficult to reconstruct using non-invasive methods due to the influence of STA such as through skin to bone translatory differences. When compared to the error associated with palpation, the magnitude of RMSE observed for both acromion cluster based methods within this investigation is acceptable. For AA, both CAST and mCAST methods differed by 0.003 m when compared to palpation (0.020 ± 0.011 m), whilst differences for both AI and TS compared to palpation were smaller with mCAST (AI difference: 0.007 m, TS difference: 0.009 m) than the CAST method (AI difference: 0.012 m, TS difference: 0.011 m). Such appreciable decreases in RMSE observed within this study are in agreement with Cappello *et al.* (1997). These findings would suggest that both CAST and mCAST methods, in regards to cricket bowling, provide methods which can establish scapula position during a dynamic movement that shows RMSE comparable to palpation.

Table 5.5 Group mean ± SD RMSE (m) associated with scapula landmarks with use of cluster methods across all static positions

Scapula Landmark	Mean ± SD RMSE (m) for all static positions							
	X		Y		Z		R	
	CAST	mCAST	CAST	mCAST	CAST	mCAST	CAST	mCAST
AA	0.008 ± 0.002	0.009 ± 0.002	0.009 ± 0.003	0.007 ± 0.002	0.019 ± 0.006	0.020 ± 0.005	0.023 ± 0.006	0.023 ± 0.005
AI	0.023 ± 0.010	0.020 ± 0.002	0.018 ± 0.010	0.013 ± 0.005	0.021 ± 0.009	0.020 ± 0.008	0.037 ± 0.015	0.032 ± 0.006
TS	0.016 ± 0.006	0.018 ± 0.003	0.014 ± 0.007	0.012 ± 0.001	0.026 ± 0.009	0.022 ± 0.005	0.034 ± 0.012	0.031 ± 0.004

Whilst the accurate reconstruction of scapula position is imperative for shoulder kinematic research, the influence methods such as mCAST may impart on establishing scapula orientation remains to be investigated. Similar to previous research reporting the appropriateness of an acromion cluster to establish scapula orientation (Brochard *et al.*, 2009; Karduna *et al.*, 2001; Meskers *et al.*, 2007; van Andel *et al.*, 2009; Warner *et al.*, 2010), in regards to this investigation it can be inferred from the RMSE affecting all scapula landmarks that both CAST and mCAST methods may either under or overestimate scapula orientation. The mCAST method mathematically aims to minimise differences between palpated scapula landmarks to those reconstructed using the CAST technique whilst acknowledging the non-linear, independent relationship that exists between each landmark and the acromion cluster. Whilst further investigation is required to substantiate the following claim, it can be argued that due to the nature of the mCAST method, scapula orientation expressed through using this technique could be technically more suitable than previously proposed methods (Karduna *et al.*, 2001; Meskers *et al.*, 2007), particularly that of Meskers *et al.* (2007) where the use of a regression model assumes uniform error affecting all scapula landmarks. Individualised responses were observed to occur when applying both the CAST and mCAST methods. For instance, mCAST was found to improve resultant RMSE associated with TS for participant 1 by 0.017 m, however for participant 3, the application of the mCAST method to TS resulted in resultant RMSE increasing by 0.013 m. As can be seen in Figure 5.5, for both individuals the mCAST method was found to affect both the X and Z coordinates more so than the Y coordinate. In this investigation these co-ordinates relate to the anterior/posterior and medial/lateral dimensions, which would be susceptible to skin to bone translatory discrepancies varying dependent on shoulder position which would be individualised regardless of similar subscapular skin fold measurements between participants.

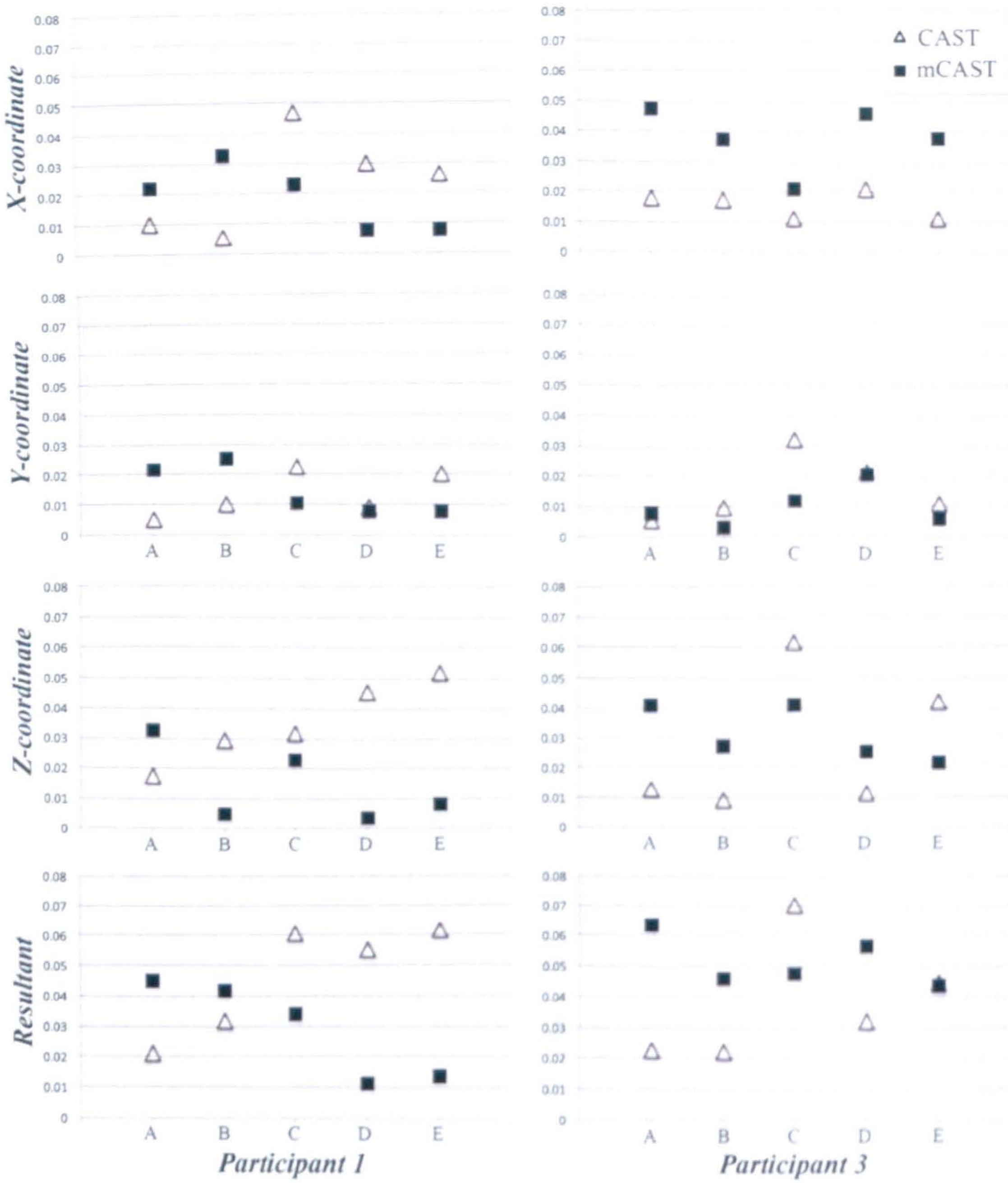


Figure 5.5 CAST and mCAST RMSE (m) associated with TS for both Participant 1 and 3 at each static position

Suitability of mCAST to establish scapula motion during cricket bowling

To the author's knowledge, this is the first research undertaken to investigate the feasibility of an acromion cluster to establish scapula position during a sport specific motion, whereby error associated each scapula landmark was assessed and corrected on an individual basis. The multi-planar motion of the shoulder that occurs during cricket bowling is in stark contrast to the controlled single plane motions investigated by Brochard *et al.* (2009), Karduna *et al.* (2001), Meskers *et al.* (2007), van Andel *et al.* (2009) and Warner *et al.* (2010). Findings from this investigation establish that both

CAST and mCAST RMSE are comparable to that associated with palpation, whilst enabling use for dynamic multi-planar movements. As the mCAST method was seen to both decrease RMSE by 0.017 m for one participant and increase RMSE by 0.013 m for another, it would suggest that the choice of applying either the CAST or mCAST methods should be done on an individual basis following a set protocol similar to the data collection protocol used within this investigation.

Conclusion

The aim of this investigation was to develop and evaluate the suitability of an acromion cluster method to establish the position of the scapula during cricket bowling. Findings from this investigation demonstrate that the use of the mCAST method, utilising multiple static calibration poses can decrease resultant anatomical landmark RMSE by up to 0.016 m compared to the CAST method. Individualised responses when applying the mCAST method are suggestive that implementation of this method should be undertaken on an individual basis through incorporating a validation procedure prior to data collection to confirm its suitability compared to the CAST method. This investigation typifies the inherent difficulty associated with establishing scapula position using non-invasive methods which varies on an individual basis through factors such as body somatotype, and is also dependent on shoulder position. Research needs to acknowledge that the accuracy of findings which are dependent on methods such as CAST and mCAST, whilst currently the most suitable for investigating dynamic movements may lead to some inaccuracies in subsequent calculations. Findings from both this investigation and those presented in chapter 4 assist in evaluating and adapting current methods to enable scapula reconstruction during cricket bowling, further research is required to evaluate errors associated with joint centre misidentification and the influence this may impart on subsequent kinematic analysis.

Chapter 6

Definition of the GHJ during cricket bowling

Introduction

The accuracy of any kinematic analysis is dependant on the underlying methods used to record and subsequently reconstruct skeletal movement (Lempereur *et al.*, 2009). The reliance on qualitative description of the bowling shoulder during cricket bowling is in part due to methodological issues, as typified by Chin *et al.* (2009) who observed quantitative measures of shoulder movement during the bowling movement were a poor reflection of the movement pattern observed. The structure of the shoulder joint imparts errors arising from both STA and difficulty in establishing anatomical landmarks (Lempereur *et al.*, 2009). Findings from chapters 4 and 5 demonstrate that current methods used to identify scapula landmarks through the use of an acromion cluster can be modified and validated for use during cricket bowling by the use of the mCAST method. In addition to the scapula, identification of the glenohumeral joint centre (GHJ), due to its role in defining the humeral anatomical coordinate system has been the focus of numerous studies (Alderson, Campbell, Chin, Lloyd & Elliott, 2008; Lempereur *et al.*, 2009; Meskers *et al.*, 1998b; Monnet, Desailly, Begon, Vallée & Lacouture, 2007; Sholukha *et al.*, 2007; Sholukha *et al.*, 2009; Stokdijk, Nagels & Rozing, 2000), however minimal research to date has investigated the suitability of such approaches during dynamic, sporting movements (Roosen, Pain & Begon, 2009).

Literature review

Misidentification of anatomical landmarks

Kinematic analysis is dependant on the accurate reconstruction of skeletal movement which when using non invasive techniques can be impaired by the misrepresentation of anatomical landmarks resulting in time variant systematic errors which can not be treated through filtering (Stagni, Fantozzi & Cappello, 2006). Underlying this error is both STA as discussed in previous chapters and, anatomical landmark misidentification. Anatomical landmark misidentification has been established by Della Croce *et al.* (1999) and Stagni, Fantozzi, Cappello & Leardini (2005), to impart significant errors on subsequent joint orientations impairing the relevance of findings. Defining joint centres, which unlike other anatomical landmarks can not be palpated, has been the focus of numerous investigations with both predictive and functional methods proposed (Alderson *et al.*, 2008; Lempereur *et al.*, 2009; Meskers *et al.*, 1998b; Monnet *et al.*, 2007; Sholukha *et al.*, 2007; Sholukha *et al.*, 2009; Stokdijk *et al.*, 2000). Research by Ehrig, Taylor, Duda & Heller (2006;2007), Lempereur *et al.* (2009), MacWilliams (2008), Monnet *et al.* (2007) and Stokdijk *et al.* (2000) have investigated the difference in joint centre location dependant on the method utilised, with both Campbell, Alderson, Lloyd & Elliott (2009) and Roosen *et al.* (2009) illustrating that the choice of technical coordinate system can further impart error on the accuracy of the reconstructed joint centre location.

Predictive methods to identify the glenohumeral joint centre

Predictive methods (Alderson *et al.*, 2008; Meskers *et al.*, 1998b; Sholukha *et al.*, 2007; Sholukha *et al.*, 2009) of identifying GHJ location utilise multiple regression equations that typically involve predictor variables reliant on either anthropometric measures or anatomical landmark identification. To date the only predictive method to be recommended by the ISB, is that proposed by Meskers *et al.* (1998b). Meskers *et al.* (1998b) proposed a method for describing *in vivo* the GHJ location estimated using bony landmarks on the humerus and scapula from thirty six cadaver specimens. The RMSE between the measured and predicted GHJ was reported to be 0.00232 m for the x coordinate, 0.00269 m for the y coordinate and 0.00304 m for the z coordinate. Subsequently Stokdijk *et al.* (2000) associated this method with poor reliability, particularly intra operator as a consequence of being sensitive to palpation error, which due to its reliance on scapula landmarks would impair its validity for overhead movements. Whilst yet to be adopted within the literature, Alderson *et al.* (2008) presented a new regression equation for the determination of the GHJ. To improve its validity *in vivo*, twenty participants underwent MRI with the addition of a standard surface marker set to enable the accurate determination of the GHJ. For the determination of the new regression equation, GHJ location using MRI images of fifteen participants was determined and used in a stepwise linear regression analysis to create regression models for each of the GHJ coordinates. Alderson *et al.* (2008) reported that the new regression equation was associated with error (x coordinate = 0.004 m, y coordinate = 0.004 m, z coordinate = 0.006 m) similar in magnitude to

Meskers *et al.* (1998b). The method of Alderson *et al.* (2008) was viewed as being more robust due to not being reliant on scapula anatomical landmarks and instead using the independent variables of subject height and mass, the 3-D distance between the sternal notch and C7, the 3D distance between the midpoint of the lateral ridge of the acromial plateau and the centre point between the sternal notch and C7 and, the 3D distance between a marker placed on the anterior aspect of the shoulder and one placed on the posterior aspect of the shoulder to define GHJ location. The reliance of population data to determine the GHJ when using predictive methods, impairs the validity of these approaches especially in the presence of shoulder pathology, and as such researchers have begun to favour the use of functional methods to predict the GHJ location.

Functional methods to identify the glenohumeral joint centre

Several functional methods (Ehrig *et al.*, 2006; Gamage & Lasenby, 2002; Halvorsen, 2003; Schwartz & Rozumalski, 2005; Siston, Daub, Giori, Goodman, & Delp, 2005) have been proposed to reconstruct the centre of rotation (CoR) of a joint. The theoretical basis of functional methods falls into two categories, the sphere fitting approach and transformation techniques (Ehrig *et al.*, 2006; Ehrig *et al.*, 2007). Sphere fitting methods (Gamage & Lasenby, 2002; Halvorsen, 2003), are a progression from the helical axis (HA) method (Woltring, Huiskes, De Lange & Veldpaus, 1985) typically used for uni-axial joints and attempts to fit cylindrical arcs to the orbits of moving segment markers, where the other segment is assumed to be at rest (Ehrig *et al.*, 2007). In comparison, transformation methods (Ehrig *et al.*, 2006; Schwartz & Rozumalski, 2005) considers the distance between markers on each joint segment to have a constant relationship between the CoR whereby either one or both segments can be assumed to be moving. Whilst research has determined that the GHJ defined by functional methods is dependant on the defining movement pattern (Monnet *et al.*, 2007; Lempereur *et al.*, 2009; Piazza, Erdemir, Okita & Cavanagh, 2004; Roosen *et al.*, 2009), movement velocity (Stokdijk *et al.*, 2000) and the technical coordinate systems used to define joint segments (Campbell *et al.*, 2009; MacWilliams, 2008; Roosen *et al.*, 2009); to date little research (Lempereur *et al.*, 2009; Monnet *et al.*, 2007; Stokdijk *et al.*, 2000) has assessed the accuracy and repeatability of functional methods to define GHJ location.

Stokdijk *et al.* (2000) investigated three different methods to determine the GHJ *in vivo*. The first method adopted the regression method outlined by Meskers *et al.* (1998b), the second incorporated a sphere-fitting method and the third method investigated was the HA approach often used for the knee and elbow (Woltring *et al.*, 1985). Stokdijk *et al.* (2000) established that each of the three methods was able to reproduce the GHJ within 0.004 m, but the location of the joint centre was found to differ significantly between methods ($p = 0.001$). The authors concluded whilst both the sphere-fitting and HA approaches were most suitable for determination of the GHJ on an individual basis, the HA method was preferred due to its ability to also determine joint axes.

Monnet *et al.* (2007) conducted an investigation comparing the symmetrical CoR estimation (SCoRE) method (Ehrig *et al.*, 2006) with the HA method (Woltring *et al.*, 1985) for locating *in vivo* the GHJ. Nine participants performed ten cycles of three different movements below shoulder level including circumduction (CR), flexion-extension (FE) and abduction-adduction (AA) and, a combination of CR, FE and AA, more commonly referred to as a star arc movement circumduction (CR). To investigate the robustness of each FJC method, participants performed each movement pattern at two different velocities. Due to the humeral anatomical coordinate system relying on the GHJ, humeral position and orientation was defined using a technical coordinate system composed of four surface markers. For the scapula, the CAST protocol was incorporated in conjunction with an acromion cluster to enable reconstruction of the scapula anatomical coordinate systems for use in functional joint centre calculations. Average GHJ location and the standard deviation were calculated, with the repeatability of the location assessed as the resultant of the co-ordinate standard deviations. In addition, two way ANOVAs were used to investigate the affect of method and the movement pattern on GHJ location. Monnet *et al.* (2007) established that due to significantly smaller error ($p < 0.05$), the SCoRE method (error: 0.0033 m) was more precise in locating the GHJ than the HA method (error: 0.0046 m). Through using the same movement trials and methods to reconstruct segment anatomical landmarks, the influence imparted due to systematic errors associated in reconstructing anatomical landmarks was standardised. Results established that whilst GHJ location was not affected by movements at different velocities, the circumduction movement was reported unreliable due to increased error compared to the other movement patterns (mean SCoRE error at medium velocity with CR = 0.0042 m; mean HA error at medium velocity with CR = 0.0076 m). Monnet *et al.* (2007) associated increased error with circumduction due to STA even though the angle of arm elevation would have been lower than that normally attributed to affecting scapula kinematics (Brochard *et al.*, 2009; Meskers *et al.*, 2007; van Andel *et al.*, 2009).

Lempereur *et al.* (2009) conducted a study *in vivo* to assess the accuracy and repeatability of functional methods to establish the GHJ by using a reference joint centre determined by MRI for comparison. Four participants performed three cycles of three movement patterns (FE, AA, CR) lying prone, whereby humeral elevation in each of the three cardinal planes did not exceed 30 °. Scapula segment position and orientation was defined using surface markers on AA, AI and TS, whilst humeral segment position and orientation was established using a surface cluster composed of four markers. Five functional joint methods were investigated: Gamage and Lasenby (Gamage & Lasenby, 2002), Halvorsen (Halvorsen, 2003), SCoRE (Ehrig *et al.*, 2006), HA (Woltring *et al.*, 1985) and the normalisation method (Chang & Pollard, 2007), using the calculations presented in the original papers. Similar to Monnet *et al.* (2007), analysis focused on GHJ location and its repeatability. In addition, accuracy was determined by computing the difference in estimated GHJ location for each method compared to the GHJ established using MRI. Lempereur *et al.* (2009) reported that whilst error associated with the repeatability of each method was less than 0.0085 m, both the HA (0.00411 m) and SCoRE (0.00436) methods were non significantly lower. The method of Gamage and Lasenby was found to have the smallest mean resultant difference compared to the GHJ location using MRI (0.01138 m), with the SCoRE method found to have an accuracy of (0.01515 m).

Whilst research (Lempereur *et al.*, 2009; Monnet *et al.*, 2007) has supported the use of the SCoRE method to define GHJ location, the suitability of this method for overhead, dynamic movements such as cricket bowling has yet to be substantiated. With the exception of Roosen *et al.* (2009), FJC research (Lempereur *et al.*, 2009; Monnet *et al.*, 2007; Stokdijk *et al.*, 2000) investigating the GHJ has relied on controlled movement patterns below the horizontal that are not reflective of either the range of motion or, STA observed during dynamic movements. Roosen *et al.* (2009) conducted a single subject analysis to investigate the suitability of the SCoRE method to define and subsequently reconstruct both the elbow joint centre and GHJ during a punch. Findings from their work support that the choice of markers used to both define and, reconstruct the FJC can have a significant impact on both the accuracy and variability of the GHJ location which was observed to vary from 0.025 to 0.138 m depending on the marker triads used. However, due to the non-standard marker set used to define segments, which would be prone to STA the direct application of these findings are limited but do illustrate that before the SCoRE method can be applied to cricket bowling, it is pertinent that research is conducted to ensure that its practical application compliments the theoretical accuracy of this method.

Study aim

Whilst Lempereur *et al.* (2009) and Monnet *et al.* (2007) have reported favourably the benefits of the SCoRE method (Ehrig *et al.*, 2006) for the reconstruction of GHJ location on an individual basis, the direct applicability of such methods for use with overhead movements such as cricket bowling is yet to be substantiated. As the SCoRE method is dependant on the accurate reconstruction of each joint segment, investigators have utilised restricted movement patterns below shoulder level to minimise the influence scapula reconstruction error can impart on subsequent GHJ location. It has been established that the bowling movement is a complex, multi-planar motion associated with high angles of elevation (chapter 3), in theory this should be reflected in the movement pattern used to define the GHJ location. The aim of this investigation was to establish a protocol to incorporate the SCoRE method into a cricket bowling specific kinematic model. As such this investigation assessed two primary components which could affect the calculation of and subsequent reconstruction of GHJ location during cricket bowling using the SCoRE method, namely, the defining joint segments and movement pattern recorded.

Method

Participants

After gaining university ethical approval, seven male bowlers from Sussex County Club, with no recent history of shoulder pathology were recruited. The mean ± SD age, height and mass of the participants were 20.29 ± 1.70 years, 1.79 ± 0.06 m and 79.71 ± 3.72 kg. Following an explanation of the experimental aims and procedures all participants provided informed consent. For bowlers under 18 years of age consent was obtained from club officials on behalf of the bowler's guardians.

Equipment

Accelerometer system:

Each scapula anatomical landmark was defined using the mCAST protocol outlined in chapter 5. To establish the five static positions reflective of the bowling delivery from the data outlined in chapter 3, an accelerometer system composed of two, tri-axial accelerometers (ADXL335, Analog Devices, Norwood, USA) positioned on the humerus and C7, were connected to a LilyPad Arduino 328 mainboard (Atmel, San Jose, USA) loaded with CSBT BentAcc (Shorter, 2010, unpublished program). To monitor shoulder position during data collection, accelerometer output was transmitted wirelessly using two XBee 1mW Chip Antennas (Digi International Inc., Minnetonka, USA) and viewed within CSBT Bent (Shorter, 2010, unpublished program).

Kinematic system:

Upper limb kinematics of the bowling arm for each participant were recorded at 100 Hz using six Basler cameras (Basler A602fc-2, Germany) synchronised with a MX Ultranet control unit (Vicon, Oxford, UK). A 16-point calibration frame (Peak Performance Technologies Inc., Colorado, USA) was positioned within the field of view to provide a calibrated volume of 1.26 m × 1.08 m × 0.90 m with a residual calibration error of 0.0021 m.

To establish scapula position, each scapula anatomical landmark (AA, AI and TS) was palpated in accordance with ISB guidelines (Wu *et al.,* 2005) by the club physiotherapist using a calibrated pointer for later reconstruction using the mCAST protocol (chapter 5). To define GHJ location using the SCoRE method (Ehrig *et al.,* 2006), technical clusters composed of three 10 mm diameter retroflective markers on semi-rigid, thermoplastic material were placed on both the acromion plateau and humerus, corresponding with locations acknowledged to be appropriate for reconstruction of the GJC due to being minimally affected by STA (Campbell *et al.,* 2009)(Figure 6.1).

Figure 6.1 Illustrative example of the location of the acromion and humerus clusters

Testing procedure

Following habituation of the testing environment, participants were requested to adopt the anatomical position to provide a standardised pose for later reconstruction of the GHJ. Each scapula anatomical landmark (AA, AI and TS) was defined using the mCAST protocol described in chapter 5, with each landmark palpated by the club physiotherapist using a calibrated pointer. To investigate the influence of movement pattern on the definition of the functional GHJ, participants were requested to undertake three repetitions of each of the two movement patterns (star arc and bowling). The star arc movement, in accordance with Lempereur *et al.* (2009) and Monnet *et al.* (2007), was defined as a movement at a self selected speed below the horizontal that incorporated flexion/extension, abduction/adduction and circumduction. The bowling movement required that each participant mimicked at a sedate velocity, the upper body action of the bowling delivery whilst standing. In addition, to establish the most appropriate method to reconstruct GHJ location during the dynamic movement of interest, participants were requested to perform an additional bowling movement trial which would be subsequently treated during data processing to provide an indication of the STA and noise expected to be observed if bowling at maximal effort.

Data processing

All digitising was conducted within Vicon Motus 9.2 software (Vicon, Los Angeles, USA) by the experimenter (average digitisation RMSE error: 0.0026 m) with all subsequent processing and analysis performed within CSBT GJCanalyser (Shorter, 2011, unpublished program)(Figure 6.2) (Appendix J).

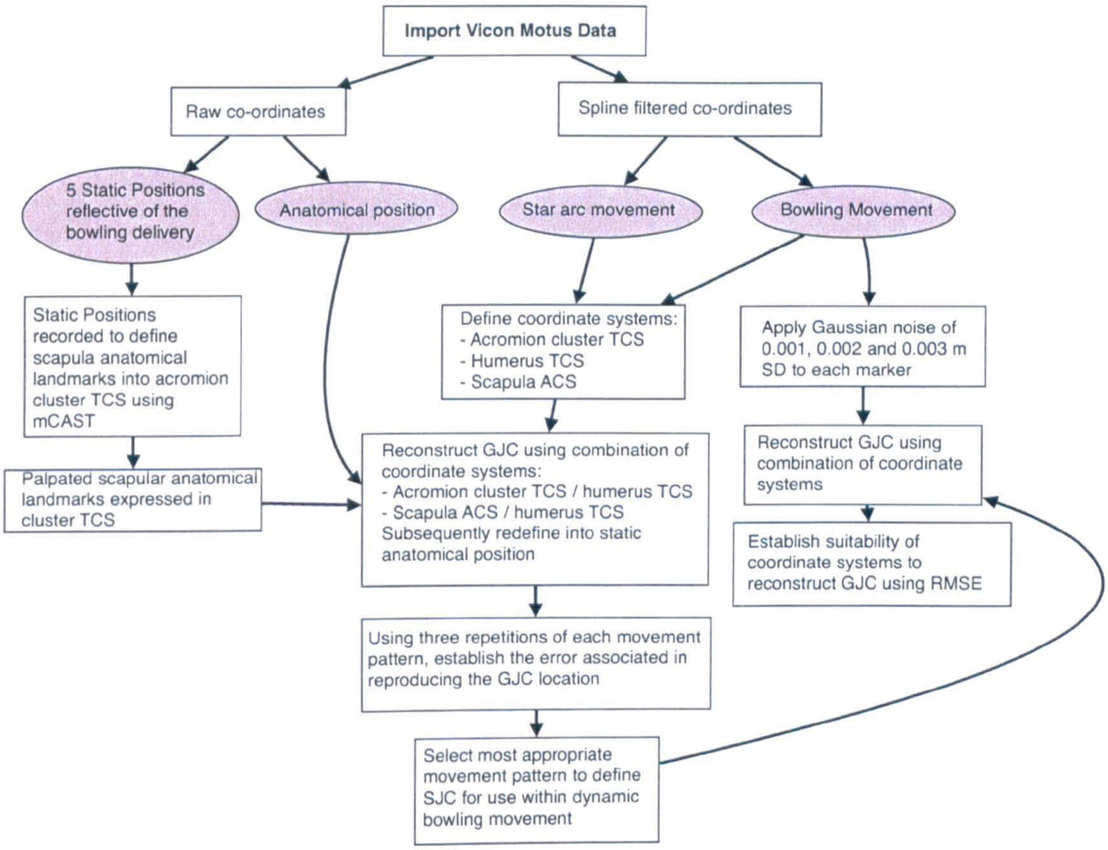


Figure 6.2 CSBT GJCanalyser (Shorter, 2011, unpublished program) explanatory program flow diagram

To define scapula anatomical landmarks (AA, AI and TS) using the mCAST protocol, both the calibrated pointer and acromion cluster were digitised for one frame of interest to provide raw three-dimensional coordinates. Using the mCAST protocol explained in chapter 5, each scapula landmark (P) was subsequently defined into the global coordinate system by the equation:

$$_{G}P^{\mathrm{Re}}(t) = {}^{cLCS}_{G}T(t)\,_{cLCS}P^{\mathrm{Re}}(st) + {}^{cLCS}_{G}R(t)\,_{cLCS}c$$

Equation 6.1

For each movement pattern, GHJ location was defined using the SCoRE method (Ehrig *et al.*, 2006). Unlike other transformation methods (Schwartz & Rozumalski, 2005; Siston *et al.*, 2005), which make the assumption that both the CoR and the proximal joint segment remain stationary during the defining movement whereby the distal coordinate system is transformed to be expressed into the proximal segment, the SCoRE method is capable of considering a moving CoR reflective of the nature of the GHJ whereby both segments are assumed to move independently (Ehrig *et al.*, 2006). The SCoRE method, through assuming that the position of the CoR must remain constant relative to each segment's local coordinate system enables the relationship to be expressed as:

$$SCoRE(c_1,c_2)=\sum_{i=1}^{n}\left\|R_i c_1+t_i-(S_i c_2+d_i)\right\|^2$$

Equation 6.2

Whereby c_1 and c_2 are the CoR expressed in the local coordinate systems and (R_i,t_i), $(S_i d_i)$ are the transformations from the respective local coordinate systems into the global coordinate system. When written in a least squares sense, equation 6.2 can be written as:

$$\begin{pmatrix} R_1 & -S_1 \\ \vdots & \vdots \\ R_n & -S_n \end{pmatrix}\begin{pmatrix} c_1 \\ c_2 \end{pmatrix}=\begin{pmatrix} d_1-t_1 \\ \vdots \\ d_n-t_n \end{pmatrix}$$

Equation 6.3

The GHJ position within the global system at each time instant is expressed as $R_i c_1 + t_i$ and $S_i c_2 + d_i$, which, as not always coincidental, the best estimation for the actual CoR within the global coordinate system is the mean of the two positions (Ehrig *et al.*, 2006).

For each repetition of each movement pattern, GHJ was described in relation to the humerus and acromion cluster coordinate systems or, in relation to the humerus and scapula coordinate systems (Table 6.1). To standardise GHJ locations, for each individual, each location was subsequently reconstructed within the anatomical pose condition within the global coordinate system. For each individual, the first repetition of the movement pattern associated with the best repeatability as defined by the lowest associated error observed between each of the three repetitions, was used to define GHJ location for subsequent reconstruction during the dynamic trial.

Table 6.1 Segment coordinate systems

Coordinate system	Axis	Definition
Humerus (technical)	X	The line perpendicular to the Z axis and Y axis, pointing to the right
	Y	Line connecting H1 to H2, pointing in a vertical direction towards H1
	Z	The line perpendicular to the plane formed by the H1, H2 and H3 markers, pointing forwards
Acromion cluster (technical)	X	The line perpendicular to the Z axis and Y axis, pointing to the right
	Y	Line connecting AC1 to AC2, pointing in a vertical direction towards AC1
	Z	The line perpendicular to the plane formed by the AC1, AC2 and AC3 markers, pointing forwards
Scapula (anatomical)	X	The line perpendicular to the plane formed by AI, AA and TS, pointing forward
	Y	The line perpendicular to the X axis and Z axis, pointing upwards
	Z	The line connecting TS and AA, pointing to AA

The bowling movement trial used for reconstruction of the previously defined GHJ, was treated with Gaussian noise with SD of 0.001, 0.002 and 0.003 m, applied to each marker position in isolation. The magnitude of the noise applied was selected to be indicative of the STA and noise observed during explosive, dynamic movements as previously applied to FJC simulations for the lower limb (Begon, Monnet, & Lacouture, 2007; Ehrig *et al.,* 2006). Due to the random nature of the noise pattern applied, reconstruction of the GHJ was performed five times for each condition and the mean position calculated for later analysis. To establish the most suitable local coordinate system or combination of, reconstruction of the GHJ was performed using either the humerus, acromion or scapula coordinate systems independently or the average of the humerus and acromion or humerus and scapula coordinate systems as advocated by Campbell *et al.* (2009).

Data analysis

Data analysis was conducted within Microsoft Excel (Microsoft Inc., Richmond, USA). In agreement with Monnet *et al.* (2007), determination of the most suitable movement pattern to establish the GHJ location was defined as an expression of the observed standard deviation for the three repetitions using the equation:

$$error = \sqrt{SD_x + SD_y + SD_z}$$

Equation 6.4

Whereby the most suitable movement pattern was qualitatively assessed to be observed to exhibit the smallest error.

Similar to Ehrig *et al.* (2006), to establish the coordinate system or combination of, most suitable for reconstruction of the GHJ during cricket bowling, RMSE was calculated using the equation:

$$\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left\|GHJn_i - GHJ_i\right\|^2}$$

Equation 6.5

Where $GHJn_i$ was the estimation of the GHJ location with noise at the *i*th moment in time and GHJ_i was the position of the GHJ with no noise applied at the *i*th moment in time. In doing so, results were qualitatively assessed as to the suitability of local segment coordinate systems to reconstruct GHJ location during cricket bowling, as the smaller RMSE, the more robust the segment or combination of, are to reconstructing the GHJ location in the presence of noise and therefore STA.

Results and Discussion

Choice of movement pattern to define GHJ location

Although six bowlers were observed to exhibit the smallest error in reproducing the GJC with the star arc, one bowler was found to display the smallest error when using the bowling movement (mean star arc error for all defining segments: 0.0276 ± 0.0023 m, mean bowling movement error for all defining segments: 0.0083 ± 0.0005 m). The large magnitude of error associated with the star arc for this bowler, compared to the mean error for the star established for the other six bowlers (0.0032 ± 0.0001 m), suggested that the data for this bowler was corrupted by systematic error due to the testing environment and, as not a true reflection of the repeatability of GHJ location, the bowler was excluded from further analysis.

For the six bowlers, whilst GHJ location defined by the star arc and bowling movement were similar between the defining segment coordinate systems (Table 6.2, 6.3). The largest variation in GHJ location was associated with the medial/lateral, z coordinate (star arc range: 0.0190 m, bowling range: 0.0102 m), with much lower variation associated with both the anterior/posterior, x coordinate (star arc range: 0.0003 m, bowling range: 0.0019 m) and vertical y coordinate (star arc range: 0.0002 m, bowling range: 0.0010 m). Similar GHJ locations were associated with the acromion and scapula segment coordinate systems compared to the humerus, suggesting that both the distance from the GHJ and STA affecting each segment contributes to the difference in calculated GHJ location in accordance with Campbell *et al.* (2009), who associated segments closest to the GHJ being most accurate in establishing GHJ location.

The star arc movement was associated with the smallest error and therefore demonstrated the greatest repeatability irrespective of the defining segment coordinate systems. Mean error associated with the star arc (0.0032 ± 0.0002 m) is in agreement with previous research investigating the repeatability of the GHJ location using the SCoRE method, with Monnet *et al.* (2007) and Lempereur *et al.* (2009) reporting errors of 0.0033 m and 0.00436 m respectively. Whilst the accuracy of GHJ location can not be quantified within this investigation, the small error associated with reproducing GHJ location supports the use of the star arc for subsequent investigations.

Table 6.2 GHJ location and repeatability associated with the star arc movement expressed in relation to the GCS

		Position (m)			Error (m)
		x	y	z	
Humerus / Acromion	Humerus TCS	0.5270 ± 0.1383	0.5811 ± 0.1365	0.6457 ± 0.1115	0.0032 ± 0.0011
	Acromion TCS	0.5273 ± 0.1366	0.5809 ± 0.1307	0.6267 ± 0.1150	0.0033 ± 0.0014
Humerus / Scapula	Humerus TCS	0.5271 ± 0.1383	0.5811 ± 0.1365	0.6457 ± 0.1114	0.0032 ± 0.0011
	Scapula ACS	0.5273 ± 0.1367	0.5809 ± 0.1307	0.6267 ± 0.1150	0.0033 ± 0.0014

Table 6.3 GHJ location and repeatability associated with the bowling movement expressed in relation to the GCS

		Position (m)			Error (m)
		x	y	z	
Humerus / Acromion	Humerus TCS	0.5092 ± 0.1339	0.5742 ± 0.1413	0.6398 ± 0.1172	0.0129 ± 0.0110
	Acromion TCS	0.5074 ± 0.1303	0.5732 ± 0.1334	0.6297 ± 0.1198	0.0131 ± 0.0097
Humerus / Scapula	Humerus TCS	0.5092 ± 0.1340	0.5742 ± 0.1413	0.6399 ± 0.1173	0.0130 ± 0.0110
	Scapula ACS	0.5073 ± 0.1304	0.5733 ± 0.1334	0.6297 ± 0.1198	0.0132 ± 0.0097

Findings from this investigation suggests that the choice of defining segment coordinate systems, whether it be the acromion cluster and humerus or scapula and humerus, is largely inconsequential in establishing the location of the GHJ, with the choice of movement pattern imparting the greatest influence on repeatability. Mean error for the the bowling movement was established to be 0.0130 ± 0.0007 m, four times greater than that associated with the star arc. The poor repeatability observed in relation to the bowling movement may be reflective of the movement pattern as findings from chapter 3 highlighted the large variability associated with bowling. Therefore, as the star arc even though incorporating a smaller range of movement not reflective of the bowling delivery, was associated with the best repeatability, findings from this investigation suggests that future bowling analysis incorporating the SCoRE method should utilise the star arc movement to define GHJ location

Sensitivity of defining joint segments to reconstruct GHJ location

Representative graphs of the influence Gaussian noise imparts on the reconstructed GHJ location during the bowling delivery are depicted in Figure 6.3 (acromion/humerus) and 6.4 (scapula/humerus). It is apparent that sensitivity to noise is dependent on each individual segment, with resultant RMSE error ranging from 0.0021 ± 0.0001 to 0.0132 ± 0.0010 (Table 6.4, 6.5, 6.6). Whilst the magnitude of RMSE was observed to increase with increasing noise, similar responses were observed between participants suggesting that the choice of defining segments to reconstruct GHJ location during bowling need not be done on an individual basis. RMSE observed when Gaussian noise of 0.001 m was applied was in agreement with Ehrig *et al.* (2006) reporting errors of approximately

0.005 m using a hip joint simulation with a range of 20 °. Findings from this investigation, suggest that although the bowling movement incorporates a large range of motion at the shoulder joint, the SCoRE method even in the presence of noise is able to reconstruct the GHJ satisfactory.

The humerus segment, irrespective if used in combination with either the scapula or acromion segments, was observed to exhibit the largest resultant RMSE. In agreement with Campbell *et al.*(2009) both the scapula and acromion due to their close proximity to the GHJ were associated with small RMSE (acromion range: 0.0038 ± 0.0002 to 0.0111 ± 0.0006 m, scapula range: 0.0021 ± 0.0001 to 0.0063 ± 0.0003 m). Averaging the GHJ location, when reconstructing the landmark using both the humerus and acromion coordinate systems, in agreement with Campbell *et al.* (2009), was observed to assist in lowering RMSE, however, the average of the humerus and scapula segments was observed to display larger RMSE compared to when reconstructing the GHJ using just the scapula coordinate system.

Through demonstrating the smallest RMSE in reconstructing the GHJ during the bowling delivery in the presence of noise, findings from this investigation support the sole use of the anatomical based, scapula coordinate system. The robustness of the scapula coordinate system in reconstructing the GHJ may occur as a consequence of defining scapula anatomical landmarks using the mCAST method. The underlying principle of the mCAST method is to incorporate a scaling factor for each scapula anatomical landmark (AA, AI and TS) in isolation to account for the varying degrees of STA affecting landmark reconstruction. As the subsequent scapula coordinate system used to reconstruct the GHJ is defined using landmarks that have been reconstructed to account for the influence of STA, the scapula coordinate system is more appropriate for use in reconstructing the GHJ compared to other segment coordinate systems, which except for the use of digital filters during data processing can not directly account for the influence of noise and STA.

Table 6.4 Resultant RMSE error (m) associated with Gaussian noise of 0.001 m SD

	Humerus / Acromion			Humerus / Scapula		
	Acromion	Humerus	Average	Scapula	Humerus	Average
Bowler 1	0.0036 ± 0.0001	0.0046 ± 0.0001	0.0029 ± 0.0001	0.0020 ± 0.0001	0.0046 ± 0.0001	0.0025 ± 0.0001
Bowler 2	0.0038 ± 0.0001	0.0040 ± 0.0001	0.0027 ± 0.0001	0.0022 ± 0.0001	0.0040 ± 0.0001	0.0023 ± 0.0001
Bowler 3	0.0039 ± 0.0002	0.0039 ± 0.0001	0.0028 ± 0.0001	0.0021 ± 0	0.0039 ± 0.0001	0.0023 ± 0.0001
Bowler 4	0.0037 ± 0.0001	0.0044 ± 0.0001	0.0029 ± 0.0001	0.0022 ± 0.0001	0.0044 ± 0.0001	0.0025 ± 0.0001
Bowler 5	0.0035 ± 0.0001	0.0047 ± 0.0002	0.0029 ± 0.0001	0.0020 ± 0.0001	0.0047 ± 0.0002	0.0026 ± 0.0001
Bowler 6	0.0041 ± 0.0001	0.0047 ± 0.0002	0.0031 ± 0.0001	0.0022 ± 0	0.0047 ± 0.0002	0.0026 ± 0.0001
Group	**0.0038 ± 0.0002**	**0.0044 ± 0.0003**	**0.0029 ± 0.0001**	**0.0021 ± 0.0001**	**0.0044 ± 0.0003**	**0.0024 ± 0.0001**

Table 6.5 Resultant RMSE error (m) associated with Gaussian noise of 0.002 m SD

	Humerus / Acromion			Humerus / Scapula		
	Acromion	Humerus	Average	Scapula	Humerus	Average
Bowler 1	0.0071 ± 0.0001	0.0093 ± 0.0004	0.0058 ± 0.0001	0.0040 ± 0.0002	0.0093 ± 0.0004	0.0051 ± 0.0002
Bowler 2	0.0080 ± 0.0002	0.0079 ± 0.0003	0.0056 ± 0.0001	0.0042 ± 0.0002	0.0079 ± 0.0003	0.0044 ± 0.0002
Bowler 3	0.0077 ± 0.0003	0.0078 ± 0.0003	0.0056 ± 0.0003	0.0045 ± 0	0.0078 ± 0.0003	0.0045 ± 0.0001
Bowler 4	0.0073 ± 0.0004	0.0087 ± 0.0001	0.0058 ± 0.0002	0.0044 ± 0.0001	0.0087 ± 0.0001	0.0049 ± 0.0001
Bowler 5	0.0069 ± 0.0004	0.0095 ± 0.0004	0.0059 ± 0.0003	0.0039 ± 0.0001	0.0095 ± 0.0004	0.0051 ± 0.0002
Bowler 6	0.0080 ± 0.0002	0.0094 ± 0.0004	0.0062 ± 0.0003	0.0044 ± 0.0001	0.0094 ± 0.0004	0.0051 ± 0.0002
Group	**0.0075 ± 0.0005**	**0.0088 ± 0.0007**	**0.0058 ± 0.0002**	**0.0042 ± 0.0002**	**0.0088 ± 0.0007**	**0.0049 ± 0.0003**

Table 6.6 Resultant RMSE error (m) associated with Gaussian noise of 0.003 m SD

	Humerus / Acromion			Humerus / Scapula		
	Acromion	**Humerus**	**Average**	**Scapula**	**Humerus**	**Average**
Bowler 1	0.0108 ± 0.0005	0.0137 ± 0.0004	0.0086 ± 0.0002	0.0061 ± 0.0002	0.0138 ± 0.0004	0.0075 ± 0.0003
Bowler 2	0.0113 ± 0.0003	0.0121 ± 0.0005	0.0084 ± 0.0004	0.0065 ± 0.0002	0.0121 ± 0.0005	0.0069 ± 0.0003
Bowler 3	0.0115 ± 0.0003	0.0118 ± 0.0003	0.0083 ± 0.0002	0.0065 ± 0.0003	0.0118 ± 0.0003	0.0067 ± 0.0002
Bowler 4	0.0109 ± 0.0003	0.0131 ± 0.0005	0.0085 ± 0.0003	0.0066 ± 0.0003	0.0131 ± 0.0005	0.0074 ± 0.0004
Bowler 5	0.0103 ± 0.0003	0.0140 ± 0.0005	0.0087 ± 0.0005	0.0059 ± 0.0002	0.0140 ± 0.0005	0.0076 ± 0.0003
Bowler 6	0.0120 ± 0.0003	0.0143 ± 0.0007	0.0094 ± 0.0004	0.0065 ± 0.0001	0.0143 ± 0.0007	0.0078 ± 0.0003
Group	**0.0111 ± 0.0006**	**0.0132 ± 0.0010**	**0.0087 ± 0.0004**	**0.0063 ± 0.0003**	**0.0132 ± 0.0010**	**0.0073 ± 0.0004**

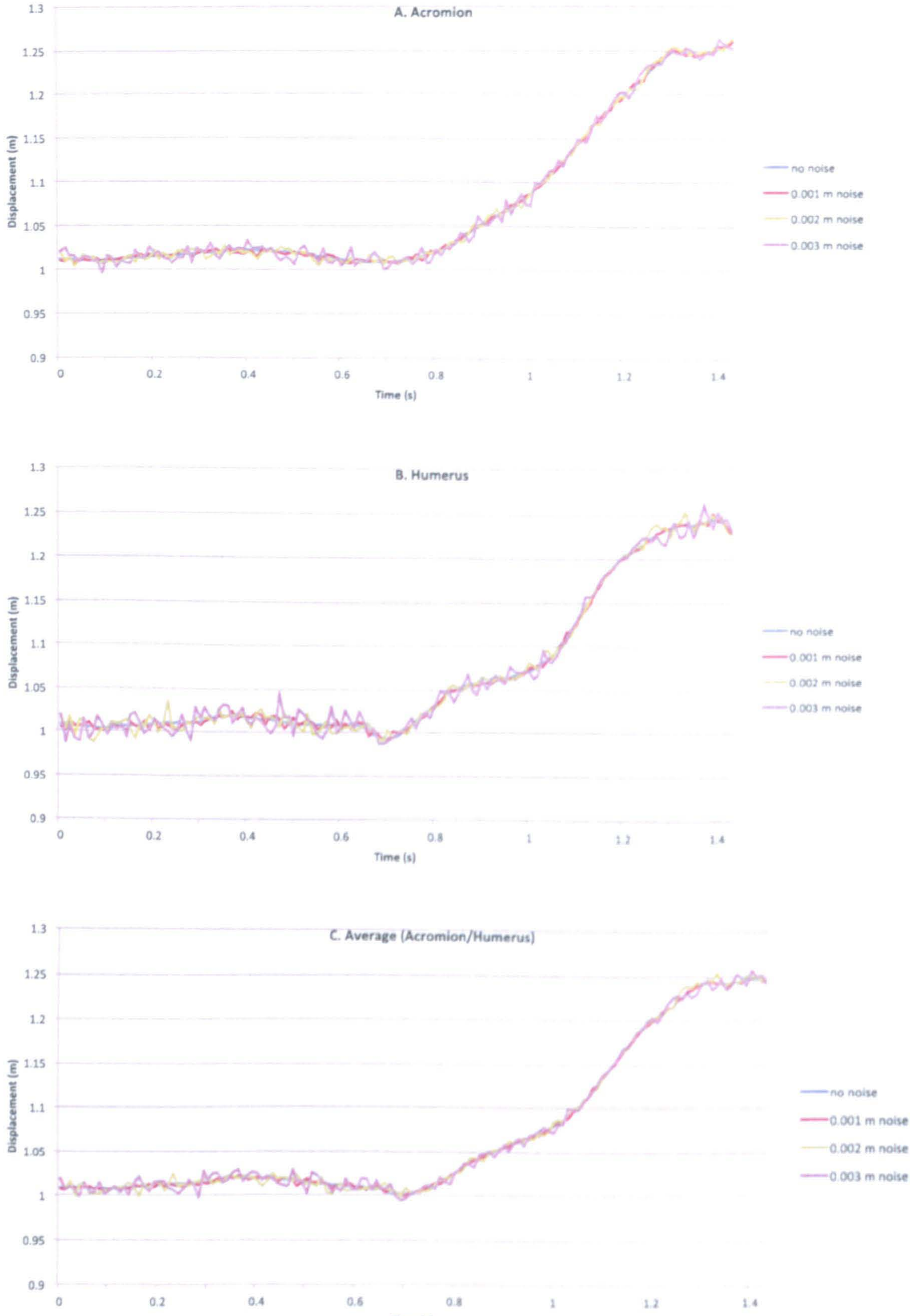


Figure 6.3 Representative resultant GHJ location during the bowling delivery under different noise conditions (acromion and humerus TCS)

Figure 6.4 Representative resultant GHJ location during the bowling delivery under different noise conditions (scapula ACS and humerus TCS)

Conclusion

The aim of this investigation was to establish a protocol to incorporate the SCoRE method into a cricket bowling specific kinematic model through investigating two factors that could affect the calculation of and subsequent reconstruction of GHJ location, namely the defining joint segments and movement pattern recorded. Findings from this investigation established that the choice of defining segment coordinate systems is largely inconsequential in establishing the location of the GHJ, with the choice of movement pattern imparting the greatest influence on repeatability. The bowling movement, whilst reflective of the dynamic movement of interest was associated with four times greater error (0.0130 ± 0.0007 m) compared to the star arc (0.0032 ± 0.002 m). As the smaller error associated with the repeatability of the GHJ location using the star arc was observed to be in agreement with the findings of Monnet *et al.* (2007) and Lempereur *et al.* (2009), findings support the incorporation of the star arc to define the GHJ location within future cricket bowling research.

Through applying Gaussian noise to a dynamic bowling trial, the ability of segment coordinate systems to reconstruct the GHJ was investigated. RMSE error observed was in agreement with that reported by Ehrig *et al.* (2006) when simulating the hip joint centre. As the anatomically based, scapula coordinate system was associated with the lowest RMSE for all noise conditions (0.001 m: 0.0021 ± 0.0001 m, 0.002 m: 0.0042 ± 0.0002 m, 0.003 m: 0.0063 ± 0.0003 m), findings from this investigation support the sole use of this segment for the reconstruction of the GHJ during the dynamic movement of interest when used in conjunction with the mCAST method.

Whilst research to date has largely investigated the use of the SCoRE method in relation to the GHJ using controlled movements (Lempereur *et al.*, 2009; Monnet *et al.*, 2007), this study aimed to investigate the suitability of the method for use during cricket bowling. Findings from this investigation support the work of Roosen *et al.* (2009), in establishing the SCoRE method, when applied using measures to ensure repeatability and robustness in the presence of noise and STA, is an appropriate method for defining the GHJ within future cricket bowling research. Findings from this chapter, when combined with those of chapters 3 and 4, present a methodological approach to investigate shoulder kinematics during cricket bowling. This cricket specific shoulder model, due to increased reliability and validity in reconstructing key anatomical landmarks through acknowledging the complex multi-planar nature of the bowling movement, enables the calculation of advanced kinematic and kinetic calculations such as quantifying the contribution of individual rotator cuff muscles to shoulder joint stability.

Chapter 7

Contribution of the rotator cuff to shoulder cuff stability during cricket bowling

Introduction

The shoulder is a biomechanically complex joint owing to the interaction between osseous structures and surrounding musculature, particularly the rotator cuff (Labriola, Lee, Debski & McMahon, 2005; Veeger & Van der Helm, 2007). Findings from chapter 2 established that both the subscapularis and supraspinatus tendons were observed to have high incidences of tendon pathology in a cohort of bowlers with no prior reported history of shoulder injury. Whilst the causation of such tendon pathology can not be solely attributed to bowling, the relevance of such findings in regard to injury prevention is limited until research is undertaken to establish the role of the shoulder musculature during the bowling delivery in regard to both bowling performance and joint stability. Understanding the contribution of surrounding musculature to joint stability invivo has received increased interest from researchers as it enables greater insight into the pathomechanics of injuries, which previously could only been estimated through the use of cadavers (Blasier, Guldberg & Rothman, 1992; Blasier, Soslowsky, Malicky & Palmer, 1997; Itoi, Newman, Kuechle, Morrey & An, 1994). Whilst several methods using an energy approach (Bergmark, 1989; Cholewicki & McGill, 1996; Granata & Wilson, 2001; Potvin & Brown, 2005; Stokes & Gardner-Morse, 2003), each with their own limitations have been proposed to estimate the contribution of muscles to joint stability, this has yet to be applied to investigate a dynamic movement such as cricket bowling.

Literature review

Shoulder joint dynamics during bowling

As discussed in chapter 3, due to methodological issues cricket research has to date largely focused on injury surveillance studies. Whilst Chin *et al.* (2009) reported concern over the validity of shoulder joint rotation using the current kinematic model advocated by the ICC (ICC, 2009), (Stuelcken, Ferdinands, Ginn, & Sinclair, 2010) has since utilised a variation of the model (Plug-in-Gait model (Oxford Metrics Ltd., Oxford, UK)) to investigate shoulder joint forces during seam bowling. Investigating a cohort of elite female fast bowlers using inverse dynamics, Stuelcken *et al.* (2010) established that peak shoulder distraction force (599 ± 111 N) occurred during the early stages of the follow through, with average distraction forces (0.92 $N.Kg^{-1}$) similar in magnitude to both baseball (1.08 $N.Kg^{-1}$) (Werner, Gill, Murray, Cook, & Hawkins, 2001) and softball (0.80 $N.Kg^{-1}$) (Werner, Jones, Guido, & Brunet, 2006) pitching. These preliminary findings aid in dispelling the assumption that cricket bowling is a movement associated with lower shoulder forces compared to reported high risk sporting activities such as throwing and pitching, however care needs to taken when interpreting these findings due to study limitations. Whilst the preliminary work of Stuelcken *et al.* (2010) quantifies the forces exerted on the shoulder, similar to prior research investigating shoulder forces during sporting activities (Chu, Fleisig, Simpson, & Andrews, 2009; Werner *et al.*, 2001 and Werner *et al.*, 2006), fails to acknowledge that such forces whilst large in magnitude may not be potentially injurious due to numerous factors that contribute to joint stability and, as such the potential relationship between joint forces and injury can only be theoretical (Fleisig, Barrentine, Zheng, Escamilla, & Andrews, 1999).

Shoulder joint stability

The function of the shoulder joint is a compromise between mobility and stability (Veeger & Van der Helm, 2007). Stability of the glenohumeral joint is largely dependant on surrounding musculature compressing the humeral head against the glenoid surface through a mechanism referred to as concavity-compression (Labriola *et al.*, 2005). This mechanism is particularly important at the end ranges of motion due to protecting and decreasing the strain placed on the capsuloligamentous structures. The concavity-compression mechanism is defined by the joint reaction force resolved into three components: compressive forces, superior-inferior forces and anterior-posterior forces; an imbalance between these forces acts to destabilise the glenohumeral joint (Labriola *et al.*, 2005). The rotator cuff muscle group, due to its arrangement and short moment arm, has been established by researchers (Blasier *et al.*, 1997; Itoi *et al.* 1994; Labriola *et al.* 2005) to be ideally positioned to ensure joint stability. Pathology affecting the rotator cuff has been established to disrupt the force balance about the shoulder joint resulting in altered muscle activation patterns of surrounding musculature as a compensatory mechanism in an attempt to maintain stability (Veeger & Van der Helm, 2007). Establishing a comprehensive understanding of the role of surrounding musculature such as the rotator cuff to joint stability and the influence this imparts on the pathomechanics of shoulder injuries has become of increasing interest for researchers with numerous invivo and invitro methods utilised (Blasier *et al.,* 1997; Itoi *et al.,* 1994; Labriola *et al.,* 2005; Steenbrink, de Groot, Veeger, Van der Helm & Rozing, 2009; Yanagawa *et al.,* 2008).

In vitro approaches to establish rotator cuff contribution to joint stability

Research (Blasier *et al.,* 1992; Blasier *et al.,* 1997; Itoi *et al.,* 1994) has been undertaken by researchers investigating shoulder stability in cadaver specimens to enable such findings to inform both researchers and clinicians on the role of surrounding shoulder musculature. In vitro research can be undertaken in isolation to investigate shoulder stability (Blasier *et al.,* 1992; Blasier *et al.,* 1997; Itoi *et al.,* 1994), or be used to define muscle moment arms to aid in providing more detailed information for computer modelling and simulation (Hughes, Niebur, Liu & An, 1998; Klein Breteler, Spoor & Van der Helm, 1999).

Itoi *et al.* (1994) conducted an investigation to determine the relative contributions of the rotator cuff and biceps brachii to the dynamic stability of the shoulder with the arm in an abducted and externally rotated position. Such joint positioning is representative of the cocking phase in throwing and pitching movements which is associated with anterior translation of the humeral head and associated joint instability (Meister, 2000). Thirteen shoulder cadavers were used with the tendons of interest simulated using strings orientated in the direction of muscle force. Measurements were made with the humerus rotated at 60, 90 and 120 ° external rotation with each of the strings loaded using forces proportional to the muscle physiological cross-sectional area. The position of the humeral head was then recorded before and after the application of an external force of 1.5 kg. Itoi *et al.* (1994) established that when the shoulder joint capsule was intact, subscapularis was found to be the least important anterior stabiliser, with the biceps increasingly contributing to anterior joint stability, more so than the rotator cuff as the capsuloligamentous integrity of the shoulder decreased.

Following on from the work of Itoi *et al.* (1994), Blasier *et al.* (1997) investigated the role of the glenohumeral and coracohumeral ligaments, as well as the surrounding musculature play in posteriorly stabilising the glenohumeral joint. Eight cadaver specimens were positioned at 90 ° forward flexion with forces mechanically applied. Several trials were conducted incorporating different configurations of ligament and capsular cuts, humeral rotation and levels of muscle force. Joint stability was established by measuring the force required to sublux the humeral head. Blasier *et al.* (1997) established that subscapularis contributed most to the subluxation force, with the long head of the biceps reported to aid in reducing the subluxation force at certain positions.

The work of Blasier *et al.* (1992), Blasier *et al.* (1997) and Itoi *et al.* (1994) provides researchers and clinicians with a greater understanding of the contribution of surrounding shoulder musculature to shoulder stability, however, the ability to generalise findings is limited. It is well documented that the in vitro mechanical properties of biological structures are known to differ to those *in vivo*, with cadaver specimens typically associated with an elderly, inactive population (Krosshaug *et al.*, 2005). Researchers (Labriola *et al.*, 2005; Steenbrink *et al.*, 2009; Yanagawa *et al.*, 2008) have instead investigated shoulder joint stability using *in vivo* methods to aid in increasing the ability to generalise findings to the greater population.

In vivo approaches to establish rotator cuff contribution to joint stability

Similar to in vitro research, several *in vivo* investigations (Gatti *et al.*, 2007; Graichen *et al.*, 2001; Holzbaur, Delp, Gold & Murray, 2007; Juul-Kristensen *et al.*, 2000) have been undertaken to establish the moment arms of the shoulder musculature. Frequently this information is used to aid in increasing the validity of existing computer models of the upper limb (Dickerson *et al.*, 2007; Holzbaur *et al.*, 2005; Van der Helm, 1994), to enable researchers (Labriola *et al.*, 2005; Steenbrink *et al.*, 2009; Yanagawa *et al.*, 2008) to run simulations to estimate the contributions of muscles to shoulder stability. Within these studies the contribution of individual muscles to shoulder stability can be indirectly estimated from the associated muscle force as the ratio of the anterior-posterior and superior-inferior shear force components to the compressive force component (Yanagawa *et al.*, 2008). Findings from both Yanagawa *et al.* (2008) and

Steenbrink *et al.* (2009) support prior knowledge regarding the contribution of the shoulder cuff during relatively controlled conditions. Using the model of Van der Helm (1994), Yanagawa *et al.* (2008) established that during abduction the rotator cuff muscles due to their line of action were ideally positioned to generate compressive force. Steenbrink *et al.* (2009) applied the Holzbaur *et al.* (2005) model to simulate rotator cuff pathology and established that an isolated tear of supraspinatus increased the effort of surrounding musculature by 8 % but did not result in shoulder instability. Validating such investigations is influenced by limitations of the computer models used which may only be suitable for static situations (Holzbaur *et al.,* 2005), are not population scalable (Van der Helm, 1994) and make assumptions regarding the physiology of the shoulder joint complex (Dickerson *et al.*, 2007; Holzbaur *et al.*, 2005; Van der Helm, 1994).

Establishing the contribution of musculature to joint stability in other joints of the body (Bergmark, 1989; Cholewicki & McGill, 1996; Derouin & Potvin, 1990; Granata & Wilson, 2001; Potvin & Derouin, 2005; Potvin & Brown, 2005; Stokes & Gardner-Morse, 2001; Stokes & Gardner-Morse, 2003) has resulted in several methods (Bergmark, 1989; Cholewicki & McGill, 1996; Granata & Wilson, 2001; Potvin & Brown, 2005; Stokes & Gardner-Morse, 2003) proposed which, whilst not reliant on existing computer models, have to the author's knowledge not been applied to the shoulder. Bergmark (1989) calculated the mechanical stability of a muscular system applying the assumption that the system must be in mechanical equilibrium when the potential energy of the entire system is at a minimum. Methods incorporating the energy approach acknowledge that a muscle can contribute to the potential energy during a perturbation and subsequent length change by either storing or releasing energy related to the physiological properties of the muscle, namely its stiffness, and through performing work. As muscle stiffness has a relationship with joint stabilisation, the contribution of an individual muscle to joint stability can be estimated. The energy approach originally presented by Bergmark (1989) was subsequently adapted by Cholewicki & McGill (1996) and Granata & Wilson (2001) who have demonstrated the relationship between muscle moment arm, length and stiffness, presenting methods to accurately establish the muscle contribution to joint stability, however this is limited to one flexor-extensor pair.

Potvin & Brown (2005) proposed and assessed a new approach for quantifying individual muscle contributions to joint stability about the three axes of a particular joint, subsequently enabling the estimation of total joint stability in a multi-muscle system. This approach has successfully been applied to the spine, hip and knee (Derouin & Potvin, 1990; Potvin & Derouin, 2005; Potvin & Brown, 2005), to provide researchers with an increased understanding of the stabilising potential of muscles in regards to injury. Potvin & Brown (2005) advocated the benefits of this approach due its ability to be applied to any two or three dimensional biomechanical analysis if the following is known: the origin and insertion coordinates of a muscle in relation to the joint of interest, muscle force and muscle stiffness. As this method relies on a state of static equilibrium, individual muscle forces must be first determined so that the net moment about each axis is zero. The benefit of this approach over other methods (Bergmark, 1989; Cholewicki & McGill, 1996; Granata & Wilson, 2001) is that whilst it only provides an estimate of a muscle's direct contribution to stability, it can be broken down two components: the capacity to generate force, and the geometric stability occurring due to the orientation of the muscle. As acknowledged by Potvin & Brown (2005), further development of this method would provide a more comprehensive understanding of muscle contribution to joint stability through acknowledging that, at particular joints, such as the shoulder, muscle force will also contribute to increasing axial compressive force.

Study aim

As the rotator cuff plays an integral role in providing dynamic shoulder joint stability, identifying the contribution of each individual muscle assists in providing researchers with a greater understanding of the pathomechanics of injury. To date, research (Labriola *et al.*, 2005; Steenbrink *et al.*, 2009; Yanagawa *et al.*, 2008) has focused on establishing the contribution of muscles through largely utilising methods in conjunction with computer simulations lacking ecological validity. The aim of this investigation was to design a comprehensive, cricket specific shoulder model incorporating findings from chapters 4, 5 and 6, to enable the application of the method of Potvin & Brown (2005) to establish the contribution of individual rotator cuff muscles to shoulder joint stability during the bowling delivery which may be incorporated into any future 3D kinematic analysis. By applying the model to an ex-county cricketer with a documented history of shoulder pathology affecting his bowling shoulder, data collected within this investigation was used to first, establish the role of each individual rotator cuff muscle to shoulder joint stability, and second, in keeping with the findings of altered bowling behaviour by Ranson & Gregory (2008), identify phases of the bowling delivery which place the shoulder at an increased risk of injury.

Method

The CSBT Shoulder Model

Model interface:

The CSBT shoulder model (Shorter, 2011, unpublished program)(Figure 7.1) was created within LabVIEW™ 2009 (National Instruments, Austin, USA) to interface with program files from Vicon Motus 9.2 (Vicon, Los Angeles, USA). The following is a concise explanation of the underlying theoretical concepts and explanation of how they have been applied to the CSBT shoulder model with a more comprehensive explanation provided in Appendix K. The software was programmed to be modular (Figure 7.2) to enable calculation of shoulder kinematics and kinetics, along with including muscle modelling parameters to enable calculation of the role of individual shoulder musculature to joint stability using the method of Potvin & Brown (2005). Unlike current shoulder models used within biomechanical and ergonomic research (Dickerson *et al.*, 2007; Holzbaur *et al.*, 2005; Van der Helm, 1994) this is the first model designed to acknowledge the unique methodological issues specific to cricket bowling that may impair the accuracy of subsequent kinematic and kinetic calculations. As such the model incorporates methodological findings and recommendations in relation to the use of the acromion cluster (chapter 4), reconstructs scapula anatomical landmarks using the mCAST method (chapter 5) and defines the GJC centre functionally in relation to the scapula ACS using the SCoRE method (Ehrig *et al.*, 2006) (chapter 6).

Figure 7.1 CSBT shoulder model main window interface

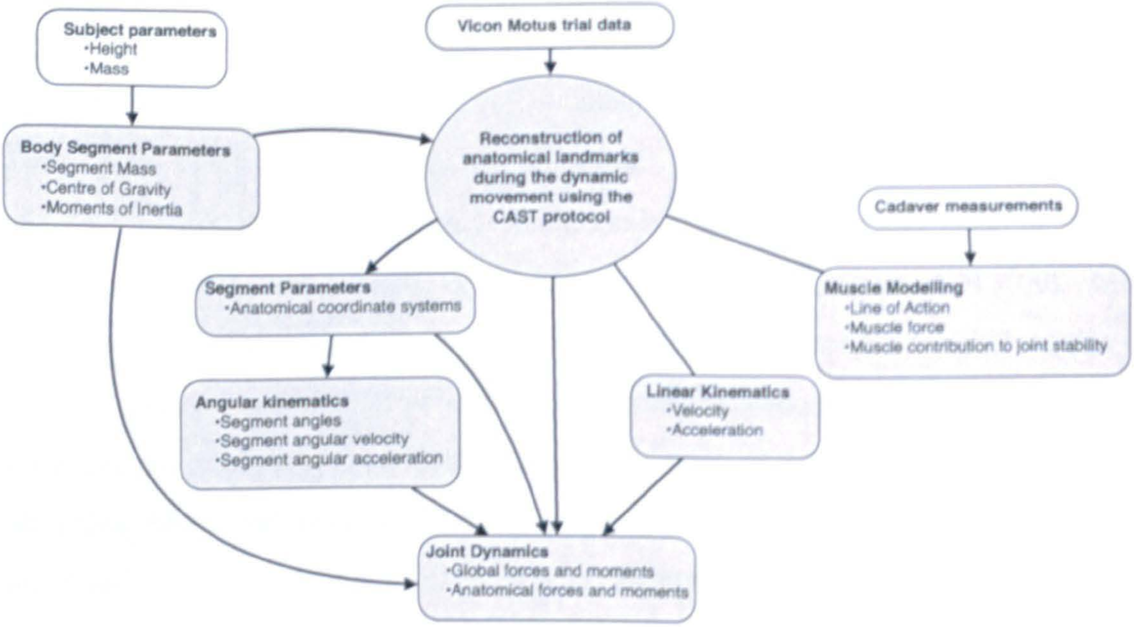


Figure 7.2 CSBT shoulder model flow diagram

Body segment parameter definitions:

The CSBT shoulder model uses subject anthropometric data to calculate segment mass, centre of gravity (COG) and moments of inertia for the hand, forearm, humerus and torso using the regression prediction equations of Zatsiorsky & Seluyanov (1983). To acknowledge the influence the ball would impart on calculations, the ball was incorporated into the hand segment prior to ball release whereby the mass of the ball was added to the mass of the hand and, the position of the COG was constrained dependant on the position of the ball in the hand using the equation:

$$P_{ball\&hand} = P_{handCOG} + \left((P_{ballCOG} - P_{handCOG}) * \left(\frac{mass_{hand}}{mass_{hand} + mass_{ball}} \right) \right) \quad \textbf{Equation 7.1}$$

Following ball release, the ball was removed from the model with the hand COG displacement data smoothed using a moving average filter during the period 5 frames before till 5 frames after ball release.

Segment parameter definitions:

The CSBT shoulder model is defined as a five segment model composed of the hand, forearm, humerus, scapula and thorax. To enable the accurate reconstruction of anatomical landmarks throughout the bowling delivery, the CSBT shoulder model incorporates both the CAST and mCAST protocols. Anatomical landmarks are subsequently used to define segment orientation and position using anatomical coordinate systems in accordance with ISB guidelines (Wu *et al.,* 2005).

Linear kinematics:

Linear kinematics for any anatomical landmark or segment COG are determined through differentiation using the central difference method. This enables the calculation linear velocity (equation 7.2) and acceleration (equation 7.3) at any instant in time where, given a time series of displacement data (p), n = sample at an instant in time and t= time between samples.

$$\dot{p}_{(n=1)} = \frac{-p_{n+2} + 4p_{n+1} - 3p_n}{2\Delta t}$$

$$\dot{p}_{(2 to n-1)} = \frac{p_{n+1} - p_{n-1}}{2\Delta t}$$

$$\dot{p}_{(n)} = \frac{p_{n-2} - 4p_{n-1} + p_n}{2\Delta t}$$

Equation 7.2

$$\ddot{p}_{(n=1)} = \frac{2p_n - 5p_{n+1} + 4p_{n+2} - p_{n+3}}{(\Delta t)^2}$$

$$\ddot{p}_{(n=2)} = \frac{p_{n+1} - 2p_n + p_{n-1}}{(\Delta t)^2}$$

$$\ddot{p}_{(n=3\,\mathrm{to}\,n-2)} = \frac{0.833(-p_{n+2} + 16p_{n+1} - 30p_n + 16p_{n-1} - p_{n-2})}{(\Delta t)^2}$$

$$\ddot{p}_{(n-1)} = \frac{p_{n-1} - 2p_{n-2} + p_{n-3}}{(\Delta t)^2}$$

$$\ddot{p}_{(n)} = \frac{-p_{n-3} + 4p_{n-2} - 5p_{n-1} + 2p_n}{(\Delta t)^2}$$

Equation 7.3

Angular kinematics:

To define anatomical joint angles the CSBT shoulder model utilises Euler and Cardan angle sequences in agreement with ISB recommendations (Wu *et al.*, 2005). Shoulder joint motion is described in relation to humerothoracic (equation 7.4), humeroscapular (equation 7.5) and scapulothoracic (equation 7.6) motion.

Humerothoracic - YXY sequence

$$\alpha = a\sin\frac{(y_{prox} \bullet x_{dis})}{\sin\beta}$$

$$\beta = a\cos(y_{prox} \bullet y_{dis})$$

$$\gamma = a\sin\frac{(x_{prox} \bullet y_{dis})}{\sin\beta}$$

Where:

$\alpha = \textit{plane of elevation}$

$\beta = \textit{angle of elevation}$

$\gamma = \textit{external}(-)/\textit{internal}(+)\ \textit{rotation}$

Equation 7.4

Humeroscapular - YXY sequence

$$\alpha = a\sin\frac{(y_{prox} \bullet x_{dis})}{\sin\beta}$$

$$\beta = a\cos(y_{prox} \bullet y_{dis})$$

$$\gamma = a\sin\frac{(x_{prox} \bullet y_{dis})}{\sin\beta}$$

Where:

$\alpha = \textit{plane of elevation}$

$\beta = \textit{angle of elevation}$

$\gamma = \textit{external}(-)/\textit{internal}(+)\ \textit{rotation}$

Equation 7.5

Scapulothoracic - YXZ sequence

$$\alpha = a\sin\frac{(z_{prox} \bullet x_{dis})}{\cos\beta}$$
$$\beta = -a\sin(z_{prox} \bullet y_{dis})$$
$$\gamma = a\cos\frac{(y_{prox} \bullet y_{dis})}{\cos\beta}$$

Where:

$\alpha = anterior(-) / posterior(+)\ tilt$

$\beta = lateral(-) / medial(+)\ rotation$

$\gamma = retraction(-) / protraction(+)$

Equation 7.6

To avoid the influence gimbal lock may impart when using segment Euler angles to calculate segment velocities and accelerations, segment angular velocity was instead calculated using Poisson's equation (Zatsiorsky, 1998). Using Poisson's equation, a skew-symmetric matrix defining segment velocity is expressed as the derivative of orthogonal segment rotational matrices whereby:

$$[\dot{\omega}] = [\dot{R}][R]^T$$

Equation 7.7

where R is the 3 × 3 segment rotation matrix defined by the anatomical coordinate system and $\dot{R}$ is the differentiation of R (Craig, 2005).

Calculation of segment angular acceleration can then be calculated using finite difference equations (Winter, 1994):

$$\ddot{\omega}_{(n=1)} = \frac{-\dot{\omega}_{n+2} + 4\dot{\omega}_{n+1} - 3\dot{\omega}_n}{2\Delta t}$$
$$\ddot{\omega}_{(2\,to\,n-1)} = \frac{\dot{\omega}_{n+1} - \dot{\omega}_{n-1}}{2\Delta t}$$
$$\ddot{\omega}_{(n)} = \frac{\dot{\omega}_{n-2} - 4\dot{\omega}_{n-1} + \dot{\omega}_n}{2\Delta t}$$

Equation 7.8

Joint dynamics:

Calculation of shoulder joint dynamics is based on a three segment linked model in agreement with Dickerson *et al.* (2007). Applying Newton' second law of motion to each segment, global joint forces are calculated as:

$$\sum F = m_{segment} \times a_{COGsegment}$$

$$where:$$

$$R_{proximalsegment} - R_{distalsegment} = m_{segment} \times a_{COGsegment}$$

Equation 7.9

Therefore, this equation acknowledges the influence external forces such as those acting on the distal ($R_{distalsegment}$) and proximal ($R_{proximalsegment}$) ends of the segment imparts on force calculations. Similarly joint torques are calculated using the angular analog of Newton's second law (Dickerson *et al.*, 2007):

$$\sum M = \dot{H}$$

Equation 7.10

Where M refers to the global joint torque which is dependant on the rate of change of angular momentum ($\dot{H}$) applied about a point of application relative to the segment's COG. Global joint forces and moments are subsequently expressed anatomically in relation to the segment anatomical axes using the rotation matrix.

$$_{ACS}F(t) = {}^{ACS}_{GCS}R(t)^{-1}\,{}_{GCS}F(t)$$
$$_{ACS}M(t) = {}^{ACS}_{GCS}R(t)^{-1}\,{}_{GCS}M(t)$$

Equation 7.11

Due to the range of motion of the shoulder observed during bowling, anatomical shoulder joint forces and moments were expressed in relation to the scapula ACS rather than the humerus ACS. As no standardised convention for reporting upper body joint kinetics exists, researchers have previously defined the compressive joint torque in relation to either the y-axis (long axis)(Feltner & Dapena, 1986) or z-axis (medial-lateral axis)(Reid, Elliott & Alderson, 2007) of the humerus ACS depending on the movement of interest. To avoid the sensitivity of joint axes depending on humerus position, for instance whether it be above or below the horizontal, and the influence this would impart of the direction of calculated joint kinetics, the scapula ACS was chosen to define shoulder joint kinetics due to its relatively constant orientation.

Muscle parameters:

The CSBT shoulder model models infraspinatus, supraspinatus, subscapularis, teres minor and the long head of the biceps (LHB). Each muscle is modelled as a series of elements representative of the orientation of muscle fibre bundles and defined at each instant of time during the movement of interest. For the purpose of this model, the LHB insertion is modified to insert as it travels through the intratubercular groove between the greater and lesser tubercles of the humerus to prevent the need to model it as a bi-articular muscle. The intratubercular groove was defined as the midpoint between the cadaver based insertions for infraspinatus and supraspinatus (greater tubercle) and subscapularis (lesser tubercle).

Whilst it is acknowledged that *in vitro* muscle properties differ to those *in vivo* (Krosshaug *et al.,* 2005), the CSBT shoulder model incorporates the cadaver data from a 57 year old male published by Klein Breteler (1996) to define muscle modelling parameters. In comparison to data utilised in other shoulder models (Dickerson *et al.,* 2007; Holzbaur *et al.,* 2005; Van der Helm, 1994), the data set from Klein Breteler (1996) presents a comprehensive, anatomically based data set related specifically to the shoulder whose age, gender and anthropometric data most closely relates to the cricket bowler. To individualise muscle origins and insertions to the bowler under investigation, muscle attachments published by Klein Breteler (1996) are scaled using the formula proposed by Matias, Andrade & Veloso (2009):

$$T(x) = BA^{-1}x \qquad \textbf{Equation 7.12}$$

Where T(x) refers to the scaled muscle attachment site, which is calculated in relation to a 3 × 3 matrix of the cadaver bony landmarks (A), a 3 × 3 matrix of the same subject specific bony landmarks (B) and, the cadaver based muscle attachment site (x) expressed as a position vector.

The path of each muscle element was calculated at each instant of time. In agreement with Van der Helm, Veeger, Pronk, Van der Woude, & Rozendal (1992), the LHB tendon was modelled as a straight line. As each rotator cuff muscle wraps around the head of the humerus, the head of the humerus in agreement with other shoulder models (Dickerson *et al.*, 2007; Holzbaur *et al.*, 2005; Van der Helm, 1994) was assumed to be a sphere, using the scaled measurements of Klein Breteler (1996). In doing so, the line of action for each rotator cuff muscle element could be defined by four points, referred to as nodes; the origin, the point at which the muscle begins to wrap around the head of the humerus, the point at which the muscle ceases to wrap around the head of the humerus and the muscle insertion. The nodes at which the muscle begins and ceases to wrap around the head of the humerus were calculated using the obstacle-set method proposed by Garner & Pandy (2000). The obstacle-set method calculates the minimum-distance path around a single sphere by creating a plane between the origin, insertion and sphere centre, allowing the nodes at which the tendon begins and ceases to wrap around the sphere to be calculated using circle tangency equations (Garner & Pandy, 2000).

Maximum muscle force for each muscle element is limited by parameters such as the contraction velocity, optimal muscle length and fibre composition characterised by the physiological cross-sectional area (PCSA) (Favre, Sheikh, Fucentese & Jacob, 2005). For the CSBT shoulder model, muscle element PCSA (cm^2) is defined using the reported values of Klein Breteler (1996) and used to determine the maximum muscle force (N) using the equation k* PCSA, where k is a constant factor of 68.94 $N.cm^{-2}$ (Wood, Meek & Jacobsen, 1989)

Contributions of individual muscles to joint stability

The CSBT shoulder model calculates an individual muscle's contribution to shoulder joint stability using the method of Potvin & Brown (2005). This method provides an estimate of a muscle's contribution to stability through acknowledging a muscle's capacity to generate force and the geometric stability a muscle can provide due to its orientation in relation to the joint of interest.

Making the assumption that a joint is stable, the potential energy can be calculated as the elastic energy stored in a muscle, plus the work done by a muscle during a rotation, resulting in an equation:

$$U(m) = F\Delta\ell + \frac{1}{2}k\Delta\ell^2$$

$$\begin{aligned}
&where:\\
&U(m) = sum\ of\ the\ energy\ stored\ and\ work\ done\ by\ a\ muscle\\
&F = muscle\ force\\
&\Delta\ell = change\ in\ muscle\ length\ for\ a\ perturbation\\
&k = muscle\ stiffness
\end{aligned}$$

Equation 7.13

Assuming the external work is negligible, applying a Taylor Series expansion and calculating the second derivative the total stability about each axis for a muscle modelled as a straight line can be calculated as:

$$S(x) = \sum_{m=1}^{N} F_m \left[\frac{A_y B_y + A_z B_z - r_x^2}{l} + \frac{q r_x^2}{L} \right]_m$$

$$S(y) = \sum_{m=1}^{N} F_m \left[\frac{A_z B_z + A_x B_x - r_y^2}{l} + \frac{q r_y^2}{L} \right]_m$$

$$S(z) = \sum_{m=1}^{N} F_m \left[\frac{A_x B_x + A_y B_y - r_z^2}{l} + \frac{q r_z^2}{L} \right]_m$$

Equation 7.14

Where *AxAyAz* and *BxByBz* refer to the muscle origin and insertion nodes expressed in relation to the GHJ, *l* refers to the length between the origin and insertion, *L* refers to the total length of the muscle, *q* is the proportionality constant relating muscle force and length to stiffness and *r* is the functional moment arm. Whilst it is acknowledged that their is a non-linear relationship between muscle stiffness and force, in agreement with Potvin & Brown (2005), *q* for each muscle was assumed to be 10. For each rotator cuff muscle, due to nodes changing the muscle line of action, the stability equations were expanded and modified to assume the muscle line of action was defined by three segments: from the origin to the point at which the muscle begins to wrap around the head of the humerus, from when the muscle begins to when it ceases to wrap around the head of the humerus and, from when the muscle ceases to wrap around the head of the humerus to the muscle insertion. Once the contribution of each muscle to joint stability was calculated about each axis in the global coordinate system, this was subsequently expressed in relation to the scapula ACS in keeping with shoulder joint kinetics.

Case Study

Participant:

To apply the CSBT shoulder model to establish the contribution of the individual rotator cuff tendons to shoulder joint stability during the bowling delivery, following University of Chichester ethical approval, a retired right armed wrist spinner with a history of shoulder injuries was recruited and provided informed consent. The physical attributes (age, height and mass) of the bowler were 36 years of age, 1.83 m and 83 kg. Throughout the bowler's career in both second XI county and premier league cricket the bowler had experienced chronic shoulder pathology resulting in surgical repair to the rotator cuff tendons and, subsequent re-stabilisation and manipulation under anaesthesia.

Equipment:

Data collection was conducted at the Old Chapel Biomechanics Laboratory at the University of Chichester. To record the kinematics of the bowling delivery, six 150 Hz Basler cameras (Basler A602fc-2, Germany) synchronised using a MX Ultranet control unit (Vicon, Oxford, UK) were positioned around the bowling crease. A multiple calibration procedure incorporating a 16-point calibration frame (Peak Performance Technologies Inc., Colorado, USA) was positioned over the bowling crease to provide a calibrated volume of 2.430 m × 0.900 m × 1.259 m with a associated residual calibration error of 0.0198 m.

To analyse skeletal movement, surface retroflective markers (10 mm diameter) were placed on the thorax and right arm of the bowler in accordance to the CBST marker set (refer to Appendix K). Each segment was defined dynamically by a minimum of three markers affixed to semi-rigid, thermoplastic material. To aid in increasing the reflectivity of the dynamic marker set (Figure 7.3) whilst ensuring natural skin movement, 1 mm thick, black latex was adhered to the skin, with each cluster affixed on top.

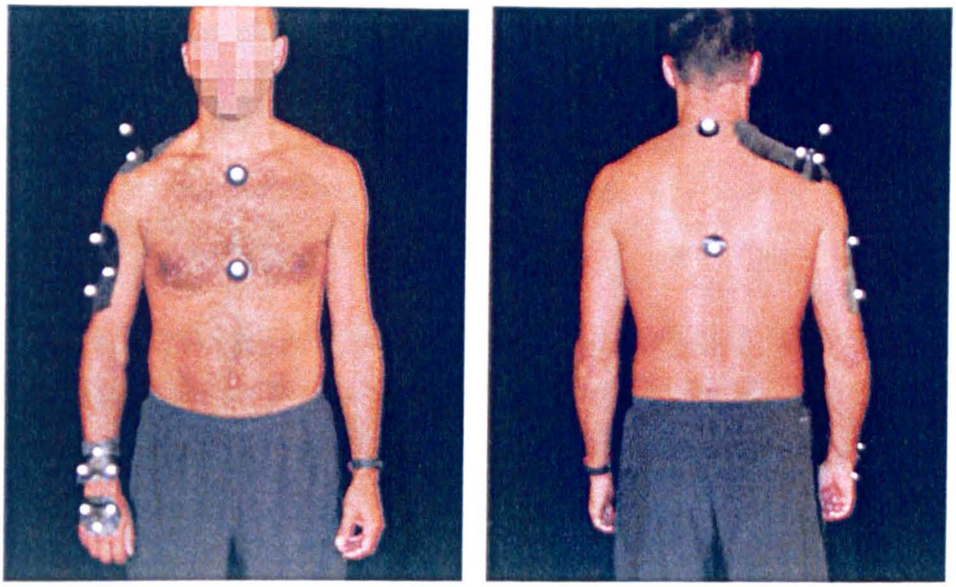


Figure 7.3 CSBT dynamic marker set

The CSBT marker set required the collection of several static trials to define anatomical landmarks using both the CAST and mCAST protocols. For each scapula anatomical landmark defined using the mCAST protocol described in chapter 5, an accelerometer system composed of two, tri-axial accelerometers (ADXL335, Analog Devices, Norwood, USA) positioned on the humerus and C7, were used to establish the five static positions reflective of the bowling delivery. As the ball was modelled as part of the hand segment within the CSBT shoulder model, a static trial was captured with the bowler holding the ball in a manner reflective of the grip used when bowling to enable subsequent calculation of the segment COG. In addition, incorporating the findings of chapter 6, the shoulder joint centre was defined functionally using the SCoRE method (Ehrig *et al.*, 2006) in conjunction with the star arc movement.

Testing procedure:

Following an adequate warm up and habituation with the testing environment, the bowler was instructed to bowl both legbreak and googly deliveries. Throughout data collection the bowler was advised to spin the ball and bowl with the same velocity that they would achieve during match conditions. Each delivery was monitored for both line and length, with the bowler providing subjective feedback to ensure that five appropriately matched deliveries for each ball were collected for subsequent analysis.

Data processing:

All static calibration trials were digitised and processed within Vicon Motus 9.2 software (Vicon, Los Angeles, USA). Each marker was digitised for one frame of interest, to provide raw three-dimensional spatial co-ordinates to enable anatomical landmarks to be defined into the relevant segment cluster technical coordinate system.

For each type of delivery, three trials associated with minimal marker dropout were digitised and processed within Vicon Motus 9.2 software (Vicon, Los Angeles, USA). Each dynamic bowling trial was processed in agreement with Chin *et al.* (2009) using a quintic spline filter (Woltring, 1986) with a mean square error of 0.20 m defined by residual analysis. To minimise the influence of back foot contact and front foot contact attenuating noise due to the composition of the acromion cluster, acromion marker cluster co-ordinate position data during each impact was smoothed though extrapolating from 5 frames prior to 5 frames after impact.

All data were then exported into a custom program, CSBT shoulder model (Shorter, 2011, unpublished program) (Appendix K) created using LabVIEW™ 2009 (National Instruments, Austin, USA) where following reconstruction of anatomical landmarks, analysis of shoulder joint motion and the role of the rotator cuff muscles during the bowling delivery could be established.

Data analysis:

Data analysis was conducted within Microsoft Excel (Microsoft Inc., Richmond, USA) where the bowling delivery was defined temporally into four phases (refer to chapter 3). To establish variance within each type of delivery, RMSE was calculated for both shoulder angular kinematics and dynamics (forces and moments) due to the dependent nature between these variables on subsequent calculations. Due to small sample sizes, comparisons between the legbreak and googly in relation to establishing the role of the shoulder and surrounding musculature during the bowling delivery was undertaken using descriptive statistics to avoid violations of statistical assumptions.

Results and Discussion

Bowling delivery variability

Whilst previous research by both Stuelcken *et al.* (2010) and Chin *et al.* (2009) advocated the use of one and three trials respectively as being representative of a bowler's technique, findings from this investigation suggests caution must be taken when using small trial numbers within future investigations. Although experimental measures were undertaken to aid in minimising variability between deliveries through monitoring of delivery speed (Table 7.1), line and length as suggested in chapter 3, large RMSE (Table 7.2) was observed. Similar variability for both the legbreak and googly suggests that for complex biomechanical analysis, researchers must recognise that the highly variable nature of the bowling motion may prevent the collection of a homogenous sample of deliveries. In agreement with (Chin *et al.*, 2009), low variability in relation to angular kinematics as defined by humerothoracic, humeroscapular and scapulothoracic angle RMSE advocates the use of three controlled deliveries for simple kinematic analysis of upper body bowling technique, however analysis incorporating inverse dynamics exhibits greater sensitivity to variability. With the above in mind, for both the legbreak and googly, two of the three deliveries demonstrating the lowest variability in relation to the average delivery were incorporated for subsequent analysis.

Table 7.1 Bowling delivery descriptive variables

Type of delivery		Ball velocity ($m.s^{-1}$)	Duration of bowling phases (s)			
			PDS to BFC	BFC to FFC	FFC to BR	BR to FT
Legbreak	1	18.69	0.09	0.35	0.05	0.13
	2	18.93	0.09	0.34	0.04	0.12
	3	18.13	0.14	0.33	0.05	0.13
Googly	1	18.17	0.10	0.34	0.07	0.12
	2	19.16	0.11	0.33	0.07	0.12
	3	19.65	0.09	0.34	0.07	0.12

Table 7.2 RMSE associated with the legbreak and googly deliveries

	Legbreak	Googly
Humerothoracic Angle		
Plane of elevation	1.92 ± 1.34 °	2.06 ± 1.47 °
Angle of elevation	2.50 ± 1.10 °	3.56 ± 1.40 °
Internal/External rotation	2.50 ± 1.33 °	3.80 ± 2.18 °
Humeroscapular Angle		
Plane of elevation	3.49 ± 2.11 °	2.07 ± 1.03 °
Angle of elevation	2.77 ± 1.98 °	1.50 ± 0.82 °
Internal/External rotation	5.73 ± 2.67 °	1.95 ± 1.11 °
Scapulothorcic Angle		
Posterior/Anterior tilt	7.07 ± 4.02 °	4.28 ± 2.78 °
Medial/Lateral rotation	4.56 ± 2.65 °	1.58 ± 1.55 °
Protraction/Retraction	2.04 ± 1.21 °	2.40 ± 1.25 °
Shoulder force		
Anterior/Posterior	281.53 ± 187.93 N	126.15 ± 73.75 N
Superior/Inferior	261.71 ± 156.84 N	190.14 ± 161.52 N
Distraction/Compression	131.93 ± 66.35 N	119.96 ± 85.80 N
Shoulder torque		
Adduction/Abduction	43.54 ± 31.92 Nm	37.12 ± 27.98 Nm
Internal/External rotation	84.59 ± 75.04 Nm	42.36 ± 31.39 Nm
Flexion/Extension	39.24 ± 23.86 Nm	26.15 ± 25.02 Nm

Shoulder motion during the bowling delivery

Normalised shoulder motion during the bowling delivery for both the legbreak and googly is shown in Figure 7.4, where regardless of the type of delivery shoulder motion was observed to be similar. Whilst for humerothoracic motion the angle of elevation during the bowling delivery was similar to that reported in chapter 3, both the plane of elevation and internal/external rotation was found to differ greatly. Although methodological differences may partly account for the differences observed it is believed that such variation is not as a consequence of experimental error and instead is a consequence of the individualised nature of the bowling delivery. This is supported by the small RMSE observed for all shoulder angles between the legbreak and googly which was much lower than the previously reported for within and between bowler variability observed in chapter 3. The sensitivity of these angles between bowlers, particularly internal/external humerothoracic rotation would be reflective of the differing techniques bowlers adopt to impart either greater speed or spin on the ball at release.

For both the legbreak and googly, humerothoracic motion was observed to place the humerus in front of the body (average plane of elevation: legbreak: 56.18 ± 0.24 °, googly: 53.44 ± 0.73 °). Throughout the bowling delivery the humerus was externally rotated in respect to the thorax, starting at its most externally rotated position during PDS to BFC (legbreak: -64.72 ± 1.76 °, googly: -63.99 ± 3.82 °). As the bowling delivery commences, external rotation decreases, with a temporary increase in external rotation coinciding with the lowest angle of elevation during the delivery (minimum angle of elevation: legbreak: 10.87 ± 0.10 °, googly: 13.68 ± 1.11 °) which would occur in conjunction with forearm supination. Following this period, the humerus continues to internally rotate reaching its minimum externally rotated position during FFC to BR (legbreak: -11.25 ± 2.41 °, googly: -17.18 ± 5.65 °).

In contrast to humerothoracic motion, the humerus was observed to be internally rotated in relation to the scapula (humeroscapular motion) throughout the majority of the bowling delivery (average internal/external rotation: legbreak: 14.96 ± 2.75 °, googly: 13.45 ± 0.66 °), with the joint only becoming externally rotated during the latter stages of BFC to FFC and early stages of FFC to BR. Rather than scapulothoracic motion making a large contribution to the observed humerothoracic motion, humerothoracic external rotation was largely influenced by the degree of posterior scapulothoracic tilt (average posterior tilt during the bowling delivery: legbreak: 60.18 ± 2.21 °, googly: 60.97 ± 1.09 °) and scapulothoracic retraction (average retraction during the bowling delivery: legbreak: -25.23 ± 0.01 °, googly: -26.25 ± 1.44 °). As this investigation focused solely on a bowler with a history of shoulder injuries, to gain an understanding of potential bowling specific compensation mechanisms adopted to account for alterations in glenohumeral joint range of motion, future research must seek to compare observed angular kinematics between bowlers with and without a history of shoulder injuries. In addition, findings from this investigation advocate that researchers aiming to establish the functional consequence of limited internal joint range of rotation observed in bowlers with shoulder injuries, must not rely solely on humerothoracic motion to quantify shoulder movement. Instead to gain a comprehensive understanding of shoulder motion, researchers must identify the contributions of both humeroscapular and scapulothoracic motion as it is acknowledged that deficits in humeroscapular motion is often compensated for by altered scapulothoracic motion (Borich *et al.*, 2006).

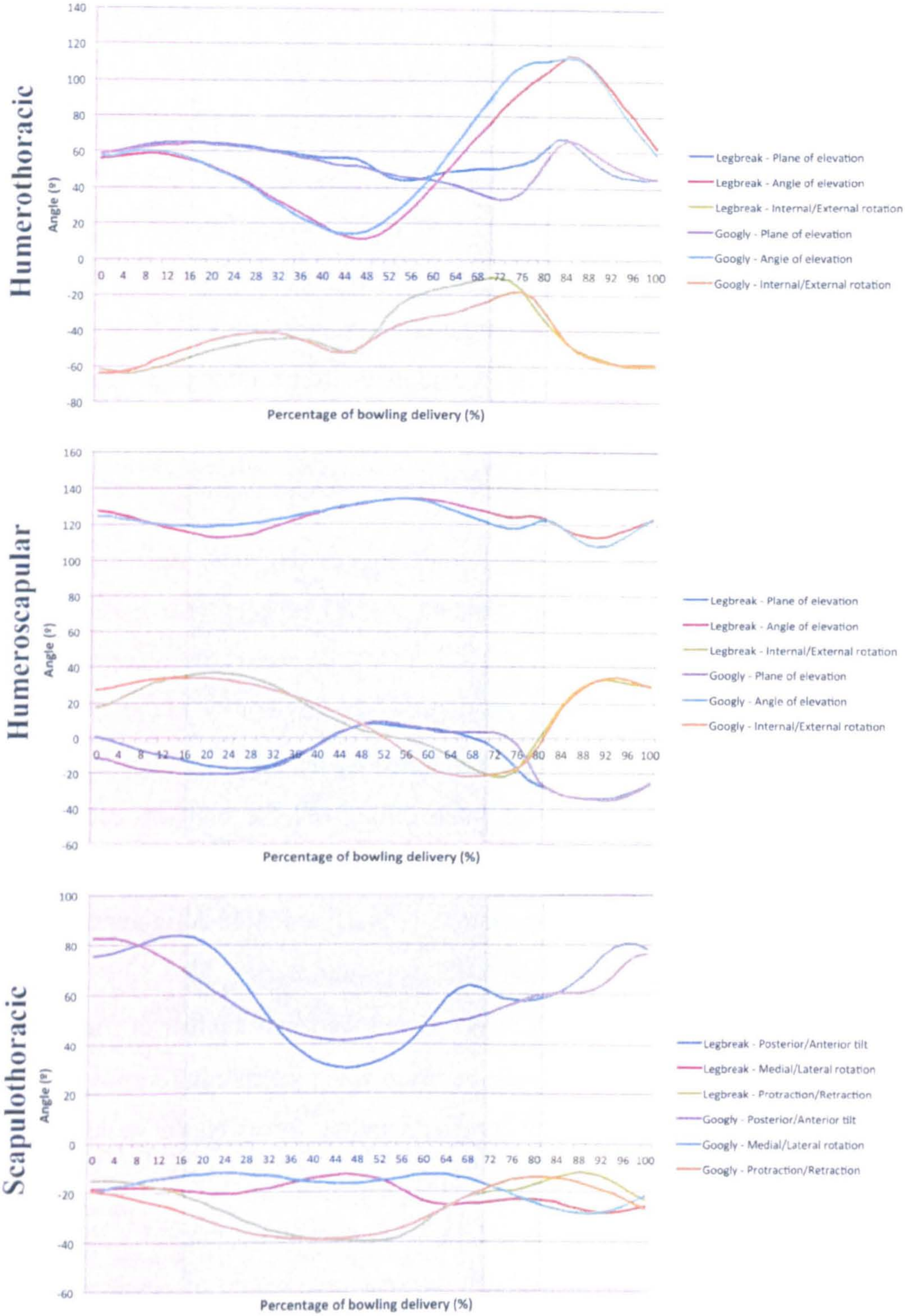


Figure 7.4 Mean shoulder angular position during the bowling delivery. Bowling phases (PDS to BFC: pink, BFC to FFC: blue, FFC to BR: green, BR to FT: yellow) are shown.

Joint Force

Mean shoulder joint forces observed during the legbreak and googly deliveries is shown in Figure 7.5. Although ball velocity at release (legbreak: 18.81 ± 0.17 $m.s^{-1}$; googly: 19.40 ± 0.35 $m.s^{-1}$), was less than that reported by Stuelcken *et al.* (2010) in a cohort of fast bowlers, peak shoulder distraction force was observed to be similar in magnitude (legbreak: 534.05 ± 28.11 N; googly: 590.17 ± 45.29 N). Whilst Stuelcken *et al.* (2010) reported peak shoulder distraction force of 599 ± 111 N occurred during the early stages of the follow through, within this investigation the occurrence of peak force was found to vary greatly between deliveries. Peak distraction force during the googly was established to occur earlier in the delivery (delivery 1: 2 %, delivery 2: 69 %), compared to the leg break delivery (delivery 1: 95 %, delivery 2: 64%).

Regardless of the direction of force, peak shear forces (legbreak: anterior/posterior: -1463.41 ± 179.84 N, superior/inferior: -1343.98 ± 32.47 N; googly: anterior/posterior: 1306.72 ± 18.42 N, superior/inferior: -791.92 ± 151.32 N) were observed to be greater than the peak distraction/compression force (legbreak: -630.26 ± 144.57 N; googly: 590.17 ± 45.29 N). This finding was also supported by the range of force experienced within each plane. Greater variation of force throughout the bowling delivery was associated with the legbreak (anterior/posterior: 2475.14 ± 299.10 N, superior/inferior: 2272.14 ± 213.73 N, distraction/compression: 1164.31 ± 116.46 N) compared to the googly (anterior/posterior: 2098.54 ± 56.67 N, superior/inferior: 1561.82 ± 166.12 N, distraction/compression: 1040.67 ± 28.76 N). Given the small number of trials used to define each type of delivery, caution must be taken when interpreting results, however, findings suggest that the legbreak delivery exerts greater forces on the shoulder which would place greater demands on the surrounding musculature to stabilise the joint. This finding is of particular importance as the legbreak constitutes the stock delivery for wrist spinners, and as such, combined with the repetitive nature of bowling, suggests that greater attention needs to be placed on educating bowlers to execute this form of delivery correctly to minimise potentially injurious forces.

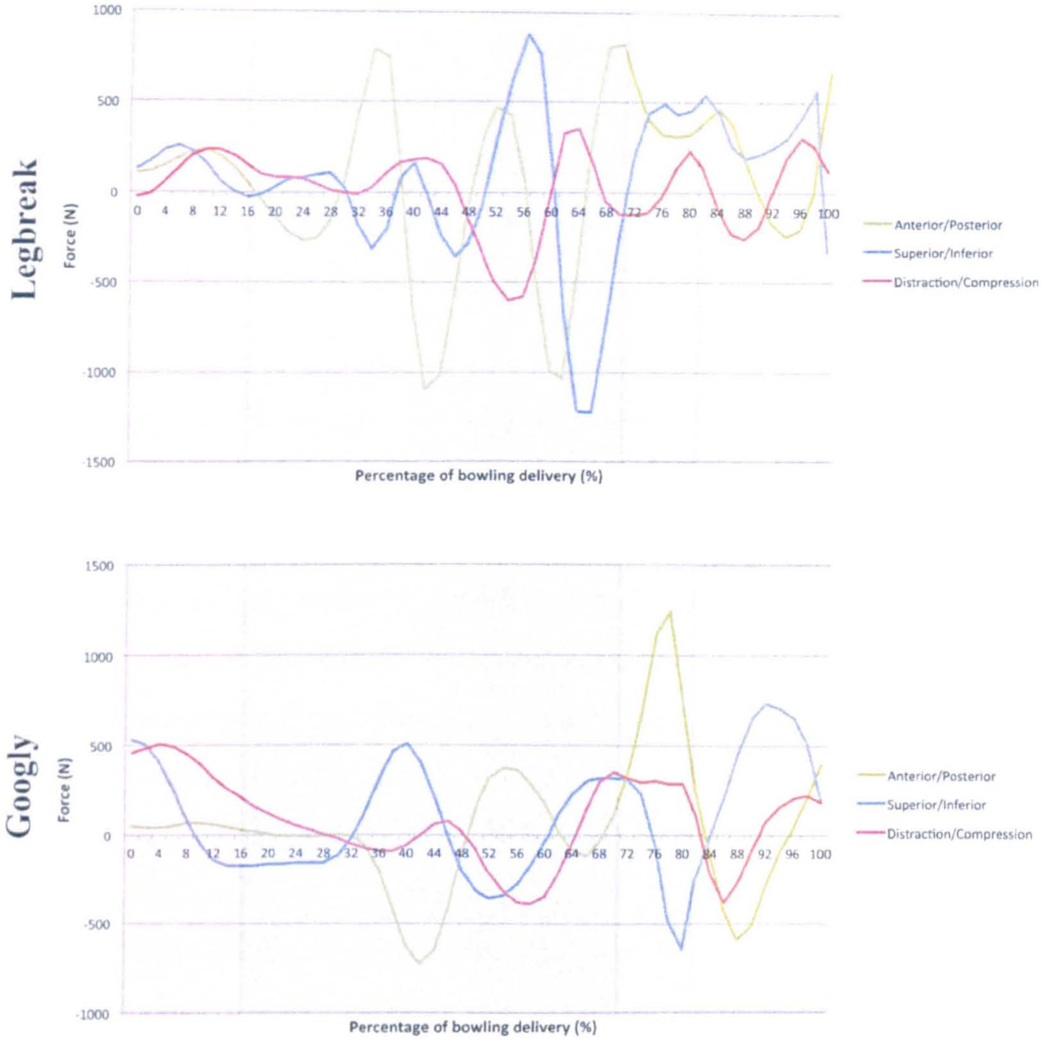


Figure 7.5 Mean shoulder force during the bowling delivery for both the legbreak and googly. Bowling phases (PDS to BFC: pink, BFC to FFC: blue, FFC to BR: green, BR to FT: yellow) are shown.

Whilst cricket research to date has focused solely on reporting peak shoulder distraction force (Stuelcken *et al.,* 2010) to quantify the load placed on the shoulder during the bowling delivery, findings from this investigation highlight that in order to gain greater understanding of the pathomechanics of shoulder injuries, researchers must acknowledge the multi-planar nature of the movement. Greater shear forces observed for both the legbreak and googly are in keeping with the bowling movement whereby the movement is characterised by the arm circumducting over a large range of motion whilst following parallel to the path of the body. As acknowledged by Yanagawa *et al.* (2008), shear force especially when exerted anteriorly and superiorly, and, greater in magnitude to the compressive force leads to anterior translation of the humeral head. Findings from this investigation therefore support that bowlers would be at increased risk of impingement injuries as acknowledged by Bell-Jenje & Gray (2005) and Myers & O'Brien (2001), but also the magnitude of shear forces would result in capsular adaptations typified by alterations in joint range of motion associated with bowlers characterised by increased external rotation and decreased internal rotation (Aginsky *et al.*, 2004; Bell-Jenje & Gray, 2005; Giles & Musa, 2008 and Stuelcken *et al.*, 2008).

Joint Torque

Variations in mean shoulder joint torques between the legbreak and googly deliveries can be observed in Figure 7.6. For both the legbreak and googly, internal/external rotation torques were established to be greater than those about the x-(abduction/ adduction) and z-(flexion/extension) axes. During both the legbreak and googly deliveries, abduction/adduction and flexion/extension torques were observed to remain low until BFC to FFC. During this phase, as the shoulder circumducts backwards though shoulder extension and adduction, both peak abduction/adduction torque (legbreak: -203.07 ± 50.00 Nm, googly: -149.26 ± 26.10 Nm) and peak flexion/ extension torque (legbreak: -176.98 ± 70.15 Nm, googly: -114.62 ± 18.01 Nm) were found to be greater in magnitude to that reported for the peak abduction torque (117 ± 34 Nm) during baseball pitching by Werner *et al.* (2001). For both types of delivery peak flexion torque was observed to occur following the peak extension torque (legbreak: 164.86 ± 56.02 Nm, googly: 130.28 ± 44.02 Nm) as the arm rapidly increased its angle of elevation approaching ball release.

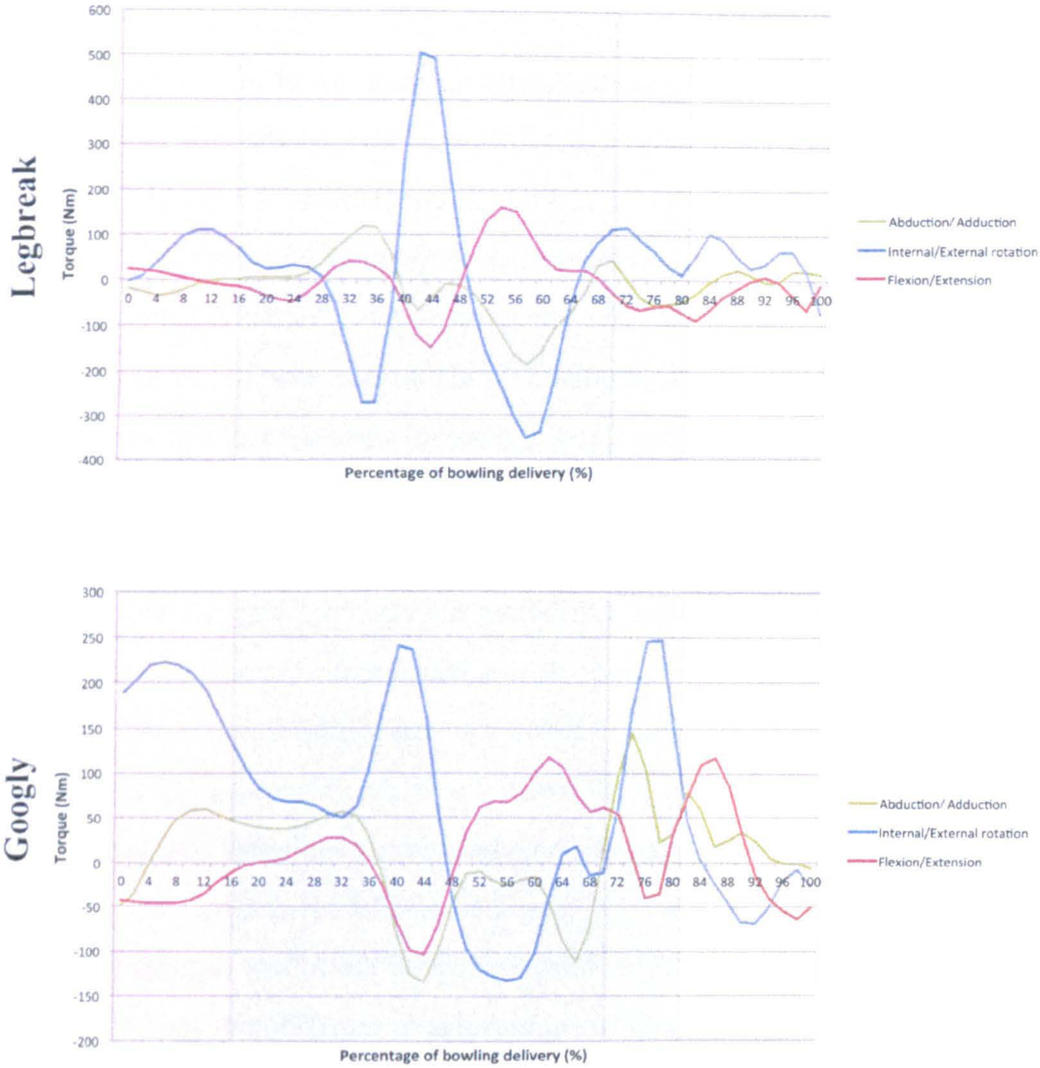


Figure 7.6 Mean shoulder torque during the bowling delivery for both the legbreak and googly. Bowling phases (PDS to BFC: pink, BFC to FFC: blue, FFC to BR: green, BR to FT: yellow) are shown.

Differences in internal/external torques between the legbreak and googly deliveries throughout the bowling delivery were observed and may be as a consequence of the torque placed on the shoulder due to the position of the wrist and forearm. In contrast to the windup phase in baseball where internal/external torques have been reported as negligible (Werner *et al.*, 2001), during the PDS to BFC average internal rotation torque was 65.48 ± 13.14 Nm for the legbreak and 204.50 ± 16.96 Nm for the googly. As the arm begins to uncoil rapidly through elbow extension and circumduction at the shoulder, for both deliveries internal rotation torque was observed to first decrease followed by a rapid increase coinciding with the peak internal rotation torque for the entire bowling delivery (legbreak: 657.99 ± 70.01 Nm, googly: 315.59 ± 71.83 Nm).

The large discrepancy in peak magnitude between the legbreak and googly may occur as a consequence of the different arm position adopted to execute each delivery. The legbreak requires the bowler at release to bowl with the palm of their hand facing the batsman enabling the bowler to impart anticlockwise spin on the ball through rapid adduction of the wrist (Woolmer *et al.,* 2008). In comparison, the googly due to its emphasis on deceiving the batsman demands that at the moment of release the back of the hand faces the batsman enabling the bowler to impart clockwise spin on the ball (Woolmer *et al.,* 2008). As peak internal rotation torque was observed to closely coincide with peak posterior shoulder force, at a period when the forearm would be in a pronated position as the arm approaches the horizontal, the subtle difference in forearm and wrist position can be perceived as a key contributing factor to destabilising shoulder stability during the bowling delivery. Attributing the observed large shoulder internal/ external torques to the potential causation of shoulder injuries in cricket bowlers would be in agreement with Aginsky *et al.* (2004) who associated bowlers with shoulder injuries as demonstrating low external rotator strength suggestive of a functional inability to oppose the large internal shoulder torques imparted on the shoulder throughout the bowling delivery. Whilst researchers (Bell-Jenje & Gray, 2005; Myers & O'Brien, 2001; Stuelcken *et al.,* 2010) have associated the follow through phase with contributing to the causation of shoulder injuries due to translation of the humeral head as the arm begins to decelerate, average shoulder torques were found to be minimal (legbreak: abduction/adduction: 3.36 ± 4.04 Nm, internal/external: 38.12 ± 43.86 Nm, flexion/extension: -32.42 ± 11.77 Nm; googly: abduction/adduction: 21.30 ± 0.12 Nm, internal/external: -28.97 ± 2.26 Nm, flexion/extension: 14.10 ± 16.88 Nm).

The role of the rotator cuff to joint stability during the bowling delivery

The contribution of each individual muscle to shoulder joint stability is shown in Figures 7.7 and 7.8 for the legbreak and googly respectively. Similar contributions to joint stability were observed between each type of delivery reflective of the similarity in shoulder joint kinematics due to the reliance of the method of Potvin & Brown (2005) on positional data. It is important to acknowledge that the contribution of each muscle to shoulder joint stability is only an estimate due to its dependance on maximal muscle force in its calculation (Potvin & Brown, 2005). This combined with modelling muscles as elements, whilst more anatomically correct may have resulted in the overestimation of the contribution of subscapularis (number of elements: 11) and potential underestimation of muscles such as the LHB (number of elements: 2).

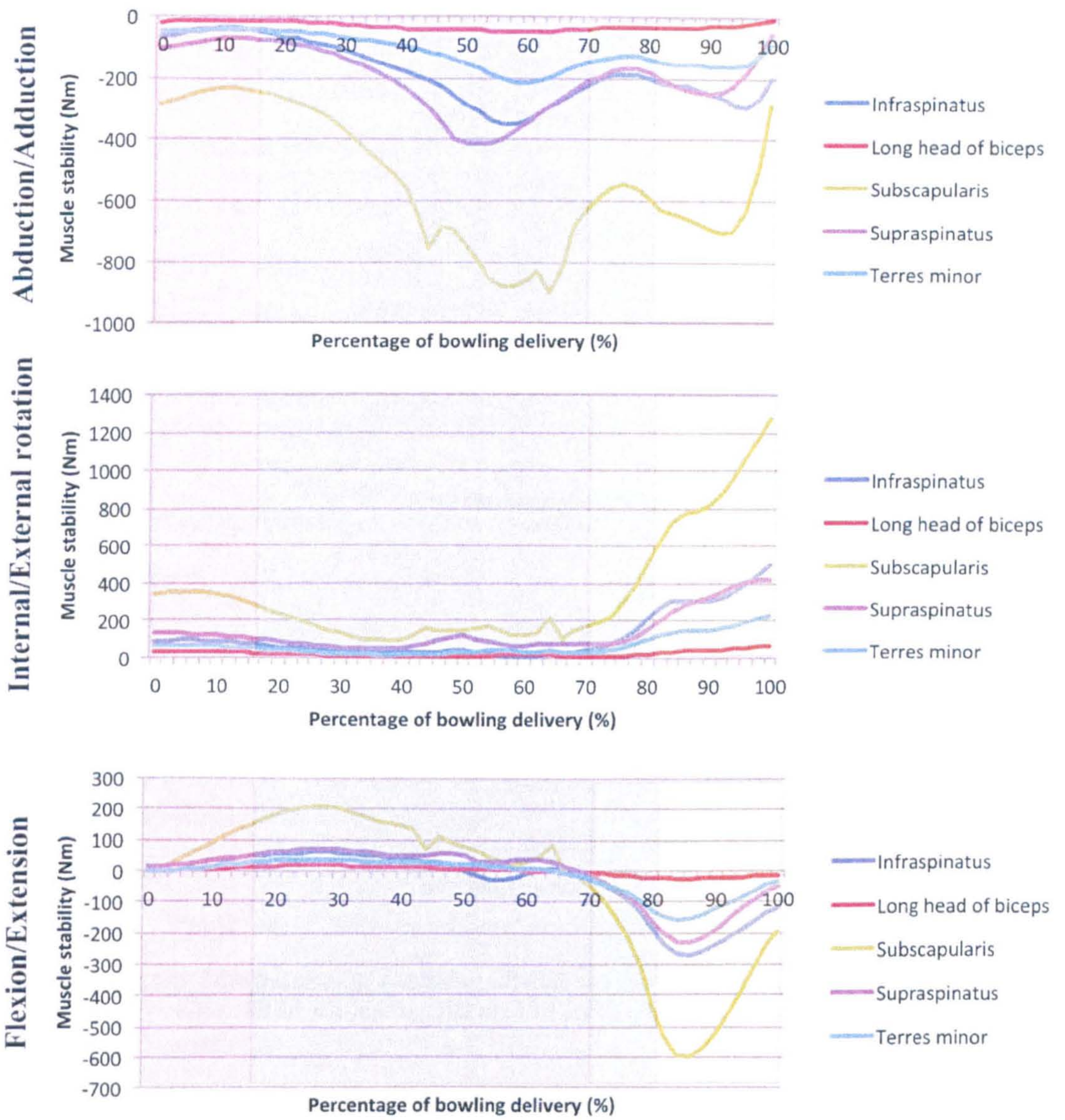


Figure 7.7 Mean muscle stability during the bowling delivery associated with the legbreak. Bowling phases (PDS to BFC: pink, BFC to FFC: blue, FFC to BR: green, BR to FT: yellow) are shown

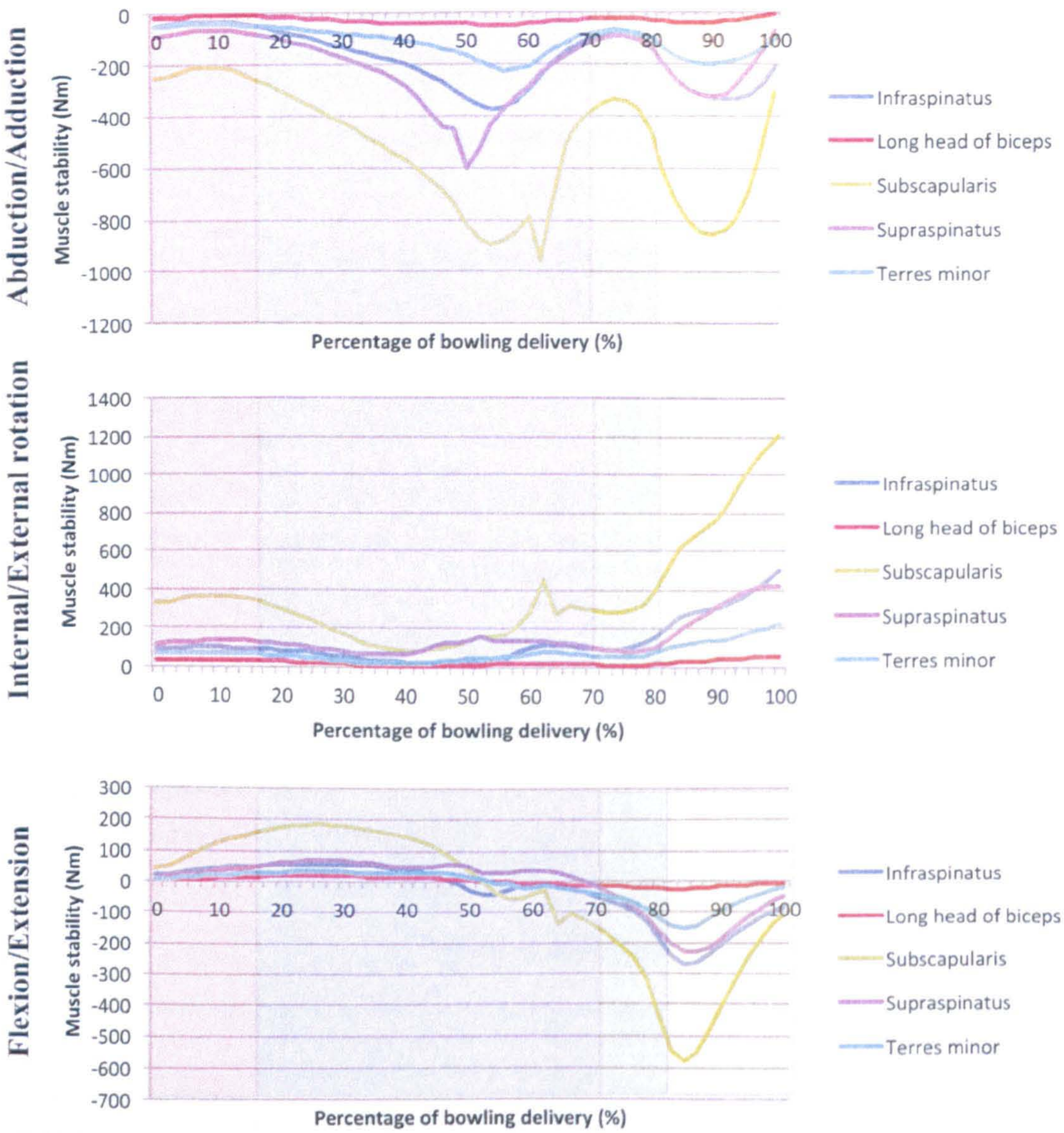


Figure 7.8 Mean muscle stability during the bowling delivery associated with the googly. Bowling phases (PDS to BFC: pink, BFC to FFC: blue, FFC to BR: green, BR to FT: yellow) are shown

Throughout the bowling delivery, subscapularis (average resultant stability: legbreak: 723.30 ± 296.13 Nm, googly: 710.87 ± 292.93 Nm) was observed to have the greatest stabilising potential, followed by supraspinatus (average resultant stability: legbreak: 275.74 ± 117.99 Nm, googly: 286.35 ± 136.43 Nm). The reliance on these muscles to provide joint stability during the bowling delivery would support the incidence of related pathology reported in chapter 2 which may occur as a consequence of repetitive loading. This finding would agree with Myers & O'Brien (2001) who attributed the repetitive bowling motion as placing strain on the rotator cuff which may lead to weakness and increased translational movement of the humeral head resulting in labral tears and superior labral anterior lesions.

During the bowling delivery both the rotator cuff musculature and the LHB act to stabilise the shoulder joint in a similar manner. Throughout the delivery the musculature stabilises through adduction with the greatest contribution occurring during BFC to FFC. In keeping with the greater shoulder joint forces associated with the legbreak delivery, the demand on musculature to stabilise the joint is greater during the legbreak delivery (infraspinatus: -200.46 ± 17.95 Nm, LHB: -35.29 ± 2.11 Nm, subscapularis: -586.29 ± 33.92 Nm, supraspinatus: -237.85 ± 4.94 Nm and terres minor: -122.05 ± 7.57 Nm) compared to the googly (infraspinatus: -188.82 ± 4.58 Nm, LHB: -33.60 ± 0.49 Nm, subscapularis: -552.94 ± 5.81 Nm, supraspinatus: -247.02 ± 9.63 Nm and terres minor: -115.93 ± 0.86 Nm).

Whilst the stabilising demand of the musculature about the abduction/adduction axis was greatest during BFC to FFC, for both the internal/external and flexion/extension axes greater musculature demand was associated with the latter stages of the bowling delivery, in particular from BR to FT. During BR to FT as the bowling arm rapidly decelerates, surrounding musculature must stabilise the shoulder joint and prevent anterior translation of the humeral head through extension (legbreak: infraspinatus: -212.32 ± 24.11 Nm, LHB: -20.15 ± 4.39 Nm, subscapularis: -444.69 ± 90.32 Nm, supraspinatus: -154.90 ± 37.29 Nm and terres minor: -103.78 ± 18.66 Nm; googly: infraspinatus: -181.04 ± 13.21 Nm, LHB: -15.09 ± 0.95 Nm, subscapularis: -347.40 ± 33.87 Nm, supraspinatus: -116.46 ± 11.15 Nm and terres minor: -84.90 ± 9.73 Nm). In addition, during this phase great demand is placed on the musculature to also stabilise through internal rotation (legbreak: infraspinatus: 352.00 ± 39.42 Nm, LHB: 48.96 ± 1.84 Nm, subscapularis: 923.60 ± 68.89 Nm, supraspinatus: 341.70 ± 21.57 Nm and terres minor: 167.25 ± 18.66 Nm; googly: infraspinatus: 354.34 ± 29.79 Nm, LHB: 44.54 ± 2.98 Nm, subscapularis: 882.92 ± 59.97 Nm, supraspinatus: 331.35 ± 13.80 Nm and terres minor: 159.29 ± 17.17 Nm).

Through applying the method of Potvin & Brown (2005) to investigate the contribution of individual muscles to shoulder joint stability during the bowling delivery, findings from this investigation aid in substantiating the causation of supraspinatus and subscapularis tendon pathology whilst establishing phases during the delivery that place the rotator cuff muscles under increased risk of injury. The high, repetitive demand on musculature to stabilise the shoulder joint during BR to FT (internal/external and flexion/extension axes), is in agreement with researchers (Bell-Jenje & Gray, 2005; Myers & O'Brien, 2001; Stuelcken *et al.*, 2010) who have attributed this phase to injury causation. However, the observed musculature demand to stabilise the shoulder joint about the abduction/adduction axis during BFC to FFC suggests that for researchers to gain a greater understanding of the pathomechanics of shoulder injuries and to ultimately formulate effective injury prevention strategies, future research should investigate the bowling delivery in its entirety.

The method of Potvin & Brown (2005) provides an estimation of the contribution of individual muscles to joint stability, however the validity of this approach has only been investigated in relation to the spine (Potvin & Brown, 2005). The application of this method to a multi-planar, spherical joint such as the shoulder presents some complexity yet to be acknowledged within the original method. Whilst work by Potvin and colleagues (Brown & Potvin, 2005; Brown & Potvin, 2007; Potvin & Brown, 2005) has advocated the application of a proportionality constant of 10 to define muscle stiffness, the appropriateness of this in relation to shoulder joint musculature is unknown particularly in the presence of shoulder pathology which would be expected to alter musculoskeletal properties. The incorporation of diagnostic imagining within future investigations would not only aid in increasing the validity of muscle modelling parameters such as subject specific origins and insertions but may also assist in defining muscle properties such as stiffness through the incorporation of elastography. The current application of the method of Potvin & Brown (2005) assumes that the contribution of muscle force to stability always occurs at its maximum. Whilst acknowledged as only providing an estimation of a muscle's contribution to joint stability the application of the method to dynamic, sporting movements must be taken with caution due to the inability to distinguish between contributions of muscle activity towards either joint stability of movement execution.

Conclusion

The aim of this investigation was to design a comprehensive, cricket specific shoulder model incorporating findings from chapters 4, 5 and 6, to enable the application of the method of Potvin & Brown (2005) to establish the contribution of individual rotator cuff muscles to shoulder joint stability during the bowling delivery. Through applying the model to an ex-county cricket with a documented history of shoulder pathology, findings from this investigation aided in not only establishing the role of the shoulder during the bowling delivery but also the contribution of surrounding musculature to shoulder joint stability.

Regardless of the type of delivery, shoulder motion during the bowling delivery for both the legbreak and googly was found to be similar. Whilst throughout the bowling delivery the humerus was externally rotated in respect to the thorax, shoulder joint position was found to be largely influenced by posterior scapulothoracic tilt (average posterior tilt: legbreak: 60.18 ± 2.21 °, googly: 60.97 ± 1.09 °) and scapulothoracic retraction (average retraction: legbreak: -25.23 ± 0.01 °, googly: -26.25 ± 1.44 °). Therefore to gain a comprehensive understanding of shoulder motion, findings from this investigation advocate the need for future research to identify the contributions of both humeroscapular and scapulothoracic motion as it is acknowledged that deficits in joint motion is often compensated for by altered scapulothoracic motion (Borich *et al.*, 2006) which may not be apparent if solely quantifying shoulder motion based on humerothoracic angles.

Whilst Stuelcken *et al.* (2010) reported only peak shoulder distraction force to quantify the load placed on the shoulder during the bowling delivery, findings from this investigation advocate that in order to gain greater understanding of the pathomechanics of shoulder injuries, researchers must acknowledge the multi-planar nature of the movement. Peak shear forces (legbreak: anterior/posterior: -1463.41 ± 179.84 N, superior/inferior: -1343.98 ± 32.47 N; googly: anterior/posterior: 1306.72 ± 18.42 N, superior/inferior: -791.92 ± 151.32 N) were observed to be greater than the peak distraction/compression force (legbreak: -630.26 ± 144.57 N; googly: 590.17 ± 45.29 N) in keeping with the bowling movement whereby the arm circumducts over a large range of motion whilst following parallel to the path of the body.

To the authors knowledge this is the first investigation which has established the contribution individual musculature to shoulder joint stability during cricket bowling. Through applying the method of Potvin & Brown (2005), subscapularis (average resultant stability: legbreak: 723.30 ± 296.13 Nm, googly: 710.87 ± 292.93 Nm) and supraspinatus (average resultant stability: legbreak: 275.74 ± 117.99 Nm, googly: 286.35 ± 136.43 Nm) were observed to have the greatest stabilising potential. The reliance on these muscles to provide joint stability during the bowling delivery would support the incidence of related pathology reported in chapter 2 which may occur as a consequence of repetitive loading. In addition, the observed demand on musculature to stabilise the shoulder joint during BFC to FFC (abduction/adduction axis) and during BR to FT (internal/external and flexion/extension axes) advocates the need for that for researchers to gain a greater understanding of the pathomechanics of shoulder injuries and to ultimately formulate effective injury prevention strategies, future research should investigate the bowling delivery in its entirety.

This chapter presents a cricket specific model to investigate shoulder motion during the the bowling delivery. Through incorporating findings from chapters 4, 5 and 6 to increase the validity and repeatability in reconstructing anatomical landmarks, the CSBT shoulder model presents a comprehensive approach to quantify shoulder motion and the contribution of surrounding musculature to joint stability using the method of Potvin & Brown (2005). The application of this model within this investigation to an ex-county bowler with a history of shoulder injury demonstrates that regardless of the complexity of the movement of interest, through adapting current methods used within biomechanical research, researchers can gain a greater understanding of the pathomechanics of injuries to aid in the formulation of injury prevention strategies.

Conclusion

Introduction

Within the literature, several injury prevention models (Finch, 2006; Meeuwisse, 1994; Van Mechelen, Hlobil & Kemper, 1992) have been proposed to aid in the formulation of prevention strategies. The successful application of such strategies is dependant on not only identifying the injury, but also gaining a comprehensive understanding of the underlying mechanisms (Finch, 2006; Krosshaug & Verhagen, 2009).

To date, injury surveillance research (Leary & White, 2000; Ranson & Gregory, 2008; Stretch, 2003) has established that over 20 % of cricket injuries are related to the upper limb, with Orchard *et al.* (2002) associating a higher prevalence of shoulder tendon injuries afflicting spin bowlers (1.1 %) compared to seam bowlers (0.9 %). Concern by researchers (Aginsky *et al.*, 2004; Bell-Jenje & Gray, 2005; Ranson & Gregory, 2008; Stuelcken *et al.*, 2008) on the inappropriateness of the sole reliance of quantifying shoulder injuries amongst cricketers using surveillance data has resulted in several studies utilising clinical assessments. Aginsky *et al.* (2004), Bell-Jenje & Gray (2005), Giles & Musa (2008) and Stuelcken *et al.* (2008), have all assessed changes in joint dynamics between cricketers with and without a history of shoulder injury through assessing shoulder joint range of motion and joint strength. To date, findings have been inconclusive but, similar to other overhead sports (Bak & Magnusson, 1997; Baltaci *et al.*, 2001; Ellenbecker *et al.*, 2002; Kibler *et al.*, 1996), bowlers have been associated with demonstrating increased external and decreased internal glenohumeral rotation. The applicability of such findings is currently limited, as inherent methodological difficulties in reconstructing shoulder motion has prevented the bowling movement from being accurately quantified. Therefore the aim of this thesis was to utilise investigative techniques to provide researchers with a greater understanding of the pathomechanics of shoulder injuries afflicting cricket bowlers though quantifying associated musculoskeletal adaptations and subsequently through the development and validation of a bowling specific kinematic model, establish the influence these may impart on bowling technique.

Experimental Findings and Recommendations

Through investigating a cohort of twenty injury free county cricket bowlers according to the injury definitions of Orchard *et al.* (2005), the aim of chapter 2 was to utilise diagnostic ultrasound to establish musculotendinous adaptations associated with cricket bowling to provide insight into the nature and commonality of shoulder injuries afflicting cricket bowlers. In contrast to injury prevalence rates reported within injury surveillance research (Leary & White (2000): 7.1%; Orchard *et al.* (2002): 6% and Ranson & Gregory (2008): 23%), this investigation found that 70 % of bowlers exhibited shoulder pathology affecting their bowling shoulder and 40 % were found to have shoulder pathology affecting their non-bowling shoulder. Forty-five percent of bowlers (academy and elite) were observed to exhibit supraspinatus tendon pathology to the bowling shoulder, substantiating the theories of Aginsky *et al.* (2004) and Myers & O'Brien (2001) that the follow-through is a period of the bowling delivery which would appear to place bowlers at an increased risk of injury. More importantly however, the high incidence of subscapularis tendinopathy affecting the bowling shoulder (academy: 33.3 %, elite: 63.6 %), yet to be documented within cricket research, provides support to the observed change in shoulder joint dynamics reported by Aginsky *et al.* (2004), Bell-Jenje & Gray (2005), Giles & Musa (2008) and Stuelcken *et al.* (2008) and suggests that both researchers and coaches should place greater emphasis on the early phases of the bowling delivery due to the contribution subscapularis imparts on internal shoulder rotation. The use of diagnostic ultrasound to establish musculotendinous adaptations to the shoulder in a cohort of bowlers yet to experience any documented incidence of shoulder pathology, provides researchers with invaluable insight into common musculotendinous pathology and adaptations which are indicative of the future potential of injury and aids researchers in gaining greater understanding of the pathomechanics of bowling related shoulder injuries.

To aid in the prevention of injuries, researchers must not only establish the nature and commonality of injuries as investigated in chapter 2 but also gain an understanding of the associated movement pattern. Due to the complexity of investigating shoulder motion during dynamic movements such as cricket bowling, a large emphasis within this thesis was to first, begin to quantify the kinematics of the shoulder throughout the bowling delivery as described by humerothoracic motion (chapter 3), and due to the contribution of scapula motion to the bowling motion, evaluate and develop the use of an acromion cluster for use in future bowling kinematic research to both define scapula motion (chapters 4 and 5) and enable the accurate reconstruction of GJC location (chapter 6). As such this body of work presents the first cricket specific shoulder model that utilises techniques that enables researchers to progress from the laboratory environment to investigating the shoulder within the field using methods aimed to address the dynamic demands of the bowling movement. Such methods may be used by by both researchers and coaching staff to investigate not only the pathomechanics of shoulder injuries during bowling but can also be adapted to investigate the contribution of the shoulder during other cricket related movements such as batting and throwing.

The aim of the experimental research presented in chapter 3 was two-fold. First, due to no prior published data, the kinematics of the shoulder during the bowling delivery was quantified in relation to humerothoracic motion. Second, the influence of rotation sequence in relation to GL incidence was investigated because of the errors this can impart on the subsequent calculations. Findings from this investigation established that due to the large degrees of freedom available about the shoulder, GL was observed to affect each of the rotation sequences investigated (YXY, ZXY, XZY), contradicting findings reported by Bonnefoy-Mazure *et al.* (2010) in relation to the tennis serve. Whilst large within and between bowler variability was observed, shoulder movement during cricket bowling was found to be typical of the observed movement pattern. Importantly, this investigation associated bowlers, regardless of bowling style, with exhibiting large degrees of internal rotation, particularly during BR to FT. This contradicts the limited internal glenohumeral rotation observed by researchers clinically (Aginsky *et al.*, 2004; Bell-Jenje & Gray, 2005; Giles & Musa, 2008; Stuelcken *et al.*, 2008), suggesting that bowlers may compensate for restricted glenohumeral motion through increased scapulothoracic motion. Although incorporating a standard kinematic model, results from this body of work emphasise that future research must incorporate a bowling specific model to accurately establish the contribution of the scapula.

Experimental data presented in chapters 4, 5 and 6 addresses the second aim outlined in the initial thesis aims through assessing the feasibility of current methods to establish scapula and GJC position during cricket bowling. Whilst numerous methods to establish scapula position have been assessed within the literature (Brochard *et al.*, 2009; Cutti *et al.*, 2008; Karduna *et al.*, 2001; Meskers *et al.*, 2007; Meskers *et al.*, 1998; van Andel *et* *al.,* 2009), the acromion cluster through decreasing the influence of STA has become readily adopted by research. As previous work by Shorter *et al.* (2010), established the contribution of deltoid muscle activity throughout the bowling delivery, chapter 4 investigated the influence changes in muscle activity, through external loading can impart on acromion cluster reliability. Findings from this investigation established whilst variations in marker coordinate position were observed between load conditions, issues pertaining to the reliability of the acromion cluster at higher levels of elevation are not as a direct result of deltoid muscle activity. In contrast to previous research (Brochard *et al.,* 2009; Meskers *et al.,* 2007; van Andel *et al.,* 2009), findings from this investigation suggested error associated with the acromion cluster occurs due to the application of the CAST protocol. With this in mind, chapter 5 aimed to devise and validate a multiple calibration procedure (mCAST) specific to the bowling movement. Whilst multiple calibration procedures have been proposed for the lower limb (Cappello *et al.,* 1997; Cappello *et al.,* 2005) and a double calibration method for the scapula (Brochard *et al.,* 2011), this is the first known investigation applying such techniques to improve the validity of the acromion cluster for dynamic, multi-planar movements. Results from this investigation established that whilst the suitability of this method compared to the CAST protocol should be assessed on an individual basis, resultant RMSE can be decreased by up to 0.016 m. To further adapt current kinematic methods for the use of a cricket specific shoulder model, the aim of chapter 6 was to establish a protocol to incorporate the SCoRE method (Ehrig *et al.,* 2006) through investigating two factors that could affect the calculation and subsequent reconstruction of GHJ location, namely, the defining joint segments and movement pattern recorded. Findings from this investigation established that whilst the defining segment coordinate systems are inconsequential in establishing GHJ location, the star arc movement due to smaller error (bowling movement error: 0.0130 ± 0.0007 m, star arc error: 0.0032 ± 0.002 m) should be used to define GHJ location and, the subsequent reconstruction of the GHJ during the dynamic movement must be undertaken using only the scapula anatomical coordinate system due to its robustness in the presence of Gaussian noise (0.001 m: 0.0021 ± 0.0001 m, 0.002 m: 0.0042 ± 0.0002 m, 0.003 m: 0.0063 ± 0.0003 m).

The focus of the experimental data presented within this body of work, highlights the inherent methodological issues in trying to adapt current methods used within clinical settings to describe dynamic sporting movements such as cricket bowling. Due to the limited number of elite cricket bowlers, sample sizes incorporated within the experimental studies of this thesis, whilst representative of the elite bowling population, are smaller than those normally associated with sports science research. The combination of small sample sizes and the highly individualised nature of the bowling movement was typified by the large variability observed throughout this body of work. Such variability, in particular that observed both in relation to the bowling movement and, the application of the acromion cluster, support the need for future research to be conducted on an individual basis. As advocated by Bates (1996) and Salter *et al.* (2007), single subject statistical analysis may provide greater insight into the both aetiological factors contributing to shoulder injuries and, compensation mechanisms adopted by bowlers in order to meet the functional demands of the movement. With this in mind, the application of the CSBT shoulder model to address the final two aims outlined in the initial thesis aims, namely to first, establish the roles of each individual rotator cuff muscle to overall shoulder joint stability and, second, to investigate the kinematics and kinetics of the shoulder during cricket bowling to identify phases of the action which place the shoulder at an increased risk of injury was undertaken in chapter 7 through a case study of a retired second XI county wrist spinner with a documented history of shoulder pathology to the bowling arm.

Through applying the CSBT shoulder model to an ex-county cricket with a documented history of shoulder pathology, findings from chapter 7 aided in not only establishing the role of the shoulder during the bowling delivery but also the contribution of surrounding musculature to shoulder joint stability. Regardless of the type of delivery, shoulder motion during the bowling delivery for both the legbreak and googly was found to be similar, with the externally rotated humerus position in respect to the thorax influenced greatly by scapulothoracic motion. Therefore to gain a comprehensive understanding of shoulder motion, findings from this investigation advocate the need for future research to identify the contributions of both humeroscapular and scapulothoracic motion rather than relying solely on humerothoracic angles. During the bowling delivery peak shear forces (legbreak: anterior/posterior: -1463.41 ± 179.84 N, superior/inferior: -1343.98 ± 32.47 N; googly: anterior/posterior: 1306.72 ± 18.42 N, superior/inferior: -791.92 ± 151.32 N) were observed to be greater than the peak distraction/compression force (legbreak: -630.26 ± 144.57 N; googly: 590.17 ± 45.29 N). Whilst not dissimilar to other overhead sports (Werner *et al.*, 2001; Werner *et al.*, 2006) findings from this investigation highlights that researchers must acknowledge the multi-planar nature of the movement, rather than relying solely on reporting peak distraction forces. Through applying the method of Potvin & Brown (2005), subscapularis (average resultant stability: legbreak: 723.30 ± 296.13 Nm, googly: 710.87 ± 292.93 Nm) and supraspinatus (average resultant stability: legbreak: 275.74 ± 117.99 Nm, googly: 286.35 ± 136.43 Nm) were observed to have the greatest stabilising potential. The reliance on these muscles to provide joint stability during the bowling delivery would supporting the observed incidence of pathology reported in chapter 2. In addition, the observed demand on musculature to stabilise the shoulder joint during BFC to FFC (abduction/adduction axis) and during BR to FT (internal/external and flexion/extension axes) advocates the need for researchers to gain a greater understanding of the pathomechanics of shoulder injuries and to ultimately formulate effective injury prevention strategies, future research should investigate the bowling delivery in its entirety.

Limitations of the Doctoral Investigation

Whilst this body of work makes a significant contribution to providing researchers with a greater understanding of the pathomechanics of shoulder injuries in cricket bowlers, as with any research, it is important to acknowledge that this work is not without its limitations given the complexity of the area.

The use of diagnostic ultrasound to investigate the nature and commonality of shoulder injuries in cricket bowlers established that 70 % of bowlers with no prior history of shoulder injury were observed to exhibit shoulder pathology. It is important to note that shoulder pathology observed included pain-free pathology, and the causation of which can not be definitively associated with bowling and may occur as a consequence of factors such as limb dominance and daily living activities. In addition, the reliance on subjects acting as their own controls, fails to establish if the observed prevalence of shoulder pathology within this cohort of cricket bowlers is greater than the general population as no age matched control group was investigated.

The use of elite cricket bowlers combined with the highly variable nature of the bowling delivery, presented several methodological difficulties. In particular, small sample sizes imposes difficulties in applying traditional statistical analysis with sufficient power. As such, the reliance on largely descriptive statistics, whilst providing an indication of the observed trends restricts the ability to confidently apply findings to the general population. Throughout this body of work the bowling delivery was associated with large within and between bowler variability. Although controlling contributing factors such as line and length were observed to assist in lowering within bowler variability in relation to shoulder kinematics, large variability associated with more advanced kinetic calculations highlights the inherent difficulty in obtaining a homogenous sample. As such whilst measures were undertaken to assist in ensuring deliveries were reflective of each type of ball of interest, the small numbers of trials may not be reflective of the range of deliveries bowlers would normally bowl during match conditions.

A large emphasis within this thesis was to adapt and validate current kinematic methods and apply them to establish shoulder motion during the bowling delivery. As such, the direct application of methods proposed within this thesis, for instance, the mCAST method, needs to be validated prior to use within other dynamic movements. Whilst theoretically the mCAST method minimises the error associated with the acromion cluster at higher levels of elevation, in comparison to the CAST method, the appropriateness of the method was observed to be individualised and as such may vary based on factors such as body somatotype which is yet to be investigated within biomechanical shoulder research.

Future Research Directions

The aim of this thesis is to investigate the pathomechanics of shoulder injuries in cricket bowlers through the application of investigative techniques to first, quantify musculotendinous adaptations, and second, to establish the affect these impart on bowling technique. Whilst an underlying focus of this body of work was to adapt and validate current kinematic methods for use in a cricket bowling specific model, future research should aim to apply these methods to other sporting and daily activities to enable a more comprehensive understanding of the pathomechanics of injuries. The CSBT shoulder model and the methods it incorporates is the first body of work progressing current laboratory methods for use within the field to investigate dynamic movements such as cricket bowling. As such, whilst the bowling movement has been the focus of numerous biomechanical investigations, future research should investigate the contribution of the shoulder during other cricket movements such as batting and throwing in regard to injury causation and, given the growing popularity of women's cricket (Stuelcken *et al.*, 2010) investigate if the nature and aetiology of injuries differs between genders.

Similar to the work of Brasseur *et al.* (2004), data presented in chapter 2 demonstrates the benefits of future research combining diagnostic imaging, such as ultrasound, to investigate the presentation of common injuries rather than the sole reliance on injury surveillance research. Whilst ultrasound could establish pathology to musculotendinous structures, and quantify adaptations such as changes in tendon thickness, future research should look to incorporate techniques such as elastography, which through being able to investigate muscle stiffness, may be able to provide a more comprehensive understanding of musculotendinous adaptations.

The CSBT shoulder model, is to the authors knowledge the first cricket specific model to investigate the role of the shoulder and, contribution of surrounding musculature to shoulder joint stability. As the model currently incorporates cadaver based data to quantify muscle modelling parameters, future research should look to incorporate subject specific data to aid in increasing model accuracy. The application of MRI data in relation to increasing accuracy of shoulder kinematic research by Campbell *et al.* (2009), supports the incorporation of MRI based data as a non-invasive approach to accurately quantify *in vivo* muscle properties, especially for the shoulder due to the inherent difficulties in establishing muscle activity using more traditional methods such as electromyography.

Concluding Statement

The aim of this thesis was to provide researchers with a greater understanding of the pathomechanics of shoulder injuries afflicting cricket bowlers though quantifying associated musculoskeletal adaptations and subsequently through the development and validation of a bowling specific kinematic model, establish the influence these may impart on bowling technique. This body of work demonstrates that regardless of the complexity of the movement of interest, through adapting current methods used within biomechanical research, researchers can gain a greater understanding of the pathomechanics of injuries to aid in the formulation of injury prevention strategies.

List of appendices

Appendix A - Ethics Form (Kinematics and Kinetics)

ETHICAL REVIEW APPLICATION

Students – submit this form in hard copy to your supervisor BEFORE commencing research.

Supervisors – if this form needs Ethics Committee scrutiny (i.e. if you judge it to be 'Category B or C'), please submit this form in hard copy to the Senior Administrator (Research) in the Academic Standards Unit.

This form should be used for all undergraduate, postgraduate research and any other research conducted under the name of the University of Chichester. IT MUST BE COMPLETED AND APPROVED by your supervisor before you start.

Supervisors and (where appropriate) the Ethics Committee will make a decision on the basis of the information you have supplied. In order for the Committee to consider your application quickly it would be very helpful if you could also attach the rationale and outline procedures which you are intending to use. This will help the Committee to reach its decision without the need to request further information. The Committee also finds it helpful to have an outline of requests to participants, questionnaires and information regarding the final destination of the results.

Applicant: Kathleen Shorter	Supervisor's Judgement	Proceed	A
		Proceed with caution	B
		Needs Committee Scrutiny (NB: Student/staff member will be invited to attend the Ethics Committee.)	C
Name of Supervisor:	**Dr. Mike Lauder/Dr. Neal Smith**		
Name of University Head of School/ named staff member with responsibility for ethical issues:	**Dr. Mike Lauder** Sports Sciences		
Programme and Module:	**MPhil/PhD**		

1. Title of study:
   Kinematics and kinetics of cricket movements.

2a. Brief description of methods:	Supervisor's /Ethics Committee comment:
To establish the kinematics and kinetics experienced by the upper limb during cricketing movements, county cricketers with no recent history of injury will be recruited from the local area. After providing informed consent, participants will be requested to execute cricket skills in a variety of conditions to not only quantify the demands placed upon the upper limb but to also assist in establishing methods to minimise forces placed on the upper limb to aid in injury prevention. Kinematics and kinetics of cricket movements will be quantified using non-invasive biomechanical techniques. Upper limb movement will be investigated through the use of synchronised high-speed video cameras using surface retroflective markers. Forces exerted upon the upper limb will be established using methods such as surface electromyography to record muscle activity, and force transducers to establish the influence of external forces acting on the body. Movement velocity data and its derivatives will be calculated by digitising (converting the video to computer generated coordinates) the video footage. Such movement data may then be processed in combination with kinetic based data to estimate internal forces acting upon the upper limb. 2b. Brief description of purpose of study/rationale: Upper limb injuries currently account for 10% of all cricket injuries (Orchard, James and Portus, 2006). Whilst scientific studies have successfully investigated cricket injuries afflicting the lower extremity, minimal research has been conducted focusing solely on the upper limb. The aim of this investigation is to record and quantify the kinematics and kinetics of the upper limb during key cricket movements to identify risk factors associated with injury and to assist in the formulation of prevention strategies.	

3. Location of study and details of any special facilities to be used (see note 1, below): Data collection will be in the Old Chapel Biomechanics Laboratory of the School of Sport, Exercise and Health Sciences, University of Chichester. All data collection will follow established guidelines		
4. Are the respondents/subjects people you normally work with? (e.g. as a social work, counselling or education professional, volunteer, or trainee; see note 5.)	No ✓	Yes
5. Basis for selection and rejection of subjects/respondents in the study: All participants will be experienced cricketers with a minimum of two years prior playing experience and must be currently playing county level cricket. Participants will receive a written and oral briefing on the exact requirements of the study and asked to provide informed consent. Participants are provided the opportunity to withdraw from the testing process anytime. All participants will be required to have no recent history of injury (up to three months before testing) and will undertake a familiarisation period of the testing environment where they will be instructed on the correct and safe procedures to minimise any potential risks.		
6a. Is the process of the study and/or its results likely to produce distress or anxiety in the subjects/respondents? (See note 2.)	No ✓	Yes
If you answered Yes to question 4 as well as question 6a: 6b. Is the process of the study and/or its results likely to produce distress or anxiety in the subjects/respondents beyond what they would normally experience in your work with them? (See note 5.)	No ✓	Yes
7a. If the answer to 6a (or 6b where applicable) is yes – please elaborate if you think this may not be clear from previous answers: 7b. What steps will you take to deal with any distress or anxiety produced?		
8. Can the study be described as being part of some role you already have, therefore not requiring any special consideration or scrutiny? (This should be confirmed by subsequent answers, and see note 5.)	No ✓	Yes
9a. Does your proposal raise other ethical issues apart from the potential for distress, anxiety, or harm? (See note 2.)	No ✓	Yes
9b. Irrespective of whether any distress is caused to subjects/respondents, might the research damage the reputation of the University, since it will be undertaken under its auspices?	No ✓	Yes

10. If your answer to 9a. was 'yes', on what grounds would you defend the proposal?		
11. Is it necessary to obtain the consent of the subjects/respondents of the study? (See note 4.)	No	Yes ✓
Date consent obtained:		
Written or oral?	Written	
(Please specify)	No ✓	Yes
Copy attached?		
12. Will any payment, gifts, rewards or inducements be offered to subjects/ respondents to take part in the study?	No ✓	Yes
Please give brief details:		
13. Will they have the right/facility to withdraw from the study?	No	Yes ✓
14. In formal/legal terms, is there anyone whose permission has to be sought in order to conduct your study? (See note 4.)	No ✓	Yes
Please give details:		
Date consent obtained:		
Written or oral?	No	Yes
(Please specify)		
Copy attached?		
15. Do you think you need to seek the permission of any other individuals or groups? (e.g. parents, carers.)	No ✓	Yes
Please give details:		
Date consent obtained:		
Written or oral?		
(Please specify)	No	Yes
Copy attached?		

	No	Yes
16. Will your results be available in the public arena? (e.g. dissertation in the library) For postgraduate research; what are your intentions for publication of the study? Please list any journals or texts in which the study will be published if relevant/ known: The studies proposed are likely to lead to publications in appropriate journals such as Journal of Sports Sciences, Journal of Biomechanics, Medicine and Science in Sport and Exercise.	No	Yes ✓
17. Is it necessary to guarantee and ensure confidentiality for the respondents?	No	Yes ✓
18. Is it necessary to guarantee and ensure anonymity for the respondents?	No	Yes ✓
19. Will the respondents have any right of comment or veto on the material you produce about them? Please elaborate if you wish:	No ✓	Yes
20. Is there any additional comment or information you consider relevant, or any additional information that you require from the Committee?		
For supervisors: In your view, does the proposed study potentially contravene any aspect of established codes of practice in your discipline? (For instance, the codes of practice of the British Sociological Association, British Psychological Association, and British Education Research Association are available on the internet.)	No	Yes
Please give details if 'yes' and you wish the Ethics Committee to resolve the issue:		

Signature of applicant: .... Date: ....

Signature of supervisor: .... Date: ....

Signature of Head of relevant School in the University
(or named staff member with responsibility for ethical issues): ....

Date of application: ....

Notes

1. Workplace settings, like classrooms, day centres or sports centres are not special facilities in this sense. Specialised measuring apparatus may be, and mention should be made of particular equipment not available at the University, where relevant.

2. The Ethics Committee makes a distinction between distress and harm. It is conceivable that research may cause distress (e.g. interviewing about a sensitive subject) and as long as due care is taken to deal with this it would not necessarily rule out a particular enquiry. Harm, however, is considered to be longer-lasting distress over which the researcher has little control. Harm can also be caused by disadvantaging respondents in some way (perhaps by being seen talking to a researcher). Studies may also involve clinical risk which will be in addition to distress or harm. Under some circumstances research which may cause distress may be sanctioned. This is extremely unlikely for any research likely to cause harm or pose a serious clinical risk.

3. The University's insurance policy covers almost all aspects of its liability in the course of its normal work to a figure of several million pounds. If the nature of your research is particularly unusual or runs a particular risk of litigation then it should be discussed with the Finance Office before seeking ethical approval.

4. Informed consent from participants/respondents/subjects is usually necessary for all social research, so it is necessary also to consider questions 12 through to 18 carefully. The issue barely arises in the case of anonymous questionnaires, but is clearly called for if you were asking 15 year olds about their smoking habits (but consent from whom?) and is unclear if you are covertly watching people's behaviour (it might be compromised by asking for consent, but such observation should only take place where people would normally expect to be in public view).

5. The Ethics Committee is concerned not to put bureaucratic obstacles in the way of the small scale research which forms a part of many students' courses, nor to intervene in established patterns of professional development. In the case of teaching, social work or nursing, for example, the 'reflective practitioner' model necessarily involves a degree of action research upon one's own practice as a means of professional development, and it would be beyond the brief of the Committee to seek to comment on this. Supervisors and students should, however, be prepared to seek Committee approval when a proposed research study goes beyond the student's usual professional role, even though it may be part of a taught course. The questions on the form are designed to clarify this. The issue of 'harm' aside, the key point in such cases is whether the study could be described as being part of a student's usual professional role and therefore not requiring any special consideration or scrutiny.

   If you decide to seek written consent the form you intend to give to respondents must be attached to this form.

6. Some institutions may require a police check. It can take time and a fee is charged.

Appendix B - Ethics Form (Diagnostic Imaging)

ETHICAL REVIEW APPLICATION

Students – submit this form in hard copy to your supervisor BEFORE commencing research.

Supervisors – if this form needs Ethics Committee scrutiny (i.e. if you judge it to be 'Category B or C'), please submit this form in hard copy to the Senior Administrator (Research) in the Academic Standards Unit.

This form should be used for all undergraduate, postgraduate research and any other research conducted under the name of the University of Chichester. IT MUST BE COMPLETED AND APPROVED by your supervisor before you start.

Supervisors and (where appropriate) the Ethics Committee will make a decision on the basis of the information you have supplied. In order for the Committee to consider your application quickly it would be very helpful if you could also attach the rationale and outline procedures which you are intending to use. This will help the Committee to reach its decision without the need to request further information. The Committee also finds it helpful to have an outline of requests to participants, questionnaires and information regarding the final destination of the results.

<table>
<tr><td rowspan="3">Applicant:

Kathleen Shorter</td><td rowspan="3">Supervisor's Judgement</td><td>Proceed</td><td>A</td></tr>
<tr><td>Proceed with caution</td><td>B</td></tr>
<tr><td>Needs Committee Scrutiny (NB: Student/staff member will be invited to attend the Ethics Committee.)</td><td>C</td></tr>
<tr><td>Name of Supervisor:</td><td colspan="3">Dr. Mike Lauder/Dr. Neal Smith</td></tr>
<tr><td>Name of University Head of School/ named staff member with responsibility for ethical issues:</td><td colspan="3">Dr. Mike Lauder
Sports Sciences</td></tr>
<tr><td>Programme and Module:</td><td colspan="3">MPhil/PhD</td></tr>
<tr><td colspan="4">1. Title of study:
Diagnostic imaging of shoulder injuries in cricket</td></tr>
<tr><td colspan="3">2a. Brief description of methods:

For this study, experienced (more than two years playing experience) county cricket players will be recruited from the local area and provide informed consent. During the cricket season, participants will undergo non-invasive diagnostic imaging of the shoulder using techniques such as ultrasonography and elastography. These non-invasive techniques not only aid in the diagnosis of shoulder injuries experienced by cricketers, but also provide insight into the mechanical properties of associated soft tissue structures. Images will be captured and assessed by a sole trained radiologist to limit inter-operator error. Diagnostic images will then be processed for use in computer modelling and simulation programs to enable research to identify positions at which the shoulder joint and its structures are at an increased risk of injury through applying the work of Potvin and Brown (2005).

2b. Brief description of purpose of study/rationale:

Upper limb injuries currently account for 10% of all cricket injuries (Orchard, James and Portus, 2006). Although diagnostic imaging has readily been utilised by other sporting codes to establish the nature of injuries suffered, to date no diagnostic based research has been conducted investigating shoulder injuries in cricket. The aim of this research is to utilise non-invasive diagnostic imaging to establish the pathomechanics of shoulder injuries afflicting cricketers.</td><td>Supervisor's /Ethics Committee comment:</td></tr>
</table>

3. Location of study and details of any special facilities to be used (see note 1, below): Data collection will be in the Old Chapel Biomechanics Laboratory of the School of Sport, Exercise and Health Sciences, University of Chichester. All data collection will follow established guidelines		
4. Are the respondents/subjects people you normally work with? (e.g. as a social work, counselling or education professional, volunteer, or trainee; see note 5.)	No ✓	Yes
5. Basis for selection and rejection of subjects/respondents in the study: All participants will be experienced cricketers with a minimum of two years prior playing experience and must be currently playing county level cricket. Participants will receive a written and oral briefing on the exact requirements of the study and asked to provide informed consent. Participants are provided the opportunity to withdraw from the testing process anytime.		
6a. Is the process of the study and/or its results likely to produce distress or anxiety in the subjects/respondents? (See note 2.)	No ✓	Yes
If you answered Yes to question 4 as well as question 6a: 6b. Is the process of the study and/or its results likely to produce distress or anxiety in the subjects/respondents beyond what they would normally experience in your work with them? (See note 5.)	No ✓	Yes
7a. If the answer to 6a (or 6b where applicable) is yes – please elaborate if you think this may not be clear from previous answers: 7b. What steps will you take to deal with any distress or anxiety produced?		
8. Can the study be described as being part of some role you already have, therefore not requiring any special consideration or scrutiny? (This should be confirmed by subsequent answers, and see note 5.)	No ✓	Yes
9a. Does your proposal raise other ethical issues apart from the potential for distress, anxiety, or harm? (See note 2.)	No ✓	Yes
9b. Irrespective of whether any distress is caused to subjects/respondents, might the research damage the reputation of the University, since it will be undertaken under its auspices?	No ✓	Yes

10. If your answer to 9a. was 'yes', on what grounds would you defend the proposal?		
11. Is it necessary to obtain the consent of the subjects/respondents of the study? (See note 4.)	No	Yes ✓
Date consent obtained:		
Written or oral? (Please specify)	Written	
Copy attached?	No ✓	Yes
12. Will any payment, gifts, rewards or inducements be offered to subjects/ respondents to take part in the study?	No ✓	Yes
Please give brief details:		
13. Will they have the right/facility to withdraw from the study?	No	Yes ✓
14. In formal/legal terms, is there anyone whose permission has to be sought in order to conduct your study? (See note 4.)	No ✓	Yes
Please give details:		
Date consent obtained:		
Written or oral? (Please specify)		
Copy attached?	No	Yes
15. Do you think you need to seek the permission of any other individuals or groups? (e.g. parents, carers.)	No ✓	Yes
Please give details:		
Date consent obtained:		
Written or oral? (Please specify)		
Copy attached?	No	Yes

16. Will your results be available in the public arena? (e.g. dissertation in the library) For postgraduate research; what are your intentions for publication of the study? Please list any journals or texts in which the study will be published if relevant/ known: The studies proposed are likely to lead to publications in appropriate journals such as Journal of Sports Sciences, Journal of Biomechanics, Medicine and Science in Sport and Exercise.	No	Yes ✓
17. Is it necessary to guarantee and ensure confidentiality for the respondents?	No	Yes ✓
18. Is it necessary to guarantee and ensure anonymity for the respondents?	No	Yes ✓
19. Will the respondents have any right of comment or veto on the material you produce about them? Please elaborate if you wish:	No ✓	Yes
20. Is there any additional comment or information you consider relevant, or any additional information that you require from the Committee?		
For supervisors: In your view, does the proposed study potentially contravene any aspect of established codes of practice in your discipline? (For instance, the codes of practice of the British Sociological Association, British Psychological Association, and British Education Research Association are available on the internet.)	No	Yes
Please give details if 'yes' and you wish the Ethics Committee to resolve the issue:		

Signature of applicant: .... Date: ....

Signature of supervisor: .... Date: ....

Signature of Head of relevant School in the University
(or named staff member with responsibility for ethical issues): ....

Date of application: ....

Notes

1. Workplace settings, like classrooms, day centres or sports centres are not special facilities in this sense. Specialised measuring apparatus may be, and mention should be made of particular equipment not available at the University, where relevant.

2. The Ethics Committee makes a distinction between distress and harm. It is conceivable that research may cause distress (e.g. interviewing about a sensitive subject) and as long as due care is taken to deal with this it would not necessarily rule out a particular enquiry. Harm, however, is considered to be longer-lasting distress over which the researcher has little control. Harm can also be caused by disadvantaging respondents in some way (perhaps by being seen talking to a researcher). Studies may also involve clinical risk which will be in addition to distress or harm. Under some circumstances research which may cause distress may be sanctioned. This is extremely unlikely for any research likely to cause harm or pose a serious clinical risk.

3. The University's insurance policy covers almost all aspects of its liability in the course of its normal work to a figure of several million pounds. If the nature of your research is particularly unusual or runs a particular risk of litigation then it should be discussed with the Finance Office before seeking ethical approval.

4. Informed consent from participants/respondents/subjects is usually necessary for all social research, so it is necessary also to consider questions 12 through to 18 carefully. The issue barely arises in the case of anonymous questionnaires, but is clearly called for if you were asking 15 year olds about their smoking habits (but consent from whom?) and is unclear if you are covertly watching people's behaviour (it might be compromised by asking for consent, but such observation should only take place where people would normally expect to be in public view).

5. The Ethics Committee is concerned not to put bureaucratic obstacles in the way of the small scale research which forms a part of many students' courses, nor to intervene in established patterns of professional development. In the case of teaching, social work or nursing, for example, the 'reflective practitioner' model necessarily involves a degree of action research upon one's own practice as a means of professional development, and it would be beyond the brief of the Committee to seek to comment on this. Supervisors and students should, however, be prepared to seek Committee approval when a proposed research study goes beyond the student's usual professional role, even though it may be part of a taught course. The questions on the form are designed to clarify this. The issue of 'harm' aside, the key point in such cases is whether the study could be described as being part of a student's usual professional role and therefore not requiring any special consideration or scrutiny.

   If you decide to seek written consent the form you intend to give to respondents must be attached to this form.

6. Some institutions may require a police check. It can take time and a fee is charged.

Appendix C - Example participant information sheet and consent form

CONSENT TO ACT AS A SUBJECT IN A RESEARCH STUDY

THIS FORM IS TO BE READ BEFORE COMPLETION OF THE ATTACHED CONSENT FORM

I am a PhD candidate at the University of Chichester investigating the pathogenesis of shoulder injuries in cricket bowling. A particular focus of this research is to measure the forces acting on the shoulder during the bowling action. In order to do this I need to collect data on the structure of bowler's shoulders using both clinical joint range of motion assessments, and non-invasive ultrasound. This information will enable me to create a computer model to simulate the shoulder and surrounding muscles during the bowling action, which may be used with video analysis to understand when a bowler may be of increased risk of injury.

With the support of Hampshire County Cricket Club, I am looking to start data collection over the coming month during matches. It is hoped that data collection for each bowler would only require thirty minutes and would involve joint range of movement assessment and ultrasound for both the bowling and non-bowling shoulders.

All personal information and data collected will remain anonymous and participants may withdraw at any stage of this study.

If you have any questions regarding any aspect of this study or your involvement in it please do not hesitate to contact me by phone on 07878 689 770, or by email at K.Shorter@chi.ac.uk

Regards,

Kath Shorter

UNIVERSITY OF
Chichester

Bishop Otter Campus
College Lane, Chichester
West Sussex, PO19 6PE

Tel: (01243) 816000
Fax: (01243) 816080
Web: www.chi.ac.uk

The University of Chichester

CONSENT FORM

I, ... (PRINT NAME)

hereby give my consent to participate in the following test/activity *[please delete as appropriate]*. **[insert details]**

Non-invasive diagnostic ultrasound and clinical joint range of motion assessment of the shoulder.

By signing this form I confirm that:

- the purpose of the test/activity has been explained to me;
- I am satisfied that I understand the procedures involved;
- the possible benefits and risks of the test/activity have been explained to me;
- any questions which I have asked about the test/activity have been answered to my satisfaction;
- I understand that, during the course of the test/activity, I have the right to ask further questions about it;
- the information which I have supplied to The University of Chichester prior to taking part in the test/activity is true and accurate to the best of my knowledge and belief and I understand that I must notify promptly of any changes to the information;
- I understand that my personal information will not be released to any third parties without my permission;
- I understand that my participation in the test/activity is voluntary and I am therefore at liberty to withdraw my involvement at any stage;
- I understand that, if there is any concern about the appropriateness of my continuing in the test/activity, I may be asked to withdraw my involvement at any stage;
- I understand that once the test/activity has been completed, the information gained as a result of it will be used for the following purposes only: **[insert details]**

PhD Research

NAME OF THE SUBJECT ....

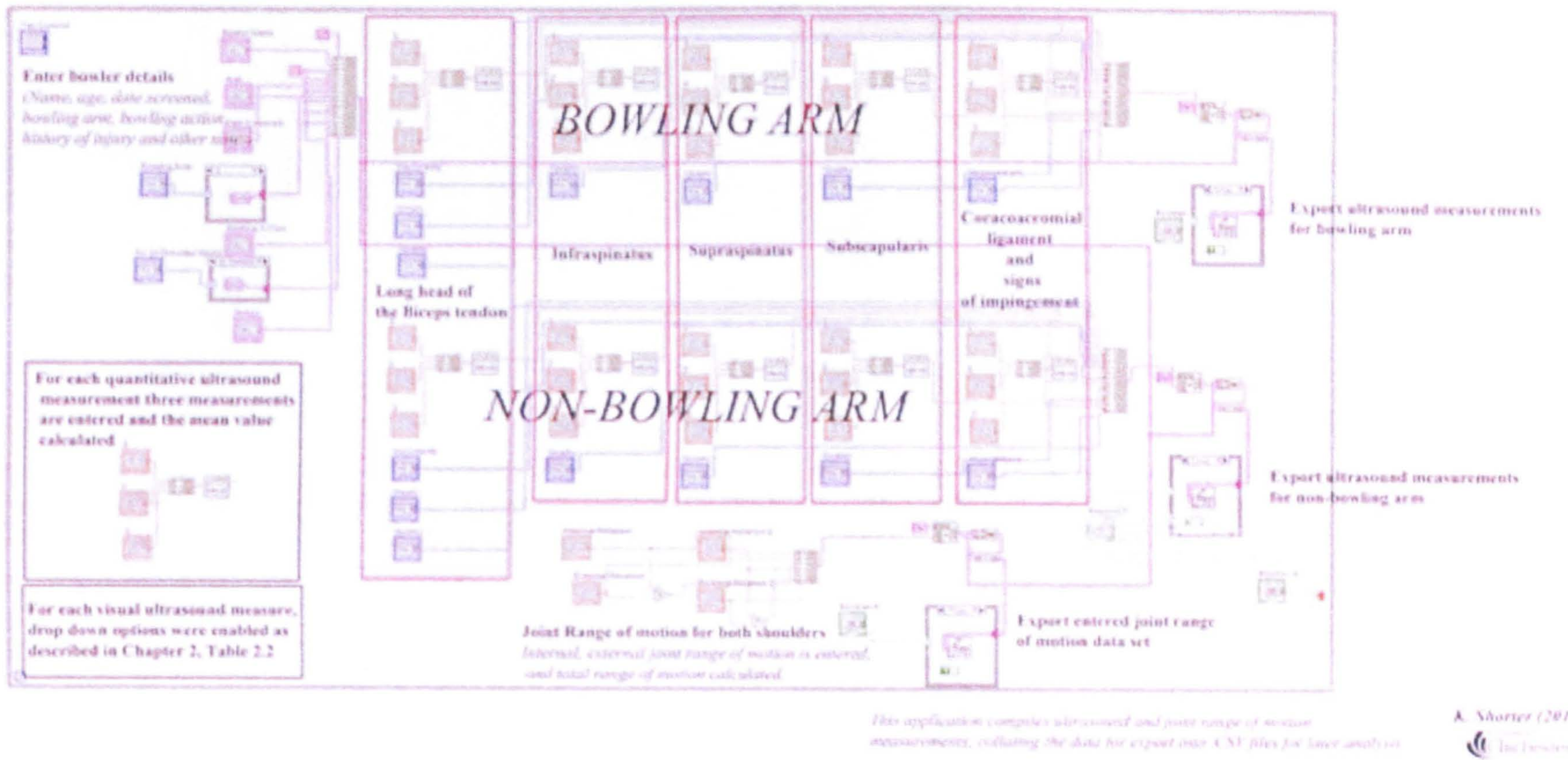
SIGNATURE OF THE SUBJECT ....

DATE ....

Committed to Celebrating Diversity and Eliminating Discrimination

Appendix D - CSBT DataCompiler (Chapter 2)

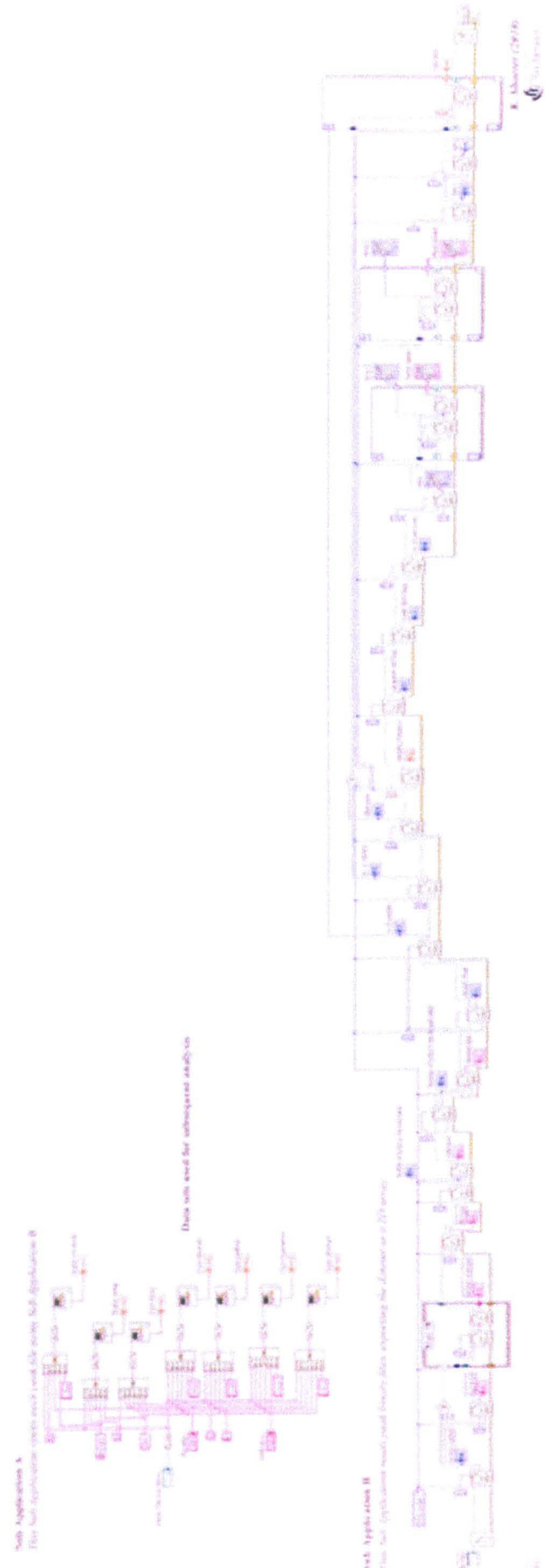
LabVIEW™ program schematic

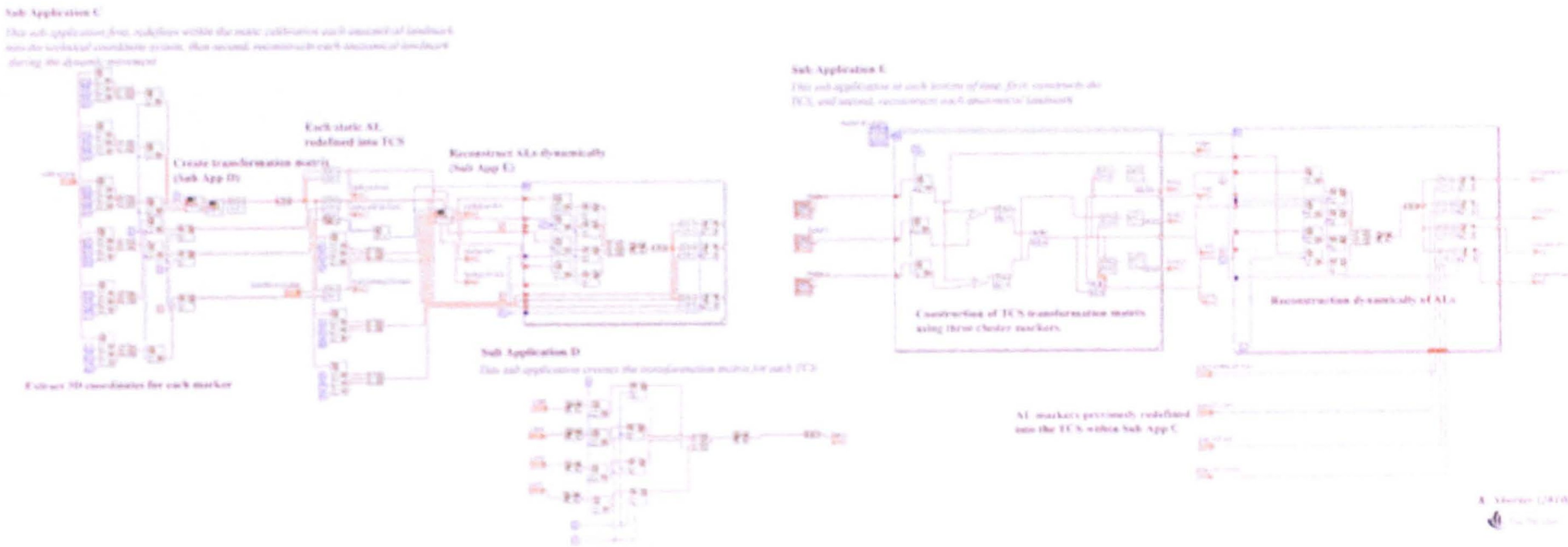

Enter bowler details
(Name, age, date screened, bowling arm, bowling action, history of injury and other notes)
BOWLING ARM
NON-BOWLING ARM
Long head of the Biceps tendon
Infraspinatus
Supraspinatus
Subscapularis
Coracoacromial ligament and signs of impingement
Export ultrasound measurements for bowling arm
Export ultrasound measurements for non-bowling arm
For each quantitative ultrasound measurement three measurements are entered and the mean value calculated
For each visual ultrasound measure, drop down options were enabled as described in Chapter 2, Table 2.2
Joint Range of motion for both shoulders
Internal, external joint range of motion is entered, and total range of motion calculated
Export entered joint range of motion data set
This application compiles ultrasound and joint range of motion measurements, collating the data for export into CSV files for later analysis
K. Shorter (2010)

Appendix E - CSBT Chucker (Chapter 3)

LabVIEW™ program schematic

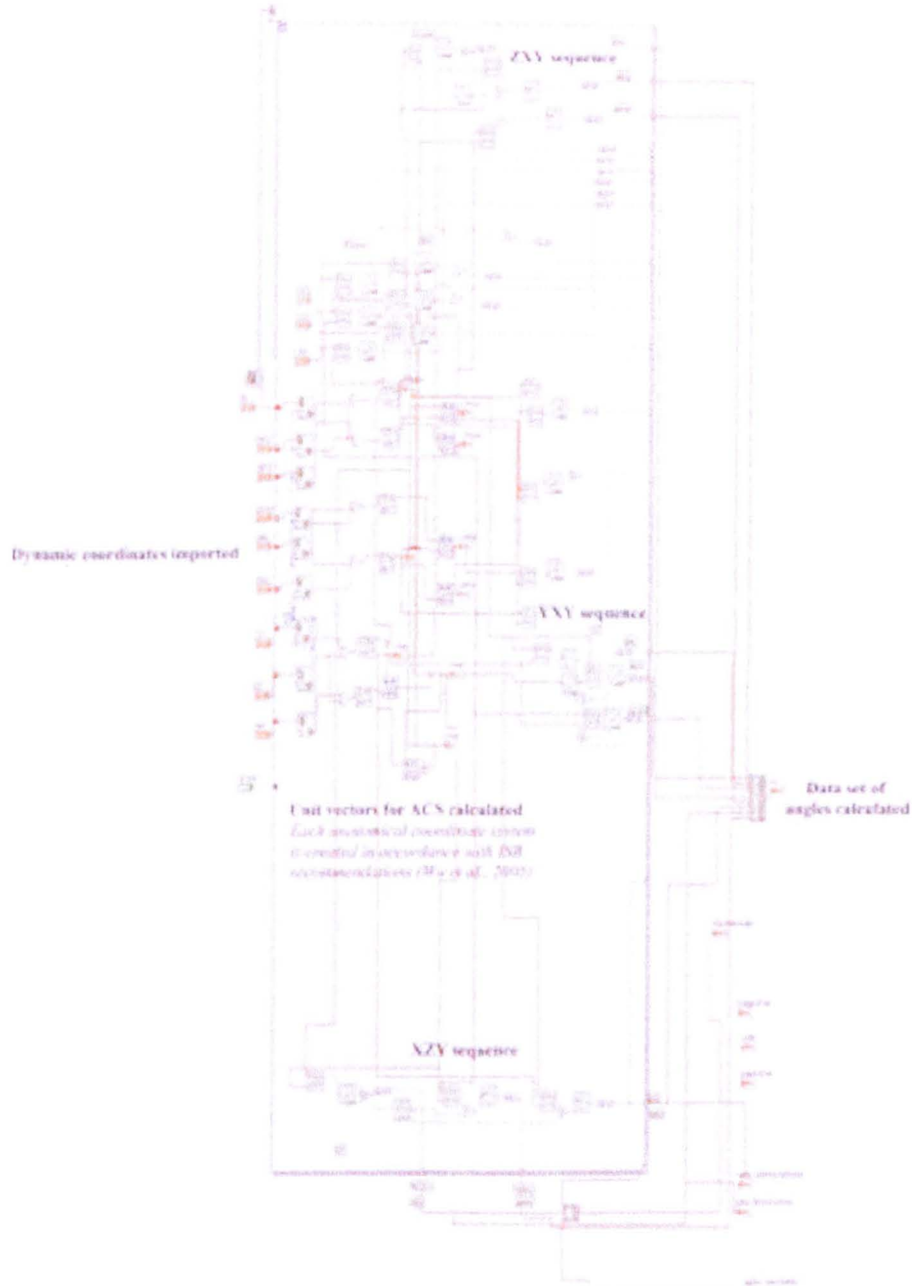
(Refer to electronic version for more detail)




Sub Application C
Each static AL
redefined into TCS
Create transformation matrix
(Sub App D)
Reconstruct ALs dynamically
(Sub App E)
Extract 3D coordinates for each marker
Sub Application D
Sub Application E
Construction of TCS transformation matrix
using three cluster markers
Reconstruction dynamically of ALs
AL markers previously redefined
into the TCS within Sub App C

Sub application F

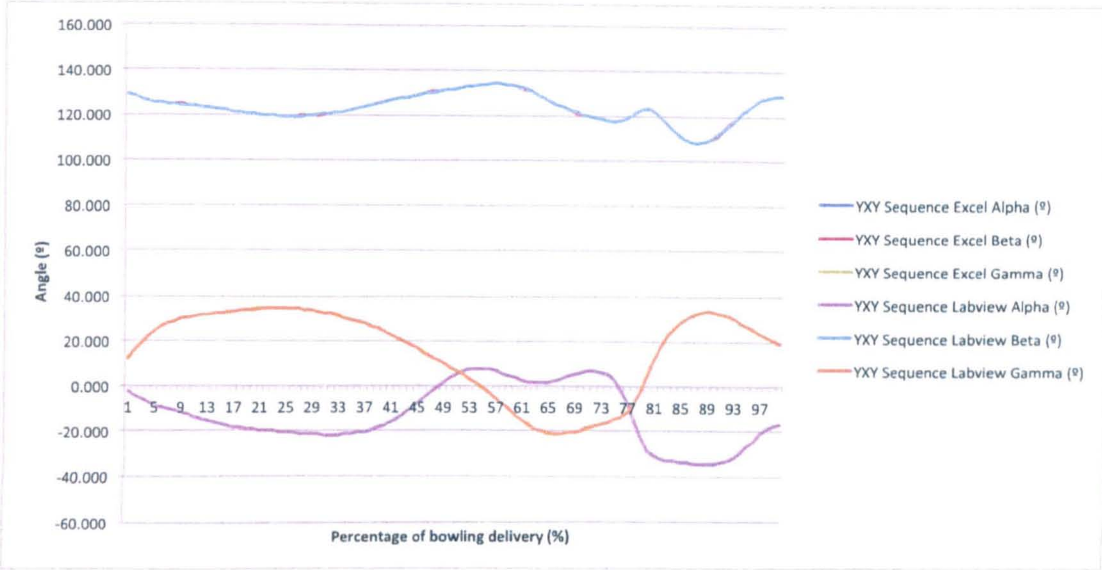
This sub application enables the calculation of [illegible] angles for each of the [illegible] sequences under investigation



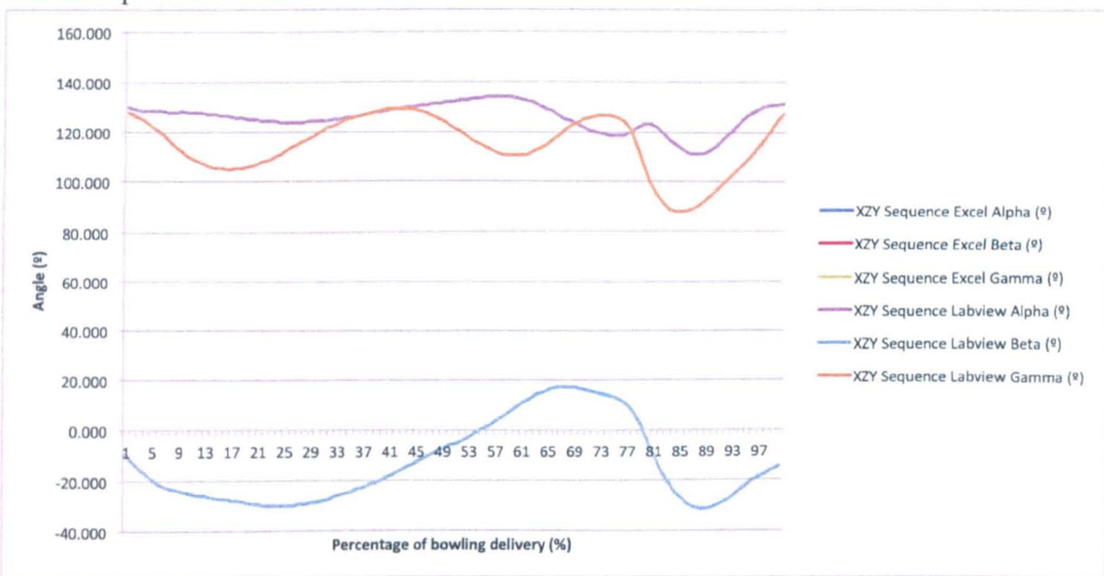
K. Shorter (2010)

Appendix F - Example dataset comparing humerothoracic angles calculated using CSBT Chucker and Microsoft Excel

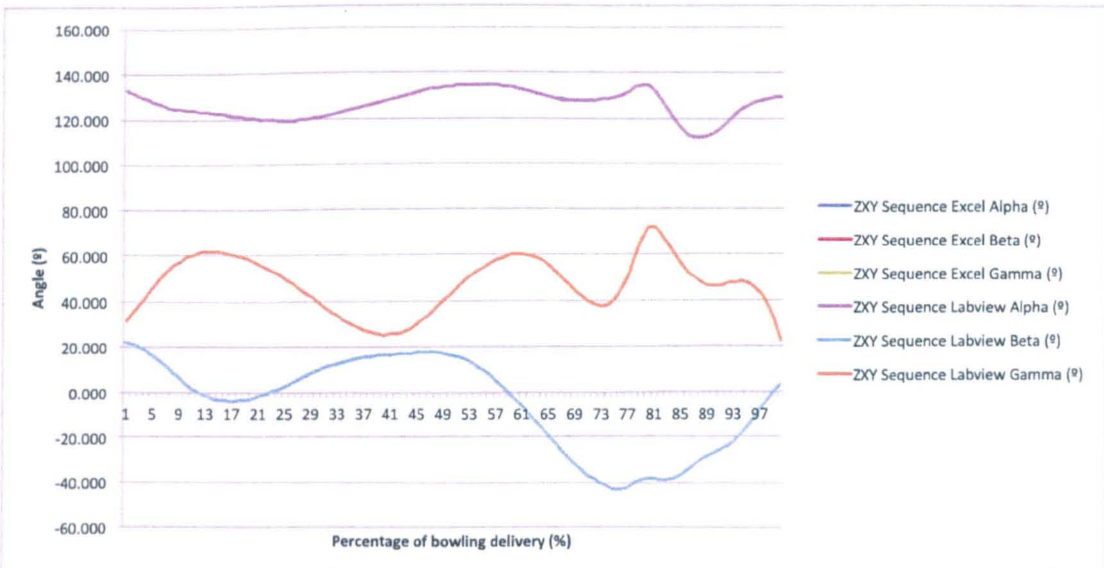
YXY Sequence



XZY Sequence



ZXY Sequence



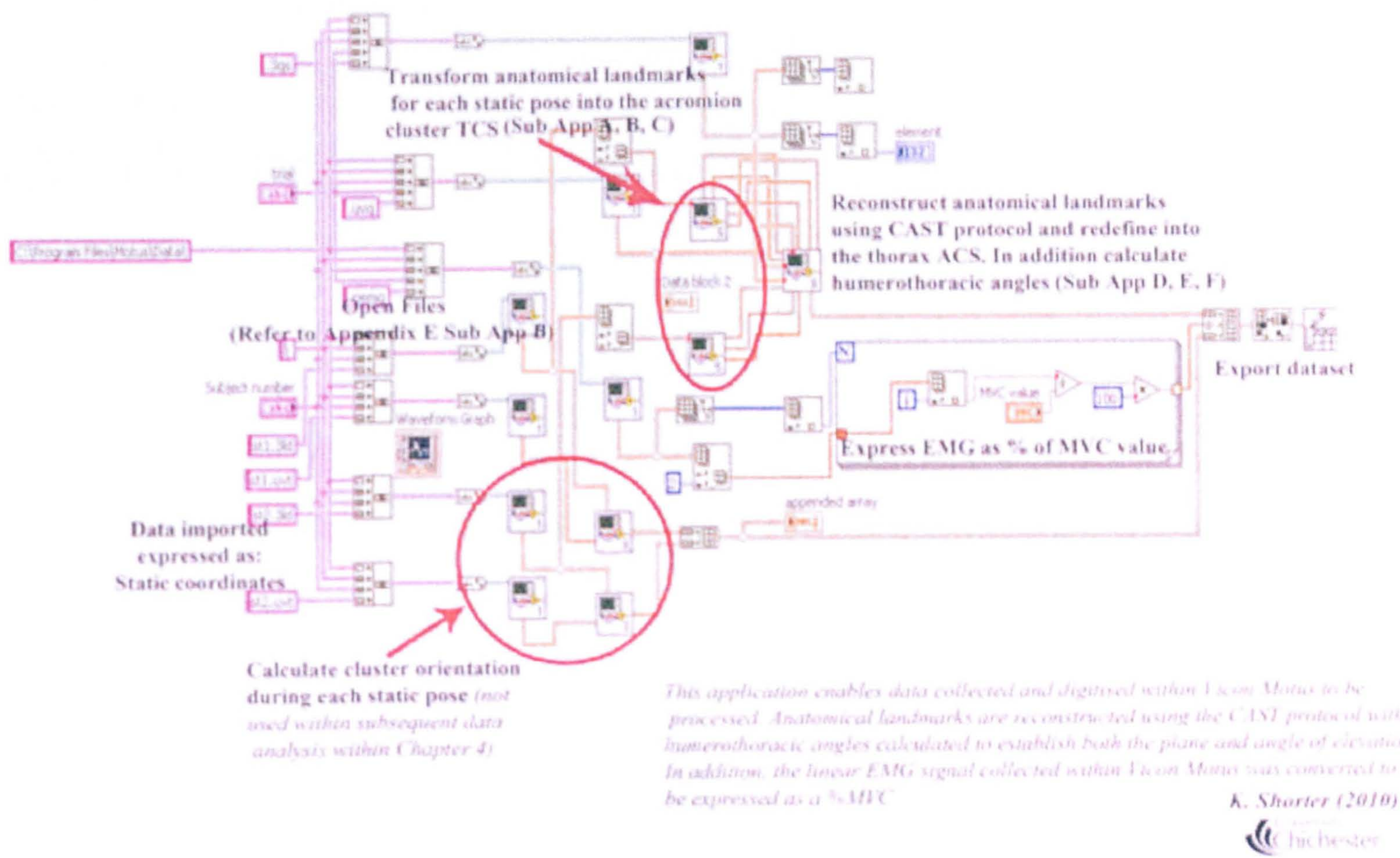
YXY Sequence								
Excel			Labview			Difference		
Alpha (°)	Beta (°)	Gamma (°)	Alpha (°)	Beta (°)	Gamma (°)	Alpha (°)	Beta (°)	Gamma (°)
-2.141	129.301	12.228	-2.144	129.234	12.237	0.003	0.067	-0.009
-4.224	128.260	15.931	-4.247	128.255	15.952	0.023	0.005	-0.021
-5.942	127.363	19.190	-5.953	127.327	19.203	0.011	0.036	-0.013
-7.255	126.509	21.960	-7.316	126.511	22.004	0.061	-0.002	-0.044
-8.381	125.812	24.349	-8.414	125.843	24.368	0.033	-0.031	-0.019
-9.347	125.352	26.309	-9.336	125.330	26.308	-0.011	0.022	0.001
-10.207	124.946	27.868	-10.169	124.948	27.850	-0.038	-0.002	0.018
-10.938	124.656	29.022	-10.981	124.656	29.031	0.043	0.000	-0.009
-11.818	124.440	29.937	-11.811	124.403	29.911	-0.007	0.037	0.026
-12.668	124.151	30.561	-12.671	124.146	30.559	0.003	0.005	0.002
-13.554	123.876	31.006	-13.545	123.856	31.047	-0.009	0.020	-0.041
-14.378	123.506	31.404	-14.408	123.519	31.439	0.030	-0.013	-0.035
-15.247	123.113	31.812	-15.234	123.136	31.784	-0.013	-0.023	0.028
-16.043	122.742	32.162	-16.000	122.715	32.117	-0.043	0.027	0.045
-16.718	122.271	32.479	-16.692	122.270	32.456	-0.026	0.001	0.023
-17.308	121.800	32.765	-17.305	121.816	32.807	-0.003	-0.016	-0.042
-17.843	121.346	33.117	-17.839	121.367	33.169	-0.004	-0.021	-0.052
-18.308	120.909	33.555	-18.300	120.936	33.532	-0.008	-0.027	0.023
-18.716	120.560	33.888	-18.697	120.535	33.881	-0.019	0.025	0.007
-19.051	120.182	34.240	-19.043	120.172	34.203	-0.008	0.010	0.037
-19.353	119.884	34.461	-19.348	119.857	34.480	-0.005	0.027	-0.019
-19.640	119.627	34.719	-19.625	119.595	34.698	-0.015	0.032	0.021
-19.851	119.405	34.828	-19.883	119.394	34.844	0.032	0.011	-0.016
-20.129	119.240	34.911	-20.130	119.259	34.906	0.001	-0.019	0.005
-20.382	119.186	34.816	-20.372	119.196	34.876	-0.010	-0.010	-0.060
-20.593	119.187	34.692	-20.609	119.207	34.750	0.016	-0.020	-0.058
-20.815	119.326	34.582	-20.841	119.297	34.527	0.026	0.029	0.055
-21.023	119.479	34.175	-21.061	119.466	34.207	0.038	0.013	-0.032
-21.285	119.735	33.773	-21.259	119.715	33.793	-0.026	0.020	-0.020
-21.435	120.003	33.297	-21.424	120.041	33.292	-0.011	-0.038	0.005
-21.577	120.426	32.710	-21.540	120.440	32.707	-0.037	-0.014	0.003
-21.588	120.924	32.049	-21.590	120.904	32.046	0.002	0.020	0.003
-21.540	121.449	31.296	-21.556	121.428	31.312	0.016	0.021	-0.016
-21.425	121.983	30.495	-21.419	122.003	30.510	-0.006	-0.020	-0.015
-21.188	122.599	29.579	-21.159	122.619	29.641	-0.029	-0.020	-0.062
-20.735	123.241	28.668	-20.757	123.269	28.706	0.022	-0.028	-0.038
-20.156	123.895	27.682	-20.193	123.944	27.702	0.037	-0.049	-0.020
-19.459	124.659	26.650	-19.446	124.636	26.626	-0.013	0.023	0.024
-18.549	125.322	25.472	-18.497	125.339	25.472	-0.052	-0.017	0.000
-17.280	126.046	24.231	-17.326	126.043	24.236	0.046	0.003	-0.005
-15.930	126.761	22.864	-15.918	126.740	22.913	-0.012	0.021	-0.049
-14.323	127.465	21.507	-14.261	127.421	21.502	-0.062	0.044	0.005
-12.347	128.100	20.002	-12.356	128.076	20.006	0.009	0.024	-0.004
-10.220	128.684	18.442	-10.219	128.695	18.435	-0.001	-0.011	0.007
-7.866	129.258	16.790	-7.890	129.272	16.807	0.024	-0.014	-0.017
-5.370	129.793	15.168	-5.433	129.805	15.143	0.063	-0.012	0.025
-2.950	130.339	13.478	-2.936	130.300	13.466	-0.014	0.039	0.012
-0.494	130.775	11.846	-0.506	130.768	11.793	0.012	0.007	0.053
1.748	131.246	10.146	1.747	131.226	10.131	0.001	0.020	0.015
3.715	131.706	8.472	3.723	131.686	8.473	-0.008	0.020	-0.001
5.347	132.163	6.837	5.343	132.156	6.797	0.004	0.007	0.040
6.575	132.615	5.085	6.559	132.632	5.068	0.016	-0.017	0.017
7.348	133.070	3.232	7.346	133.095	3.249	0.002	-0.025	-0.017
7.738	133.513	1.350	7.707	133.513	1.304	0.031	0.000	0.046
7.627	133.866	-0.762	7.662	133.845	-0.792	-0.035	0.021	0.030
7.240	134.024	-3.071	7.253	134.044	-3.046	-0.013	-0.020	-0.025
6.585	134.073	-5.423	6.542	134.065	-5.440	0.043	0.008	0.017
5.631	133.834	-7.864	5.612	133.866	-7.928	0.019	-0.032	0.064
4.614	133.427	-10.469	4.566	133.423	-10.438	0.048	0.004	-0.031
3.554	132.691	-12.839	3.525	132.725	-12.875	0.029	-0.034	0.036
2.602	131.736	-15.129	2.611	131.784	-15.135	-0.009	-0.048	0.006
1.933	130.646	-17.077	1.936	130.635	-17.119	-0.003	0.011	0.042
1.614	129.353	-18.779	1.580	129.329	-18.744	0.034	0.024	-0.035
1.567	127.886	-19.935	1.580	127.929	-19.956	-0.013	-0.043	0.021
1.923	126.513	-20.790	1.926	126.502	-20.734	-0.003	0.011	-0.056
2.580	125.104	-21.070	2.561	125.109	-21.094	0.019	-0.005	0.024
3.373	123.770	-21.049	3.397	123.796	-21.076	-0.024	-0.026	0.027
4.325	122.616	-20.726	4.327	122.593	-20.743	-0.002	0.023	0.017
5.275	121.498	-20.138	5.236	121.510	-20.165	0.039	-0.012	0.027
5.996	120.594	-19.396	6.012	120.540	-19.416	-0.016	0.054	0.020
6.542	119.655	-18.605	6.538	119.673	-18.562	0.004	-0.018	-0.043
6.667	118.916	-17.678	6.686	118.899	-17.660	-0.019	0.017	-0.018
6.315	118.191	-16.796	6.290	118.236	-16.751	0.025	-0.045	-0.045
5.112	117.730	-15.848	5.112	117.749	-15.846	0.000	-0.019	-0.002
2.804	117.556	-14.860	2.795	117.596	-14.892	0.009	-0.040	0.032
-1.152	118.098	-13.667	-1.149	118.049	-13.678	-0.003	0.049	0.011
-7.181	119.457	-11.713	-7.186	119.407	-11.683	0.005	0.050	-0.030
-15.050	121.520	-8.021	-15.075	121.558	-8.014	0.025	-0.038	-0.007
-22.862	123.386	-2.100	-22.867	123.395	-2.066	0.005	-0.009	-0.034
-28.115	123.457	5.305	-28.119	123.450	5.291	0.004	0.007	0.014
-30.737	121.454	12.339	-30.754	121.471	12.298	0.017	-0.017	0.041
-31.989	118.321	18.023	-31.996	118.349	18.037	0.007	-0.028	-0.014
-32.625	115.082	22.556	-32.631	115.053	22.527	0.006	0.029	0.029
-33.048	112.195	26.041	-33.032	112.176	26.039	-0.016	0.019	0.002
-33.429	110.002	28.724	-33.390	109.997	28.777	-0.039	0.005	-0.053
-33.774	108.599	30.821	-33.771	108.621	30.851	-0.003	-0.022	-0.030
-34.148	108.076	32.281	-34.153	108.077	32.315	0.005	-0.001	-0.034
-34.429	108.355	33.172	-34.456	108.363	33.196	0.027	-0.008	-0.024
-34.543	109.453	33.542	-34.573	109.444	33.507	0.030	0.009	0.035
-34.446	111.233	33.250	-34.390	111.245	33.267	-0.056	-0.012	-0.017
-33.818	113.606	32.480	-33.796	113.623	32.513	-0.022	-0.017	-0.033
-32.711	116.370	31.332	-32.701	116.366	31.332	-0.010	0.004	0.000
-31.078	119.230	29.867	-31.072	119.206	29.866	-0.006	0.024	0.001
-28.909	121.891	28.325	-28.957	121.884	28.285	0.048	0.007	0.040
-26.471	124.203	26.721	-26.489	124.211	26.724	0.018	-0.008	-0.003
-23.833	126.095	25.225	-23.854	126.092	25.229	0.021	0.003	-0.004
-21.201	127.529	23.764	-21.267	127.516	23.744	0.066	0.013	0.020
-18.979	128.498	22.170	-18.981	128.516	22.169	0.002	-0.018	0.001
-17.393	129.139	20.554	-17.364	129.133	20.535	-0.029	0.006	0.019
-17.013	129.384	19.300	-17.021	129.360	19.297	0.008	0.024	0.003

XZY Sequence								
Excel			Labview			Difference		
Alpha (°)	Beta (°)	Gamma (°)	Alpha (°)	Beta (°)	Gamma (°)	Alpha (°)	Beta (°)	Gamma (°)
129.947	-9.433	128.291	129.947	-9.433	128.291	0.000	0.000	0.000
129.356	-12.446	126.905	129.356	-12.446	126.905	0.000	0.000	0.000
128.954	-15.145	125.319	128.954	-15.145	125.319	0.000	0.000	0.000
128.594	-17.492	123.398	128.594	-17.492	123.398	0.000	0.000	0.000
128.379	-19.532	121.271	128.379	-19.532	121.271	0.000	0.000	0.000
128.357	-21.192	119.026	128.357	-21.192	119.026	0.000	0.000	0.000
128.325	-22.529	116.604	128.325	-22.529	116.604	0.000	0.000	0.000
128.329	-23.520	114.259	128.329	-23.520	114.259	0.000	0.000	0.000
128.356	-24.303	112.067	128.356	-24.303	112.067	0.000	0.000	0.000
128.230	-24.883	110.160	128.230	-24.883	110.160	0.000	0.000	0.000
128.071	-25.321	108.456	128.071	-25.321	108.456	0.000	0.000	0.000
127.799	-25.752	107.113	127.799	-25.752	107.113	0.000	0.000	0.000
127.506	-26.201	106.111	127.507	-26.201	106.111	-0.001	0.000	0.000
127.219	-26.599	105.418	127.219	-26.599	105.418	0.000	0.000	0.000
126.816	-27.003	105.068	126.816	-27.003	105.068	0.000	0.000	0.000
126.403	-27.385	104.948	126.403	-27.385	104.948	0.000	0.000	0.000
126.027	-27.814	105.085	126.027	-27.814	105.085	0.000	0.000	0.000
125.694	-28.310	105.484	125.694	-28.310	105.484	0.000	0.000	0.000
125.423	-28.693	106.080	125.423	-28.693	106.080	0.000	0.000	0.000
125.127	-29.103	106.872	125.127	-29.103	106.872	0.000	0.000	0.000
124.875	-29.381	107.866	124.875	-29.381	107.866	0.000	0.000	0.000
124.679	-29.676	108.979	124.679	-29.676	108.979	0.000	0.000	0.000
124.473	-29.838	110.200	124.473	-29.838	110.200	0.000	0.000	0.000
124.320	-29.959	111.609	124.320	-29.959	111.609	0.000	0.000	0.000
124.229	-29.898	113.053	124.229	-29.898	113.053	0.000	0.000	0.000
124.190	-29.795	114.536	124.190	-29.795	114.536	0.000	0.000	0.000
124.307	-29.660	116.070	124.307	-29.660	116.070	0.000	0.000	0.000
124.344	-29.275	117.475	124.344	-29.275	117.475	0.000	0.000	0.000
124.495	-28.863	118.907	124.495	-28.863	118.907	0.000	0.000	0.000
124.638	-28.386	120.307	124.638	-28.386	120.307	0.000	0.000	0.000
124.915	-27.773	121.683	124.915	-27.773	121.683	0.000	0.000	0.000
125.252	-27.078	122.867	125.252	-27.078	122.867	0.000	0.000	0.000
125.592	-26.305	123.965	125.592	-26.305	123.965	0.000	0.000	0.000
125.931	-25.495	125.047	125.931	-25.495	125.047	0.000	0.000	0.000
126.329	-24.573	125.928	126.329	-24.573	125.928	0.000	0.000	0.000
126.759	-23.655	126.807	126.759	-23.655	126.807	0.000	0.000	0.000
127.187	-22.682	127.480	127.187	-22.682	127.480	0.000	0.000	0.000
127.724	-21.651	128.137	127.724	-21.651	128.137	0.000	0.000	0.000
128.129	-20.543	128.646	128.129	-20.543	128.646	0.000	0.000	0.000
128.592	-19.381	129.103	128.592	-19.381	129.103	0.000	0.000	0.000
129.033	-18.136	129.362	129.033	-18.136	129.362	0.000	0.000	0.000
129.478	-16.917	129.493	129.478	-16.917	129.493	0.000	0.000	0.000
129.842	-15.615	129.441	129.842	-15.615	129.441	0.000	0.000	0.000
130.165	-14.296	129.230	130.165	-14.296	129.230	0.000	0.000	0.000
130.486	-12.925	128.723	130.486	-12.925	128.723	0.000	0.000	0.000
130.795	-11.598	127.890	130.795	-11.598	127.890	0.000	0.000	0.000
131.131	-10.233	126.769	131.131	-10.233	126.769	0.000	0.000	0.000
131.386	-8.944	125.479	131.386	-8.944	125.479	0.000	0.000	0.000
131.694	-7.611	123.880	131.694	-7.611	123.880	0.000	0.000	0.000
132.019	-6.315	122.205	132.019	-6.315	122.205	0.000	0.000	0.000
132.367	-5.063	120.445	132.367	-5.063	120.445	0.000	0.000	0.000
132.727	-3.740	118.648	132.727	-3.740	118.648	0.000	0.000	0.000
133.115	-2.361	116.975	133.115	-2.361	116.975	0.000	0.000	0.000
133.521	-0.979	115.293	133.521	-0.979	115.293	0.000	0.000	0.000
133.868	0.549	113.865	133.868	0.549	113.865	0.000	0.000	0.000
134.066	2.207	112.561	134.066	2.207	112.561	0.000	0.000	0.000
134.201	3.893	111.539	134.201	3.893	111.539	0.000	0.000	0.000
134.104	5.664	110.815	134.104	5.664	110.815	0.000	0.000	0.000
133.907	7.583	110.443	133.907	7.583	110.443	0.000	0.000	0.000
133.415	9.400	110.487	133.415	9.400	110.487	0.000	0.000	0.000
132.742	11.231	110.990	132.742	11.231	110.990	0.000	0.000	0.000
131.927	12.874	111.912	131.927	12.874	111.912	0.000	0.000	0.000
130.897	14.414	113.294	130.897	14.414	113.294	0.000	0.000	0.000
129.614	15.610	114.961	129.614	15.610	114.961	0.000	0.000	0.000
128.374	16.576	116.792	128.374	16.576	116.792	0.000	0.000	0.000
126.990	17.104	118.774	126.990	17.104	118.774	0.000	0.000	0.000
125.621	17.371	120.646	125.621	17.371	120.646	0.000	0.000	0.000
124.380	17.343	122.396	124.380	17.343	122.396	0.000	0.000	0.000
123.131	17.071	123.825	123.131	17.071	123.825	0.000	0.000	0.000
122.081	16.610	125.067	122.081	16.610	125.067	0.000	0.000	0.000
120.995	16.096	125.978	120.995	16.096	125.978	0.000	0.000	0.000
120.104	15.415	126.561	120.104	15.415	126.561	0.000	0.000	0.000
119.243	14.755	126.863	119.243	14.755	126.863	0.000	0.000	0.000
118.655	13.988	126.818	118.655	13.988	126.818	0.000	0.000	0.000
118.363	13.142	126.262	118.363	13.142	126.262	0.000	0.000	0.000
118.787	12.030	124.684	118.787	12.030	124.684	0.000	0.000	0.000
119.976	10.182	121.179	119.976	10.182	121.179	0.000	0.000	0.000
121.772	6.832	114.990	121.772	6.832	114.990	0.000	0.000	0.000
123.404	1.753	106.981	123.404	1.753	106.981	0.000	0.000	0.000
123.570	-4.424	99.625	123.570	-4.424	99.625	0.000	0.000	0.000
122.054	-10.503	94.429	122.054	-10.503	94.429	0.000	0.000	0.000
119.541	-15.805	91.093	119.541	-15.805	91.093	0.000	0.000	0.000
116.877	-20.330	88.977	116.877	-20.330	88.977	0.000	0.000	0.000
114.422	-23.984	87.980	114.422	-23.984	87.980	0.000	0.000	0.000
112.543	-26.847	87.864	112.543	-26.847	87.864	0.000	0.000	0.000
111.399	-29.052	88.520	111.399	-29.052	88.520	0.000	0.000	0.000
111.109	-30.512	89.857	111.109	-30.512	89.857	0.000	0.000	0.000
111.622	-31.287	91.726	111.622	-31.287	91.726	0.000	0.000	0.000
112.965	-31.400	93.993	112.965	-31.400	93.993	0.000	0.000	0.000
114.919	-30.735	96.531	114.919	-30.735	96.531	0.000	0.000	0.000
117.387	-29.476	99.184	117.387	-29.476	99.184	0.000	0.000	0.000
120.130	-27.768	101.897	120.130	-27.768	101.897	0.000	0.000	0.000
122.833	-25.758	104.632	122.833	-25.758	104.632	0.000	0.000	0.000
125.255	-23.757	107.376	125.255	-23.757	107.376	0.000	0.000	0.000
127.269	-21.832	110.256	127.269	-21.832	110.256	0.000	0.000	0.000
128.866	-20.143	113.362	128.866	-20.143	113.362	0.000	0.000	0.000
130.007	-18.637	116.869	130.007	-18.637	116.869	0.000	0.000	0.000
130.659	-17.177	120.588	130.659	-17.177	120.588	0.000	0.000	0.000
130.995	-15.802	124.407	130.995	-15.802	124.407	0.000	0.000	0.000
131.018	-14.801	127.658	131.018	-14.801	127.658	0.000	0.000	0.000

ZXY Sequence								
Excel			Labview			Difference		
Alpha (°)	Beta (°)	Gamma (°)	Alpha (°)	Beta (°)	Gamma (°)	Alpha (°)	Beta (°)	Gamma (°)
133.003	21.772	31.667	133.003	21.772	31.667	0.000	0.000	0.000
131.628	21.226	35.433	131.628	21.226	35.433	0.000	0.000	0.000
130.265	20.126	39.304	130.265	20.126	39.304	0.000	0.000	0.000
128.889	18.618	43.020	128.889	18.618	43.020	0.000	0.000	0.000
127.619	16.546	46.549	127.619	16.546	46.549	0.000	0.000	0.000
126.656	14.268	49.820	126.656	14.268	49.820	0.000	0.000	0.000
125.799	11.694	52.892	125.799	11.694	52.892	0.000	0.000	0.000
125.152	9.008	55.535	125.152	9.008	55.535	0.000	0.000	0.000
124.695	6.508	57.639	124.695	6.508	57.639	0.000	0.000	0.000
124.249	4.062	59.380	124.249	4.062	59.380	0.000	0.000	0.000
123.897	1.896	60.614	123.897	1.896	60.614	0.000	0.000	0.000
123.506	0.069	61.418	123.506	0.069	61.418	0.000	0.000	0.000
123.124	-1.381	61.764	123.124	-1.381	61.764	0.000	0.000	0.000
122.778	-2.549	61.824	122.778	-2.549	61.824	0.000	0.000	0.000
122.334	-3.379	61.609	122.334	-3.379	61.609	0.000	0.000	0.000
121.876	-3.758	61.178	121.876	-3.758	61.178	0.000	0.000	0.000
121.429	-3.930	60.437	121.429	-3.930	60.437	0.000	0.000	0.000
120.982	-3.735	59.563	120.982	-3.735	59.563	0.000	0.000	0.000
120.617	-3.327	58.497	120.617	-3.327	58.497	0.000	0.000	0.000
120.216	-2.610	57.270	120.216	-2.610	57.270	0.000	0.000	0.000
119.898	-1.692	55.905	119.898	-1.692	55.905	0.000	0.000	0.000
119.629	-0.625	54.447	119.629	-0.625	54.447	0.000	0.000	0.000
119.407	0.580	52.885	119.407	0.580	52.885	0.000	0.000	0.000
119.258	1.890	51.223	119.258	1.890	51.223	0.000	0.000	0.000
119.238	3.281	49.513	119.238	3.281	49.513	0.000	0.000	0.000
119.295	4.703	47.564	119.295	4.703	47.564	0.000	0.000	0.000
119.509	6.097	45.774	119.509	6.097	45.774	0.000	0.000	0.000
119.754	7.432	43.686	119.754	7.432	43.686	0.000	0.000	0.000
120.125	8.794	41.610	120.125	8.794	41.610	0.000	0.000	0.000
120.508	9.927	39.624	120.508	9.927	39.624	0.000	0.000	0.000
121.064	11.049	37.572	121.064	11.049	37.572	0.000	0.000	0.000
121.706	12.090	35.490	121.706	12.090	35.490	0.000	0.000	0.000
122.362	12.911	33.555	122.362	12.911	33.555	0.000	0.000	0.000
123.022	13.607	31.806	123.022	13.607	31.806	0.000	0.000	0.000
123.768	14.237	30.027	123.768	14.237	30.027	0.000	0.000	0.000
124.543	14.819	28.635	124.543	14.819	28.635	0.000	0.000	0.000
125.316	15.269	27.314	125.316	15.269	27.314	0.000	0.000	0.000
126.196	15.636	26.362	126.196	15.636	26.362	0.000	0.000	0.000
126.964	15.945	25.631	126.964	15.945	25.631	0.000	0.000	0.000
127.803	16.261	25.212	127.803	16.261	25.212	0.000	0.000	0.000
128.615	16.470	25.465	128.615	16.470	25.465	0.000	0.000	0.000
129.436	16.745	25.786	129.436	16.745	25.786	0.000	0.000	0.000
130.176	16.974	26.718	130.176	16.974	26.718	0.000	0.000	0.000
130.871	17.220	28.133	130.871	17.220	28.133	0.000	0.000	0.000
131.542	17.403	29.962	131.542	17.403	29.962	0.000	0.000	0.000
132.145	17.484	32.177	132.145	17.484	32.177	0.000	0.000	0.000
132.752	17.528	34.592	132.752	17.528	34.592	0.000	0.000	0.000
133.193	17.412	37.348	133.193	17.412	37.348	0.000	0.000	0.000
133.609	17.086	40.238	133.609	17.086	40.238	0.000	0.000	0.000
133.962	16.582	42.916	133.962	16.582	42.916	0.000	0.000	0.000
134.216	15.731	45.644	134.216	15.731	45.644	0.000	0.000	0.000
134.379	14.518	48.275	134.379	14.518	48.275	0.000	0.000	0.000
134.515	13.085	50.579	134.515	13.085	50.579	0.000	0.000	0.000
134.600	11.307	52.826	134.600	11.307	52.826	0.000	0.000	0.000
134.605	9.309	54.674	134.605	9.309	54.674	0.000	0.000	0.000
134.454	7.102	56.465	134.454	7.102	56.465	0.000	0.000	0.000
134.253	4.613	57.899	134.253	4.613	57.899	0.000	0.000	0.000
133.867	1.981	59.137	133.867	1.981	59.137	0.000	0.000	0.000
133.432	-0.827	59.908	133.432	-0.827	59.908	0.000	0.000	0.000
132.804	-3.740	60.308	132.804	-3.740	60.308	0.000	0.000	0.000
132.096	-6.770	60.317	132.096	-6.770	60.317	0.000	0.000	0.000
131.400	-9.938	59.723	131.400	-9.938	59.723	0.000	0.000	0.000
130.616	-13.078	58.648	130.616	-13.078	58.648	0.000	0.000	0.000
129.779	-16.306	57.053	129.779	-16.306	57.053	0.000	0.000	0.000
129.136	-19.489	54.990	129.136	-19.489	54.990	0.000	0.000	0.000
128.570	-22.728	52.515	128.570	-22.728	52.515	0.000	0.000	0.000
128.100	-25.730	49.868	128.100	-25.730	49.868	0.000	0.000	0.000
127.894	-28.648	47.083	127.894	-28.648	47.083	0.000	0.000	0.000
127.741	-31.396	44.272	127.741	-31.396	44.272	0.000	0.000	0.000
127.821	-33.902	41.832	127.821	-33.902	41.832	0.000	0.000	0.000
127.865	-36.286	39.688	127.865	-36.286	39.688	0.000	0.000	0.000
128.071	-38.359	38.271	128.071	-38.359	38.271	0.000	0.000	0.000
128.277	-40.306	37.663	128.277	-40.306	37.663	0.000	0.000	0.000
128.605	-41.777	38.207	128.605	-41.777	38.207	0.000	0.000	0.000
129.102	-42.820	40.418	129.102	-42.820	40.418	0.000	0.000	0.000
130.096	-43.008	44.529	130.096	-43.008	44.529	0.000	0.000	0.000
131.503	-42.089	51.040	131.503	-42.089	51.040	0.000	0.000	0.000
133.273	-40.298	59.192	133.273	-40.298	59.192	0.000	0.000	0.000
134.629	-38.437	67.149	134.629	-38.437	67.149	0.000	0.000	0.000
134.201	-37.742	71.875	134.201	-37.742	71.875	0.000	0.000	0.000
131.603	-38.195	72.273	131.603	-38.195	72.273	0.000	0.000	0.000
127.555	-38.892	69.411	127.555	-38.892	69.411	0.000	0.000	0.000
123.005	-38.901	65.018	123.005	-38.901	65.018	0.000	0.000	0.000
118.623	-37.947	60.295	118.623	-37.947	60.295	0.000	0.000	0.000
115.103	-36.267	56.054	115.103	-36.267	56.054	0.000	0.000	0.000
112.669	-34.151	52.529	112.669	-34.151	52.529	0.000	0.000	0.000
111.497	-32.147	49.654	111.497	-32.147	49.654	0.000	0.000	0.000
111.366	-30.193	47.779	111.366	-30.193	47.779	0.000	0.000	0.000
112.251	-28.421	46.677	112.251	-28.421	46.677	0.000	0.000	0.000
113.988	-27.024	46.259	113.988	-27.024	46.259	0.000	0.000	0.000
116.341	-25.512	46.627	116.341	-25.512	46.627	0.000	0.000	0.000
119.033	-23.765	47.439	119.033	-23.765	47.439	0.000	0.000	0.000
121.683	-21.606	48.091	121.683	-21.606	48.091	0.000	0.000	0.000
123.928	-18.823	48.287	123.928	-18.823	48.287	0.000	0.000	0.000
125.662	-15.379	47.582	125.662	-15.379	47.582	0.000	0.000	0.000
126.953	-11.486	45.755	126.953	-11.486	45.755	0.000	0.000	0.000
127.895	-7.355	42.301	127.895	-7.355	42.301	0.000	0.000	0.000
128.569	-3.189	37.377	128.569	-3.189	37.377	0.000	0.000	0.000
129.140	0.487	30.673	129.140	0.487	30.673	0.000	0.000	0.000
129.447	2.944	22.381	129.447	2.944	22.381	0.000	0.000	0.000

Appendix G - CSBT DynACRel (Chapter 4) LabVIEW™ program schematic

(Refer to electronic version for more detail)


Transform anatomical landmarks for each static pose into the acromion cluster TCS (Sub App A, B, C)
Reconstruct anatomical landmarks using CAST protocol and redefine into the thorax ACS. In addition calculate humerothoracic angles (Sub App D, E, F)
Open Files (Refer to Appendix E Sub App B)
Subject number
Waveform Graph
Data block 2
element
Express EMG as % of MVC value
MVC value
appended array
Export dataset
Data imported expressed as: Static coordinates
Calculate cluster orientation during each static pose (not used within subsequent data analysis within Chapter 4)
This application enables data collected and digitised within Vicon Motus to be processed. Anatomical landmarks are reconstructed using the CAST protocol with humerothoracic angles calculated to establish both the plane and angle of elevation. In addition, the linear EMG signal collected within Vicon Motus was converted to be expressed as a %MVC
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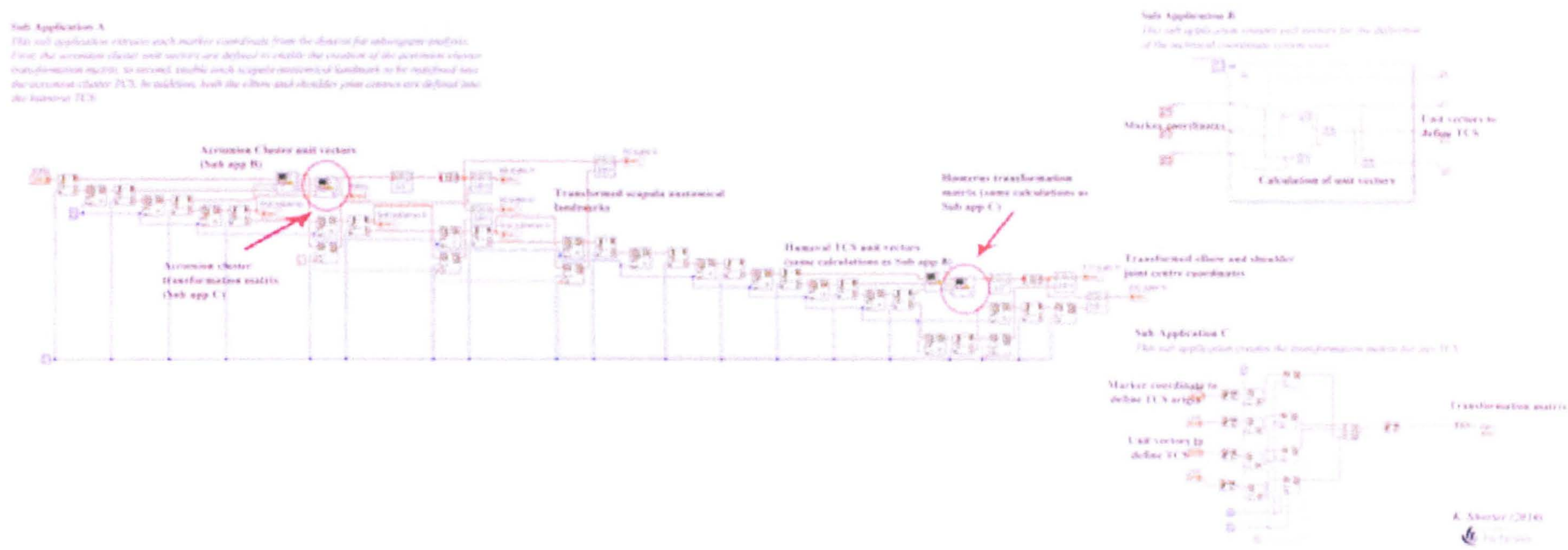
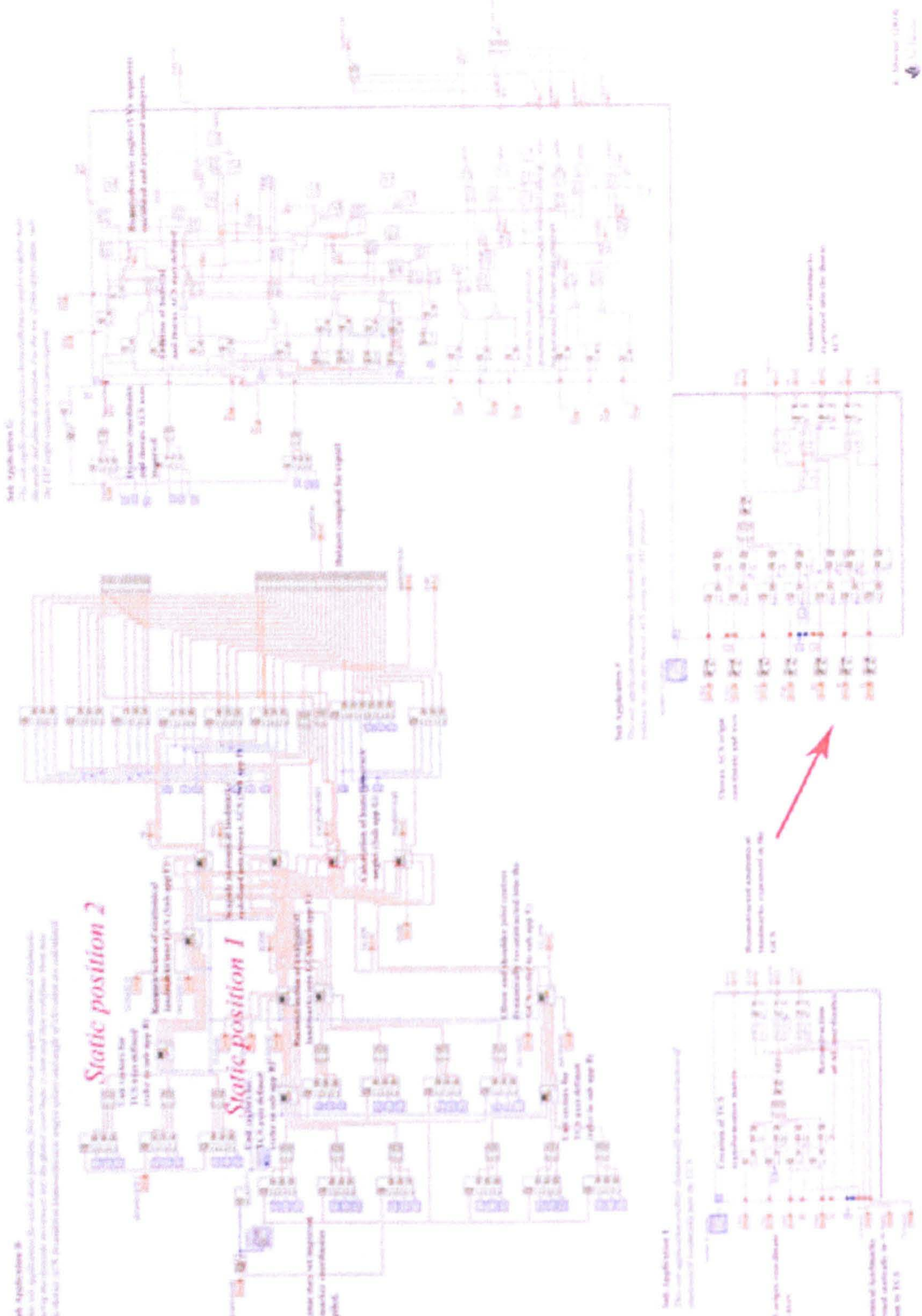

Sub Application A
Acromion Cluster unit vectors
(Sub app B)
Acromion cluster
transformation matrix
(Sub app C)
Transformed scapula anatomical
landmarks
Humeral TCS unit vectors
(same calculations as Sub app B)
Humerus transformation
matrix (same calculations as
Sub app C)
Transformed elbow and shoulder
joint centre coordinates
Sub Application B
Marker coordinates
Unit vectors to
define TCS
Calculation of unit vectors
Sub Application C
Marker coordinates to
define TCS origin
Unit vectors to
define TCS
Transformation matrix


Static position 2
Static position 1

Appendix H - CSBT BentAcc and CSBT Bent (Chapter 5)

Arduino code and LabVIEW™ program schematic

CSBT BentAcc

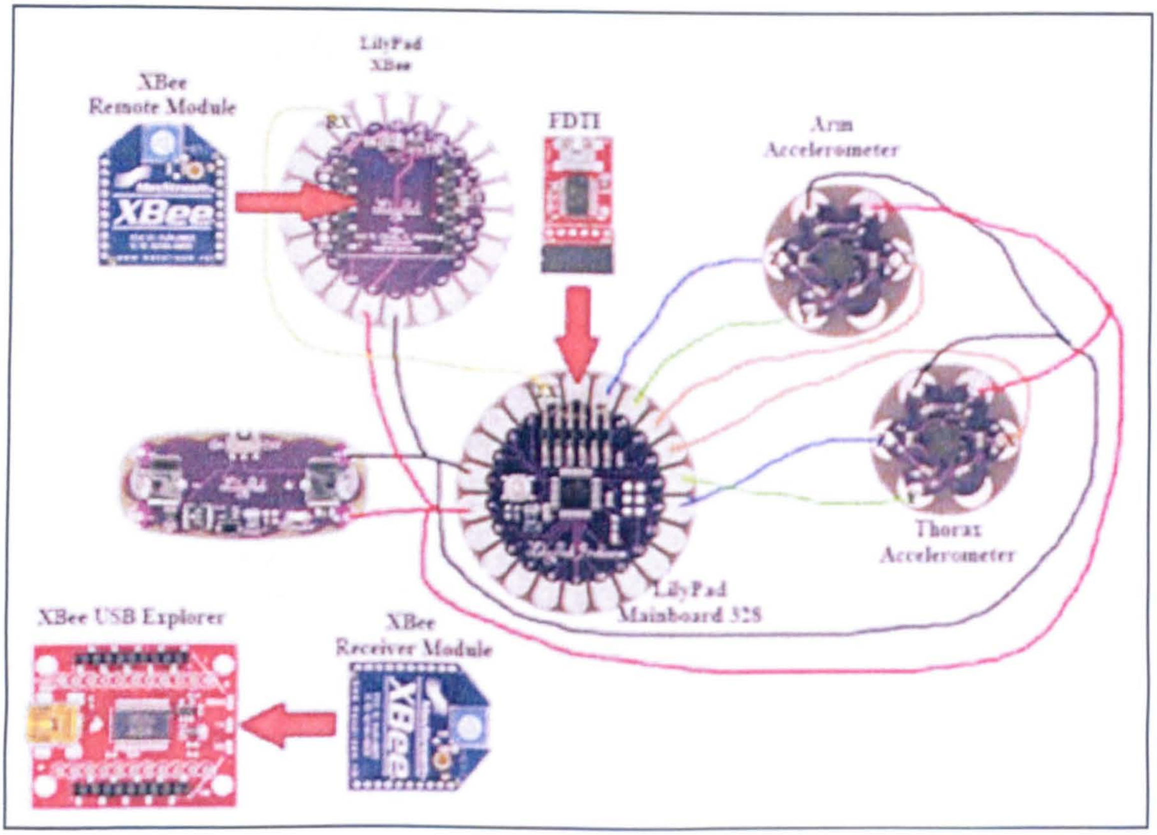
Accelerometer based monitoring system for shoulder position

Hardware

Equipment:

Two LilyPad Accelerometers (ADXL335)
LilyPad Mainboard 328
LilyPad Xbee
LilyPad Power Supply
FTDI Basic Breakout
Two Xbee 1mW Chip Antennas
Xbee Explorer USB
Mini USB Cable

Schematic:



The Xbee network is configured using a Xbee Explorer USB and X-CTU software (Digi International Inc., Minnetonka, USA). Once configured using default settings, the remote module is connected to the LilyPad Xbee board, and the receiver remains connected to the Xbee Explorer USB to create the XBee wireless network.

Software

Arduino:

Calibration:

The following program code is uploaded via the FTDI breakout board to the LilyPad Mainboard 328. The program is designed to collect data from each accelerometer axis, and offset this using default values gained from static tests. For each accelerometer, pitch, roll and theta angles are calculated using trigonometry. Calibration values are collected with the participant statically standing in the anatomical position, with the accelerometers aligned according to the anatomical axes.

```
#define txoffset 513
#define tyoffset 509
#define tzoffset 510.5
#define hxoffset 513
#define hyoffset 496.5
#define hzoffset 549
int thorx = 2;  //1st accelerometer - thorax
int thory = 1;
int thorz = 0;
int humx = 3;  //2nd accelerometer - arm
int humy = 4;
int humz = 5;
int corrtx;
int corrty;
int corrtz;
int corrhx;
int corrhy;
int corrhz;
int ac1p;
int ac1r;
int ac1t;
int ac2p;
int ac2r;
int ac2t;
int pitch;
int roll;
int theta;

void setup() {
 Serial.begin(9600);
}
void loop(){

 corrtx = analogRead(thorx)-txoffset;
 corrty = analogRead(thory)-tyoffset;
 corrtz = analogRead(thorz)-tzoffset;
 corrhx = analogRead(humx)-hxoffset;
 corrhy = analogRead(humy)-hyoffset;
 corrhz = analogRead(humz)-hzoffset;

 ac1p = degrees((atan2((corrtx),sqrt(sq(corrty)+sq(corrtz)))));
 ac1r = degrees((atan2((corrty),sqrt(sq(corrtx)+sq(corrtz)))));
 ac1t = degrees((atan2( sqrt(sq(corrtx)+sq(corrty)),(corrtz))));
 ac2p = degrees((atan2((corrhx),sqrt(sq(corrhy)+sq(corrhz)))));
 ac2r = degrees((atan2((corrhy),sqrt(sq(corrhx)+sq(corrhz)))));
 ac2t = degrees((atan2( sqrt(sq(corrhx)+sq(corrhy)),(corrhz))));

// print the sensor values:
```

```
 Serial.print(ac1p);
 Serial.print("\t");
 Serial.print(ac1r);
 Serial.print("\t");
 Serial.print(ac1t);
 Serial.print("\t");
 Serial.print(ac2p);
 Serial.print("\t");
 Serial.print(ac2r);
 Serial.print("\t");
 Serial.print(ac2t);
 Serial.print("\t");
 Serial.println();
 // delay before next reading:
 delay(100);
}
```

Data collection:

Once the calibration procedure has been performed, the calibration values are inputted into the code below, with the program then being uploaded to the mainboard using the FTDI breakout. Resultant pitch, roll and theta angles are calculated as the difference between the thorax and arm accelerometers.

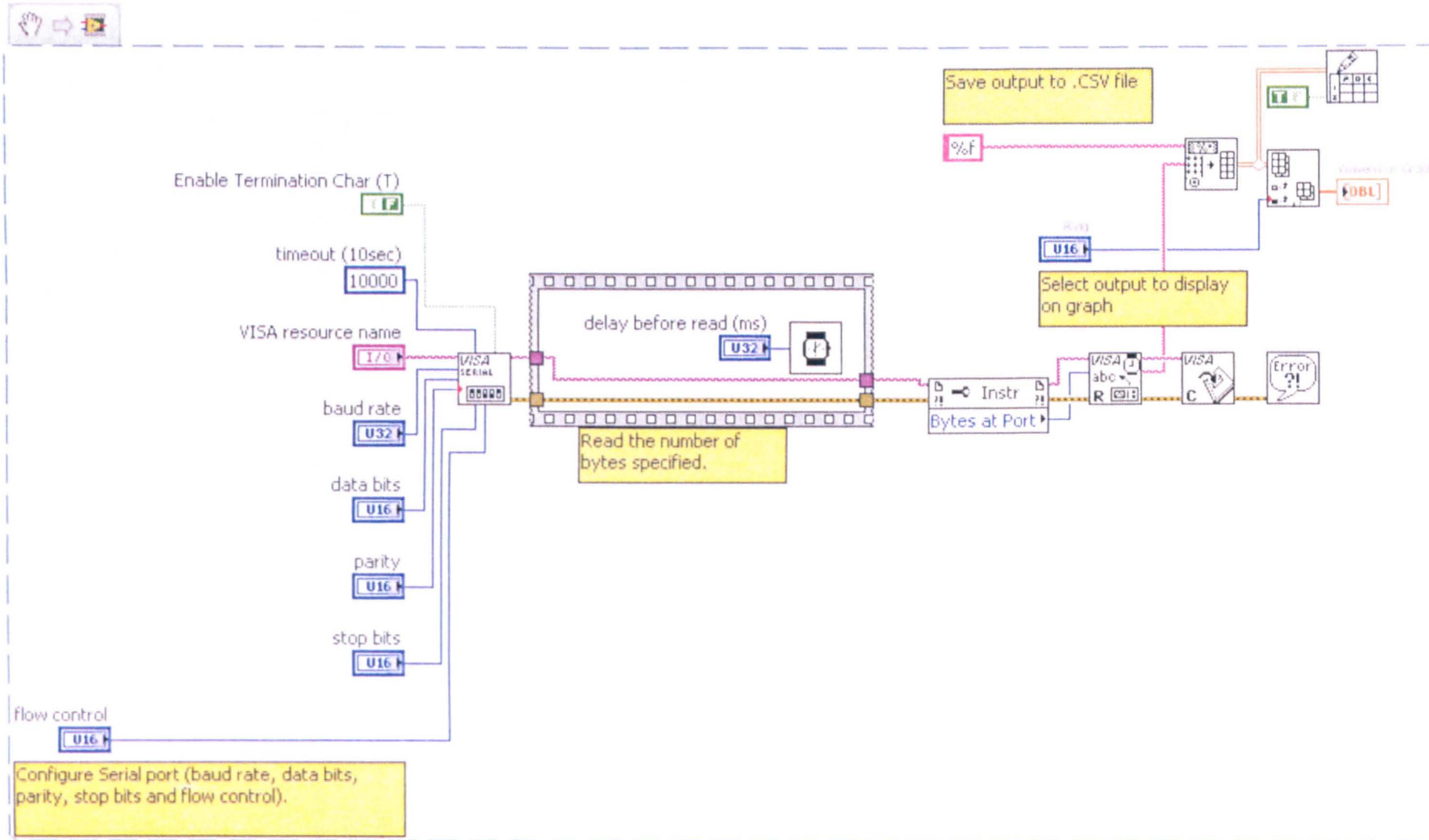
```
#define txoffset 513
#define tyoffset 509
#define tzoffset 510.5
#define hxoffset 513
#define hyoffset 496.5
#define hzoffset 549
int thorx = 2;   //1st accelerometer - thorax
int thory = 1;
int thorz = 0;
int humx = 3;  //2nd accelerometer - arm
int humy = 4;
int humz = 5;
int corrtx;
int corrty;
int corrtz;
int corrhx;
int corrhy;
int corrhz;
int ac1p;
int ac1r;
int ac1t;
int ac2p;
int ac2r;
int ac2t;
int pitch;
int roll;
int theta;

void setup() {
 Serial.begin(9600);
}
void loop(){

 corrtx = analogRead(thorx)-txoffset;
 corrty = analogRead(thory)-tyoffset;
 corrtz = analogRead(thorz)-tzoffset;
 corrhx = analogRead(humx)-hxoffset;
 corrhy = analogRead(humy)-hyoffset;
 corrhz = analogRead(humz)-hzoffset;
```

```
 ac1p = degrees((atan2((corrtx),sqrt(sq(corrty)+sq(corrtz)))))+(-1-**);          //** insert static
calibration value
 ac1r = degrees((atan2((corrty),sqrt(sq(corrtx)+sq(corrtz)))))+(88-**);          //** insert static
calibration value
 ac1t = degrees((atan2( sqrt(sq(corrtx)+sq(corrty)),(corrtz))))+(90-**);         //** insert static
calibration value
 ac2p = degrees((atan2((corrhx),sqrt(sq(corrhy)+sq(corrhz)))))+(0- **);          //** insert static
calibration value
 ac2r = degrees((atan2((corrhy),sqrt(sq(corrhx)+sq(corrhz)))))+(88-**);          //** insert static
calibration value
 ac2t = degrees((atan2( sqrt(sq(corrhx)+sq(corrhy)),(corrhz))))+(91-**);         //** insert static
calibration value

 pitch = ac2p - ac1p;
 roll = ac2r - ac1r;
 theta = ac2t - ac1t;

 // print the sensor values:
  Serial.print(ac1p);
 Serial.print("\t");
 Serial.print(ac1r);
 Serial.print("\t");
 Serial.print(ac1t);
 Serial.print("\t");
 Serial.print(ac2p);
 Serial.print("\t");
 Serial.print(ac2r);
 Serial.print("\t");
 Serial.print(ac2t);
 Serial.print("\t");
 Serial.print(pitch);
 Serial.print("\t");
 Serial.print(roll);
 Serial.print("\t");
 Serial.print(theta);
 Serial.println();
 // delay before next reading:
 delay(100);
}
```

CSBT Bent

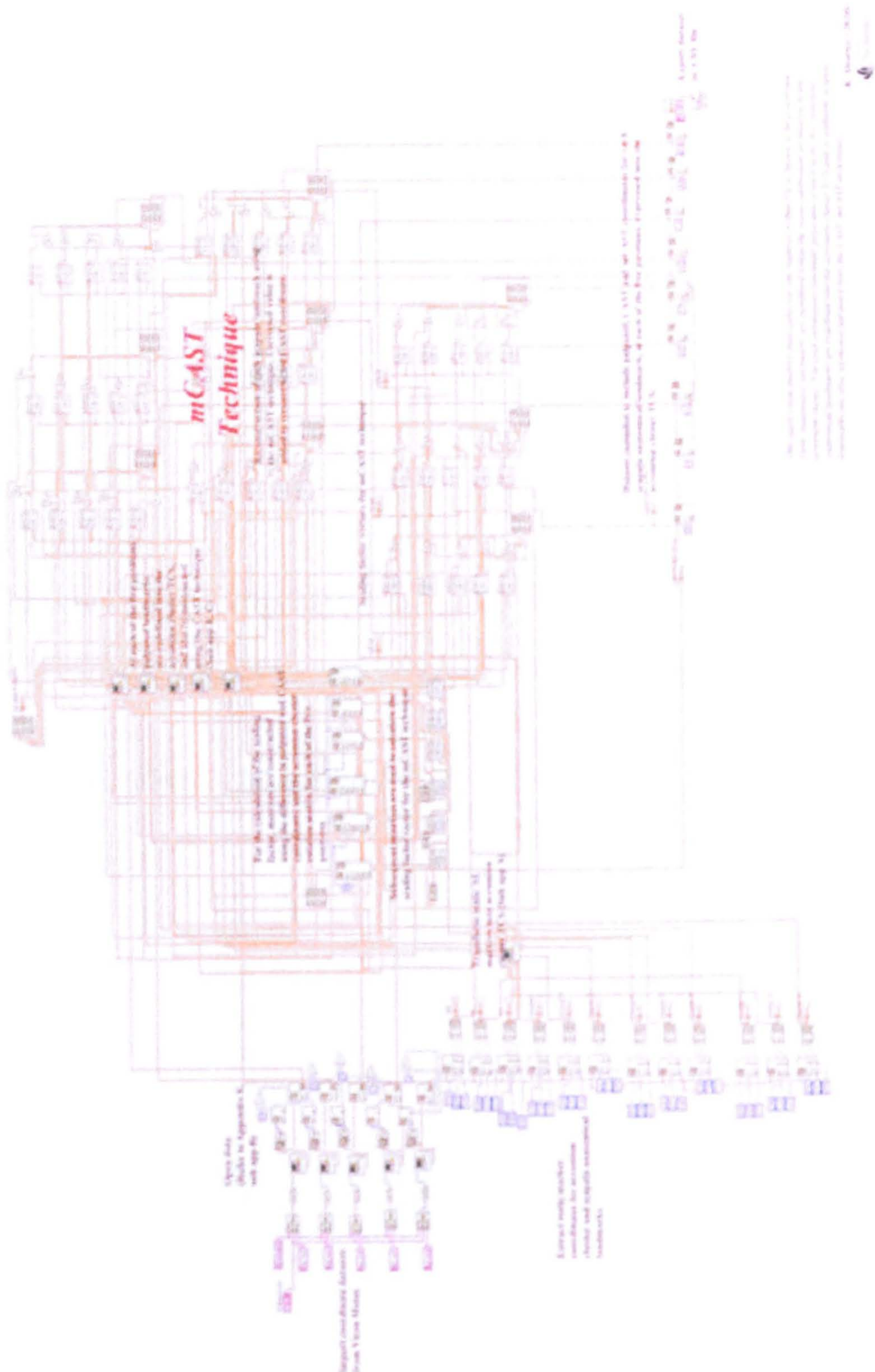
LabVIEW™:

The following block diagram represents a program schematic used to collect CSBT BentAcc data wirelessly using LabVIEW™ 2009 (National Instruments, Austin, USA) and either graphically display pitch, roll and theta angles or save the output as a .CSV file.


Save output to .CSV file
%f
Enable Termination Char (T)
timeout (10sec)
10000
VISA resource name
I/O
baud rate
U32
data bits
U16
parity
U16
stop bits
U16
flow control
U16
delay before read (ms)
U32
Read the number of bytes specified.
Instr
Bytes at Port
U16
Select output to display on graph
DBL
Configure Serial port (baud rate, data bits, parity, stop bits and flow control).

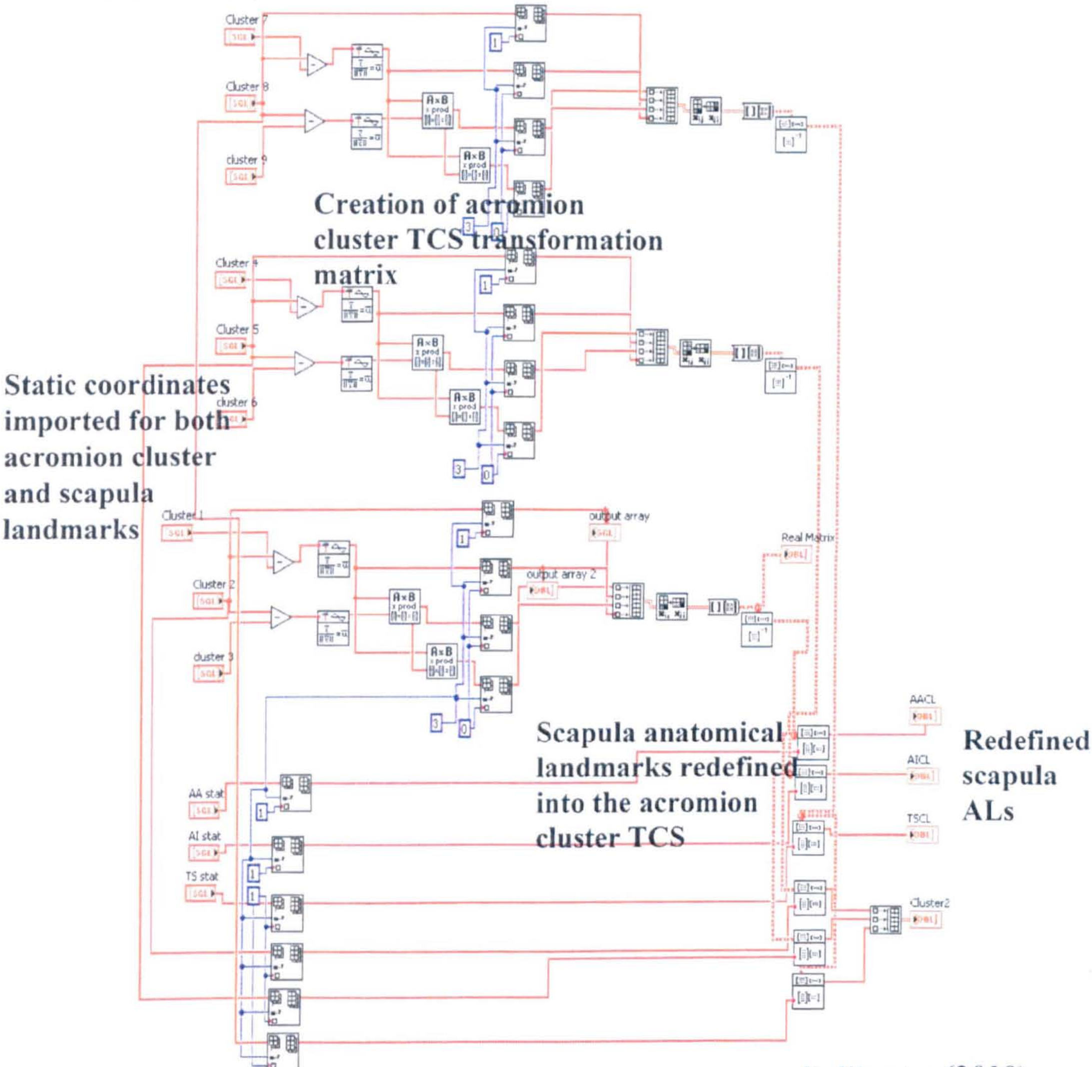
Appendix I - CSBT mCASTanalyser (Chapter 5) LabVIEW™ program schematic

(Refer to electronic version for more detail)


mCAST Technique

Sub Application A

This sub application transforms each anatomical scapula landmark into the acromion cluster TCS using the CAST protocol (each landmark is transformed at a different time instant requiring each to be redefined on an individual basis).



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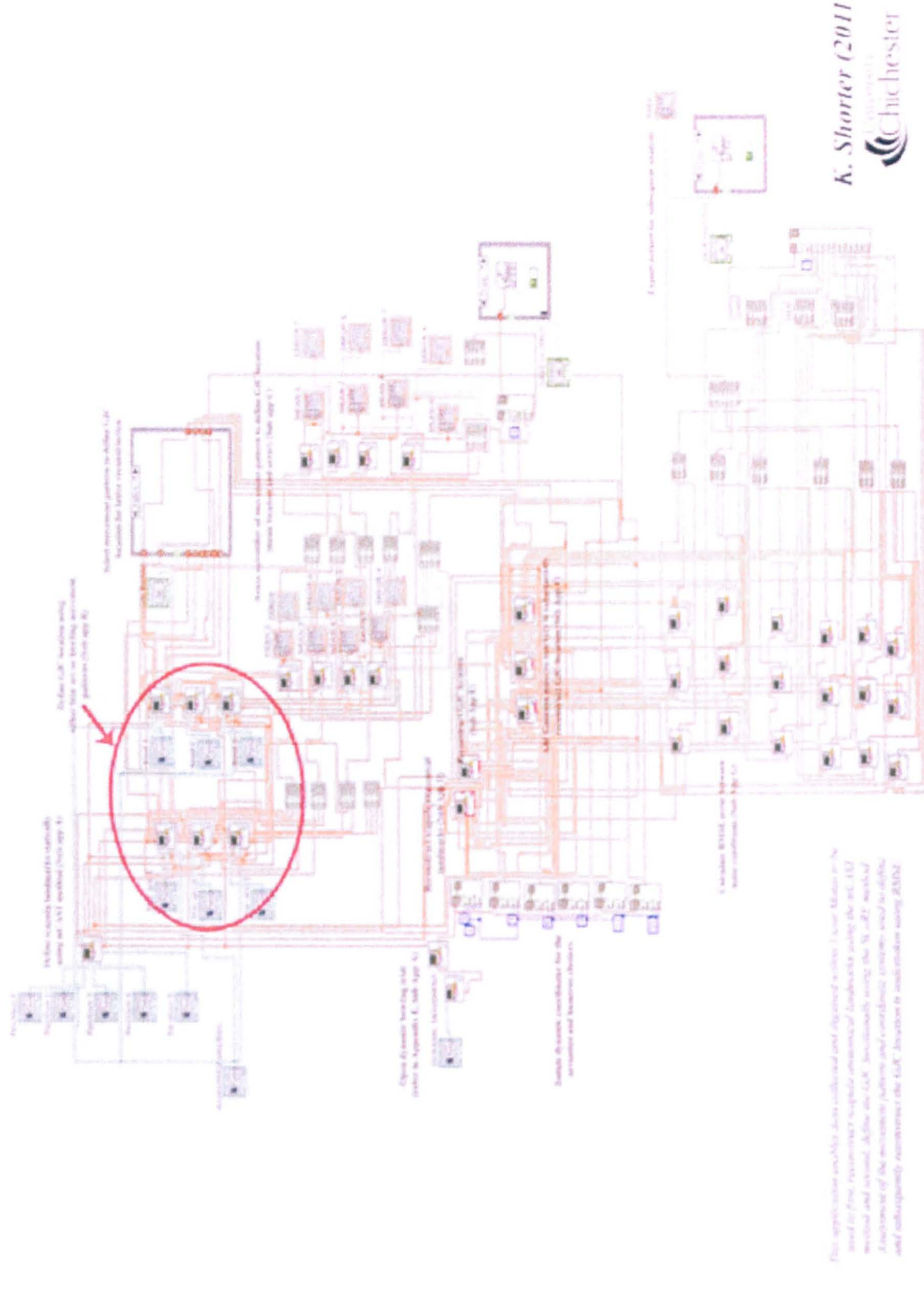
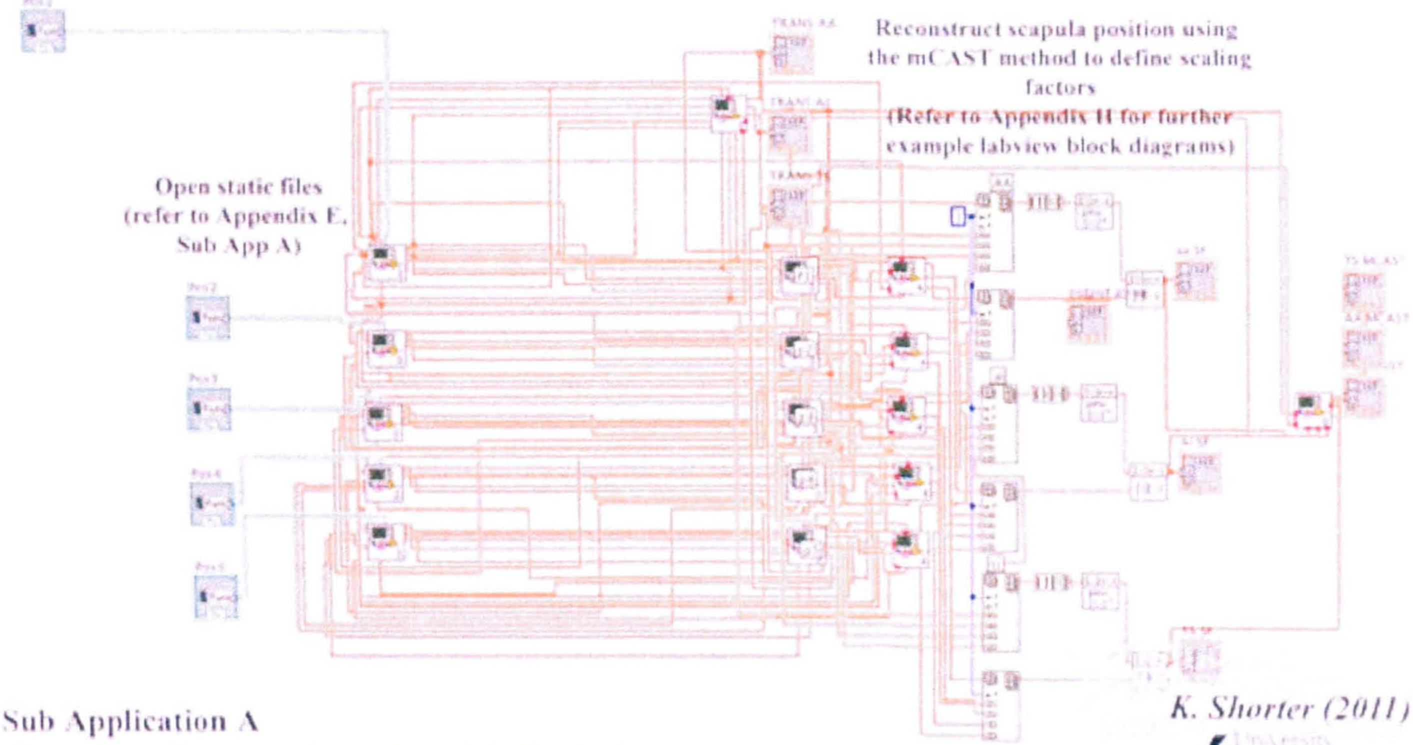
Palpation 1
Palpation 2
Palpation 3

Appendix J - CSBT GJCanalyser (Chapter 6) LabVIEW™ program schematic

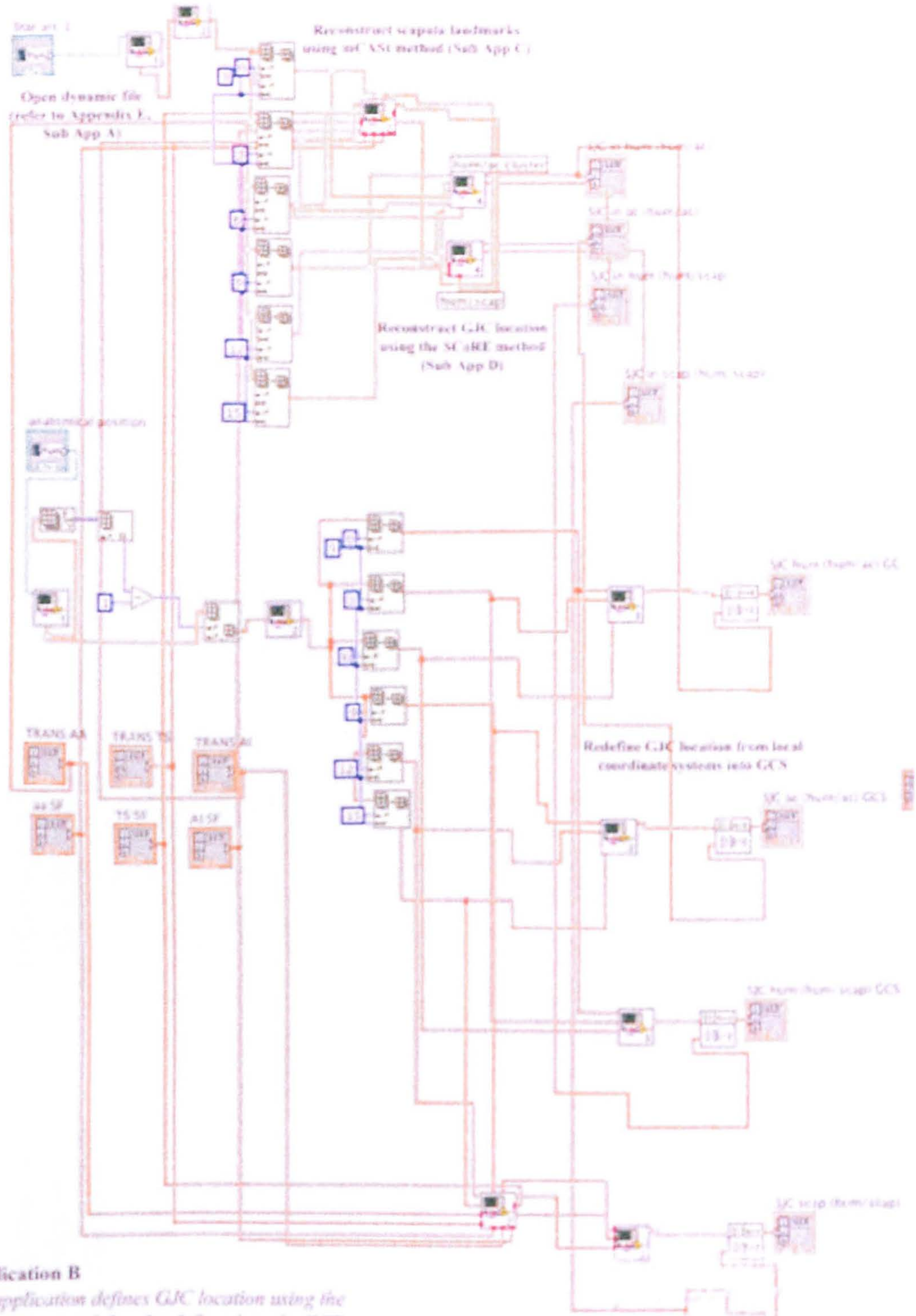
(Refer to electronic version for more detail)


K. Shorter (2011)
Chichester



Sub Application A

This sub application utilises the mCAST method
to enable reconstruction of scapula anatomical landmarks



Sub Application B

This sub application defines GJC location using the selected movement trial and redefines into the GCS

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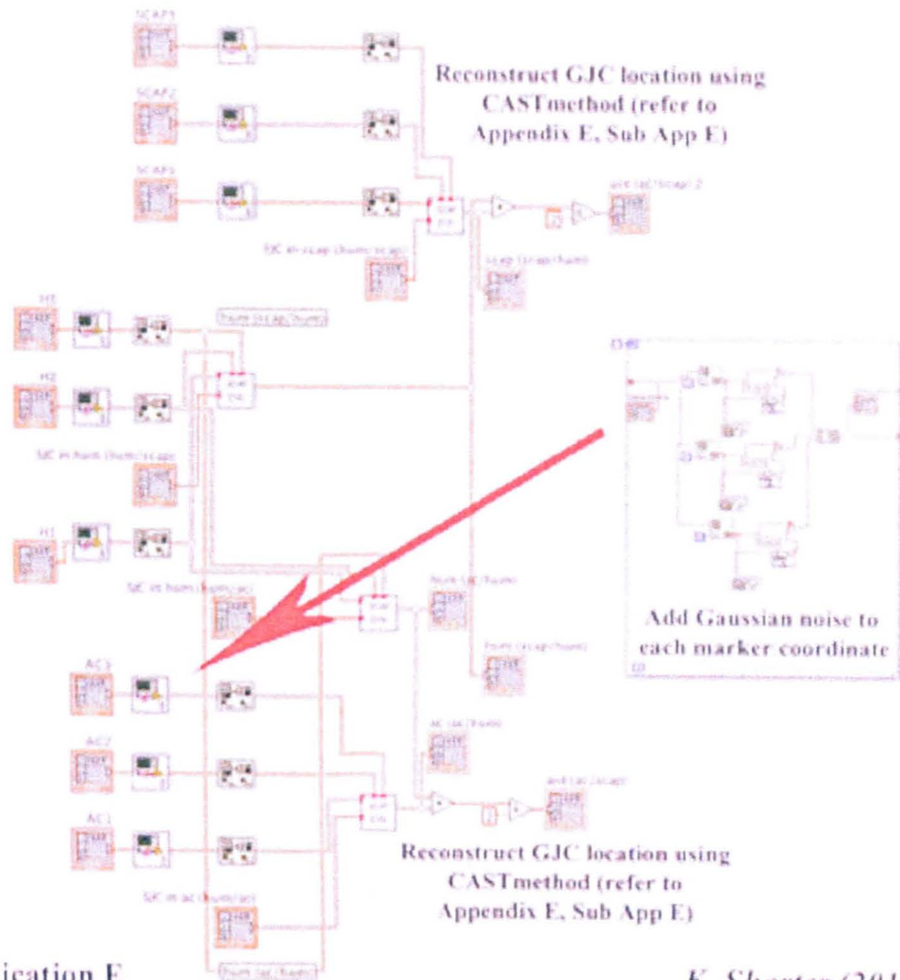

Sub Application E

This sub application adds Gaussian noise to marker coordinates prior to reconstructing GJC location

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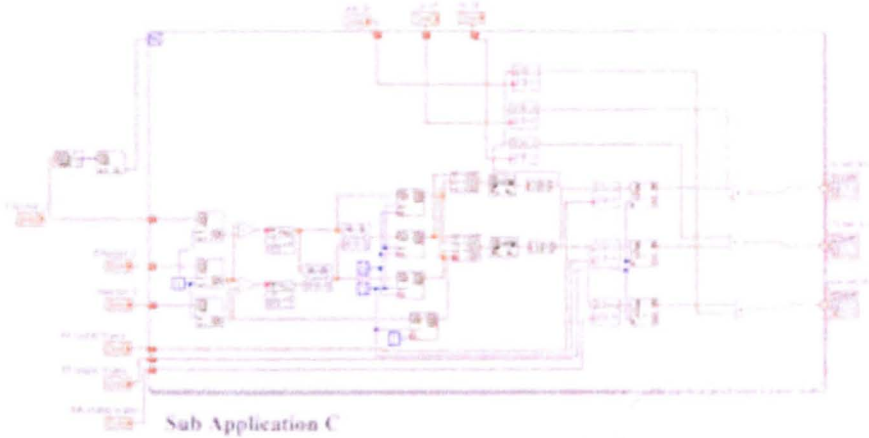
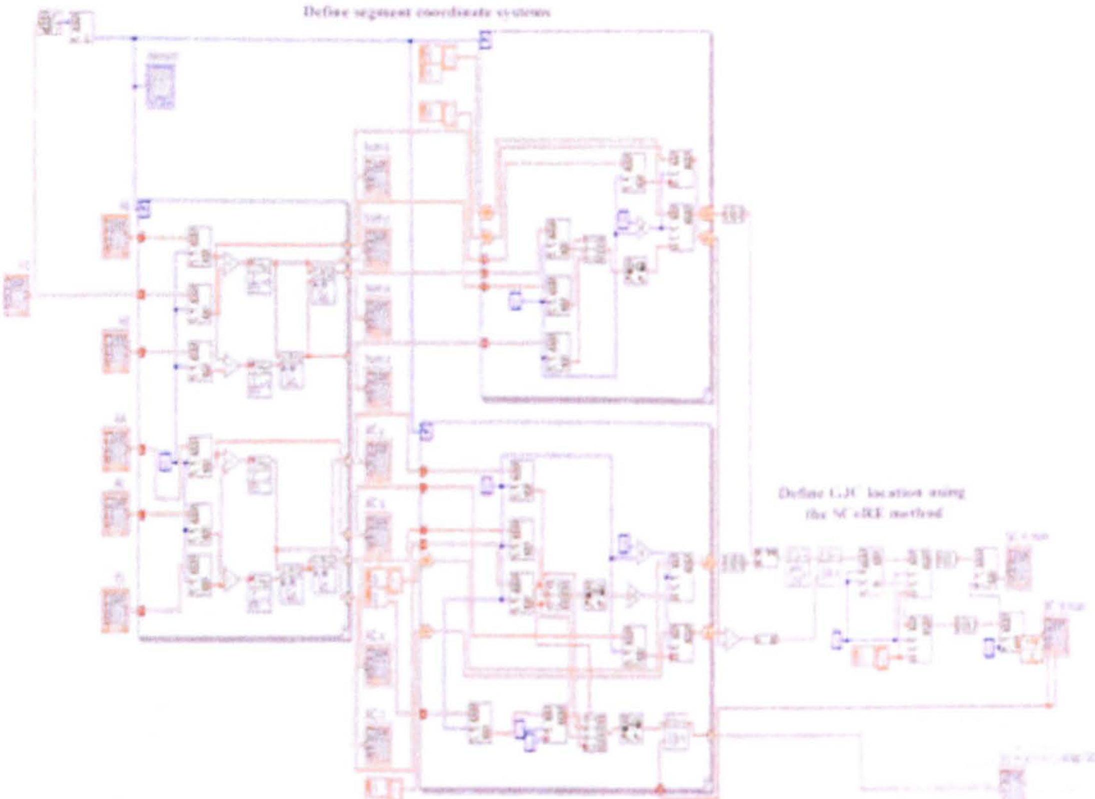


Sub Application C

This sub application reconstructs scapula landmarks during the dynamic trial using the mCAST method



Sub Application D

This sub application defines the GJC location using a combination of chosen coordinate systems

K. Shorter (2011)

Appendix K - CSBT Shoulder Model (Chapter 7)

CSBT Shoulder Model Program Interface

The CSBT shoulder model has been created within LabVIEW™ 2009 (National Instruments, Austin, USA) to interface with trial files from Vicon Motus 9.2 (Vicon, Los Angeles, USA). The program is designed with a main window (Figure 1), allowing to the user to select the appropriate files for analysis and contains individual tabs for data analysis (Figure 2).

Figure 1. CSBT shoulder model main window interface

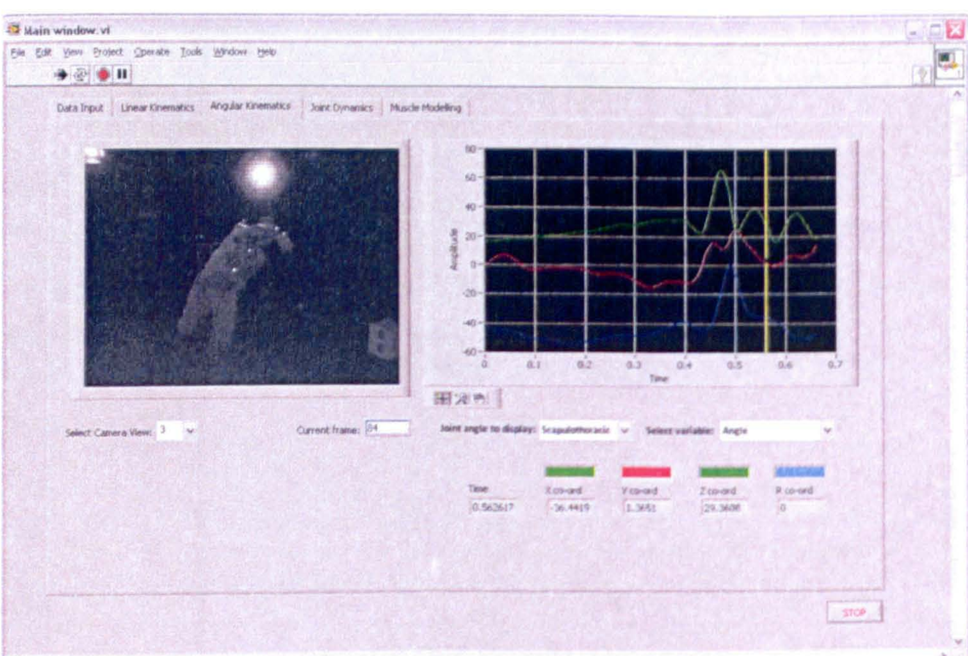


Figure 1. CSBT shoulder model example data analysis window

Body Segment Parameters

This model uses the calculations from Zatsiorsky & Seluyanov (1983) to calculate the required body segment parameters.

Segment Mass

Segment mass (kg) is calculated based on body weight (kg) and height (cm).

$$mass_{upper\ torso} = 8.21440 + (0.18620 * weight) - (0.05840 * height)$$
$$mass_{upper\ arm} = 0.25000 + (0.03012 * weight) - (0.00270 * height)$$
$$mass_{forearm} = 0.31850 + (0.01445 * weight) - (0.00114 * height)$$
$$mass_{hand} = -0.11650 + (0.00360 * weight) + (0.00175 * height)$$

<u>*Cricket specific:*</u> Mass of the ball (0.1559 kg) added to the mass of the hand up to ball release (Figure 3)

LabVIEW™ Input

To calculate each segment's mass (Figure 3) the user inputs the subject's height and weight.

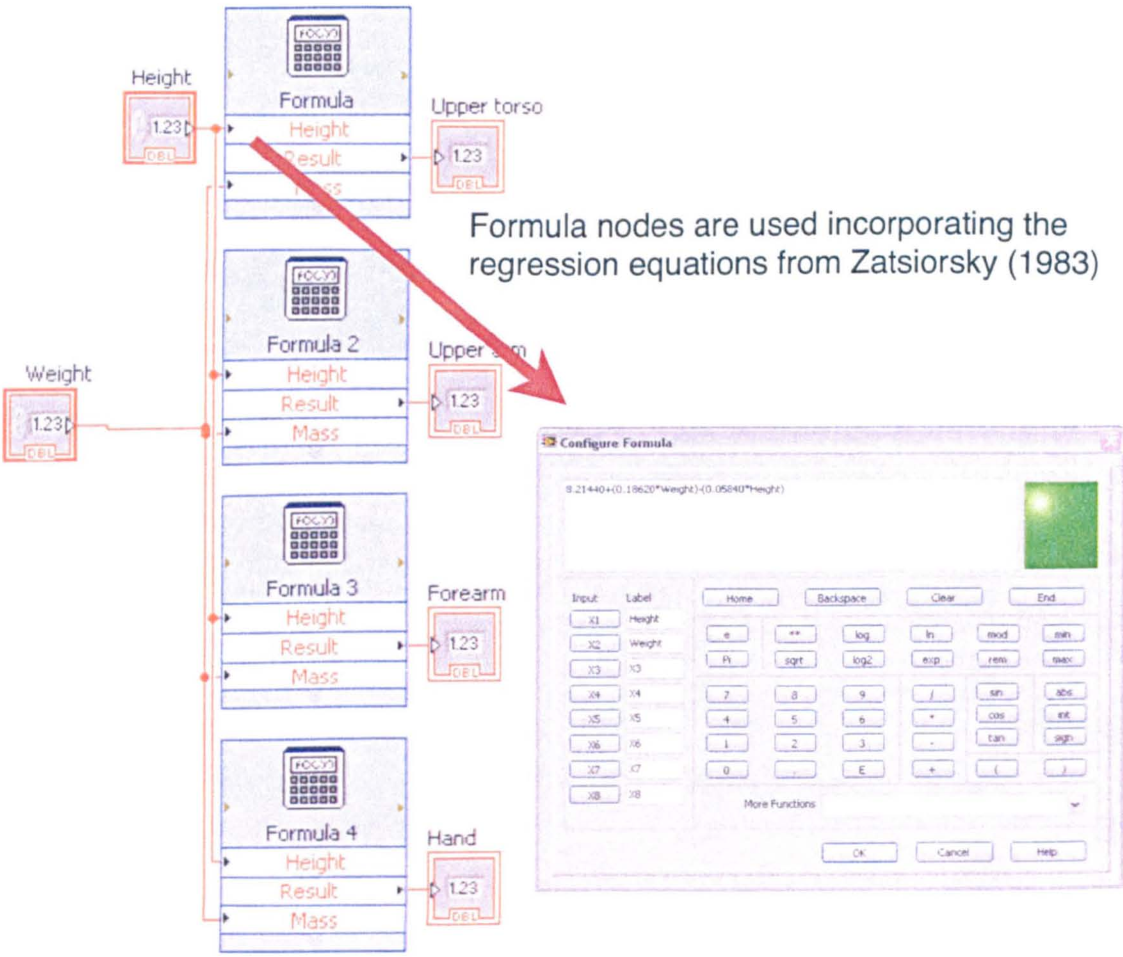


Figure 3. LabVIEW™ block diagram for calculation of segment mass

Centre of Gravity

Segment centres of gravity are calculated using the parameters of body weight (kg) and height (cm) and are defined in relation to the segment joint centres.

$$p_{torsoCOG} = p_{midSN/C7} + ((((3.32000 + (0.00760 * weight) + (0.04700 * height)) / 100) * (p_{midXP/T8} - p_{midSN/C7})))$$
$$p_{upper\ armCOG} = p_{SJC} + ((((1.67000 + (0.03000 * weight) + (0.05400 * height)) / 100) * (p_{EJC} - p_{SJC})))$$
$$p_{forearmCOG} = p_{EJC} + ((((0.19200 - (0.02800 * weight) + (0.09300 * height)) / 100) * (p_{WJC} - p_{EJC})))$$
$$p_{handCOG} = p_{3MC} + ((((4.11000 + (0.02600 * weight) + (0.03300 * height)) / 100) * (p_{3MC} - p_{WJC})))$$

LabVIEW™ Input

To calculate the centre of gravity for each segment (Figure 4), the user must input the height (cm) and weight (kg) of the participant. The position of the centre of mass is subsequently expressed in relation to the length of the segment defined using anatomical landmarks.

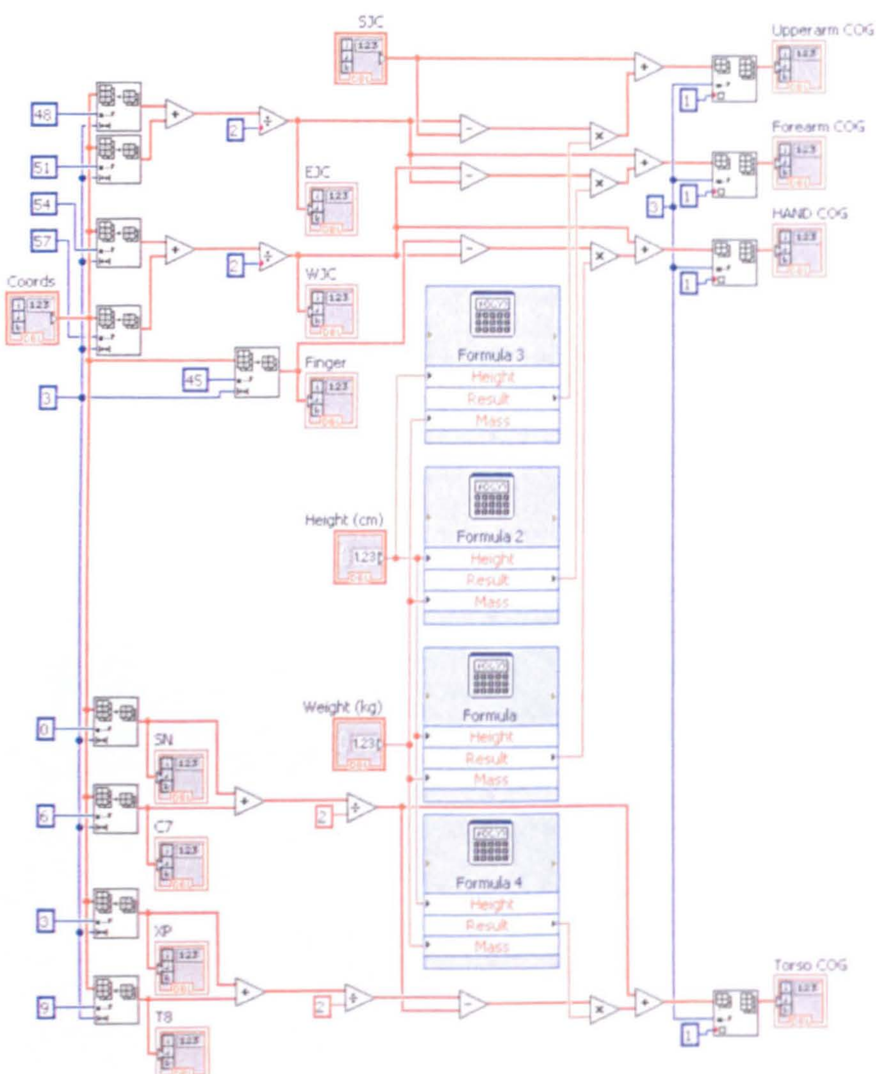


Figure 4. LabVIEW™ block diagram for the calculation of segment centre of gravity

<u>*Cricket specific:*</u> Defined using static trial where the bowler holds the ball in their hand to mimic the hand position used during the bowling delivery. The ball centre of gravity ($P_{ballCOG}$) is defined by two markers positioned on either side of the ball:

$$P_{ballCOG} = 0.5 * (P_{ballmed} + P_{balllat})$$

Subsequently the centre of gravity of the hand segment when holding the ball is redefined in relation to the ratio of the mass of the hand and ball (Figure 5):

$$P_{ball\,\&\,hand} = P_{handCOG} + \left((P_{ballCOG} - P_{handCOG}) * \left(\frac{mass_{hand}}{mass_{hand} + mass_{ball}} \right) \right)$$

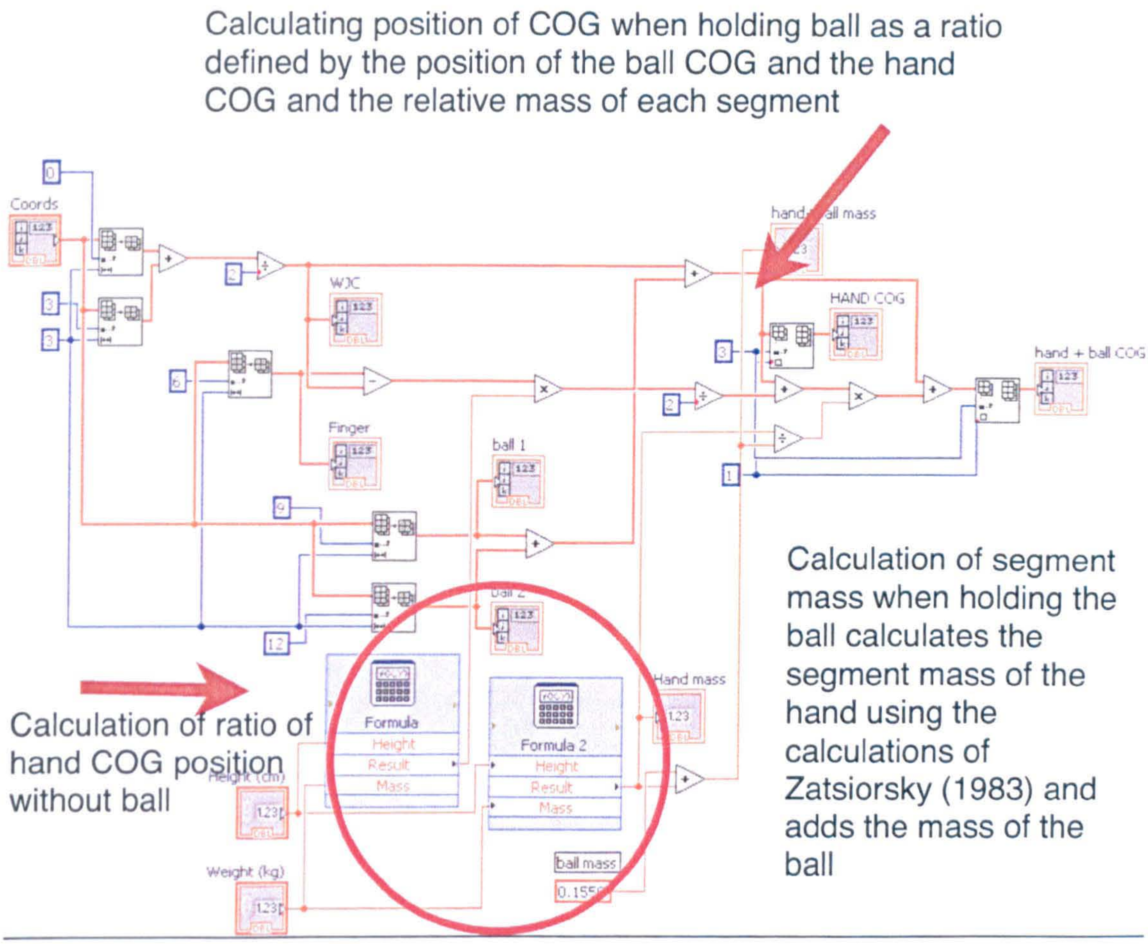


Figure 5. LabVIEW™ block diagram for the calculation of cricket specific values for both the centre of gravity and mass of the hand whilst holding the ball

Moments of Inertia

Moments of inertia ($kg{\cdot}m^2$) for each segment are calculated based on both body weight (kg) and height (cm).

Movement about each axis:

X-axis: abduction/adduction

$$MOI_{torso.x} = 81.2 + (36.73 * weight) - (5.97 * (height / 100))$$
$$MOI_{upper\,arm.x} = -250.7 + (1.56 * weight) + (1.512 * (height / 100))$$
$$MOI_{forearm.x} = -64 + (0.95 * weight) + (0.34 * (height / 100))$$
$$MOI_{hand.x} = -19.5 + (0.17 * weight) + (0.116 * (height / 100))$$

Y-axis: internal/external rotation

$$MOI_{torso.y} = 561 + (36.03 * weight) - (9.98 * (height / 100))$$
$$MOI_{upper\,arm.y} = -16.9 + (0.662 * weight) + (0.0435 * (height / 100))$$
$$MOI_{forearm.y} = 5.66 + (0.306 * weight) - (0.088 * (height / 100))$$
$$MOI_{hand.y} = -6.26 + (0.0762 * weight) + (0.0347 * (height / 100))$$

Z-axis: flexion/extension

$$MOI_{torso.z} = 367 + (18.3 * weight) - (5.73 * (height / 100))$$
$$MOI_{upper\,arm.z} = -232 + (1.525 * weight) + (1.343 * (height / 100))$$
$$MOI_{forearm.z} = -67.9 + (0.855 * weight) + (0.376 * (height / 100))$$
$$MOI_{hand.z} = -13.68 + (0.088 * weight) + (0.092 * (height / 100))$$

LabVIEW™ Input

To calculate the moments of inertia for each segment (Figure 6), the user must input the height (cm) and weight (kg) of the participant.

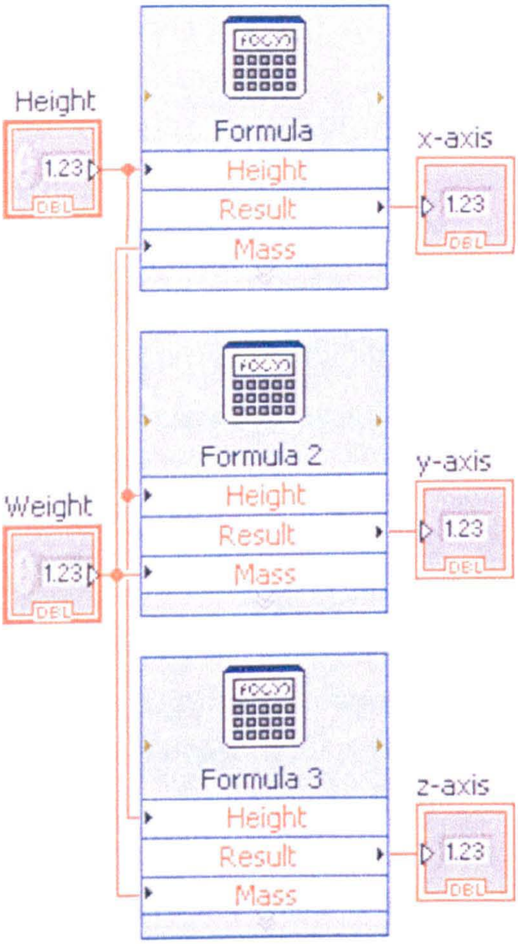


Figure 6. LabVIEW™ block diagram for the calculation of segment moments of inertia

Marker Set

The CSBT shoulder model requires both static and dynamic marker sets (Figure 7).

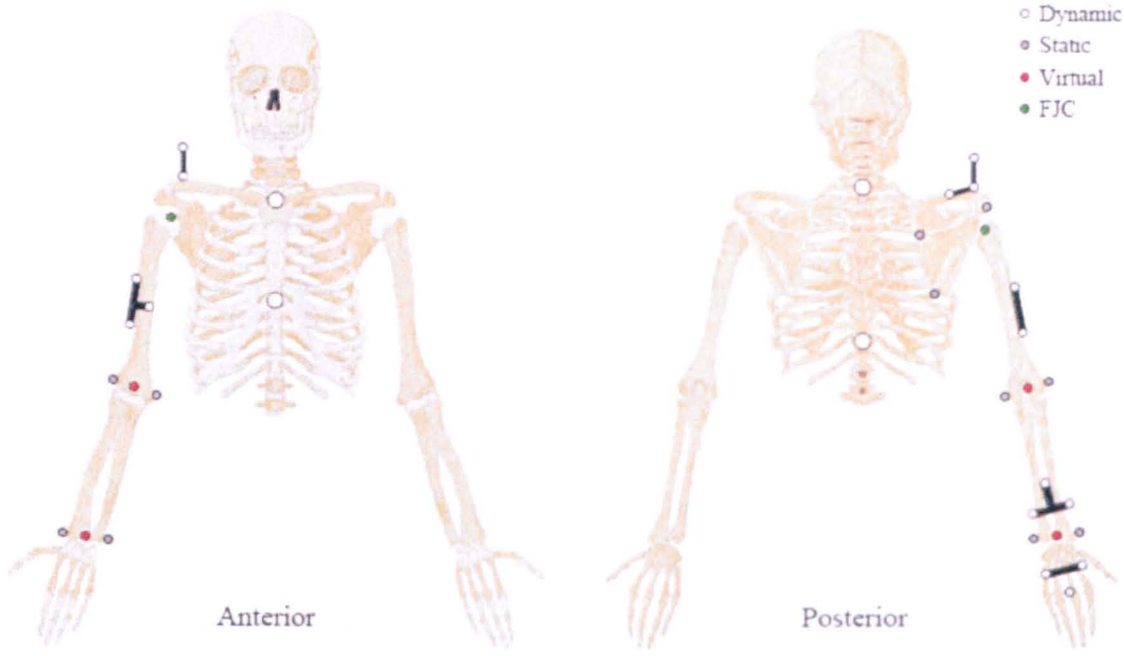


Figure 7. CSBT shoulder model marker sets.

Static Marker Set

An initial static capture with the participant in the anatomical position is collected incorporating static markers to define the anatomical landmarks. Each landmark can be defined within Vicon Motus using either surface retroflective markers or a calibrated pointer. Each static anatomical landmark is then redefined into segment technical coordinate systems using the CAST protocol.

<u>*Static Anatomical Landmarks*</u>
<u>*Scapula:*</u>
AA (p_{AA}), AI (p_{AI}), TS (p_{TS}) - for dynamic movements these landmarks may be more accurately defined using the mCAST protocol.

<u>*Humerus*</u>
Medial epicondyle (p_{ME}), Lateral epicondyle (p_{LE})

<u>*Forearm*</u>
Ulna Styloid (p_{US}), Radial Styloid (p_{RS})

Joint centre definition

Within this shoulder model both the elbow and wrist joint centres are defined as the midpoint between medial and lateral joint anatomical landmarks:

$$p_{EJC} = 0.5 \times (p_{ME} + p_{LE})$$
$$p_{WJC} = 0.5 \times (p_{US} + p_{RS})$$

<u>*Functional Joint Centre*</u>

The shoulder joint centre (P_{GJC}) is defined functionally in relation to both the humerus and scapula using the SCoRE method (Ehrig *et al.*, 2006) where it is assumed that the position of the GJC with respect to both the humerus TCS and scapula ACS is constant and can be expressed using the following equation:

$$[R^H - R^S]\begin{bmatrix} v \\ u \end{bmatrix} = p^S - p^H$$

where:

R^H *is the rotation matrix associated with the humerus*

R^S *is the rotation matrix associated with the scapula*

p^H *is the position vector from the GCS to the humerus TCS*

p^S *is the position vector from the GCS to the scapula ACS*

v is the position vector of the GJC with respect to the humerus

u is the position vector of the GJC with respect to the scapula

Whilst the position vectors v and u can be estimated with at least two different configurations, a dynamic movement trial whereby the arm moves throughout its range of motion is recorded with v and u estimated in a least squares sense:

$$\begin{bmatrix} v \\ u \end{bmatrix} = (B^T B)^{-1} B^T C$$

with:

$$B = \begin{bmatrix} R_1^H & -R_1^S \\ \vdots & \vdots \\ R_n^H & -R_n^S \end{bmatrix} \text{ and } C = \begin{bmatrix} p_1^S & -p_1^H \\ \vdots & \vdots \\ p_n^S & -p_n^H \end{bmatrix}$$

As discussed within Chapter 6, the shoulder joint centre during the dynamic bowling movement is reconstructed using only the scapula ACS.

Dynamic Marker set

The dynamic marker set involves a combination of anatomically based and technical markers to define body segments:

Thorax
SN, XP, C7 and T8 - all anatomical landmarks

Scapula
Acromion cluster made of three orthogonal markers (10mm diameter) on a rigid structure positioned on the acromion plateau medial to the origin of the posterior deltoid.

Upper arm
Humerus cluster made of three markers (10mm diameter) on a semi-rigid structure, positioned on the lateral aspect of the upper arm in an area least affected by soft tissue artefact.

Forearm
Forearm cluster made of three markers (10mm diameter) on a semi-rigid structure, positioned on the distal forearm (anterior).

Hand
Three 10mm retroflective markers positioned on the dorsal surface of the hand. To define a functional coordinate system reflective of the axes of the hand, one marker is positioned over the 3rd metacarpal joint, with the other two placed medial and lateral to the midline formed between the 3rd metacarpal joint and the mid point of the wrist over the carpal bones.

Reconstruction of markers using the CAST technique

Static trial anatomical landmarks are defined in relation to the technical coordinate system of the appropriate segment to enable their reconstruction during the dynamic movement.

Local technical coordinate systems
Local technical coordinate systems (TCS) enable the reconstruction of anatomical landmark markers. For each body segment a cluster made of a minimum of three markers in a fixed arrangement are used to define each segment.

For each cluster associated with the scapula, upper arm, forearm and hand the following TCS is defined:

$$TCS_{origin} = p_{cluster1}$$

$$TCS_{x-axis} = \frac{(p_{cluster1} - p_{cluster2})}{[p_{cluster1} - p_{cluster2}]}$$

$$TCS_{y-axis} = \frac{(p_{cluster1} - p_{cluster2})}{[p_{cluster1} - p_{cluster2}]} \times \frac{(p_{cluster1} - p_{cluster3})}{[p_{cluster1} - p_{cluster3}]}$$

$$TCS_{z-axis} = TCS_{x-axis} \times TCS_{y-axis}$$

Theory behind reconstructing anatomical markers

The underpinning theory of the CAST technique is that the positional relationship between an anatomical landmark marker and the associated segment cluster remains constant. For each segment a transformation matrix is defined relative to the global coordinate system is constructed. This is defined by each axis of the segment TCS as unit vectors and the TCS origin as a position vector. This transformation matrix then gives both the position and orientation of the segment in relation to the global coordinate system.

$$^{TCS}_{G}T(t) = \begin{pmatrix} X_x & Y_x & Z_x & o_x \\ X_y & Y_y & Z_y & o_y \\ X_z & Y_z & Z_z & o_z \end{pmatrix}$$

Each anatomical landmark marker captured during the static trial is then redefined in relation to the appropriate segment TCS.

$$_{TCS}p(st) = {}^{TCS}_{G}T(st)^{-1}\, _{G}p(st)$$

During the dynamic trial, at any instant, markers can then be reconstructed using the following formula, where a marker is then described in relation to the global coordinate system.

$$_{G}p(t) = {}^{TCS}_{G}T(t)\, _{TCS}p(st)$$

Reconstruction of markers using the mCAST technique

The mCAST technique is designed to minimise the error associated with reconstructing scapula anatomical landmarks using the CAST technique as discussed in Chapter 5. For any given movement, 5 individual static positions (defined based on the data presented in Chapter 3) reflecting the the range of motion expected during the dynamic movement are recorded, whereby using the calibrated pointer each scapula anatomical landmark is palpated.

Using the CAST technique, each scapula landmark is reconstructed (p^{RE}) (refer to CAST section) and the difference (d) between the known palpated position (p^{AL}) calculated:

$$d = P^{AL} - P^{Re}$$

As the magnitude of d varies dependant on the shoulder position on an individual basis, the mCAST method adapts the multiple calibration method proposed by Cappello *et al.* (1997) utilising a least squares approach whereby the magnitude of d for each scapula landmark can be established independently in relation to the orientation of the acromion cluster (${}^{ACS}_{G}R$) at any given time:

$$d = {}^{ACS}_{G}R\,{}_{ACS}c$$

Giving the equation:

$${}^{ACS}_{G}R\,{}_{ACS}c = {}_{ACS}P^{AL} - {}_{ACS}P^{Re}$$

Therefore using each of the five static positions, the following can be minimised to provide a correction factor (c):

$$c_{ACS} = ({}^{ACS}_{G}R^{T}\,{}^{ACS}_{G}R)^{-1}\,{}^{ACS}_{G}R^{T}\left[{}_{ACS}p^{AL} - {}_{ACS}p^{Re}\right]$$

Whereby the mCAST method subsequently calculates each scapula landmark as:

$${}_{G}P^{mCAST}(t) = {}^{ACS}_{G}T(t)\,{}_{ACS}P^{Re}(st) + {}^{ACS}_{G}R(t)\,{}_{ACS}c$$

LabVIEW™ Input

Definition and reconstruction of anatomical landmarks is intertwined within the CSBT shoulder model due largely to the dependance of the MCAST method to define each scapula anatomical landmark to first, enable the definition of the GJC functionally and second, enable GJC reconstruction during the dynamic movement.

The block diagram enabling the definition of each scapula anatomical landmark using the MCAST method and the definition of the GJC functionally is shown in Figure 8.

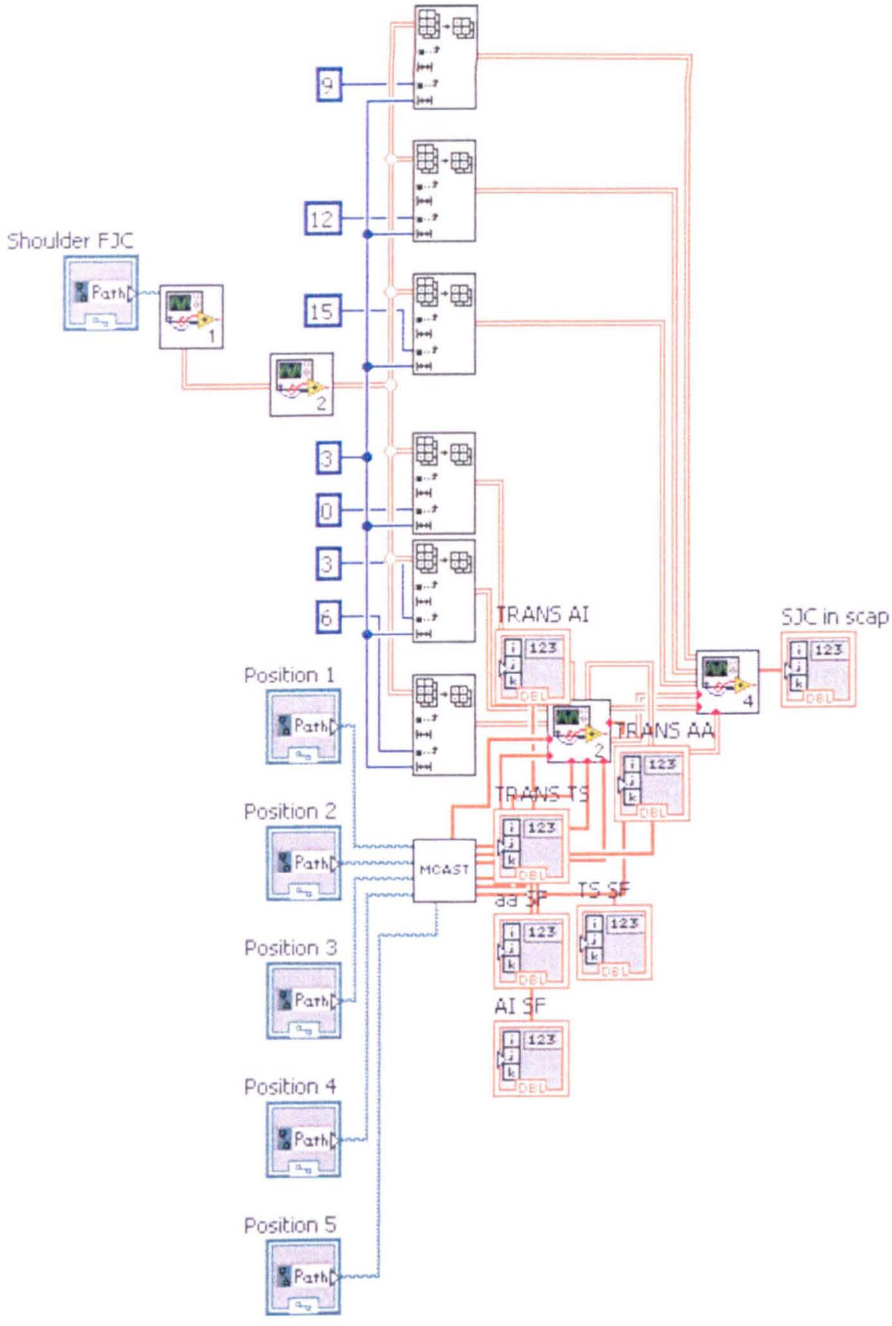


Figure 8. LabVIEW™ block diagram for both the MCAST method and definition of GJC location functionally

The block diagram to calculate scapula landmarks using the MCAST system is incorporated as a sub VI (Figure 9).

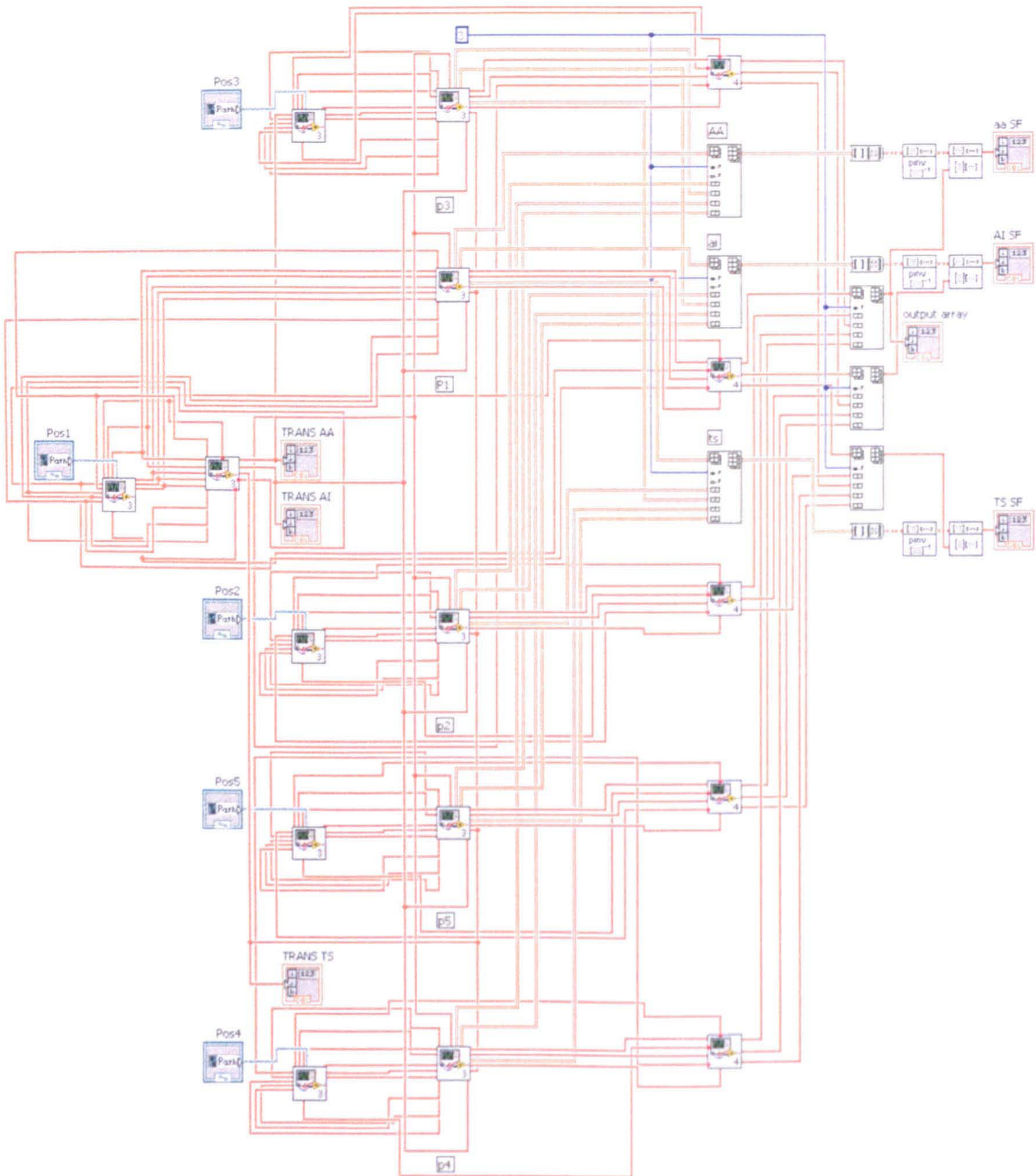


Figure 9. LabVIEW™ block diagram for definition of scapula anatomical landmarks using the MCAST method (for more detail refer to Appendix H)

Definition of the GJC functionally within the CSBT shoulder model is undertaken using both the humerus TCS and scapula ACS as a sub VI (Figure 10). This sub VI first defines each coordinate system prior to then calculating the location using the SCoRE method (Ehrig *et al.*, 2006).

For anatomical landmarks reconstructed using the CAST method, landmarks are first defined in relation to the appropriate TCS for subsequent reconstruction during the dynamic movement (Figure 11).

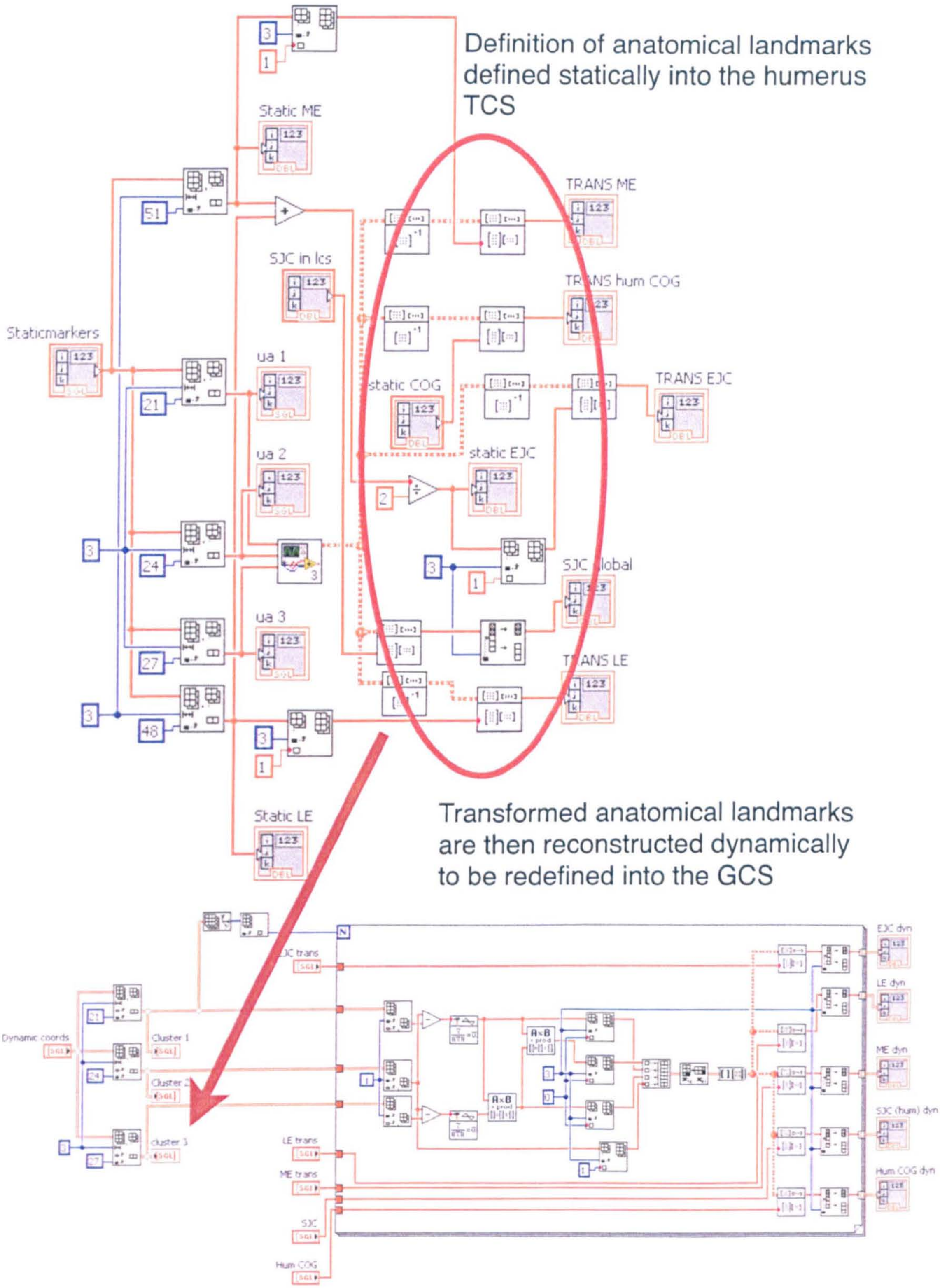


Figure 11. LabVIEW™ block diagram for definition and reconstruction of anatomical landmarks using the CAST technique

Anatomical coordinate systems

Anatomical coordinate systems (ACS) are used to describe the position and orientation of each body segment. The CSBT shoulder model follows the ISB recommendations for the upper body (Wu *et al.*, 2005). For the left arm for each segment z-axis=-z.

Torso

$$TorsoACS_{origin} = p_{SN}$$

$$TorsoACS_x = TorsoACS_y \times TorsoACS_z$$

$$TorsoACS_y = \frac{\left(p_{midSN/C7} - p_{midXP/T8}\right)}{\left[p_{midSN/C7} - p_{midXP/T8}\right]}$$

$$TorsoACS_z = \frac{\left(p_{midSN/C7} - p_{midXP/T8}\right)}{\left[p_{midSN/C7} - p_{midXP/T8}\right]} \times \frac{\left(p_{C7} - p_{SN}\right)}{\left[p_{C7} - p_{SN}\right]}$$

Scapula

$$ScapulaACS_{origin} = p_{AA}$$

$$ScapulaACS_x = \frac{\left(p_{AA} - p_{TS}\right)}{\left[p_{AA} - p_{TS}\right]} \times \frac{\left(p_{AI} - p_{TS}\right)}{\left[p_{AI} - p_{TS}\right]}$$

$$ScapulaACS_y = ScapulaACS_z \times ScapulaACS_x$$

$$ScapulaACS_z = \frac{\left(p_{AA} - p_{TS}\right)}{\left[p_{AA} - p_{TS}\right]}$$

Humerus

$$HumerusACS_{origin} = p_{GJC}$$

$$HumerusACS_x = \frac{\left(p_{GJC} - p_{EJC}\right)}{\left[p_{GJC} - p_{EJC}\right]} \times \frac{\left(p_{LE} - p_{ME}\right)}{\left[p_{LE} - p_{ME}\right]}$$

$$HumerusACS_y = \frac{\left(p_{GJC} - p_{EJC}\right)}{\left[p_{GJC} - p_{EJC}\right]}$$

$$HumerusACS_z = HumerusACS_x \times HumerusACS_y$$

Forearm

$$ForearmACS_{origin} = p_{US}$$

$$ForearmACS_x = \frac{(p_{EJC} - p_{WJC})}{[p_{EJC} - p_{WJC}]} \times \frac{(p_{RS} - p_{US})}{[p_{RS} - p_{US}]}$$

$$ForearmACS_y = \frac{(p_{EJC} - p_{WJC})}{[p_{EJC} - p_{WJC}]}$$

$$ForearmACS_z = ForearmACS_x \times ForearmACS_y$$

Hand

$$HandACS_{origin} = p_{3Mc}$$

$$HandACS_x = \frac{(p_{WJC} - p_{3MC})}{[p_{WJC} - p_{3MC}]} \times \frac{(p_{Lhand} - p_{Mhand})}{[p_{Lhand} - p_{Mhand}]}$$

$$HandACS_y = \frac{(p_{WJC} - p_{3MC})}{[p_{WJC} - p_{3MC}]}$$

$$HandACS_z = HandACS_x \times HandACS_y$$

LabVIEW™ Input

Definition of each segment ACS is defined using sub VIs. Example for the humerus ACS including the calculation of segment velocity is shown in Figure 12.

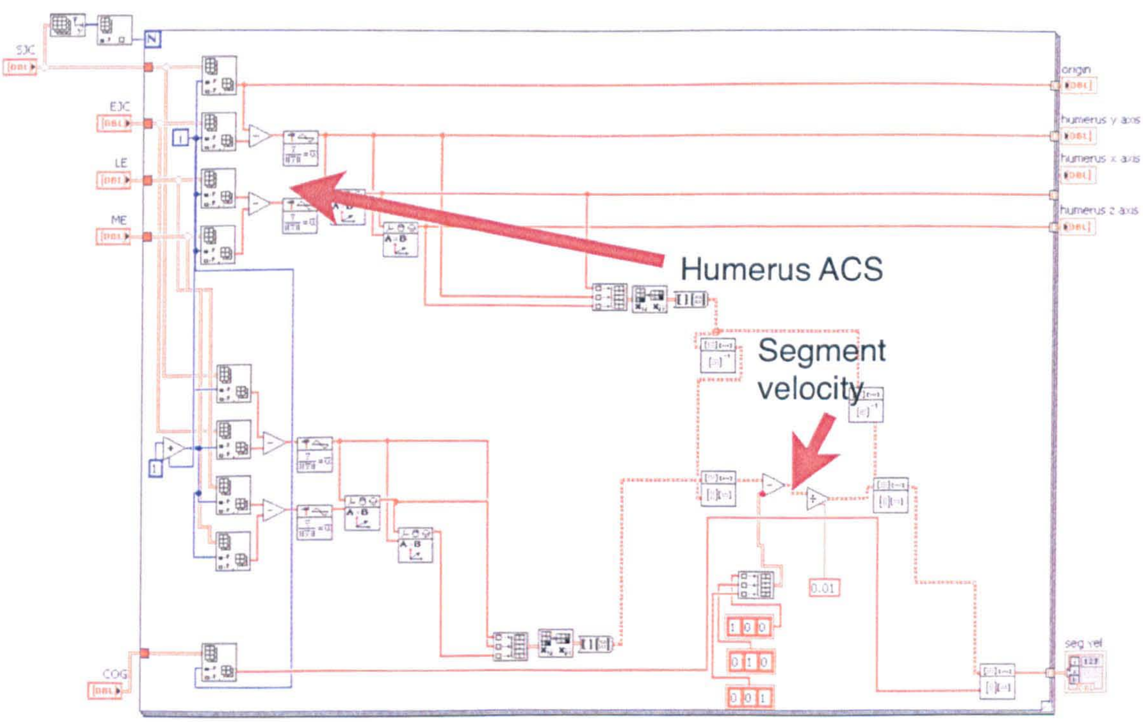


Figure 12. LabVIEW™ block diagram for definition of the humerus ACS and humerus segment velocity

Linear Kinematics

For any marker linear kinematics is calculated using the central difference method (Winter *et al.,* 1994). This method enables the calculation of velocity and acceleration at an instant in time, rather than calculating the average by using the simplified method (such as change in position over change in time).

Linear Velocity

Where given a time series of displacement data, n = sample at an instant in time and t= time between samples

$$\dot{p}_{(n=1)} = \frac{-p_{n+2} + 4p_{n+1} - 3p_n}{2\Delta t}$$

$$\dot{p}_{(2\,to\,n-1)} = \frac{p_{n+1} - p_{n-1}}{2\Delta t}$$

$$\dot{p}_{(n)} = \frac{p_{n-2} - 4p_{n-1} + p_n}{2\Delta t}$$

Linear Acceleration

Where given a time series of displacement data, n = sample at an instant in time and t= time between samples

$$\ddot{p}_{(n=1)} = \frac{2p_n - 5p_{n+1} + 4p_{n+2} - p_{n+3}}{(\Delta t)^2}$$

$$\ddot{p}_{(n=2)} = \frac{p_{n+1} - 2p_n + p_{n-1}}{(\Delta t)^2}$$

$$\ddot{p}_{(n=3\,to\,n-2)} = \frac{0.833(-p_{n+2} + 16p_{n+1} - 30p_n + 16p_{n-1} - p_{n-2})}{(\Delta t)^2}$$

$$\ddot{p}_{(n-1)} = \frac{p_{n-1} - 2p_{n-2} + p_{n-3}}{(\Delta t)^2}$$

$$\ddot{p}_{(n)} = \frac{-p_{n-3} + 4p_{n-2} - 5p_{n-1} + 2p_n}{(\Delta t)^2}$$

LabVIEW™ Input

The block diagram incorporating sub VIs for the calculation of linear velocity and acceleration for each marker coordinate is shown in Figure 13.

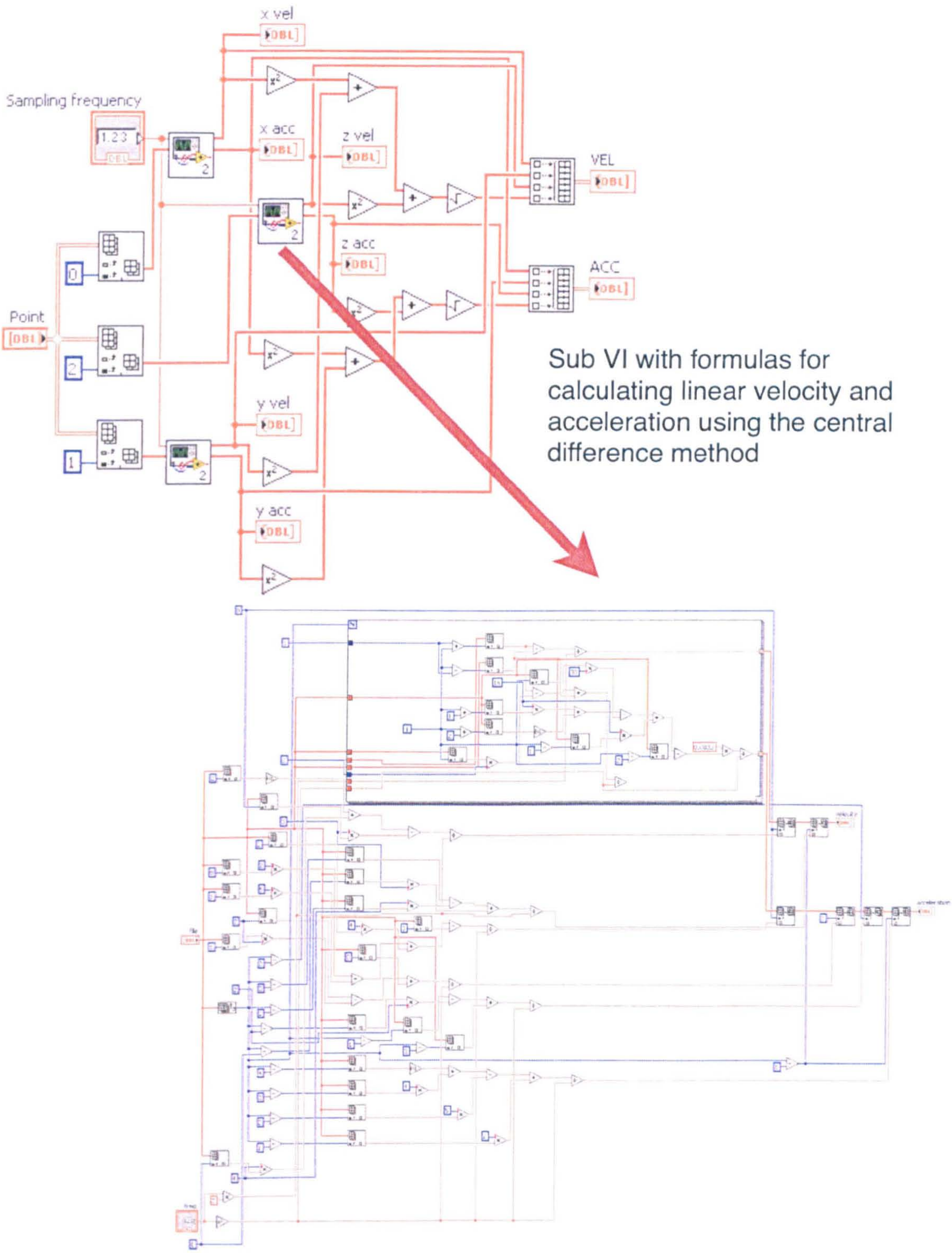


Figure 13. LabVIEW™ block diagram for the calculation of linear velocity and acceleration

Angular Kinematics

Anatomical Joint Angles

Calculating anatomical joint angles is firstly determined by calculating the ACS rotation matrix of the distal segment relative to the proximal system:

$$ {}^{dis}_{prox}R(t) = {}^{prox}_{GCS}R(t)^{-1}\, {}^{dis}_{GCS}R(t) $$

Where a rotation matrix is a 3*3 matrix composed of each ACS axis in vector form.

$$ R(t) = \begin{bmatrix} x_x & y_x & z_x \\ x_y & y_y & z_y \\ x_z & y_z & z_z \end{bmatrix} $$

Therefore:

$$ {}^{dis}_{prox}R(t) = \begin{bmatrix} x_{prox} \bullet x_{dis} & y_{prox} \bullet x_{dis} & z_{prox} \bullet x_{dis} \\ x_{prox} \bullet y_{dis} & y_{prox} \bullet y_{dis} & z_{prox} \bullet y_{dis} \\ x_{prox} \bullet z_{dis} & y_{prox} \bullet z_{dis} & z_{prox} \bullet z_{dis} \end{bmatrix} $$

The euler angle sequences for the CSBT shoulder model are written in accordance with ISB recommendations (Wu *et al.*, 2005). The following angle sequences are used to define joint motion:

Scapulothoracic - YXZ

$$ \alpha = a\sin\frac{(z_{prox} \bullet x_{dis})}{\cos\beta} $$

$$ \beta = -a\sin(z_{prox} \bullet y_{dis}) $$

$$ \gamma = a\cos\frac{(y_{prox} \bullet y_{dis})}{\cos\beta} $$

Where :

$\alpha = anterior(-)\,/\,posterior(+)\ tilt$

$\beta = lateral(-)\,/\,medial(+)\ rotation$

$\gamma = retraction(-)\,/\,protraction(+)$

Humerothoracic - YXY

$$\alpha = a\sin\frac{(y_{prox} \bullet x_{dis})}{\sin\beta}$$
$$\beta = a\cos(y_{prox} \bullet y_{dis})$$
$$\gamma = a\sin\frac{(x_{prox} \bullet y_{dis})}{\sin\beta}$$

Where :

$\alpha = plane\ of\ elevation$

$\beta = angle\ of\ elevation$

$\gamma = external(-) / internal(+)\ rotation$

Humeroscapular - YXY

$$\alpha = a\sin\frac{(y_{prox} \bullet x_{dis})}{\sin\beta}$$
$$\beta = a\cos(y_{prox} \bullet y_{dis})$$
$$\gamma = a\sin\frac{(x_{prox} \bullet y_{dis})}{\sin\beta}$$

Where :

$\alpha = plane\ of\ elevation$

$\beta = angle\ of\ elevation$

$\gamma = external(-) / internal(+)\ rotation$

Elbow - ZXY

$$\alpha = a\cos\frac{(y_{prox} \bullet y_{dis})}{\cos\beta}$$
$$\beta = a\sin(y_{prox} \bullet z_{dis})$$
$$\gamma = a\cos\frac{(z_{prox} \bullet z_{dis})}{\cos\beta}$$

Where :

$\alpha = flexion(+) / extension(-)$

$\beta = carrying\ angle$

$\gamma = supination(-) / pronation(+)$

Wrist - ZXY

$$\alpha = a\cos\frac{(y_{prox} \bullet y_{dis})}{\cos\beta}$$
$$\beta = a\sin(y_{prox} \bullet z_{dis})$$
$$\gamma = a\cos\frac{(z_{prox} \bullet z_{dis})}{\cos\beta}$$
$$Where:$$
$$\alpha = flexion(+) / extension(-)$$
$$\beta = abduction(+) / adduction(-)$$
$$\gamma = external(-) / internal(+)$$

LabVIEW™ Input

For each euler angle sequence a sub VI is incorporated into the CSBT shoulder model. An example for the YXY sequence is shown in Figure 14.

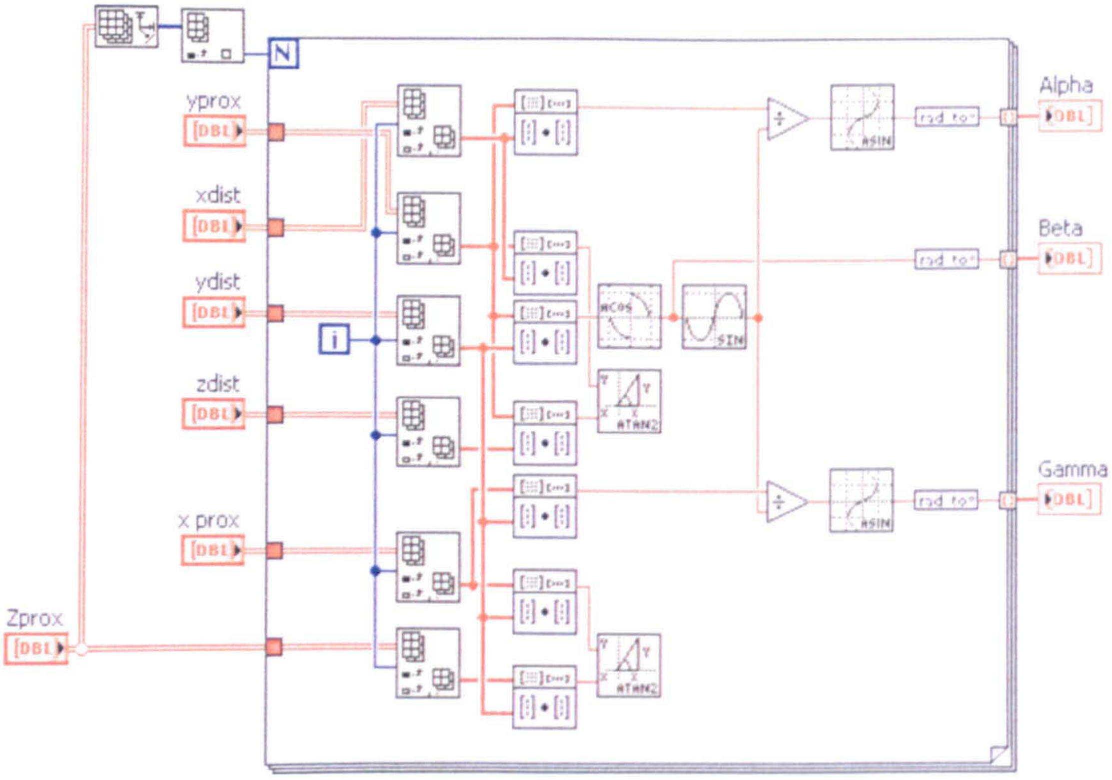


Figure 14. LabVIEW™ block diagram for the YXY Euler angle sequence

Segment Orientation

To avoid the influence gimbal lock may impart when using segment Euler angles to calculate segment velocities and accelerations, segment angular velocity was instead calculated using Poisson's equation (Zatsiorsky, 1998).

Segment Angular Velocity

Segment angular velocities are expressed as the rate of change about an axis defined in relation to the segment rotation matrix whereby:

$$[\dot{\omega}]=[\dot{R}][R]^T$$

LabVIEW™ Input

Refer to Figure 12 for block diagram description for the calculation of segment velocity.

Segment Angular Acceleration

In accordance with Winter (1994), segment angular acceleration is calculated using finite difference equations:

$$\ddot{\omega}_{(n=1)}=\frac{-\dot{\omega}_{n+2}+4\dot{\omega}_{n+1}-3\dot{\omega}_n}{2\Delta t}$$

$$\ddot{\omega}_{(2\,to\,n-1)}=\frac{\dot{\omega}_{n+1}-\dot{\omega}_{n-1}}{2\Delta t}$$

$$\ddot{\omega}_{(n)}=\frac{\dot{\omega}_{n-2}-4\dot{\omega}_{n-1}+\dot{\omega}_n}{2\Delta t}$$

LabVIEW™ Input

Refer to Figure 13 for block diagram depicting calculation of segment angular acceleration within the CSBT shoulder model.

Joint Dynamics

Rate of Change of Angular Momentum

The formula for calculating the rate of change of angular momentum is the same for each segment and is expressed in terms of the anatomical co-ordinate system.

$$\dot{H}_{segment.x} = MOI_{segment.x}\ddot{\omega}_{segment.x} + (MOI_{segment.z} - MOI_{segment.y})\dot{\omega}_{segment.z}\dot{\omega}_{segment.y}$$
$$\dot{H}_{segment.y} = MOI_{segment.y}\ddot{\omega}_{segment.y} + (MOI_{segment.x} - MOI_{segment.z})\dot{\omega}_{segment.x}\dot{\omega}_{segment.z}$$
$$\dot{H}_{segment.z} = MOI_{segment.z}\ddot{\omega}_{segment.z} + (MOI_{segment.y} - MOI_{segment.x})\dot{\omega}_{segment.y}\dot{\omega}_{segment.x}$$
$$\dot{H}_{segment} = \dot{H}_{segment.x}x_{segment} + \dot{H}_{segment.y}y_{segment} + \dot{H}_{segment.z}z_{segment}$$

LabVIEW™ Input

The block diagram for calculation of the rate of change of angular momentum for each segment is shown in Figure 15.

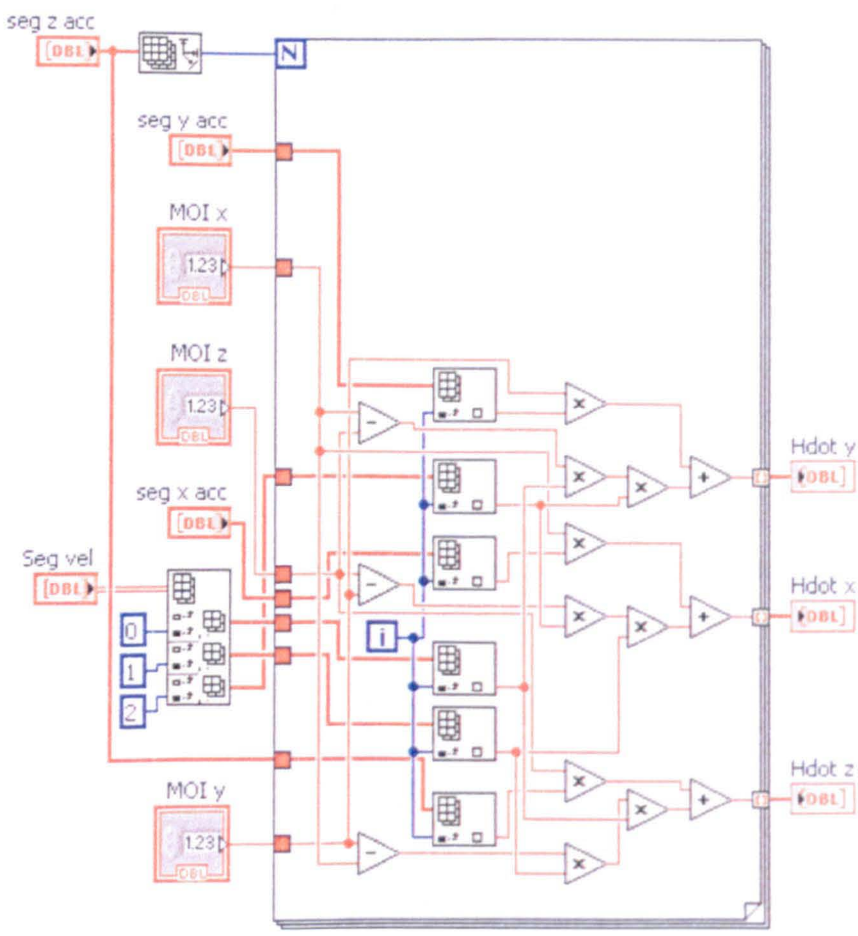


Figure 15. LabVIEW™ block diagram for the calculation of the rate of change of angular momentum for each segment

Global Joint Forces

Calculates the linear forces exerted on each segment relative to the global coordinate system.

$$F_{segment.x} = mass_{segment}\ddot{X}_{segmentCOG} + F_{distal.segment.x}$$
$$F_{segment.y} = mass_{segment}(\ddot{Y}_{segmentCOG} + g) + F_{distal.segment.y}$$
$$F_{segment.z} = mass_{segment}\ddot{Z}_{segmentCOG} + F_{distal.segment.z}$$
$$F_{segment} = F_{segment.x}x_{segment} + F_{segment.y}y_{segment} + F_{segment.z}z_{segment}$$

LabVIEW™ Input

The block diagram for calculation of global joint forces for the hand (Figure 16) and all other segments (figure 17) is shown below. Global joint forces for the hand is calculated twice, first including the mass of the hand and ball and second with only the mass of the ball, the output is then corrected using the moment of ball release to join the two data sets

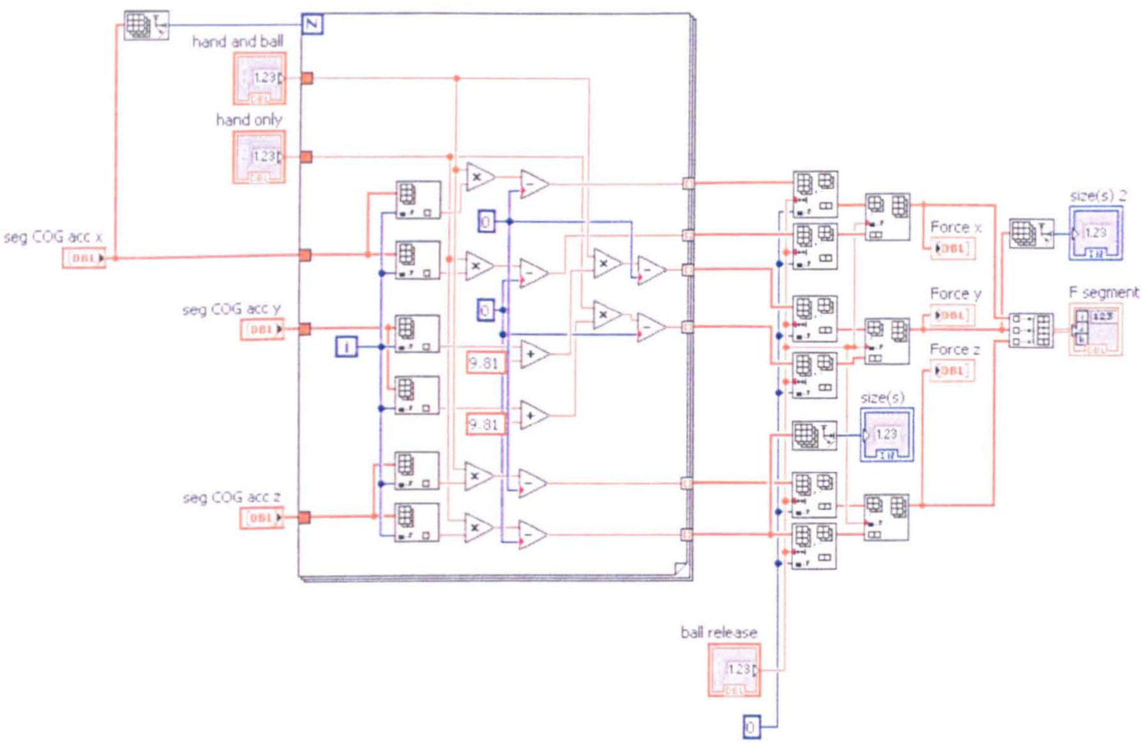


Figure 16. LabVIEW™ block diagram for the calculation of the global joint forces for the hand

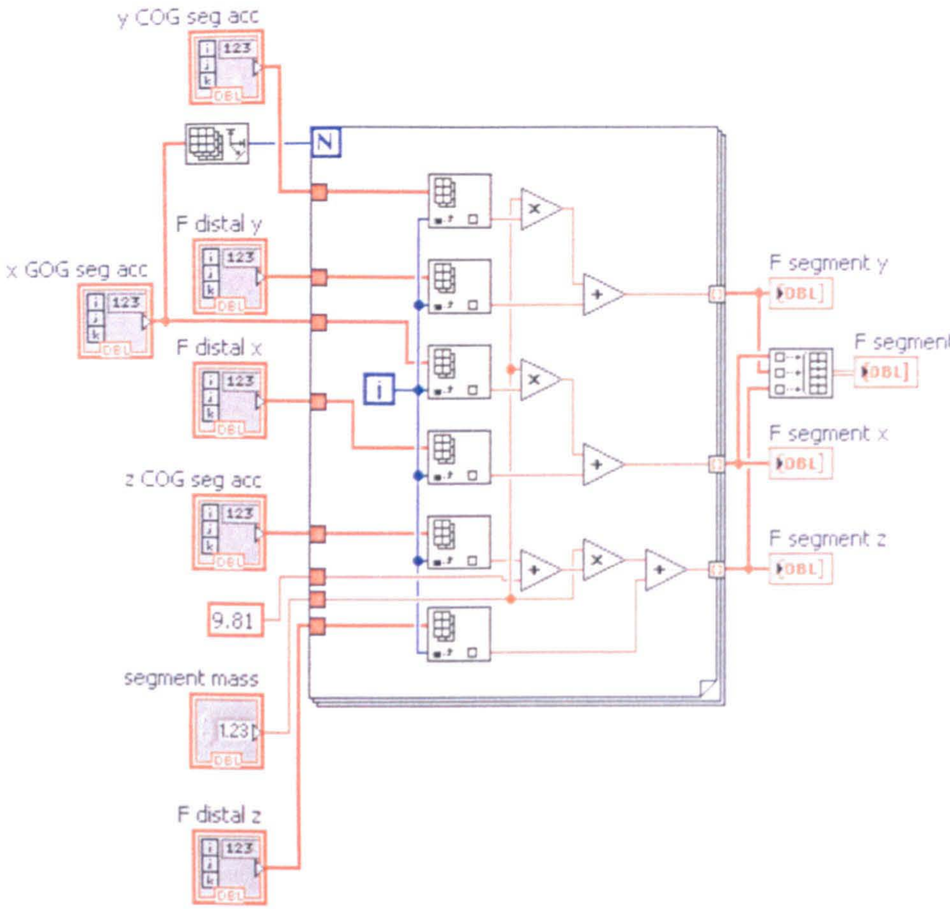


Figure 17. LabVIEW™ block diagram for the calculation of global joint forces for all segments proximal to the hand

Moment Arms

A moment arm is a position vector which locates the point of force application on a segment relative to the segments centre of gravity.

$$l_{segment} = -M_{distal.segment} - ((p_{distal.JC} - p_{segmentCOG}) \times F_{distal.segment}) + ((p_{proximal.JC} - p_{segmentCOG}) \times F_{proximal.segment})$$

Global Joint Moments

Expresses the moments exerted on each joint relative to the global coordinate system.

$$M_{segment.x} = \dot{H}_{segment.x} - (x_{segment} \bullet l_{segment})$$
$$M_{segment.y} = \dot{H}_{segment.y} - (y_{segment} \bullet l_{segment})$$
$$M_{segment.z} = \dot{H}_{segment.z} - (z_{segment} \bullet l_{segment})$$
$$M_{segment} = M_{segment.x} x_{segment} + M_{segment.y} y_{segment} + M_{segment.z} z_{segment}$$

LabVIEW™ Input

The block diagram for calculation of global joint moments for the hand (Figure 18) and all other segments (figure 19) is shown below.

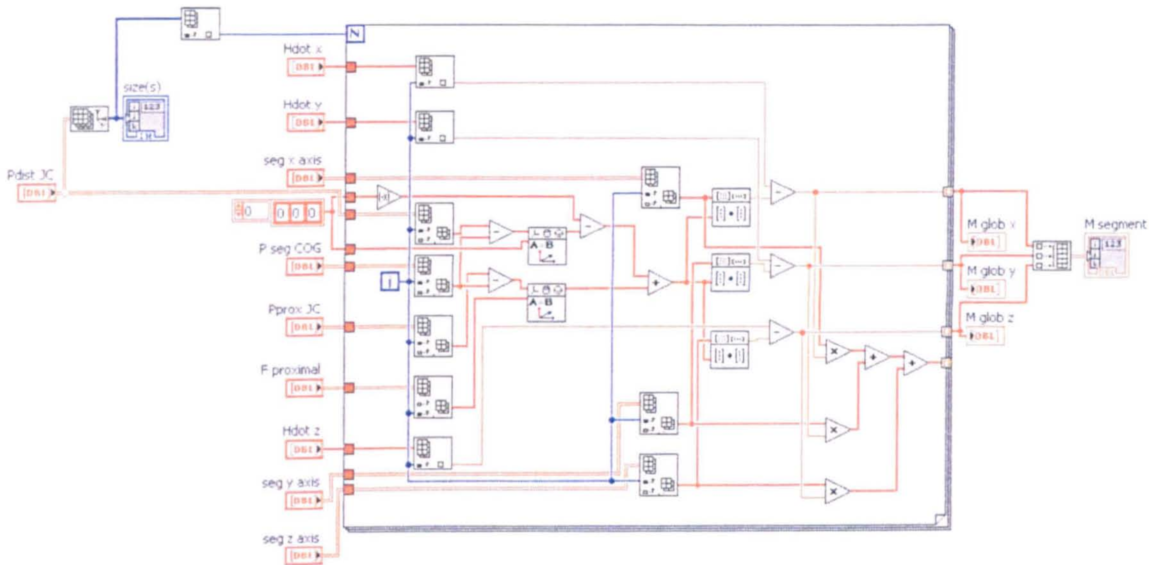


Figure 18. LabVIEW™ block diagram for the calculation of global joint moments for the hand

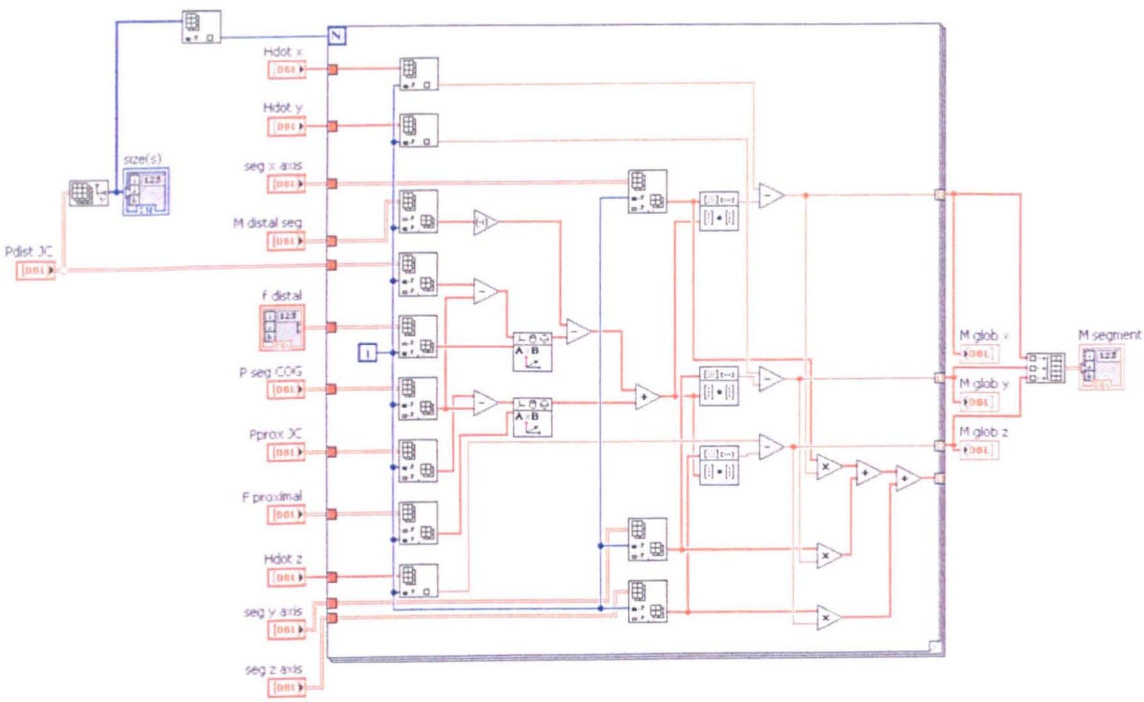


Figure 19. LabVIEW™ block diagram for the calculation of global joint moments for all segments proximal to the hand

Anatomical joint forces and moments

Segment joint forces and moments can be redefined in relation to the segment anatomical axes using the rotation matrix.

$$
{}_{ACS}F(t) = {}^{ACS}_{GCS}R(t)^{-1}\,{}_{GCS}F(t)
$$
$$
{}_{ACS}M(t) = {}^{ACS}_{GCS}R(t)^{-1}\,{}_{GCS}M(t)
$$

<u>*Cricket specific:*</u> Due to the range of motion of the shoulder observed during bowling, anatomical shoulder joint forces and moments were expressed in relation to the scapula ACS rather than the humerus ACS. As no standardised convention for reporting upper body joint kinetics exists, researchers have previously defined the compressive joint torque in relation to either the y-axis (long axis)(Feltner & Dapena, 1986) or z-axis (medial-lateral axis)(Reid, Elliott & Alderson, 2007) of the humerus ACS depending on the movement of interest. To avoid the sensitivity of joint axes depending on humerus position, for instance whether it be above or below the horizontal, and the influence this would impart of the direction of calculated joint kinetics, the scapula ACS was chosen to define shoulder joint kinetics due to its relatively constant orientation.

LabVIEW™ Input

The block diagram for conversion of global joint forces and moments into anatomically based joint forces and moments is shown below in Figure 20.

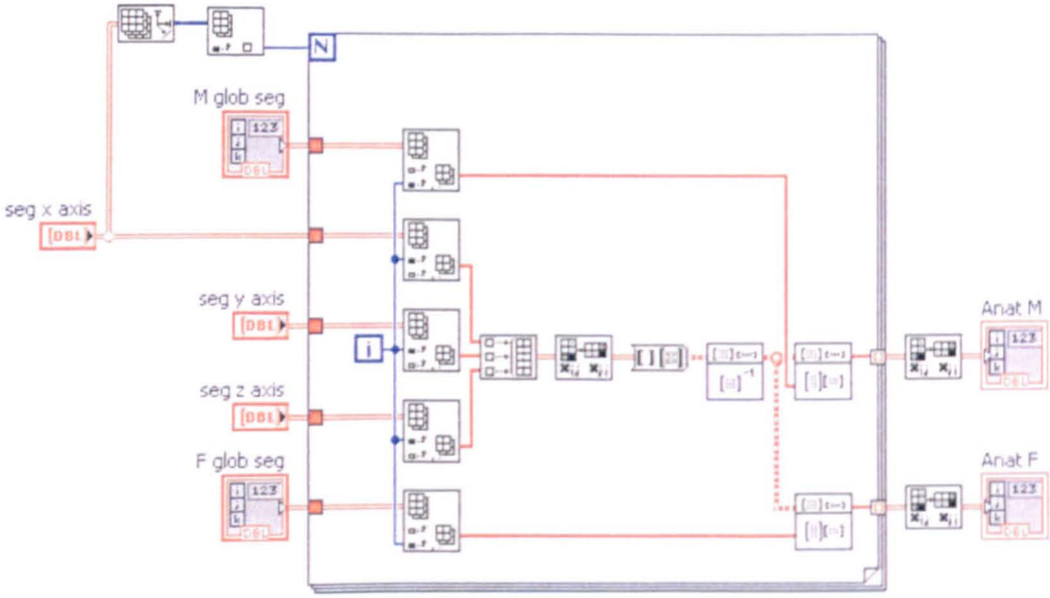


Figure 20. LabVIEW™ block diagram for the conversion of global joint forces and moments into anatomically based joint forces and moments

Muscle Modelling

Muscle Origins and Insertions

Using the cadaver data from a 57 year old male published by Klein Breteler (1996), muscle attachments can be scaled using the formula proposed by Matias, Andrade & Veloso (2009):

$$T(x) = BA^{-1}x$$

Where T(x) refers to the scaled muscle attachment site, which is calculated in relation to a 3*3 matrix of the cadaver bony landmarks (A), a 3*3 matrix of the same subject specific bony landmarks (B) and, the cadaver based muscle attachment site (x) expressed as a position vector.

LabVIEW™ Input

An example of the block diagram used to convert cadaver based muscle origin and insertion to subject specific sites is shown below in Figure 21.

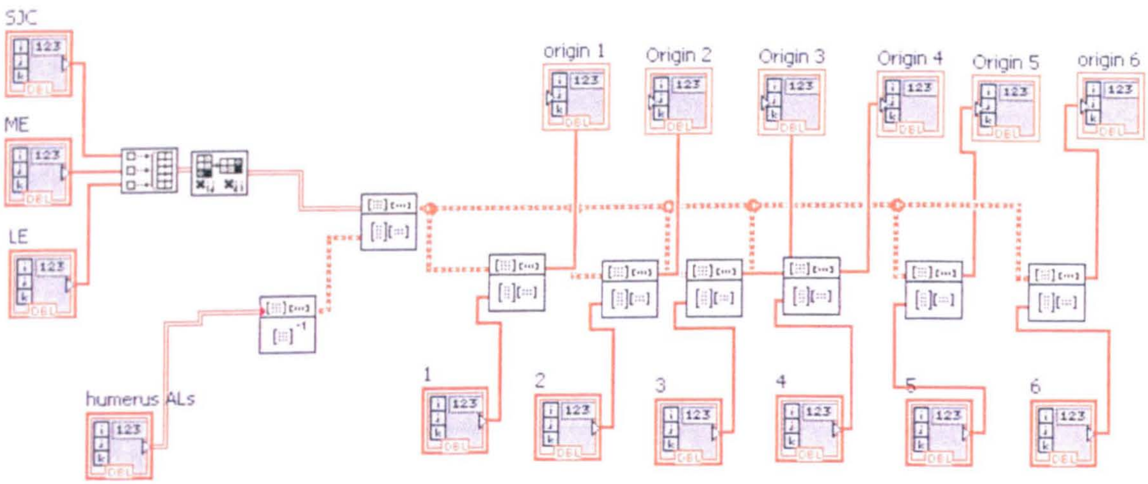


Figure 21. LabVIEW™ block diagram for the conversion of cadaver based muscle attachment sites to subject specific sites

The CSBT shoulder model models infraspinatus, supraspinatus, subscapularis, teres minor and the long head of the biceps. Each muscle is modelled as a series of elements representative of the orientation of muscle fibre bundles and defined at each instant of time during the movement of interest. For the purpose of this model, the long head of the biceps insertion is modified to instead 'insert' as it travels through the intratubercular groove between the greater and lesser tubercles of the humerus to prevent the need to model it as a bi-articular muscle. The intratubercular groove was defined as the midpoint between the cadaver based insertions for infraspinatus and supraspinatus (greater tubercle) and subscapularis (lesser tubercle).

Cadaver data from Klein Breteler (1996) incorporated into muscle parameters for the CSBT shoulder model:

Anatomical landmarks:

All landmarks are measured from the sternal notch (SN) in meters:

Landmark	X	Y	Z
AA	0.171703	-0.122083	0.007663
TS	0.059828	-0.166030	-0.01261
AI	0.086178	-0.166030	-0.125780
EL	0.207075	-0.092330	-0.302128
EM	0.145530	-0.120881	-0.307685
GJC	0.1637	-0.08114	-0.01791

Muscle origins and insertions:

Infraspinatus (6 elements):

Element	Origin			Insertion		
	X	Y	Z	X	Y	Z
1	0.116715	-0.126272	-0.044540	0.186553	-0.083201	-0.007757
2	0.072284	-0.169435	-0.102442	0.182532	-0.078173	-0.002216
3	0.085397	-0.161837	-0.080291	0.182532	-0.078173	-0.002216
4	0.079280	-0.159666	-0.057979	0.180313	-0.079007	0.000926
5	0.074454	-0.147615	-0.026400	0.180313	-0.079007	0.000926
6	0.096984	-0.149459	-0.005077	0.184047	-0.079531	-0.005318

Teres Minor (3 elements)

Element	Origin			Insertion		
	X	Y	Z	X	Y	Z
1	0.127792	-0.130276	-0.067477	0.191127	-0.078953	-0.024843
2	0.121281	-0.140941	-0.070786	0.192611	-0.076760	-0.019229
3	0.138582	-0.120536	-0.040956	0.191127	-0.078953	-0.024843

Supraspinatus (4 elements):

Element	Origin			Insertion		
	X	Y	Z	X	Y	Z
1	0.108974	-0.124454	-0.000242	0.176841	-0.067197	-0.003548
2	0.111947	-0.134896	0.008748	0.176841	-0.067197	-0.003548
3	0.072031	-0.129122	0.011051	0.176841	-0.067197	-0.003548
4	0.086127	-0.107781	0.012976	0.176841	-0.067197	-0.003548

Subscapularis (11 elements):

Element	Origin			Insertion		
	X	Y	Z	X	Y	Z
1	0.109262	-0.121769	-0.017034	0.153153	-0.064822	-0.005466
2	0.082648	-0.123104	0.003642	0.154282	-0.061775	-0.008850
3	0.072365	-0.144474	-0.024352	0.153153	-0.064822	-0.005466
4	0.090112	-0.147856	-0.050507	0.153467	-0.057682	-0.014950
5	0.097204	-0.142263	-0.063095	0.157158	-0.056155	-0.012757
6	0.086998	-0.157568	-0.086726	0.153709	-0.054648	-0.019393
7	0.093425	-0.150225	-0.101783	0.150507	-0.057762	-0.020724
8	0.113908	-0.129011	-0.069038	0.150507	-0.057762	-0.020724
9	0.110814	-0.141235	-0.096232	0.148434	-0.063132	-0.024856
10	0.131875	-0.119956	-0.054618	0.151323	-0.071525	-0.037387
11	0.137269	-0.108867	-0.045412	0.151617	-0.077733	-0.042712

Long head of the biceps (2 elements):

Element	Origin			Insertion		
	X	Y	Z	X	Y	Z
1	0.146956	-0.085567	-0.002158	0.166424	-0.068559	-0.011187
2	0.146956	-0.085567	-0.002158	0.166424	-0.068559	-0.011187

Muscle Line of Action

The path of each muscle element was calculated at each instant of time. In agreement with Van der Helm, Veeger, Pronk, Van der Woude, & Rozendal (1992), the LHB tendon was modelled as a straight line. As each rotator cuff muscle wraps around the head of the humerus, the head of the humerus in keeping with other shoulder models (Dickerson *et al.*, 2007; Holzbaur *et al.*, 2005; Van der Helm, 1994) was assumed to be a sphere, using the scaled measurements of Klein Breteler (1996) (sphere centre: 0.1650, -0,0785, -0.0199 ; radius: 0.2723). In doing so, the line of action for each rotator cuff muscle element could be defined by four points, referred to as nodes; the origin, the point at which the muscle begins to wrap around the head of the humerus, the point at which the muscle ceases to wrap around the head of the humerus and the muscle insertion. The nodes at which the muscle begins and ceases to wrap around the head of the humerus were calculated using the obstacle-set method proposed by Garner & Pandy (2000). The obstacle-set method calculates the minimum-distance path around a single sphere by creating a plane between the origin, insertion and sphere centre, allowing the nodes at which the tendon begins and ceases to wrap around the sphere to be calculated using circle tangency equations (Garner & Pandy, 2000).

Assuming that the origin (O), insertion (I) and sphere centre (C) are known, the origin and insertion are first expressed in relation to (C):

$$O_c = O_{GCS} - C_{GCS}$$
$$I_c = I_{GCS} - C_{GCS}$$

A rotation frame [R] is then calculated using Oc and Ic to enable the transformation of O and I into the 2D reference plane, composed of two axes:

$$\overline{CI} = \frac{|I_x, I_y, I_z|}{\sqrt{I_x^2 + I_y^2 + I_z^2}}$$
$$N = \frac{|O_x, O_y, O_z|}{\sqrt{O_x^2 + O_y^2 + O_z^2}} \times \frac{|I_x, I_y, I_z|}{\sqrt{I_x^2 + I_y^2 + I_z^2}}$$

Whereby each point can be expressed as:

$$o = [R]O$$
$$i = [R]O$$

The circle tangency calculations can then locate the points at which the tendon begins (b) and ceases to wrap (s) around the head of the humerus when the radius (R) is known:

$$b_x = \frac{o_x R^2 + R o_y \sqrt{o_x^2 + o_y^2 - R^2}}{(o_x^2 + o_y^2)}$$

$$b_y = \frac{o_y R^2 - R o_x \sqrt{o_x^2 + o_y^2 - R^2}}{(o_x^2 + o_y^2)}$$

$$b_z = 0$$

$$s_x = \frac{i_x R^2 + R i_y \sqrt{i_x^2 + i_y^2 - R^2}}{(i_x^2 + i_y^2)}$$

$$s_y = \frac{i_y R^2 - R i_x \sqrt{i_x^2 + i_y^2 - R^2}}{(i_x^2 + i_y^2)}$$

$$s_z = 0$$

Which can subsequently be transformed into the global coordinate system

$$B = [R]^T b$$

$$S = [R]^T s$$

LabVIEW™ Input

An example of the block diagram used to calculate the points at which the tendon begins and ceases to wrap around the head of the humerus is shown below in Figure 22.

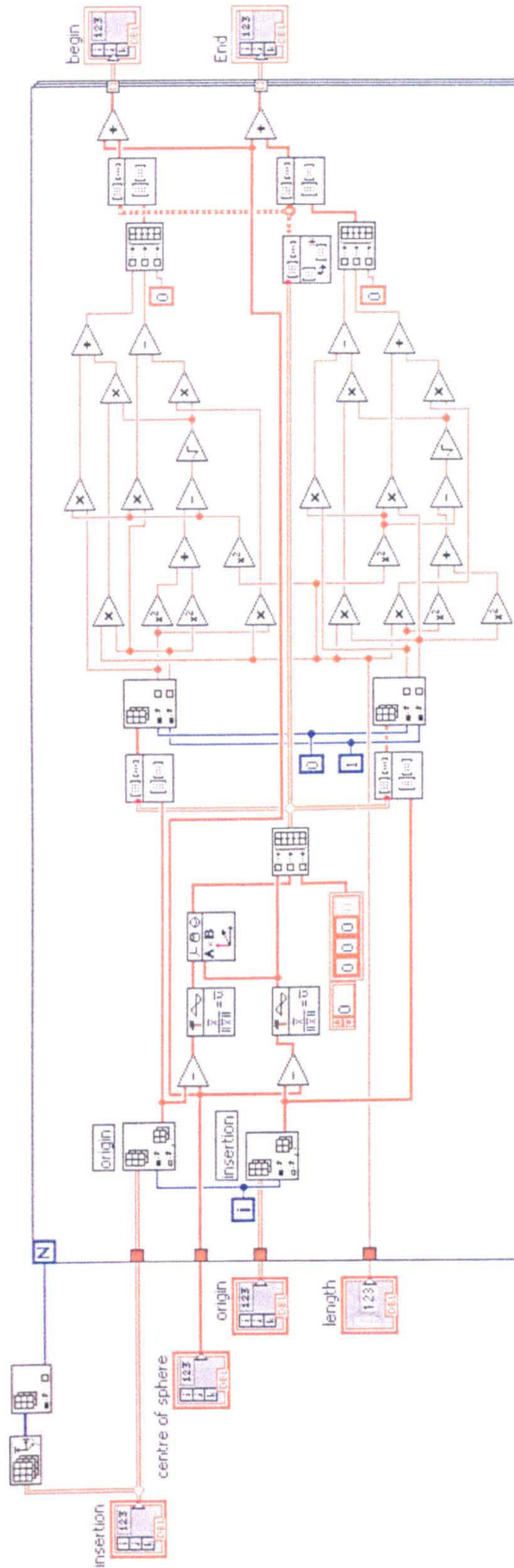


Figure 22. LabVIEW™ block diagram for calculation of the points at which the tendon begins and ceases to wrap around the humerus

Muscle Force

Maximum muscle force for each muscle element is limited by parameters such as the contraction velocity, optimal muscle length and fibre composition characterised by the physiological cross-sectional area (PCSA) (Favre, Sheikh, Fucentese & Jacob, 2005). For the CSBT shoulder model, muscle element PCSA (cm^2) is defined using the reported values of Klein Breteler (1996) and used to determine the maximum muscle force (N) using the equation k* PCSA, where k is a constant factor of 68.94 Ncm^{-2} (Wood, Meek & Jacobsen, 1989)

PCSA values for each muscle element:

Muscle	Element	PCSA (cm^2)	Muscle	Element	PCSA (cm^2)
Infraspinatus	1	2.8972	Subscapularis	1	0.4453
	2	3.0325		2	0.7995
	3	2.0792		3	2.7965
	4	2.1223		4	2.8803
	5	3.0434		5	1.3081
	6	1.9630		6	1.6659
Teres minor	1	1.5003		7	1.9075
	2	2.2937		8	0.7019
	3	1.9686		9	2.6074
Supraspinatus	1	1.1165		10	0.5306
	2	1.0776		11	0.1735
	3	2.3894	Long head of the biceps	1	1.2904
	4	1.1914		2	1.9499

Contribution of Muscles to Joint Stability

The CSBT shoulder model calculates an individual muscle's contribution to shoulder joint stability using the method of Potvin & Brown (2005). This method provides an estimate of a muscle's contribution to stability through acknowledging a muscle's capacity to generate force and the geometric stability a muscle can provide due to its orientation in relation to the joint of interest based on the equation:

$$U(m) = F\Delta\ell + \frac{1}{2}k\Delta\ell^2$$

where:

$U(m) =$ *sum of the energy stored and work done by a muscle*

$F =$ *muscle force*

$\Delta\ell =$ *change in muscle length for a perturbation*

$k =$ *muscle stiffness*

Assuming the external work is negligible, applying a Taylor Series expansion and calculating the second derivative the total stability about each axis for a muscle modelled as a straight line can be calculated as:

$$S(x) = \sum_{m=1}^{N} F_m \left[\frac{A_y B_y + A_z B_z - r_x^2}{l} + \frac{q r_x^2}{L} \right]_m$$

$$S(y) = \sum_{m=1}^{N} F_m \left[\frac{A_z B_z + A_x B_x - r_y^2}{l} + \frac{q r_y^2}{L} \right]_m$$

$$S(z) = \sum_{m=1}^{N} F_m \left[\frac{A_x B_x + A_y B_y - r_z^2}{l} + \frac{q r_z^2}{L} \right]_m$$

Where *AxAyAz* and *BxByBz* refer to the muscle origin and insertion nodes expressed in relation to the GHJ, *l* refers to the length between the origin and insertion, *L* refers to the total length of the muscle, *q* is the proportionality constant relating muscle force and length to stiffness and *r* is the functional moment arm. The functional moment arm is calculated as:

$$r_x = \frac{B_y A_z - A_y B_z}{l}$$

$$r_y = \frac{B_z A_x - A_z B_x}{l}$$

$$r_z = \frac{B_x A_y - A_x B_y}{l}$$

Whilst it is acknowledged that their is a non-linear relationship between muscle stiffness and force, in agreement with Potvin & Brown (2005), q for each muscle was assumed to be 10. For each rotator cuff muscle, due to nodes changing the muscle line of action, the stability equations were expanded and modified to assume the muscle line of action was defined by three segments: from the origin to the point at which the muscle begins to wrap around the head of the humerus, from when the muscle begins to when it ceases to wrap around the head of the humerus and, from when the muscle ceases to wrap around the head of the humerus to the muscle insertion.

Once the contribution of each muscle to joint stability was calculated about each axis in the global coordinate system, this was subsequently expressed in relation to the scapula ACS in keeping with shoulder joint kinetics.

LabVIEW™ Input

An example of the block diagram used to calculate the the contribution of a muscle (without nodes) to joint stability is shown below in Figure 23, where stability for each muscle element is calculated prior, with the length of the muscle calculated with a sub vi (Figure 24), and the stability equation for each muscle element calculated with a separate sub vi (Figure 25).

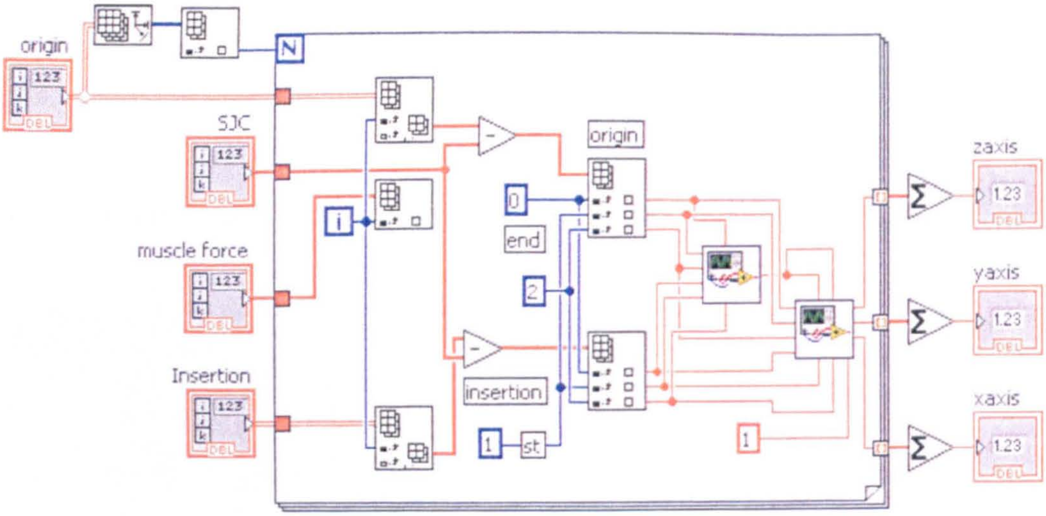


Figure 23. LabVIEW™ block diagram for calculation of the contribution of individual muscles to joint stability.

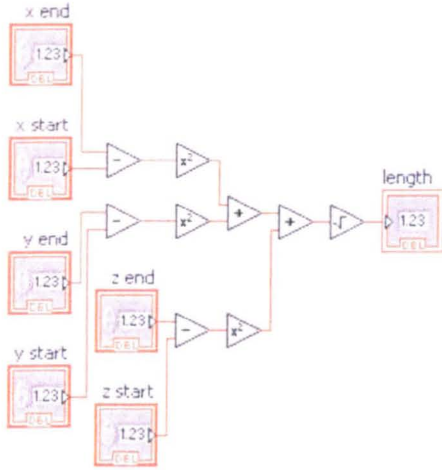


Figure 24. LabVIEW™ block diagram for calculation of the calculation of muscle length.

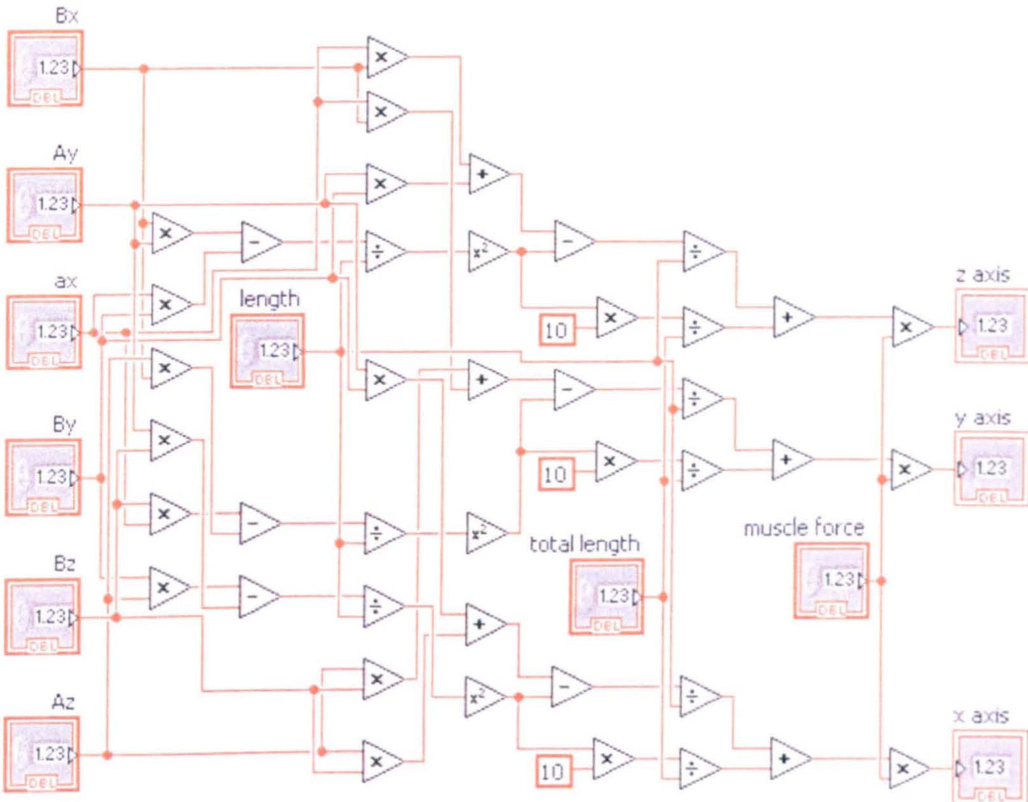


Figure 25. LabVIEW™ block diagram for calculation of the muscle stability according to the equations of Potvin & Brown (2005).

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