Shoulder position sense and kinesthetically guided reaching accuracy in individuals with anterior shoulder instability

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University of Iowa

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SHOULDER POSITION SENSE AND KINESTHETICALLY GUIDED
REACHING ACCURACY IN INDIVIDUALS WITH ANTERIOR
SHOULDER INSTABILITY

by

You-jou Hung

An Abstract

Of a thesis submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree
in Integrative Physiology in
The Graduate College of
The University of Iowa

December 2008

Thesis Supervisor: Professor Warren G. Darling
Altered neuromuscular control due to compromised position sense may contribute to shoulder instability. The purpose of this study was to investigate whether unstable shoulder subjects exhibit larger errors than intact shoulder subjects in kinesthetically guided active positioning and reaching that are of greater functional significance than passive testing of shoulder position sense.

Ten subjects with a history of anterior shoulder dislocation and 15 intact shoulder subjects participated in the study. Shoulder position sense was examined with three different protocols (imposed motion to remembered shoulder rotation angles and active shoulder abduction/rotation to verbally specified positions) with targets located in both the mid- and end-range of rotation. Three dimensional end-point accuracy of kinesthetically guided reaches to visually specified targets, along with the shoulder rotation angle and scapula orientations at the end-point, were also analyzed.

In agreement with previous studies, unstable shoulder subjects exhibited significantly larger errors in perception of shoulder joint angles than healthy controls in a protocol involving imposed motion to remembered shoulder rotation rotations. However, the clinical significance of the observed deficit is questionable because the averaged rms error differences between unstable and intact shoulders were relatively small (average: 1.8°). During tests of active positioning, unstable shoulder subjects were able to move the shoulder to verbally defined angles as accurately as healthy controls in both shoulder abduction and rotation.

Unstable and intact shoulder subjects exhibited similar reaching accuracy and scapular orientations in the kinesthetically guided reaching test, but unstable shoulder subjects consistently used less shoulder rotation angle than healthy controls. However,
they were able to point to a remembered target as accurately as intact shoulder subjects, suggesting that a different reaching strategy was adopted by unstable shoulder subjects to minimize shoulder rotation.

Results of this study show that unstable shoulder subjects can perceive shoulder angles and reach to visually specified targets in space as accurately as healthy controls in functional activities with voluntarily arm movements. The results suggest that less sensitive joint receptors due to over-stretched shoulder stabilizers following shoulder injury have little impact on the neuromuscular control of the shoulder joint.

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ABSTRACT

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CHAPTER I: INTRODUCTION

The glenohumeral joint (GHJ) is prone to instability because the glenoid fossa is a shallow structure that provides little bony constraint for the humeral head. To have superior mobility as well as sufficient stability, the GHJ depends primarily on surrounding soft tissue strength of both passive structures (such as the glenoid labrum, GHJ capsule, and glenohumeral ligaments) and active stabilizers (such as the shoulder girdle muscles) to provide its functional stability (Nyland et al. 1998; Wuelker et al. 1998; Lee et al. 2000; Myers and Lephart 2000; Van de Graaff 2000; Janwantanakul et al. 2001). Without a stable articulation, a decrease in shoulder stability due to compromised soft tissues is commonly seen in athletes whose sport demands strong repetitive overhead movements such as baseball, as well as in individuals who once experienced GHJ dislocation/subluxation as a result of acute trauma (Simonet and Cofield 1997; Mahaffey and Smith 1999).

After the first episode of anterior shoulder dislocation, injured passive shoulder stabilizers may not be able to provide sufficient mechanical stabilization to maintain the humeral head within the glenoid cavity, especially during active movements involving abduction and external rotations (Turkel et al. 1981; Itoi et al. 1996; Brenneke et al. 2000; von Eisenhart-Rothe 2002). Altered neuromuscular control over shoulder girdle muscles due to compromised proprioceptive sensation may also contribute to recurrent shoulder instability (Matthews 1988; Smith and Brunolli 1989; Davies and Dickoff-Hoffman 1993; Lephart et al. 1994; Ghez and Sainburg 1995; Nyland et al. 1998; Myers and Lephart 2000; Zuckerman et al. 2003). If a person’s awareness of shoulder joint orientation is impaired, he/she may not be able to reach to precise locations in space...
without visual feedback or engage appropriate muscle activities at positions in which active joint stabilizers may be crucial for shoulder stability. The lack of sufficient static and dynamic restraints of the GHJ may contribute to the high recurrence rate of anterior GHJ dislocation, ranging from 30% for non-athletes (Simonet and Cofield 1997) to up to 92% for athletes (Wheller et al. 1989).

To reduce recurrent shoulder dislocation and increase the awareness of shoulder position (especially towards unstable positions such as the end range of external rotation with abduction), clinicians often implement proprioceptive training for individuals with shoulder instability (Prentice 1994; Lehart et al. 1997; Myers et al. 2000; Kibler and McMullen 2003; Myers et al. 2006). It has been suggested that unstable shoulders exhibit position sense deficits which might contribute to recurrent injuries (Smith and Brunolli 1989; Lehart et al. 1994; Simonet and Cofield 1997; Mahaffey and Smith 1999). Significant position sense differences have been reported between healthy controls and subjects with anterior shoulder instability (Smith and Brunolli 1989; Lehart et al. 1994; Zuckerman et al. 2003). However, shoulder position sense was mostly studied under relaxed conditions (reproduction of imposed shoulder angles) without voluntary muscle contraction. Moreover, some studies only examined the mid-range of motion (Lehart et al. 1994; Zuckerman et al. 2003) or shoulder forward flexion (Forwell and Carnahan 1996) where anterior shoulder dislocations are less likely to occur. Thus, results of previous studies may not accurately reflect shoulder position sense at a functional level because muscle spindles are not as sensitive during imposed movements with muscles relaxed as during active movements, in which muscle spindles of shoulder
girdle muscles may become more sensitive to muscle length changes due to co-activation of $\alpha$, $\gamma$, and $\beta$ motor neurons (McCloskey 1978; Gandevia et al. 1992; Kandel et al. 2000).

Clearly, the final position of the hand in space is most important for the majority of daily upper limb activities. No previous study has examined kinesthetically guided reaching accuracy in unstable shoulder subjects using a functional testing protocol with shoulder, elbow, wrist, and finger motions unrestrained. In kinesthetically guided reaching to external targets, subjects need to transform visually specified target locations into proper upper limb muscle contractions and joint configurations that would place the fingertip at the remembered target location in space. Although unstable shoulder subjects may experience shoulder position sense deficits at a conscious level, it is unknown whether they can accurately point to a remembered target in 3-dimensional (3-D) space with no instructions concerning shoulder orientation. It is also unknown whether such individuals would implement a different reaching strategy to protect the unstable shoulder when reaching towards some vulnerable positions.

Proper scapula motion during upper-limb movements is thought to be important in maintaining shoulder stability (Itoi et al. 1992; Matias and Pascoal 2006) as well as preventing injuries (Ludewig and Cook 2000; Graichen et al. 2001; McClure et al. 2006). Scapular orientation changes may alter the alignment of the humeral head in relation to the glenoid fossa, potentially predisposing the GHJ to recurrent injuries for subjects with shoulder instability. Previous studies have found muscle activation (EMG) changes in scapular stabilizers (e.g., serratus anterior) and shoulder rotator cuff muscles (e.g., supraspinatus) in unstable shoulders, which may have an impact on scapular motion during upper limb movements (Glousman et al. 1988; McMahon et al. 1996). Warner et
al. (1992) applied Moiré topographic analysis and found scapulothoracic asymmetry in 32% of the subjects with anterior-inferior shoulder instability versus 14% of asymptomatic subjects in a humeral anterior flexion test. However, no studies have compared scapular orientations in 3-D between subjects with anterior instability and intact shoulders in a functional reaching task.

Purpose of Study

The main purpose of the study was to examine whether individuals with anterior shoulder instability exhibit larger errors in perception of shoulder joint angles and in 3-D kinesthetically guided voluntary reaching end-points than intact shoulder subjects with testing protocols that resemble daily/functional activities. The second aim of the study was to investigate whether unstable shoulder subjects employed different reaching strategies and/or scapula orientations from healthy controls while reaching to targets at various locations. To answer these questions, subjects were asked to reproduce specific shoulder angles during imposed motion, actively move the shoulder to verbally specified targets (three levels of abduction and rotation), and point to visually specified targets in space with unrestrained shoulder, elbow, wrist, and finger motion. The results of the present study are expected to assist clinicians and researchers in developing appropriate shoulder position sense diagnostic/testing techniques and to improve rehabilitation programs for individuals with anterior shoulder instability.

Hypotheses

1. Subjects with unstable shoulders will exhibit larger errors than subjects with intact shoulders in reproduction of remembered shoulder rotation angles during imposed motion testing.
Rationale for Hypothesis #1

It has been shown that joint receptors (e.g., Ruffini-like endings, Pacinian-like corpuscles) can contribute to joint position sense (Gandevia and McCloskey 1976; Ferrell et al. 1987; Clark et al. 1989; Tibone et al. 1997). Because activation of joint receptors is triggered by the deformation and changing of tension of the structures that stabilize the joint, over-stretched or lax anterior/inferior shoulder capsule/ligaments may cause position sense deficits in unstable shoulder subjects (Smith and Brunolli 1989; Lephart et al. 1994, 1997; Zuckerman et al. 2003). In addition, greater than normal anterior-inferior translation of the humeral head was observed in subjects with anterior instability during imposed motion with subjects instructed to relax their shoulder muscles (Hawkins et al. 1996; von Eisenhart-Rothe et al. 2002). Alterations in shoulder girdle muscle length due to altered humeral head positioning may also have an impact on the perceived shoulder orientation. Previous studies have found significant differences in shoulder position sense between unstable and intact shoulder subjects (Smith and Brunolli 1989; Lephart et al. 1994; Zuckerman et al. 2003).

2. Subjects with unstable shoulders will exhibit similar position sense errors when compared to intact shoulder subjects in active positioning testing (active shoulder abduction and active shoulder rotation).

Rationale for Hypothesis #2

It has been suggested that muscle receptors contribute to proprioceptive sensations over the full range of motion and have a greater contribution in signaling joint position/orientation than the other receptors (McCloskey 1978; Gandevia et al. 1983; Matthews 1988; Zuckerman et al. 1999). When subjects actively move the unsupported
arm to various shoulder locations, muscle spindles of shoulder girdle muscles may become more sensitive to muscle length changes due to co-activation of α, γ, and β motor neurons (McCloskey 1978; Gandevia et al. 1992; Kandel et al. 2000). Although laxity of the shoulder capsule or ligaments may compromise joint receptors, muscle receptors in unstable shoulder subjects may provide accurate and sufficient position sense to move the shoulder to a desired location. In addition, greater than normal anterior-inferior translation of the humeral head was observed in subjects with anterior instability during passive positioning due to over-stretched anterior shoulder capsule/ligaments (Hawkins et al. 1996; von Eisenhart-Rothe et al. 2002). Researchers have found that active shoulder abduction and rotation reduced anterior translation of the humeral head (Wuelker et al. 1998; Graichen et al. 2000; Hsu et al. 2000; Lee et al. 2000; von Eisenhart-Rothe et al. 2002; Kido et al. 2003). Thus, muscle receptors may provide better position sense concerning muscle length and joint orientations with shoulder muscle contraction in active positioning testing.

3. Unstable and intact shoulder subjects will exhibit similar kinesthetically guided end-point reaching accuracy to visually specified targets in space but with different upper limb configurations.

Rationale for Hypothesis #3

As described earlier, muscle spindles of shoulder girdle muscles may provide better information regarding shoulder orientations due to more sensitive muscle spindles (McCloskey 1978; Gandevia et al. 1992; Kandel et al. 2000) and a more centered humeral head during voluntary arm movements in the reaching test (Hawkins et al. 1996; von Eisenhart-Rothe et al. 2002). Therefore, unstable shoulder subjects may have
sufficient kinesthetic information concerning upper limb configuration to point to the target as accurately as intact shoulder subjects. In addition, when there is no mechanical restraint for any of the upper limb joints during reaching, unstable shoulder subjects may adopt a reaching strategy with different upper-limb configurations (e.g., less shoulder external rotation) to protect the injured shoulder.

4. Unstable and intact shoulder subjects will exhibit similar scapular orientations in the kinesthetically guided reaching test.

Rationale for Hypothesis #4

No study has directly compared scapular orientations in 3-D movements between subjects with anterior shoulder instability and intact shoulder subjects during a functional reaching task with unrestrained shoulder, elbow, wrist, and finger motion. Factors such as pain, muscle weakness, and reduced range of motion observed in subjects with shoulder impingement syndrome or multidirectional shoulder instability may influence scapular orientations during upper limb movements (Ludewig and Cook 2000; Kibler and McMullen 2003; Ogston and Ludewig 2007). However, those factors may not have an impact on the present study because all participating subjects have normal shoulder muscle strength, range of motion, and can reach to all targets without pain.
CHAPTER II: REVIEW OF LITERATURE

Shoulder Instability

Joint stability, defined as the ability of a joint to resist dislocation, is essential for proper joint function (Hall 2003). Moreover, shoulder instability occurs when the humeral head is not maintained within the center of the glenoid cavity during active movement of the arm (Lippitt and Matsen 1993; Friedman et al. 1995). The glenohumeral joint (GHJ) is a multi-axial ball-and-socket synovial joint that has great mobility (with three degrees of freedom) but poor stability (Arnheim and Prentice 1993; Prentice 1994; Friedman et al. 1995; Mahaffey and Smith 1999; Van De Graaff 2000). The glenoid fossa is a shallow bony structure that is one-fourth to one-third the area of the humeral articular surface with a depth of approximately 2.5mm, which provides inadequate bony constraint for the humeral head (Lippitt and Matsen 1993; Prentice and Thein 1994; Friedman et al. 1995; Liu and Henry 1996; Mahaffey and Smith 1999; McCluskey and Getz 2000). Although a ring of fibrocartilage (the glenoid labrum) around the glenoid fossa deepens the glenoid cavity to improve stability, the GHJ depends primarily on surrounding soft tissue integrity of both static (e.g., GHJ capsule and glenohumeral ligaments) and dynamic joint stabilizers (e.g., shoulder girdle muscles) to provide its functional stability (Lippitt and Matsen 1993; Liu and Henry 1996; Nyland et al. 1998; Wuelker et al. 1998; Lee et al. 2000; Myers and Lephart 2000; Van De Graaff 2000; Janwantanakul et al. 2001).

Without a stable articulation, a decrease in shoulder stability due to compromised static/dynamic stabilizers is commonly seen in athletes whose sports demand powerful repetitive overhead movements such as baseball, as well as in individuals who once
experienced GHJ dislocation/subluxation as a result of acute trauma (Liu and Henry 1996; Simonet and Cofield 1997; Mahaffey and Smith 1999). Hawkins et al. (1996) compared humeral anterior translation under anesthesia between intact and unstable shoulders and found much greater humeral translation in unstable shoulders (29% of the diameter of the glenoid from anterior to posterior) than in intact shoulders (17%). In addition, von Eisenhart-Rothe et al. (2002) observed 2.5 times greater than normal anterior-inferior translation of the humeral head in subjects with traumatic anterior instability at 90° of abduction and external rotation, suggesting a functional deficiency of stabilizers in unstable shoulders.

**Classification of Shoulder Instability**

Shoulder instability may be classified according to the degree of laxity, frequency of symptoms, specific anatomic lesion, etiology of injury, and direction of instability (Friedman et al. 1995; McCluskey and Getz 2000). Classifying shoulder instability by injury etiology (i.e., traumatic and atraumatic) and/or direction (i.e., anterior, posterior, or multidirectional) is most frequently used by clinicians because it assists explaining the injury mechanism and identifying the location of damaged shoulder structures (Mahaffey and Smith 1999). Individuals with traumatic shoulder instability usually exhibit instability for a specific direction and/or shoulder position and have normal shoulder girdle muscle strength. In contrast, individuals who suffer from atraumatic shoulder instability may encounter symptoms in more than one position/direction and have relatively weaker shoulder muscle strength (Rowe 1956; von Eisenhart-Rothe et al. 2002). Traumatic shoulder instability is more common than atraumatic instability with 96% of unstable shoulders resulting from trauma (Rowe 1956). In terms of instability direction,
the most common type of shoulder instability is anterior instability, ranging from 84% to 98% of all shoulder instabilities (Rowe 1956; Arnheim and Prentice 1993; Liu and Henry 1996).

Shoulder instability refers to a spectrum of disorders with various severity, including laxity, subluxation, and dislocation (Mahaffey and Smith 1999; McCluskey and Getz 2000). Laxity is defined as a partial loss of proper articulation and individuals with laxity are often asymptomatic. Subluxation is also a partial loss of proper articulation but to a degree that symptoms (such as pain) occur. Dislocation is defined as complete separation of the articular surface with no immediate spontaneous relocation. Shoulder laxity and subluxation are often seen in athletes (e.g., pitchers, swimmers, and gymnasts) and workers due to repetitive stretch of shoulder stabilizers (e.g., shoulder ligaments). However, shoulder dislocation often occurs when the upper limb experiences a powerful unexpected force pushing the humeral head out of the glenoid fossa or the trunk suddenly moves against a stabilized arm. It usually happens in contact sports (e.g., football and basketball) and when falling on an out-stretched arm (Liu and Henry 1996; Mahaffey and Smith 1999).

**Recurrent Shoulder Dislocation**

After an episode of GHJ dislocation, damaged static and/or dynamic stabilizers may not be able to provide essential restraint to the humeral head, especially near vulnerable positions such as external rotation with abduction (Rowe 1956; Smith and Brunolli 1989; Wheller et al. 1989; Lephart et al. 1994, 1997; Simonet and Cofield 1997). Therefore, recurrent shoulder dislocation is a common problem for those who suffered from shoulder instability, especially for young adults with an active lifestyle. Rowe
(1956) examined 500 shoulders with a history of dislocation and reported a high recurrence rate of 83% in subjects who are under 20 years of age and 63% in subjects between 20 and 40 years of age. In addition to age, activity level affects the recurrence rate of GHJ dislocation, ranging from 30% for non-athletes (Simonet and Cofield 1997) to up to 92% for athletes (Wheeler et al. 1989).

**Etiology of Recurrent Shoulder Dislocation**

After the first episode of anterior shoulder dislocation, damaged static and/or dynamic shoulder stabilizers may not be able to provide sufficient mechanical restraint to maintain the humeral head within the glenoid cavity (Turkel et al. 1981; Itoi et al. 1996; Brenneke et al. 2000; von Eisenhart-Rothe 2002). Excessive displacement of the humeral head may loosen or damage static GHJ stabilizers (e.g., shoulder ligaments, capsule). Moreover, GHJ dislocation may also avulse the glenoid labrum, thereby further decreasing the glenoid concavity and shoulder stability (Rowe 1956; Lippitt and Matsen 1993; Liu and Henry 1996; Mahaffey and Smith 1999). In addition, anterior shoulder dislocation may cause rotator cuff tears, which further compromises stability of the humeral head (Lippitt and Matsen 1993; Liu and Henry 1996; Mahaffey and Smith 1999).

In addition to the damage to shoulder mechanical stabilizers, altered neuromuscular control over shoulder girdle muscles may occur due to compromised proprioceptive sensation and may contribute to recurrent shoulder instability (Smith and Brunolli 1989; Davies and Dickoff-Hoffman 1993; Lephart et al. 1994; Nyland et al. 1998; Myers and Lephart 2000; Aydin et al. 2001; Zuckerman et al. 2003). The shoulder capsule and ligaments contain mechanoreceptors that, along with skin and muscle...
receptors, provide information concerning joint orientation to the CNS. When a subject’s awareness of shoulder joint orientation is hindered due to compromised proprioceptors, he/she may not engage appropriate muscle activities to stabilize the GHJ at vulnerable shoulder positions such as abduction with external rotation for individuals with anterior shoulder instability. The lack of awareness of shoulder orientation may lead to a vicious cycle of microtrauma of shoulder stabilizers and recurrent injuries.

The Importance of Proprioception

Proprioception is defined as the sense of limb position (i.e., position sense) and movement (i.e., kinesthesia) of one’s own body without using vision (Grigg 1994; Lephart et al. 1994, 1997; Kandel et al. 2000; Lönn et al. 2000; Diederichsen et al. 2002; Pötzl et al. 2004; Suprak et al. 2005). Originating from peripheral receptors such as joint receptors and muscle spindles, proprioception is conveyed to higher levels (e.g., somatosensory cortex) through the dorsal lateral tracts and is crucial for proper movements and muscle activations in order to accomplish a desired task (Sanes et al. 1984, 1985; Sainburg et al. 1993; Ghez et al. 1995; Gordon et al. 1995; Shumway-Cook and Woollacott 1995; Kandel et al. 2000). Proprioception is used unconsciously for automatic adjustments at the brain stem (e.g., maintaining posture and balance) and spinal cord levels (e.g., modulating reflex muscle contraction and locomotor movements) (Shumway-Cook and Woollacott 1995; Kandel et al. 2000; Proske 2005). Proprioceptive information is also utilized at a subconscious level in movement control and at a conscious level for perceiving limb/joint orientations (position sense) such as moving a joint to a specified angle or repositioning the limb to a remembered target position.
Proprioceptive sensations are necessary for accurate coordinated limb movements, as inferred from observations of altered movement control in deafferented patients such as those who suffer from large-fiber sensory neuropathy (Sanes et al. 1984, 1985; Sainburg et al. 1993; Ghez et al. 1995; Gordon et al. 1995). Individuals who were deprived of proprioceptive feedback were not able to maintain a steady joint angle (Sanes et al. 1984, 1985), nor could they exhibit normal interjoint coordination while performing a common movement without vision (Sainburg et al. 1993; Ghez et al. 1995). Ghez and Sainburg (1995) examined deafferented patients and found de-synchronization of elbow and shoulder joints in both planar reversal movements with the subject’s arm supported by a brace and in a simple unconstrained upper limb movement (similar to slicing a loaf of bread). Similarly, Ghez et al. (1995) also reported large spatial errors and hand trajectory variations during a reaching movement in subjects with large-fiber sensory neuropathy.

In addition, researchers have also reported proprioception deficits when muscle, joint, or skin receptors were selectively disengaged (Gandevia et al. 1976, 1983; Clark et al. 1985, 1986, 1989; Ferrell et al. 1987, 1988). Moreover, studies have shown disturbed control of voluntary movements or position sense deficits when proprioception was altered through muscle fatigue (Voight et al. 1996; Carpenter et al. 1998; Myers et al. 1999; Bjerklund et al. 2000; Walsh et al. 2004) or tendon vibration (Goodwin et al. 1972; Capaday and Cooke 1981, 1983; Inglis and Frank 1990; Cordo et al. 1995; Forwell and Carnahan 1996; Verschueren et al. 1999). When proprioceptive information is temporarily altered or severely degraded, an individual may not be able to perform daily activities such as reaching to a target or catching a ball with precision.
The Role of Proprioception in Motor Control

In order to reach under kinesthetic guidance to a visually specified target in space, one needs to have accurate visual representation of the target location, correctly specify the starting position of the hand in relation to the target, and be able to incorporate proprioceptive information into motor commands to properly activate muscles and achieve the desired joint configurations for the upper limb (Soechting and Flanders 1989ab, 1992; Tillery et al. 1991; Darling and Miller 1993; Gordon et al. 1995; Verschueren et al. 1999). Vision of the limb before movement can provide joint configuration for motor planning while vision of the limb during movements enables the subject to detect and correct errors (Sanes et al. 1984, 1985; Gordon et al. 1995; Ghez et al. 1995). Proprioceptive information concerning limb orientation is also essential for specifying the initial position of the limb and generating proper motor responses vital to coordinated movements to achieve reaching accuracy (Sanes et al. 1984, 1985; Soechting and Flanders 1989a; Ghez et al. 1990; Darling and Miller 1993; Gordon et al. 1995; Ghez et al. 1995; Ghez and Sainburg 1995; Verschueren et al. 1999).

Studies of patients with large-fiber sensory neuropathy have shown large deficits in motor control in both static and dynamic phases of movements (Rothwell et al. 1982; Sanes et al. 1984, 1985; Sainburg et al. 1993; Gordon et al. 1995; Ghez et al. 1995). Rothwell et al. (1982) and Sanes et al. (1985) found their patients unable to maintain a constant limb position and consistent muscle activation pattern without visual feedback. Gordon et al. (1995) found larger spatial errors in these neuropathy patients in both movement direction and extent, suggesting improper motor planning due to the absence of proprioceptive information. Moreover, Sainburg et al. (1993) and Ghez et al. (1995)
compared neuropathy patients with healthy individuals and found their patients exhibited
temporal decoupling between the shoulder and elbow joints (with faster elbow joint
reversal than shoulder reversal) while performing a 3D slicing-type movement. Hence,
proper proprioceptive sensation may also be crucial for inter-joint coordination in
functional movements. It is also important to note that a complete lack of proprioceptive
information (such as in neuropathy patients) does not totally compromise reaching
accuracy without visual guidance (Gordon et al., 1995; Ghez et al. 1995). In movements
where the upper limb is supported or not moving largely against gravity, deafferented
subjects can still reach with some accuracy to a visually specified target if they see their
hand and the target before initiation of the movement. However, end-point reaching
accuracy could be greatly enhanced when a deafferented subject was provided with visual
feedback during the movement and/or prior vision of the moving arm (Ghez et al. 1995).

Peripheral Receptors and Their Contribution to

Proprioception

Proprioception is a compound sense that originates at the level of peripheral
receptors (proprioceptors) that are located within tissues such as skin, joint capsule,
ligaments, tendons, and muscles about a joint (Grigg 1994; Lephart et al. 1997; Kandel et
al. 2000; Myers et al. 2006). Peripheral receptors are often described as
mechanoreceptors because the majority of the receptors are mechanically sensitive,
converting the magnitude of tissue deformation as frequency modulated neural signals to
the central nervous system (Grigg 1994; Prentice 1994; Van De Graaff 2000; Myers et al.
2006).
Skin proprioceptors consist of several stretch/touch sensitive receptors such as Ruffini endings (Shumway-Cook and Woollacott 1995; Zuckerman et al. 1999; Kandel et al. 2000). The contribution of skin receptors to proprioception has been examined by removing cutaneous feedback with anesthesia of the skin (Gandevia and McCloskey 1976; Clark et al. 1986, 1989; Rao and Gordon 2001; Refshauge et al. 2003) or by stimulating cutaneous receptors with skin stretching (Collins et al. 2005). Results show that removal of cutaneous feedback by anesthesia around the fingers impaired movement detection ability (Gandevia and McCloskey 1976; Clark et al. 1986, 1989; Refshauge et al. 2003), pointing accuracy (Rao and Gordon 2001), and skin stretch evoked illusory movements at the index finger, elbow, and knee joints (Collins et al. 2005). Although Collins et al. (2005) found skin receptors contributed to proprioception at the index finger, elbow, and knee, most investigators have only examined the role of skin receptors in finger joints (Gandevia and McCloskey 1976; Clark et al. 1986, 1989; Refshauge et al. 2003). Movement illusions evoked by cutaneous stimuli were greater and evident in more subjects at the finger (6/8) than at the elbow (5/10) or knee joints (3/10) (Collins et al. 2005). This suggests that skin receptors may contribute to proprioception at both distal and proximal joints, but the relative importance of such contribution at proximal joints is still unclear.

Joint mechanoreceptors also contribute to proprioception. They consist of Ruffini-like endings, Pacinian-like corpuscles, Golgi tendon organ-like endings, and free nerve endings that are located in and around joints (Newton 1982; Grigg 1994; Prentice 1994; Shumway-Cook and Woollacott 1995; Lephart et al. 1997; Zuckerman et al. 1999; Diederichsen et al. 2002). Studies have shown that subjects’ ability to detect movement
was compromised after the joint capsule was surgically removed (Grigg et al. 1973) or
during local anesthetic block of the joint (Clark et al. 1989; Ferrell et al. 1987; Ferrell and
Smith 1988) but enhanced after injecting dextran into the intracapsular space of the distal
interphalangeal joint to stretch the joint capsule (Ferrell et al. 1987). In addition, joint
receptors also exhibit different adaptive properties based on their responses to continuous
stimuli. Fast adapting receptors (e.g., Pacinian-like corpuscles) decrease their discharge
rate shortly after the onset of a continuous stimulus, and are therefore thought to mediate
the sensation of joint motion (Newton 1982; Prentice 1994; Zuckerman et al. 1999).
Slowly adapting receptors (e.g., Ruffini-like endings) continue their discharge in
response to a continuous stimulus, and are therefore thought to mediate the sensation of
joint position and the change in joint position (Newton 1982; Prentice 1994; Zuckerman
et al. 1999). However, joint receptors may not contribute to proprioception equally
throughout the range of motion. Clark et al. (1989) examined the activity of
interphalangeal joint receptors of monkeys over a wide range of motion and found
receptor activities increased as the joint approached its end range of motion. Although
some joint receptors can still provide joint information at the mid-range, it has been
suggested that joint receptors have a larger contribution to proprioception at the end/limit
of the range of motion (Burgess and Clark 1969; McCloskey 1978; Clark et al. 1989;
Borsa et al. 1994; Grigg 1994; Shumway-Cook and Woollacott 1995).

Golgi tendon organs (GTOs) are peripheral receptors located at the junction
between muscle fibers and tendon (Shumway-Cook and Woollacott 1995; Kandel et al.
2000). They have low activation threshold and are most sensitive to changes in active
muscle tension as their firing frequency increases when muscle force increases (Crago et
Although tendon organs are preferentially sensitive to tension by active muscle contraction, they also respond to passive muscle stretch (Prentice 1994; Shumway-Cook and Woollacott 1995; Gregory et al. 2002, 2003). In addition to sending afferents to spinal cord inhibitory interneurons to prevent injuries to the contracting muscle fibers, tendon organs also provide the CNS with information about the state of the muscle under both static and dynamic conditions and contribute to proprioception (Stauffer and Stephens 1977; Crago et al. 1982; Gandevia et al. 1992; Kandel et al. 2000; Gregory et al. 2002).

Muscle spindles are spindle-shaped peripheral receptors located inside the muscle belly. Their main function is to signal muscle length change, which is closely associated with the joint angle changes at joints spanned by the muscle (Shumway-Cook and Woollacott 1995; Kandel et al. 2000). Information from muscle spindles is utilized at many levels of the CNS motor system hierarchy, including reflex activation at the spinal level and in complex motor control at a higher level (Shumway-Cook and Woollacott 1995; Kandel et al. 2000). To examine the role of muscle receptors, Gandevia and McCloskey (1976) disengaged the muscles controlling the distal interphalangeal joint and found decreased proprioceptive acuity in the ability of detecting passive movements. In addition, Clark et al. (1985) also reported that the ability for the subjects to detect passive movements at the ankle and metacarpophalangeal joints was impaired after blocking the ulnar and common peroneal nerves to paralyze interosseous muscles and ankle dorsiflexors. Moreover, previous research has shown that altered muscle spindle sensation due to tendon vibration can greatly hamper joint proprioception (Goodwin et al. 1972; Craske 1977; Inglis and Frank 1990; Cordo et al. 1995; Forwell and Carnahan...
1996; Verschueren et al. 1999). Vibrating a lengthening muscle excites primary muscle spindle afferents and creates perceptions that the muscle is longer and moving faster than it actually is. As a result, tendon vibration often causes undershoot errors when moving a joint to a certain angle or reaching to a desired target in space (Capaday and Cooke 1981, 1983; Inglis and Frank 1990; Cordo et al. 1995; Forwell and Carnahan 1996; Verschueren et al. 1999). Hence, there is strong evidence that sensory information originating from muscle spindles play a significant role in position matching (at the perceptual/conscious level) and motor control (at a subconscious level).

The relative importance of different types of proprioceptors may differ with joint angle and limb position (Clark et al. 1986, 1989; Rogol et al. 1998; Myers et al. 1999). Joint receptors probably contribute most at end-range of motion (McCloskey 1978, Clark et al. 1989; Smith and Brunolli 1989; Grigg 1994; Nyland et al. 1998; Rogol et al. 1998; Myers and Lephart 2000), whereas muscle spindles contribute over the full range of motion and may have a greater contribution in signaling joint position than the other receptors (Clark et al. 1979; McCloskey 1978; Gandevia et al. 1983; Matthews 1988; Zuckerman et al. 1999). However, it is most likely that peripheral proprioceptive information provided by skin, joint, and muscle receptors all complement each other to provide the most comprehensive proprioceptive sensation (Gandevia and McCloskey 1976; Ferrell and Smith 1988; Gandevia et al. 1983, 1992; Myers and Lephart 2000).

The Role of Central Signals in Sensing Limb Position and Motion

In addition to the information from peripheral receptors (e.g., skin/joint receptors and muscle spindles), individuals may also rely on signals of central origin to sense
position of the limb (Barden et al. 2004; Pötzl et al. 2004; Fremerey et al. 2006; Gandevia et al. 2006; Myers et al. 2006; Héroux and Tremblay 2006; Hundza and Zehr 2007). Several researchers found systematic matching errors with various external torque applications on the elbow joint during a forearm angle matching task, suggesting signals of central origin may provide information about elbow position (Watson et al. 1984; Worringham and Stelmach 1985; Gooey et al. 2000; Winter et al. 2005). Recent studies of position matching at the elbow and wrist joints further support that an effort-based signal of central origin contributes to position sense. Walsh et al. (2004) and Allen and Proske (2005) examined the impact of muscle fatigue on elbow proprioception and found systematic matching errors with fatigued elbow flexors. Moreover, Gandevia et al. (2006) investigated the role of efferent signals (effort) in position sense by eliminating afferent inputs from cutaneous, joint, and muscle receptors with ischaemia. Without proprioceptive information, the perceived wrist position was altered more than 20 degrees when subjects were trying to flex/extend the paralyzed wrist and the size of wrist position error (movement illusion) increased as the level of effort increased. These results suggest that individuals may also use signals of motor command to achieve/maintain a given limb orientation or to match a remembered joint angle. In summary, peripheral receptors may provide proprioceptive information to the central nervous system (CNS) where it is integrated with signals of central origin to provide accurate position sense (Barden et al. 2004; Pötzl et al. 2004; Fremerey et al. 2006; Gandevia et al. 2006; Myers et al. 2006; Héroux and Tremblay 2006; Hundza and Zehr 2007).
Position Sense Testing in Unstable Shoulder Subjects

Various testing techniques have been used to examine shoulder position sense in subjects with shoulder instability. Smith and Brunolli (1989), Lephart et al. (1994), and Zuckerman et al. (2003) examined shoulder position sense with the “passive reproduction of passive positioning” protocol, in which the subject’s arm was moved by a machine and the subject was instructed to relax his/her shoulder muscles during the process. After staying at the target location for a short period of time for the subject to remember the location, the machine returned the limb back to the starting position. The limb was then passively moved through the same range of motion until the subject identified the remembered location and stopped the machine. It is important to note that the so called “passive” testing protocols in shoulder position sense literature only referred to the specific testing protocols in which the examined shoulder was “passively” positioned in both the initial trials (to the target angle) and matching trials (to the remembered target angle). Shoulder muscle activations were not closely monitored in earlier studies. Thus, one might suspect some muscle activation occurred due to apprehension when the injured shoulder was moved towards a vulnerable position for subjects with anterior shoulder instability. Therefore, an imposed motion testing protocol may be a better term to describe earlier studies.

Other protocols that involved using active movement to reproduce a remembered shoulder angle were also implemented in shoulder position sense testing. Aydin et al. (2001) first moved the subject’s arm to a target location (passive positioning) and then the subject was asked to actively move the limb to the remembered location (active repositioning). Moreover, subjects of Pötzl et al. (2004) were instructed to move the examined limb to the target location first (active positioning), followed by the subject repositioning the arm to the remembered location (active repositioning).
Several studies have reported small but significant shoulder position sense differences between intact shoulder subjects and subjects with anterior shoulder instability when examined with a reproduction of imposed shoulder joint angles protocol (Smith and Brunolli 1989; Lephart et al. 1994; Zuckerman et al. 2003). Smith and Brunolli (1989) compared 10 healthy subjects with 8 patients with a history of anterior shoulder dislocation and found patients exhibited significantly larger position errors in both mid-range (1.3° larger) and end-range (2° larger) of shoulder external rotation. In addition, both Lephart et al. (1994) and Zuckerman et al (2003) reported significantly larger position errors in subjects with anterior shoulder instability than intact shoulder subjects in the mid-range of shoulder external rotation (0.6°- 1.5° difference for Lephart et al. and 2.3° difference for Zuckerman et al.).

Results from studies that involved active movement of the limb were inconclusive. Forwell and Carnahan (1996) asked their subjects to generate a forward pointing movement with the intact limb and then actively match the target position with the unstable shoulder. Their unstable shoulder subjects were able to match the reference arm as well as healthy controls. In contrast, a study using active movement to reproduce a remembered shoulder angle found larger positioning errors in the mid-range of shoulder rotation in subjects with anterior instability than in subjects with intact shoulders (Pötzl et al. 2004). Moreover, Forwell and Carnahan (1996) only examined shoulder forward flexion and Pötzl et al. (2004) only examined the mid-range of shoulder rotation (from 45° of internal rotation to 45° of external rotation), where vulnerable shoulder structures are not stressed and anterior shoulder dislocations are less likely to occur. Thus, results of previous active positioning studies may not accurately reflect shoulder position sense at a functional level to provide clinicians the most objective analysis of potential position sense deficits after an injury.
Summary

Glenohumeral joint instability is commonly seen in athletes whose sport demands strong repetitive overhead movements as well as in individuals who once experienced GHJ dislocation/subluxation as a result of acute trauma (Liu and Henry 1996; Simonet et al. 1997; Mahaffey and Smith 1999). In addition to the over-stretched static stabilizers (e.g., shoulder ligaments), altered neuromuscular control due to compromised shoulder position sense may also contribute to shoulder instability (Smith and Brunolli 1989; Lephart et al. 1994; Simonet and Cofield 1997; Mahaffey and Smith 1999).

In previous shoulder position sense studies, unstable shoulder subjects were either restricted to imposed movements of the shoulder joint (Smith and Brunolli 1989; Lephart et al. 1994; Zuckerman et al. 2003) or asked to perform active shoulder movements to shoulder forward flexion (Forwell and Carnahan 1996) or mid-range of external rotation (Pötzl et al. 2004) where anterior shoulder dislocations were less likely to occur. Moreover, no previous study has examined whether individuals with anterior shoulder instability exhibit larger errors in perception of shoulder joint angles and in 3-D kinesthetically guided reaching accuracy than intact shoulder subjects with testing protocols that better resemble functional activities.
CHAPTER III: PROCEDURE FOR DATA COLLECTION

Subjects

Ten subjects with a history of anterior shoulder dislocation (3 females and 7 males, age 19-37 years old, Table 1) and 15 subjects with un-injured shoulders (4 females and 11 males, age 20-39 years old, Table 2) participated in the study. Inclusion criteria for the subjects with unstable shoulders (experimental group) included individuals with a minimum of one episode of anterior shoulder dislocation, a positive apprehension test administered by the primary investigator, and no surgical repair prior to the testing. Persons with multidirectional instability, degenerative arthritis, significant muscle weakness/soreness, and the inability to achieve the designated shoulder positions without pain or apprehension were excluded from the study.

Physical and injury characteristics of unstable shoulder subjects are listed in Table 1. Nine of the 10 unstable shoulder subjects were physically active and participated in either recreational sports (7 subjects) or competitive (2 subjects) sports on a regular basis. The first episode of anterior shoulder dislocation of 8 subjects was due to sport related injuries. Among the 7 subjects who experienced recurrent dislocations, five of them re-dislocated the shoulder while playing the same sport. Similar to the fitness level of unstable shoulder subjects, the majority (13 out of 15) of the intact/uninjured shoulder subjects were also physically active and participated in recreational (12 subjects) or competitive (1 subject) sports (Table 2).

Both gender (Bjérklund et al. 2000) and age (Skinner et al. 1984; Kaplan et al. 1985; Nyland et al. 1998; Zuckerman et al. 1999) may have an impact on position sense.
Table 1: Physical and injury characteristics of subjects with unstable shoulders

<table>
<thead>
<tr>
<th></th>
<th>Gender</th>
<th>Age</th>
<th>Dominant arm</th>
<th>Unstable arm</th>
<th>Number of dislocations</th>
<th>Time since last injury (month)</th>
<th>Frequent activities</th>
<th>First dislocation activity</th>
<th>Recurrent dislocation activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>M</td>
<td>19</td>
<td>R</td>
<td>R</td>
<td>2</td>
<td>16</td>
<td>recreational skateboarding/weight training</td>
<td>skateboarding</td>
<td>skateboarding</td>
</tr>
<tr>
<td>U2</td>
<td>F</td>
<td>21</td>
<td>R</td>
<td>L</td>
<td>3</td>
<td>19</td>
<td>competitive gymnastic</td>
<td>gymnastic</td>
<td>gymnastic</td>
</tr>
<tr>
<td>U3</td>
<td>M</td>
<td>27</td>
<td>R</td>
<td>R</td>
<td>2</td>
<td>12</td>
<td>weight training</td>
<td>fall</td>
<td>fall</td>
</tr>
<tr>
<td>U4</td>
<td>F</td>
<td>37</td>
<td>R</td>
<td>R</td>
<td>1</td>
<td>7</td>
<td>none</td>
<td>fall</td>
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<td>M</td>
<td>19</td>
<td>R</td>
<td>L</td>
<td>5</td>
<td>6</td>
<td>recreational basketball</td>
<td>ski</td>
<td>ski, soccer, water tubing</td>
</tr>
<tr>
<td>U6</td>
<td>M</td>
<td>23</td>
<td>R</td>
<td>R</td>
<td>1</td>
<td>18</td>
<td>recreational basketball</td>
<td>basketball</td>
<td>NA</td>
</tr>
<tr>
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<td>M</td>
<td>28</td>
<td>L</td>
<td>L</td>
<td>2</td>
<td>12</td>
<td>recreational basketball/weight training</td>
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<td>basketball</td>
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<td>M</td>
<td>22</td>
<td>R</td>
<td>R</td>
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<td>recreational football/basketball</td>
<td>football</td>
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<td>F</td>
<td>20</td>
<td>R</td>
<td>L</td>
<td>2</td>
<td>14</td>
<td>competitive soccer, recreational swimming</td>
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<td>soccer</td>
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<tr>
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<td>M</td>
<td>25</td>
<td>R</td>
<td>L</td>
<td>3</td>
<td>4</td>
<td>weight training</td>
<td>skateboarding</td>
<td>snowboarding, biking</td>
</tr>
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</table>
Table 2: Physical characteristics of subjects with intact shoulders

<table>
<thead>
<tr>
<th>Gender</th>
<th>Age</th>
<th>Dominant arm</th>
<th>Compared arm</th>
<th>Frequent activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>M</td>
<td>28</td>
<td>R</td>
<td>L</td>
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<tr>
<td>S2</td>
<td>M</td>
<td>21</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>S3</td>
<td>M</td>
<td>23</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>S4</td>
<td>F</td>
<td>24</td>
<td>R</td>
<td>L</td>
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<tr>
<td>S5</td>
<td>M</td>
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<td>R</td>
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<td>S8</td>
<td>F</td>
<td>29</td>
<td>R</td>
<td>R</td>
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<td>S9</td>
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<td>L</td>
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<td>S10</td>
<td>M</td>
<td>25</td>
<td>R</td>
<td>L</td>
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<td>R</td>
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<tr>
<td>S15</td>
<td>M</td>
<td>39</td>
<td>R</td>
<td>R</td>
</tr>
</tbody>
</table>
Thus, to reduce potential innate proprioception differences between the two groups, 15 healthy subjects with a similar gender ratio and age range as the experimental group were recruited as the control group. Inclusion criteria for the control group included no known history of severe shoulder injury that required medical treatments and being able to move their shoulders to the target positions without discomfort or limitations. All 25 subjects participated in active positioning and kinesthetically guided reaching protocols.

However, 2 intact shoulder subjects and 3 unstable shoulder subjects did not participate in the imposed motion protocol due to time limitations or not being able to position the arm to 45° of internal rotation (blocked by the trunk). All subjects signed informed consent forms approved by the University of Iowa Human Subjects Review Committee prior to participation in the study.

**Apparatus**

Ascension Technology’s minibird (MB) electromagnetic tracking system was used to record shoulder kinematics and three-dimensional (3-D) reaching movements (74 Hz sampling rate). This system utilizes a pulsed direct-current (DC) magnetic field produced by a transmitter to detect the position and orientation of several small (1 cm³) receivers in space. The system’s validity for motion analysis has been well documented (Milne et al. 1996; Meskers et al. 1998, 1999), and the measured positional and rotational errors were less than 2% of the range of motion when utilized within its optimal operating range between 22.5 and 64.0 cm from the transmitter (Milne et al. 1996). Furthermore, electromagnetic tracking device has been validated for measurement of scapula and humerus motion against bone-fixed 3-D kinematic evaluations. Karduna et al. (2001) compared scapular orientations measured by a similar electromagnetic system (Polhemus FASTRAK) against bone-fixed measurements and found small root mean square (rms) errors (2°) for scapular upward rotation but larger rms errors for posterior tipping (6.6°) and lateral rotation (9.4°) during humeral abduction (up to 120°) in the
scapular plane. Moreover, Ludewig et al. (2002) examined the validity of the Polhemus system against bone-fixed measurements for humeral orientation and found small rms errors (1°) in humeral elevation but larger errors (maximum of 5.7°) in humeral rotation, which is likely due to humerus rotation under the skin not being fully represented by the receiver attached to the humeral cuff (Ludewig et al. 2002). To better represent humerus movements, the elbow of the target arm was placed in a padded brace with 90 degrees of elbow flexion and neutral forearm rotation and the humeral receiver was placed on the brace over the lateral epicondyle of the humerus.

Five electromagnetic receivers of the MB system were secured on the skin over subject’s manubrium, the distal end of acromion of the scapula, the lateral epicondyle of the humerus (on the brace over the lateral epicondyle for active positioning testing), the wrist cuff over the styloid process of the ulna, and over the index finger tip (Fig. 1). For active abduction, rotation, and 3-D kinesthetically guided reaching, the transmitter was placed at the glenohumeral joint (GHJ) level right behind the examined shoulder. For imposed motion to remembered shoulder angles testing, the transmitter was placed at the GHJ level in front of the subject to avoid electromagnetic interference from the metal part of the manipulandum.

A custom made plexiglass manipulandum consisting of a moving arm that rotates in the horizontal plane on a stationary vertical axis (with minimal friction) under the elbow joint center was used for imposed motion testing (Fig. 2). The handle location on the manipulandum was adjusted to assure a comfortable grip with the subject’s wrist in its neutral position. A flat piece of cardboard marked with the target angles was positioned under the manipulandum during the testing to provide visual cues for the primary investigator.

For the 3-D kinesthetically guided reaching to visual targets test, a bright yellow ¾” by ¾” square fixed to a black tripod was used as the visual target for the subject. The intended tripod locations were marked on the floor based on each subject’s arm length
Procedure

After giving their consent, all potential subjects first attended a screening test (the first visit) prior to the data collection phase of the study. The primary investigator first examined if subjects could reach to all predetermined target angles/locations freely without limitation, pain, or apprehension with both arms. Secondly, the primary investigator applied manual resistance to examine if subjects had muscle weakness of their shoulder external/internal rotators and flexors/abductors and if there was muscle strength discrepancy between the two shoulders. Only subjects who could reach to all targets freely without limitation or apprehension with both arms, and had no significant muscle strength discrepancy between the shoulders further participated in the study. For those who passed the screening test, the primary investigator took 4 measurements (height of the ASIS, GHJ, top of the head, and the distance from the index finger tip to the GHJ with elbow fully extended) with the subject seated in an upright position to set up the apparatus for the 3-D reaching task according to each subject’s body dimensions and arm length.

Before the second visit, subjects were instructed to avoid strenuous or repetitive upper extremity activities at least one day prior to the scheduled testing to avoid muscle fatigue that might influence shoulder proprioception (Voight et al. 1996; Carpenter et al. 1998; Myers et al. 1999; Björklund et al. 2000). Five electromagnetic receivers of the electromagnetic tracking system were secured on the skin over subject’s manubrium, the distal end of acromion of the scapula, the lateral epicondyle of the humerus (on the brace over the lateral epicondyle for active positioning testing), the wrist cuff over the styloid process of the ulna, and over the index finger tip. Specific testing procedures/directions and practice sessions were given just before each testing protocol. The 4 testing
protocols (imposed motion, active rotation, active abduction, and active 3-D reaching) were conducted in random order and subjects took at least one minute break between the protocols. To investigate the impact of arm dominance on the specific testing protocols of the present study, 14 of the 25 subjects agreed to have their un-injured shoulders (experimental group) or non-dominant arms (control group) examined during a third visit or a minimum of 15 minutes after the previous testing. Testing orders of the un-injured shoulders or non-dominant arms were also random but, for each subject, differed from the order of their opposite arm.

Reproduction of Shoulder Rotation Angles with Imposed Motion

Blindfolded subjects were instructed to sit upright, relax the tested arm, and place the ulnar surface of the forearm on the moving arm of the manipulandum with the elbow placed over the rotational axis on the manipulandum (Fig. 2). The height and handle location of the manipulandum were further adjusted according to each subject’s body dimensions. The primary investigator first explained the testing procedures to the subjects and then the subjects practiced 3-5 trials to some random angles while blindfolded. Without informing subjects of the intended target locations, the primary investigator first moved the forearm (by moving the handle) in the horizontal plane to rotate the shoulder towards one of the 3 target shoulder rotation angles (45° internal rotation, 45° external rotation, and 75° external rotation). Seventy-five degrees of external rotation was chosen to represent the end-range of motion for passive testing because most subjects (including healthy controls) could not externally rotate to 90° when rotating the forearm in the horizontal plane with a small abduction angle. After staying at the target for 3 seconds for the subject to remember the target location, the examiner then moved the shoulder to a new position which was approximately 15°, 30°, 45°, or 60° from the original target location. The starting position for the reproduction phase was
varied to emphasize the target position and discourage the subject from remembering the amplitude and time used to reach to the target as a cue in reproducing the target angle. Subsequently, the investigator moved the forearm slowly back toward the previous (remembered) target angle and subjects were instructed to say “stop” when they felt they had been returned to the remembered target location. Subjects could request to rotate the shoulder back in the opposite direction if he/she felt that the examiner had overshot the target. Subjects performed 8 trials for each target (three targets in total) in a random order.

Active Shoulder Abduction Testing

The primary investigator first described the testing procedures and the spatial definition of each target angle (45°, 90°, and 135° of shoulder abduction in the frontal plane) before demonstrating the task for the subject. In order to avoid subject using visual feedback to remember the designated target location during practice, subjects were not allowed to practice during the investigator’s demonstration and only practiced while blindfolded later without receiving position accuracy feedback from the investigator.

At the starting position, subjects were instructed to sit upright against a back support with the unsupported shoulder resting by the side. After being given the target location for a specific trial (i.e., 45°, 90°, or 135° of shoulder abduction), blindfolded subjects actively moved the examined shoulder from the starting position to the target position with a comfortable speed. After staying at the target location for one second, subjects then returned the arm to its starting position and were encouraged to relax the shoulder after each trial. Subjects performed 8 trials for each target (for a total of 24 trials) in a random order.
Active Shoulder Rotation Testing

The same demonstration and practice protocols were implemented in active rotation testing as in active abduction testing. Subjects only practiced while blindfolded without movement accuracy feedback from the investigator. Subjects were instructed to sit upright against a back support with the unsupported shoulder resting by the side with 90° of elbow flexion (in a padded brace) and neutral arm rotation. After being given the target location for a specific trial, subjects first actively moved the shoulder to approximately 90° of abduction and then to one of the 3 shoulder rotation angles (45° IR, 45° ER, and 90° ER with 90° of shoulder abduction) with a comfortable speed (Fig. 3). After staying at the target location for one second, subjects then returned the arm to its starting position. Subjects performed 8 trials for each target in a random order for a total of 24 trials.

Kinesthetically Guided Reaching Test

In the kinesthetically guided reaching test, reaching accuracy was examined for 9 different targets located in 3 different planes in which various shoulder abduction/rotation angles could be adopted to accomplish the task. The three planes were the para-sagittal plane (SP) through the GHJ of the moving limb, the frontal plane (FP) through the GHJ of the moving limb, and a vertically oriented oblique plane (OP) through the subject’s GHJ that equally bisected the previous two planes (Fig. 4). There were 3 targets in each of the 3 reference planes. The height of the 3 targets was determined by the height of each subject’s ASIS (low target), GHJ (middle target), and the top of the head (top target) when measured from a seated position during the screening visit. The distance between the targets and the GHJ was determined for each subject as 2/3 of the distance from the
index finger tip to the GHJ. Before data collection, subject performed a few practice trials without receiving any feedback from the investigator concerning accuracy of the end-points. At the starting position, subjects were instructed to sit upright against a back support with the unsupported shoulder resting by the side. After the primary investigator verbally specified the target for the trial (top, middle, or low targets that were fixed on the tripod), subjects first located the target visually for a second and then reached to the remembered 3-D location in a comfortable speed with the index fingertip with their eyes closed (Fig. 4). Subjects kept the index finger at the target locations for a second before returning to the starting position. After the subject viewed the instructed target, the investigator moved the tripod away during the subjects’ reaching movement to prevent any tactile feedback indicating the target location. Subjects performed the task one plane at a time with 8 trials for each target in each plane. The orders of planes and targets were randomly assigned to each subject. After finishing the reaching tests in all three planes, subjects reached to touch each target (with the tripod in place) for one second with vision allowed. Fingertip position from these trials were used as the reference location to compute reaching errors when compared to earlier reaching trials without vision.

**Data Analysis**

Skill Technology’s 6D Research software and the associated “Skill to Run” program computed positions and orientations of the minibird receivers and converted the data to a format that was further analyzed with DATAPAC 2K2 software (Run Technologies). The minibird system detects the position and orientation of a receiver in six degrees of freedom, three positions (x, y, z) and three Cardan angles (yaw, elevation, rotation) were computed. Before each test, the axes of the electromagnetic receivers
were aligned to the transmitter with the subjects sitting in an upright position with 90° of shoulder forward flexion, 90° of elbow flexion, and vertical forearm orientation. The positions and orientations of the receivers were computed relative to this aligned position.

Humerus orientation was computed relative to the trunk coordinate system, which was positioned parallel to the global coordinate system. In order to reduce humerus orientation measurement errors caused by the humerus receiver moving on the skin or the skin moving on the lateral epicondyle, shoulder rotation and abduction angles were computed by constructing a local humeral coordinate system (X’, Y’, Z’), followed by 3 ordered rotations about axes fixed to the humerus. Absolute position data from 3 non-linear points (the acromion, elbow, and wrist receivers) were used to construct a local coordinate system for the humerus (Fig. 5). The orientation of the humerus was calculated by relating the local coordinate system to the global system with a series of rotations in the order of Z’, X’, Y’ about the humerus axes. The local coordinate system of the humerus (X’, Y’, Z’) was constructed with the following steps:

Y’ axis: the unit vector \( \mathbf{U}_Y \) of the longitudinal axis of the humerus is defined by \( \mathbf{U}_Y = \mathbf{r}_{EA} / |\mathbf{r}_{EA}| \), where A represents the acromion receiver (located over the distal end of acromion of the scapula) and E represents the elbow receiver (located over the lateral epicondyle at the elbow joint). \( \mathbf{U}_{EA} \) corresponds to the new Y’ axis of the local coordinate system that projects in a vertical direction to the X-Y plane of the global coordinate system relative to the anatomical position. The first order of rotation (yaw) is about the Z’ axis with \( \theta_Y \) degrees (Fig. 6).

Z’ axis: the second unit vector \( \mathbf{U}_Z \) was calculated as the cross-product of two vectors, one representing the longitudinal axis of the humerus (\( \mathbf{U}_{EA} \)) and the other being the longitudinal axis of its distal segment (forearm): \( \mathbf{U}_Z = \mathbf{U}_{E/A} \times \mathbf{U}_{WE} \) (Fig. 5). W
represents the wrist receiver (located over the styloid process of the ulna) and $\hat{U}_{W/E} = r_{W/E} / | r_{W/E} |$. The new $Z'$ axis represents an axis that is perpendicular to the plane of forearm and humerus and projects in a medial-lateral direction to the Y-Z plane of the global coordinate system relative to the anatomical position. The second rotation (abduction) is about the X' axis with $\theta_{Z'}$ degrees (Fig. 7).

X’ axis: the third axis was calculated as the cross-product of the first two axes: $\hat{U}_{X'} = \hat{U}_{Z'} \times \hat{U}_{Y'}$ (Fig. 5). The new X’ axis is perpendicular to the Y’-Z’ plane of the humerus and projects in an anterior-posterior direction to the X-Z plane of the global coordinate system relative to the anatomical position. The third rotation (rotation) is about the Y’ axis with $\theta_{X'}$ degrees (Fig. 8).

Scapular orientation was provided by a single receiver that is located over the acromion of scapula and was computed relative to the trunk (manubrium) receiver about axes fixed within the scapula. Scapular rotations were represented with a Cardan angle rotation sequence about axes fixed to the scapula. The first order of rotation described the amount of medial-lateral rotation about the Z axis (vertical in the standard position), the second rotation described the amount of anterior-posterior tipping about the X (medial-lateral) axis, and the third rotation described the amount of upward/downward rotation about the Y (anterior-posterior) axis (Fig. 9). The scapular orientation definition of the present study differs from that defined by the International Society of Biomechanics (ISB) which uses 3-dimensional positions of 3 scapular bony landmarks (acromial angle, root of the scapula spine, inferior angle) to establish a local coordinate system for scapula (Wu et al. 2005).
For reproduction of shoulder angles with imposed motion testing, shoulder rotation angles obtained when subjects felt they had reached the remembered target (in the matching trial) were compared to the target rotation angles positioned earlier by the primary investigator (in the initial trial). For active abduction and rotation testing, the perceived shoulder angle by the subject (when they felt they had reached the target location) was compared to the specific target angle given to the subject at the beginning of each trial. In addition to the final shoulder abduction angles, scapular orientations were also recorded at the perceived target locations for future group comparison. For the reaching study, the fingertip endpoint locations of the blindfolded trials were compared with the reference trials with vision allowed (obtained at the end of the testing). In addition, shoulder rotation and scapular orientations at each end-point were collected for further analysis. Constant and variable errors were calculated from the eight repeated trials for each target angle for both the perceptual tasks (passive and active positioning) and the 3-D reaching task. The rms (root mean square) errors, which combined both the constant and variable errors, were computed to represent the overall positioning errors for group comparison.

**Dominant vs. Non-dominant Arms**

Because some of the subjects in unstable shoulder group had injured the shoulder of the non-dominant upper limb it was important to consider whether position sense differences between the dominant and non-dominant upper limb would affect between group comparisons of position sense. Previous studies have shown that shoulder position sense is of similar accuracy for the dominant and non-dominant arms of healthy subjects (Smith and Brunolli 1989; Lephart et al. 1994; Jerosch et al. 1996; Zuckerman et al.)
1999; Aydin et al. 2001). However, the majority of previous studies only examined mid-range of motion. Data from 9 healthy subjects in this study showed a small (less than 1.5° rms error) but significant difference between the two arms in the reproduction of shoulder angles during the imposed motion protocol ($F_{1,8}=9.52, P < .02$). In contrast, no significant differences were found in the active abduction ($F_{1,8}=1.62, P > .23$), active rotation ($F_{1,8}=1.87, P > .20$), and the 3-D reaching protocols ($F_{1,8}=0.14, P > .72$). In the experimental group (unstable shoulder subjects), 6 subjects injured their dominant arms and 4 subjects injured their non-dominant arms (Table 1). In order to reduce potential effect of innate proprioception differences between the two groups, dominant arm data of 9 healthy subjects and non-dominant arm data of 6 healthy subjects were randomly chosen to match the arm dominance ratio in unstable shoulders (dominant: non-dominant = 3:2) for all between group comparisons.

**Statistical Analysis**

Statistica software was used to analyze the data of the study. Two-way analysis of variance (ANOVA) with one between group factor (injured vs. intact shoulders) and one repeated measures factor (three target positions) was used to analyze the data for imposed motion and active abduction/rotation testing. Three-way ANOVA with one between group factor (injured vs. intact shoulders) and two repeated measure factors (three planes and three target positions) was used to analyze kinesthetically guided 3-D reaching. Tukey’s HSD test was used for post-hoc testing of significant main and interaction effects. Because there were 3 levels (3 targets) for the repeated measure factors, adjustments in degrees of freedom using Greenhouse-Geisser correction were applied. Significance level ($P$-values) was set at 0.05 for all comparisons.
Figure 1: Electromagnetic receiver placements for kinesthetically guided reaching and passive positioning. For active positioning testing, the humerus receiver was placed on a brace over the lateral epicondyle of the humerus.
Figure 2: Apparatus for reproduction of shoulder joint angles with imposed motion testing. The blindfolded subject rested his arm on the moving arm of the manipulandum, which was moved by the experimenter to the target angle (in this case, 45° of external rotation)
Figure 3: Active positioning testing. The blindfolded subject actively moved his unsupported arm to the target angle, in this case 45° of external rotation, with 90° of abduction.
Figure 4: Apparatus for kinesthetically guided reaching. Subjects first located the target visually and then reached to the remembered location with their index fingertip without vision. The target for the trial shown here is the middle target (same height as the subject’s GHJ) in the oblique plane (OP). The three planes are the para-sagittal plane (SP) through the GHJ of the moving limb (in red), the frontal plane (FP) through the GHJ of the moving limb (in yellow), and a vertically oriented oblique plane (OP) through the subject’s GHJ that equally bisected the previous two planes (in green).
Figure 5: Global (X, Y, Z) and local (X', Y', Z') coordinate system of the humerus. A, E, and W represent the acromion receiver (located over the distal end of acromion of the scapula), the elbow/humerus receiver (located over the lateral epicondyle at the elbow joint), and the wrist receiver (located over the styloid process of the ulna) respectively. The local humeral axes are defined as described on the right side of the figure.
Figure 6: First order of rotation (about the Z' axis) for the humerus. (a) calculation of angle \( \theta_{Y'} \) in the X-Y plane. (b) local X', Y', Z' coordinate system of humerus before the rotation. (c) local X', Y', Z' coordinate system of humerus after the rotation.
Figure 7: Second order of rotation (about the X’ axis) for the humerus. (a) calculation of angle $\theta_{Z'}$ in the Y-Z plane. (b) local X’, Y’, Z’ coordinate system of humerus before the rotation. (c) local X’, Y’, Z’ coordinate system of humerus after the rotation.
Figure 8: Third order of rotation (about the Y’ axis) for the humerus. (a) calculation of angle $\theta_{X'}$ in the X-Z plane. (b) local X’, Y’, Z’ coordinate system of humerus before the rotation. (c) local X’, Y’, Z’ coordinate system of humerus after the rotation.
Figure 9: Scapular orientation about the M-L axis (anterior/posterior tipping), A-P axis (upward/downward rotation), and vertical axis (medial/lateral rotation).
CHAPTER IV: RESULTS

Reproduction of Shoulder Rotation Angles with Imposed Motion

For the 20 subjects (13 intact and 7 unstable shoulder subjects) who participated in the imposed motion protocol, unstable shoulder subjects exhibited significantly larger overall positioning errors (rms errors) than healthy controls in passive reproduction of shoulder rotation angles ($F_{1,18}=4.64, P < .05$, Fig. 7). Target location (shoulder rotation angle) affected the repositioning accuracy and the group difference depended on test angles as there were significant angle ($F_{2,36}=22.17, P < .01$) and group x angle interaction effects ($F_{2,36}=8.85, P < .01$). Post-hoc tests (Tukey’ HSD) showed subjects of both groups had greater difficulty matching the target angle near 45° of internal rotation than the other two angles (45° and 75° of external rotations). At 45° of internal rotation, rms errors for unstable shoulder subjects (ranging from 6.1° to 18.9°) were significantly larger than intact shoulder subjects (ranging from 3.1° to 11.3°). At 45° and 90° of external rotation, rms errors for unstable shoulder subjects (ranging from 4.9° to 7.7° and 2.2° to 6.9° respectively) were not different from intact shoulder subjects (ranging from 2.9° to 9.7° and 2.0° to 7.7° respectively). Despite the significant group effect, it is important to note that the overall group difference is relatively small (1.8°) and unstable shoulders only showed significantly larger errors than controls near 45° of internal rotation (group difference of 4.7°) but not at the other two angles (Fig. 10).

Additional analyses showed unstable shoulder subjects only exhibited slightly larger constant and variable errors than healthy controls and the group differences were not significant ($F_{1,18}=2.84, P > .10$ for constant errors, Fig. 11; $F_{1,18}=2.04, P > .17$ for
variable errors, Fig. 12). Results of constant error analysis showed intact and unstable shoulder subjects slightly undershot the 45° ER (by an average of 3.9°) and 75° ER (by 3.7°) targets with less shoulder external rotation but greatly overshot the 45° IR target (by 7.4°) with larger shoulder external rotation (Fig. 11). As observed in rms error analysis, target location affected both constant and variable errors and the group difference depended on the target angle as there were significant angle \((F_{2,36} = 92.51, P < .01\) for constant errors and \(F_{2,36} = 9.20, P < .01\) for variable errors\) and group x angle interaction effects \((F_{2,36} = 5.21, P < .02\) and \(F_{2,36} = 3.61, P < .04\) for variable errors). Post-hoc tests showed subjects of both groups exhibited larger constant and variable errors near 45° of internal rotation than near 45° and 75° of external rotations. Furthermore, unstable shoulders had larger constant and variable errors than controls near 45° of internal rotation but not at the other two external rotation angles (Fig. 11, 12).

**Active Positioning (AP): Shoulder Abduction**

For the 25 subjects (15 intact and 10 unstable shoulder subjects) who participated in active positioning, unstable shoulder subjects actively moved the free arm to three different verbally instructed abduction angles as accurately as healthy controls \((F_{1,23} = 0.69, P > .41\), Fig. 13). At 45°, 90°, and 135° of shoulder abduction, rms errors for unstable shoulder subjects (ranging from 4.6° to 28.4°, 3.2° to 15.7°, and 2.1° to 20.2° respectively) were not different from intact shoulder subjects (ranging from 3.2° to 24.9°, 3.8° to 17.4°, and 4.0° to 27.9° respectively). However, target shoulder abduction angle had a significant impact on shoulder positioning accuracy \((F_{2,46} = 11.41, P < .01\), which was similar for both groups as there was no significant angle x group interaction effect \((F_{2,46} = 0.49, P > .56\). Post–hoc comparison showed subjects made significantly greater
errors when moving their shoulders to 45° ($P < .01$) and 135° ($P < .04$) of abduction than to 90° of abduction (Fig. 13).

Analysis of constant and variable errors also showed that unstable shoulder subjects moved their free arm to the instructed abduction angles as accurately as healthy subjects ($F_{1,23}=0.74, P > .39$, Fig. 14 for constant errors; $F_{1,23}=1.11, P > .30$, Fig. 15 for variable errors). Results of constant error analysis showed intact and unstable shoulder subjects overshot the 45° and 90° abduction targets by an average of 16.4° and 6.6° respectively, but undershot the 135° abduction target by 12.3° (Fig. 14). Moreover, subjects performed differently at different target angles in both constant ($F_{2,46}=86.01, P < .01$) and variable errors ($F_{2,46}=11.35, P < .01$) with the smallest errors observed at 90° of abduction for constant errors but at 135° of abduction for variable errors. The angle effect was similar for both groups as there was no significant angle x group interaction effect for both constant ($P > .66$) and variable errors ($P > .77$).

Scapular orientations associated with shoulder abduction were similar in healthy subjects and those with unstable shoulders (Fig. 16). Scapular upward rotation about an A-P axis ($F_{1,23}=0.33, P > .56$), lateral rotation about a vertical axis ($F_{1,23}=0.22, P > .64$), and posterior tipping about a M-L axis ($F_{1,23}=0.26, P > .62$) were similar between the two groups of subjects when comparing the changes in scapula position relative to the trunk during two phases of shoulder abduction: 45° to 90° and 90° to 135° of abduction (Fig. 16). There was no significant phase effect or group x phase interaction effect for scapular lateral rotation ($F_{1,23}=0.26, P > .61$ and $F_{1,23}=1.45, P > .24$ respectively) and posterior tipping ($F_{1,23}=0.52, P > .47$ and $F_{1,23}=0.22, P > .64$ respectively). However, subjects of both groups exhibited larger scapular upward rotation angle from 90° to 135° than from
45° to 90° of abduction with an average difference of 4.8° ($F_{1,23}=7.99, P < .01$). There was no significant group x phase interaction effect for scapular upward rotation ($F_{1,23}=0.37, P > .55$).

**Active Positioning (AP): Shoulder Rotation**

Unstable shoulder subjects internally/externally rotated the humerus to the three verbally instructed target locations as accurately as healthy controls ($F_{1,23}=1.16, P > .29$, Fig. 17). At 45° of internal rotation and 45° and 90° of external rotation, rms errors for unstable shoulder subjects (ranging from 3.0° to 12.4°, 4.3° to 9.6°, and 4.3° to 17.4° respectively) were not different from intact shoulder subjects (ranging from 2.9° to 31.3°, 3.8° to 14.7°, and 2.8° to 17.5° respectively). Target shoulder rotation angles did not affect positioning accuracy ($F_{2,46}=2.50, P > .10$), and both groups of subjects responded similarly to the three target angles as there was no significant group x angle interaction ($F_{2,46}=2.66, P > .09$). However, it is worth noting that subjects of both groups exhibited the smallest position errors at 45° of external rotation where shoulder stabilizers were not greatly stretched. Furthermore, subjects with unstable shoulders only showed larger rms errors than healthy controls near the end-range of shoulder rotation (90° of external rotation), with smaller errors near the other two rotation angles.

Further analyses of constant and variable errors during active shoulder rotation also showed that unstable shoulder subjects performed as accurate and consistent as intact shoulder subjects ($F_{1,23}=0.45, P > .50$, Fig. 18 for constant error; $F_{1,23}=0.39, P > .55$, Fig. 19 for variable error). Results of constant error analysis showed intact and unstable shoulder subjects overshot the 45° IR target and the 45° ER target by an average of 5.8° and 1.1° respectively, but undershot the 90° ER target by an average of 6.6° (Fig. 18).
Target shoulder rotation angles had an impact on both groups as a significant angle effect was found in both constant ($F_{2,46}=14.84, P < .01$) and variable error ($F_{2,46}=3.65, P < .04$) analyses. Post-hoc tests showed subjects made significantly larger constant errors at $90^\circ$ than at $45^\circ$ of external rotation ($P < .01$, Fig. 18), but smaller variable errors ($P < .02$, Fig. 19) at $90^\circ$ than at $45^\circ$ of external rotation.

**Kinesthetically Guided Reaching Accuracy**

For the overall rms error in all three dimensions (3-D), unstable shoulder subjects reached to all targets as accurately as healthy controls (11.6 cm vs. 10.6 cm) ($F_{1,23}=1.03, P > .32$; Fig. 20). However, there was a significant plane effect ($F_{2,46}=26.32, P < .01$), and the two groups of subjects performed differently in different planes as there was also a significant group x plane interaction effect ($F_{2,46}=4.08, P < .03$). Follow up tests (Tukey’ HSD) showed that all subjects exhibited the smallest reaching errors in the sagittal plane (average: 8.6 cm) and the largest errors in the frontal plane (average: 13.4 cm). In the sagittal plane, rms errors for unstable shoulder subjects (ranging from 4.4 cm to 15.6 cm for the top target, 5.6 cm to 15.3 cm for the middle target, and 5.6 cm to 10.0 cm for the low target) were similar to intact shoulder subjects (ranging from 3.9 cm to 13.6 cm for the top target, 5.8 cm to 14.0 cm for the middle target, and 3.1 cm to 8.9 cm for the low target). In the oblique plane, rms errors for unstable shoulder subjects (ranging from 5.3 cm to 18.4 cm for the top target, 7.6 cm to 16.4 cm for the middle target, and 7.1 cm to 14.8 cm for the low target) were also similar to intact shoulder subjects (ranging from 5.2 cm to 22.1 cm for the top target, 5.4 cm to 23.6 cm for the middle target, and 4.6 cm to 19.3 cm for the low target). However, in the frontal plane, rms errors for unstable shoulder subjects (ranging from 8.4 cm to 21.9 cm for the top
target, 9.3 cm to 21.0 cm for the middle target, and 8.2 cm to 35.7 cm for the low target) were consistently larger than intact shoulder subjects (ranging from 5.3 cm to 17.6 cm for the top target, 8.1 cm to 21.1 cm for the middle target, and 5.2 cm to 17.9 cm for the low target). Finally, a significant target height effect ($F_{2,46}=11.01, P < .01$) was also found. Post–hoc comparison showed reaching accuracy to the low target (with 9.7 cm rms errors) is better than to the middle (with 12.2 cm rms errors; $P < .01$) and the top targets (with 11.4 cm rms errors; $P < .01$). The 3-way interaction effect was not significant for the testing ($F_{4,92}=0.69, P > .48$).

Reaching rms errors were further analyzed in three separate dimensions: medial-lateral (M-L), anterior-posterior (A-P), and vertical. Consistent with the 3-D combined analysis, subjects with unstable shoulders performed as well as healthy controls in the A-P dimension ($F_{1,23}=0.00, P > .99$, Fig. 21), M-L dimension ($F_{1,23}=1.75, P > .19$, Fig. 22), and the vertical dimension ($F_{1,23}=1.31, P > .26$, Fig. 23). Furthermore, performance between the two groups was similar in different planes and at different target heights because no significant interaction was found between the group and other main effects in all three dimensions.

Further analyses on constant error in three separate dimensions also shown that subjects with unstable shoulders performed as well as healthy controls in the A-P dimension ($F_{1,23}=0.00, P > .96$, Fig. 24), M-L dimension ($F_{1,23}=1.25, P > .27$, Fig. 25), and the vertical dimension ($F_{1,23}=0.36, P > .55$, Fig. 26). In the A-P dimension, both groups of subjects over-reached in all target positions with intact shoulder subjects exhibited larger errors to targets located in the sagittal plane and unstable shoulder subjects exhibited larger errors to targets located in the frontal plane (Fig. 24). In the M-
L dimension, unstable shoulder subjects undershot the targets during most of the trials (except for low target in the frontal plane) while intact shoulder subjects exhibited lower constant errors overall (Fig. 25). In the vertical dimension, both intact and unstable shoulder subjects generally undershot the target location with larger constant errors occurred while reaching to the top and middle targets and to the frontal plane (Fig. 26). Moreover, analyses on variable error in three separate dimensions also shown that subjects with unstable shoulders performed as well as healthy controls in the A-P dimension ($F_{1,23}=0.86, P > .36$), M-L dimension ($F_{1,23}=3.55, P > .07$), and the vertical dimension ($F_{1,23}=2.3, P > .14$). Although variable errors between the two groups in the M-L dimension is approaching a significant level, unstable shoulder subjects consistently exhibited larger variable errors than intact shoulder subjects with an average error of only 0.55 cm.

Shoulder Rotation in Kinesthetically Guided Reaching

Subjects with unstable shoulders exhibited significantly less external rotation when compared with stable shoulders during kinesthetically guided reaching (average: 47.6° vs. 59.2°; $F_{1,23}=7.54, P < .02$, Fig. 27). In the sagittal plane, shoulder rotation angle for unstable shoulder subjects ranged from 46.0° ER to 74.7° ER for the top target, 39.0° ER to 56.4° ER for the middle target, and 1.3° IR to 47.2° ER for the low target with shoulder rotation angle for intact shoulder subjects ranged from 53.8° ER to 81.6° ER for the top target, 35.3° ER to 78.1° ER for the middle target, and 13.6° ER to 63.6° ER for the low target. In the oblique plane, shoulder rotation angle for unstable shoulder subjects ranged from 53.5° ER to 76.1° ER for the top target, 43.6° ER to 72.0° ER for the middle target, and 6.4° IR to 62.3° ER for the low target with shoulder rotation angle
for intact shoulder subjects ranged from 59.5° ER to 85.4° ER for the top target, 46.5° ER to 82.5° ER for the middle target, and 0.0° ER to 74.1° ER for the low target. In the frontal plane, shoulder rotation angle for unstable shoulder subjects ranged from 51.2° ER to 83.6° ER for the top target, 33.1° ER to 81.7° ER for the middle target, and 3.8° IR to 59.2° ER for the low target with shoulder rotation angle for intact shoulder subjects ranged from 68.6° ER to 99.4° ER for the top target, 36.6° ER to 85.6° ER for the middle target, and 19.8° IR to 67.7° ER for the low target. Although target location had a significant impact on shoulder rotation angles used in this reaching task ($P < .01$ for both the plane and height effect), group differences did not depend on target locations as there were no significant group x plane ($F_{2,46}=0.23, P > .72$), group x height ($F_{2,46}=0.82, P > .38$), and group x plane x height ($F_{4,92}=0.25, P > .10$) interaction effects. Post-hoc tests showed both groups had the largest shoulder rotation angles while reaching to the targets in the frontal plane and the smallest rotation angles to the targets in the sagittal plane (average: 56.6° and 49.6° respectively). Subjects also used the largest rotation angles to the highest targets and the smallest rotation angles to the lowest targets (average: 69.2° and 32.7° respectively).

To examine whether shoulder instability had an impact on the consistency of shoulder rotation angles at various target locations, the standard deviation (SD) across the eight trials to each target were compared between the two groups. Results showed that subjects with unstable shoulders actively rotated the shoulders to each of the different targets as consistently as healthy controls ($F_{1,23}=2.74, P > .11$, Fig. 28). In addition, both plane ($F_{2,46}=22.69, P < .01$) and height ($F_{2,46}=46.40, P < .01$) factors had significant effects on rotation consistency but the impact was similar on both groups as there were
no significant group x plane \((F_{2,46}=0.06, P > .92)\), group x height \((F_{2,46}=0.01, P > .98)\), and group x plane x height \((F_{4,92}=0.25, P > .85)\) interaction effects. Post-hoc test showed that shoulder rotation angles to targets in the frontal plane were less consistent (i.e., higher trial-to-trial SDs for each target) than to the oblique \((P < .01)\) and sagittal planes \((P < .01)\). Finally, the SD of the shoulder rotation angles at different target heights was significantly differed \((P < .01)\), with the largest SD to the lowest targets and the smallest SD to the highest targets.

**Scapula Orientation in Kinesthetically Guided Reaching**

Unstable and intact shoulder subjects exhibited similar scapular orientation changes in upward-downward rotation \((F_{1,23}=0.62, P > .43)\), anterior-posterior tipping \((F_{1,23}=0.60, P > .44)\), and medial-lateral rotation \((F_{1,23}=3.87, P > .06)\) during kinesthetically guided reaching when comparing the changes in scapula position during the two phases: from middle to top targets and from low to middle targets (Fig. 29, 30, 31). Unstable and intact shoulder subjects exhibited very similar scapular orientation changes (less than 2°) during the reaching task except for scapular upward rotation in the frontal plane from the low to middle targets with about a 2.5° difference (Fig. 29). Although there was a trend for larger scapula lateral rotation in intact shoulders subjects than unstable shoulder subjects \((P > .06)\), the mean difference between the two groups was only 0.47° (Fig. 31). Scapula orientation similarities between intact and unstable shoulder subjects were consistent as there were no significant group x plane \((F_{2,46}=1.92, P > .16)\) for upward rotation, \(F_{2,46}=0.69, P > .48\) for tipping; \(F_{2,46}=0.02, P > .96\) for M-L rotation), group x phase \((F_{1,23}=0.08, P > .77\) for upward rotation; \(F_{1,23}=0.29, P > .59\) for tipping; \(F_{1,23}=0.09, P > .76\) for M-L rotation), and group x plane x phase interaction
(\(F_{2,46}=0.85, P > .43\) for upward rotation; \(F_{2,46}=0.14, P > .84\) for tipping; \(F_{2,46}=0.04, P > .93\) for M-L rotation) effects.

**Dominant vs. Non-dominant Arms**

Position sense and reaching accuracy differences between dominant and non-dominant arms were consistent with the pilot data. For intact shoulder subjects, non-dominant arms exhibited slightly larger rms errors than dominant arms with the imposed motion protocol (1.7° difference, \(P = .05\)) but with similar errors in active abduction (\(P > .45\)), active rotation (\(P > .85\)), and kinesthetically guided reaching (\(P > .13\)). For unstable shoulder subjects, injured dominant and non-dominant arms exhibited similar rms errors with the imposed motion (\(P > .09\)), active abduction (\(P > .09\)), active rotation (\(P > .65\)), and kinesthetically guided reaching protocols (\(P > .90\)). Thus, balancing the proportion of dominant and non-dominant arms in the two groups was appropriate.
Figure 10: Mean rms errors of healthy controls and subjects with unstable shoulders at three different shoulder rotation angles in the reproduction of shoulder rotation angles with imposed motion protocol. Error bars denote 1 SD.
Figure 11: Mean constant errors of healthy controls and subjects with unstable shoulders at three different shoulder rotation angles in the reproduction of shoulder rotation angles with imposed motion protocol. Error bars denote 1 SD.
Figure 12: Mean variable errors of healthy controls and subjects with unstable shoulders at three different shoulder rotation angles in the reproduction of shoulder rotation angles with imposed motion protocol. Error bars denote 1 SD.
Figure 13: Mean rms errors of healthy controls and subjects with unstable shoulders at three different shoulder abduction angles under the active movement paradigm. Error bars denote 1 SD.
Figure 14: Mean constant errors of healthy controls and subjects with unstable shoulders at three different shoulder abduction angles under the active movement paradigm. Error bars denote 1 SD.
Figure 15: Mean variable errors of healthy controls and subjects with unstable shoulders at three different shoulder abduction angles under the active movement paradigm. Error bars denote 1 SD.
Figure 16: Mean scapula orientation changes of healthy controls and subjects with unstable shoulders between the two phases (from 45° to 90° and from 90° to 135° of abduction) under the active abduction paradigm. Error bars denote 1 SD.
Figure 17: Mean rms errors of healthy controls and subjects with unstable shoulders at three different shoulder rotation angles under the active movement paradigm. Error bars denote 1 SD.
Figure 18: Mean constant errors of healthy controls and subjects with unstable shoulders at three different shoulder rotation angles under the active movement paradigm. Error bars denote 1 SD.
Figure 19: Mean variable errors of healthy controls and subjects with unstable shoulders at three different shoulder rotation angles under the active movement paradigm. Error bars denote 1 SD.
Figure 20: Mean three dimensional rms errors of intact and unstable shoulder subjects while reaching to targets at three different heights (top, mid, low) in 3 different planes (sagittal, oblique, frontal). Error bars denote 1 SD.
Figure 21: Mean rms errors in the anterior-posterior dimension of intact and unstable shoulder subjects while reaching to targets at three different heights (top, mid, low) in 3 different planes (sagittal, oblique, frontal). Error bars denote 1 SD.
Figure 22: Mean rms errors in the medial-lateral dimension of intact and unstable shoulder subjects while reaching to targets at three different heights (top, mid, low) in 3 different planes (sagittal, oblique, frontal). Error bars denote 1 SD.
Figure 23: Mean rms errors about in the vertical dimension of intact and unstable shoulder subjects while reaching to targets at three different heights (top, mid, low) in 3 different planes (sagittal, oblique, frontal). Error bars denote 1 SD.
Figure 24: Mean constant errors in the anterior-posterior dimension of intact and unstable shoulder subjects while reaching to targets at three different heights (top, mid, low) in 3 different planes (sagittal, oblique, frontal). Error bars denote 1 SD.
Figure 25: Mean constant errors in the medial-lateral dimension of intact and unstable shoulder subjects while reaching to targets at three different heights (top, mid, low) in 3 different planes (sagittal, oblique, frontal). Error bars denote 1 SD.
Figure 26: Mean constant errors in the vertical dimension of intact and unstable shoulder subjects while reaching to targets at three different heights (top, mid, low) in 3 different planes (sagittal, oblique, frontal). Error bars denote 1 SD.
Figure 27: Mean shoulder rotation angle of healthy controls and unstable shoulders while reaching to targets at three different heights (top, mid, low) in 3 different planes (sagittal, oblique, frontal). Error bars denote 1 SD.
Figure 28: Mean of SD of shoulder rotation angle of healthy controls and unstable shoulders while reaching to targets at three different heights (top, mid, low) in 3 different planes (sagittal, oblique, frontal). Error bars denote 1 SD.
Figure 29: Mean scapula upward rotation changes of healthy controls and subjects with unstable shoulders between the two phases (from middle to top targets and from low to middle targets) under the 3-D reaching paradigm. Error bars denote 1 SD.
Figure 30: Mean scapula tipping changes of healthy controls and subjects with unstable shoulders between the two phases (from middle to top targets and from low to middle targets) under the 3-D reaching paradigm. Error bars denote 1 SD.
Figure 31: Mean scapula M-L rotation changes of healthy controls and subjects with unstable shoulders between the two phases (from middle to top targets and from low to middle targets) under the 3-D reaching paradigm. Error bars denote 1 SD.
CHAPTER V: DISCUSSION

Introduction

The primary purpose of this investigation was to determine whether individuals with an unstable shoulder due to a history of anterior shoulder dislocation exhibit position sense and 3-D reaching accuracy deficits when compared with subjects with intact, stable shoulders. The majority of previous studies that examined unstable shoulders applied reproduction of remembered shoulder rotation angles during imposed motion of the arm with the instruction to relax upper limb muscles and focused on the mid-range of external rotation (Lephart et al. 1994; Zuckerman et al. 2003). This study adopted a similar passive testing protocol to examine shoulder position sense at both the mid-range and end-range of shoulder external rotation. A novel testing protocol (active abduction and rotation) that involved active shoulder muscle contraction to position the arm was implemented to examine shoulder position sense. Furthermore, kinesthetically guided reaching accuracy (with unrestrained shoulder, elbow, wrist, and finger motion) to visually specified targets in space was also studied. Results of this study show that unstable shoulder subjects can perceive shoulder angles and reach to visually specified targets in space as accurately as healthy controls in functional activities with voluntarily arm movements. It suggests that less sensitive joint receptors due to over-stretched shoulder capsule/ligaments following shoulder injury have little impact on the neuromuscular control of the shoulder joint.
Reproduction of Shoulder Rotation Angles with Imposed Motion

Subjects with a history of anterior shoulder dislocation exhibited position sense deficits when examined with a technique involving reproduction of remembered shoulder rotation angles with imposed motion and the instruction to relax upper limb muscles. They showed significantly larger rms (total) errors in perception of shoulder joint angles than subjects with intact/stable shoulders. This is consistent with previous findings that unstable shoulders exhibited position sense deficits with this type of protocol (Smith and Brunolli 1989; Lephart et al. 1994; Zuckerman et al. 2003). After an incident of anterior shoulder dislocation, over-stretched passive stabilizers (e.g., the middle/inferior glenohumeral ligaments and shoulder capsule) may not be able to properly maintain the humeral head within the glenoid fossa (Turkel et al. 1981; Itoi et al. 1996; Brenneke et al. 2000; von Eisenhart-Rothe et al. 2002).

Compromised joint and muscle receptors may contribute to the position sense deficits observed in unstable shoulder subjects with this imposed motion protocol. Because activation of joint receptors is triggered by the deformation and changing of tension of the structures that stabilize the joint, over-stretched or lax anterior and inferior shoulder capsule/ligaments may contribute to the observed position sense deficits (Smith and Brunolli 1989; Lephart et al. 1994, 1997; Zuckerman et al. 2003). More importantly, compromised muscle receptors of shoulder girdle muscles may also contribute to the deficits (Smith and Brunolli 1989; Forwell and Carnahan 1996). Because subjects were instructed to relax the arm, during reproduction of shoulder rotation angles with imposed motion testing, muscle spindles will not be as sensitive as during voluntary movements.
when muscle activity, and activation of fusimotor neurons, is greater. In other words, subjects were not able to receive comprehensive joint information from muscle receptors as in most (if not all) of the daily activities. Another possible explanation is that muscle receptors of shoulder girdle muscles may not be able to provide accurate shoulder position sense without a stable humeral head position. Because shoulder girdle muscles such as the external rotators (e.g., supraspinatus and infraspinatus) and internal rotators (e.g., subscapularis) insert into the humeral head, altered humeral head location due to instability may change the length of shoulder rotators and therefore the perceived shoulder rotation angles (von Eisenhart-Rothe et al. 2002). It has been suggested that damage of both joint and muscle receptors contribute to the observed position sense deficits in unstable shoulders (Smith and Brunolli, 1989; Lephart et al. 1994; Zuckerman et al. 2003). However, the contribution of joint receptors to position sense is probably not as prominent as muscle receptors (McCloskey 1978; Gandevia et al. 1983; Clark et al. 1979, 1985, 1986, 1989; Matthews 1988; Zuckerman et al. 1999).

Both intact and unstable shoulder subjects exhibited better position sense (smaller errors) with increased shoulder external rotation angle in the imposed motion testing protocol (Fig. 10). For subjects with intact shoulders, this is consistent with the previous finding of Smith and Brunolli (1989) who reported slightly better repositioning accuracy at the end-range than at the mid-range of shoulder external rotation, probably due to greater stretch of both joint and muscle receptors. However, the results of unstable shoulder subjects contradict the findings of Smith and Brunolli (1989) who reported larger matching errors at the end-range than at the mid-range of shoulder external rotation. It has been suggested that joint receptors are sensitive to stretch and mainly
contribute near the limits of a joint’s range of motion (Clark and Burgess 1975; Grigg and Hoffman 1982; Grigg 1994; Borsa et al. 1994; Clark et al. 1985, 1986, 1989). Thus, it is surprising that the unstable shoulder subjects could accurately reproduce external rotation angles near the limit of external rotation with overstretched anterior shoulder stabilizers. For the current study, better position sense near the end range of shoulder external rotation may be due to greater stimulation (stretching the anterior shoulder capsule/ligaments and shoulder internal rotators) to both joint and muscle receptors. Moreover, it is possible that unstable shoulder subjects may engage greater shoulder muscle activations due to apprehension of moving towards a vulnerable position such as 75° of external rotation. Greater shoulder muscle activation, especially rotator cuff muscles, can reduce abnormal anterior displacement of the humeral head due to anterior shoulder laxity. Moreover, spindles of these muscles, especially the internal rotators which are stretched during external rotation, may become more sensitive to muscle length changes due to co-activation of α, γ, and β motor neurons near the end-range of shoulder external rotation.

Another unexpected finding of the imposed motion testing is that unstable shoulder subjects exhibited significantly larger errors (rms, constant, and variable errors) than healthy controls only near 45° of internal rotation, not at the two external rotation angles (Fig. 10, 11, 12). Because muscle receptors are the main contributor to position sense in intermediate positions, alterations in fusimotor activation in unstable shoulder subjects likely contributed to the larger errors observed near 45° of internal rotation (Smith and Brunolli 1989; Zuckerman et al. 2003). As previously described, muscle receptors of shoulder girdle muscles may be less capable of providing accurate position
sense without a stable humeral head position in subjects with unstable shoulders. Without additional position sense information from joint receptors (due to stretching) and more sensitive muscle spindles (due to apprehension and activation of muscles and of the fusimotor system to increase spindle sensitivity) near the end-range of rotation, compromised muscle receptors may be less capable of providing accurate position sense near 45° of internal rotation in a relaxed condition. Moreover, the group difference at 45° of internal rotation of the present study (4.7°) is much larger than the differences reported in other studies that examined the intermediate range of shoulder external/internal rotation (ranging from 0.6° to 2.3°) (Smith and Brunolli, 1989; Lephart et al. 1994; Zuckerman et al. 2003). One possible explanation for the smaller group difference in earlier position sense studies is that the initial trial and the following matching trial often had the same starting position, range of motion, and the same machine controlled movement speed (except for Lephart et al. who varied the speed between the two trials). Therefore, subjects in earlier studies might use the amplitude and/or time to reach the target as additional cues for shoulder perception. Use of imposed motion amplitude/time, in addition to perceived joint angle indicated by proprioceptors, to assist reproduction of target shoulder angles likely causes the lower errors observed previously. 

The magnitude (1.8° overall group difference) and nature (most prominent near 45° of internal rotation) of the position sense deficits observed in unstable shoulders may not have a significant impact on a subject’s daily activities at a functional level. Despite the significant overall group effect in rms errors, it is important to note that the group difference was small in 2 of the 3 target angles (0.3° difference at 75° ER and 0.9° difference at 45° ER) and in previous studies (1.3° to 2.0° for Smith and Brunolli, 0.6° to
1.5° for Lephart et al., and 2.3° for Zuckerman et al.). Although unstable shoulder subjects exhibited significantly larger matching errors (4.7°) than healthy controls near 45° IR, this target shoulder angle is not considered a vulnerable/unstable position for individuals with anterior shoulder instability. Considering that the GHJ joint is most vulnerable near the end-range of external rotation for subjects with anterior instability, results of this investigation show that unstable shoulder subjects have precise position sense at the perceptual level (of similar accuracy to subjects with stable shoulders) at those vulnerable positions at which anterior dislocations often occur. These data seem to contradict the general belief that altered neuromuscular control due to position sense deficits in unstable shoulders is one of the main contributors to the high recurrence rate of anterior dislocation in unstable shoulders.

**Active Positioning-Abduction and Rotation**

Subjects with unstable shoulders did not exhibit position sense deficits when they actively moved the arm to verbally defined shoulder angles. For abduction testing, unstable shoulder subjects actively moved the examined shoulder to the three instructed abduction angles (45°, 90°, and 135°) as accurately as healthy controls with a group difference of 0.85° in rms errors (Fig. 13). No comparative study had examined shoulder position sense with the same testing protocol. However, results of this study are consistent with studies that required subjects to “actively” move their shoulders to match a remembered target (Forwell and Carnahan 1996; Pötzl et al. 2004), although without requiring memory of a target in the present work. For rotation testing, unstable shoulder subjects also moved to the three targets (45° IR, 45°ER, and 90°ER) as accurately as healthy controls with a group difference of 0.99° in rms errors (Fig. 17). These findings
agree with the hypothesis of this investigation that subjects with a history of anterior shoulder dislocation would not exhibit position sense deficits when examined with an active testing protocol that better resembles functional activities than passive testing techniques. With accurate awareness of shoulder orientation, unstable shoulder subjects may be able to position the shoulder to a desired location for daily activities, as well as exert proper shoulder muscle activation to stabilize the GHJ when moving towards vulnerable positions.

Increased firing rate of muscle spindle afferents during active positioning testing may provide accurate position sense for individuals with anterior shoulder instability. When subjects actively moved the unsupported arm to various target positions, muscle spindles of shoulder girdle muscles may become more sensitive to muscle length changes due to co-activation of \( \alpha, \gamma, \) and \( \beta \) motor neurons (McCloskey 1978; Gandevia et al. 1992; Kandel et al. 2000). Previous studies have shown that subjects greatly improved their movement detection capability (Goodwin et al. 1972; Gandevia et al. 1976, 1992) and shoulder angle matching accuracy (Lönn et al. 2000) with increased voluntary muscle contraction but experienced poor upper-limb position sense in a microgravity environment when muscle activation is minimal (von Beckh 1954; Gerathewohl et al. 1957; Fisk et al. 1993; Young et al. 1993). Moreover, Hulliger and Vallbo (1979) and Edin and Vallbo (1990) reported increased discharge of muscle spindle afferents with increased voluntary muscle activation. These studies suggest that position sense could be enhanced with voluntary muscle contraction, which may explain why unstable shoulder subjects performed as well as intact shoulder subjects with the active testing protocol.
Another potential mechanism underlying the absence of position sense difference between unstable and intact shoulders is that shoulder girdle muscle lengths would be less altered for unstable shoulders during active positioning than during passive positioning. For subjects with anterior shoulder instability, compromised passive stabilizers (such as over-stretched anterior shoulder capsule and ligaments) may not be able to provide sufficient mechanical restraints for the humeral head (Turkel et al. 1981; Itoi et al. 1996; Brenneke et al. 2000; von Eisenhart-Rothe et al. 2002). As a result, greater than normal anterior-inferior translation of the humeral head was observed in subjects with anterior instability during passive positioning (Hawkins et al. 1996; von Eisenhart-Rothe et al. 2002). Because muscle spindles are sensitive to muscle length changes, altered muscle length likely impacts firing rate of muscle spindle afferents and, thus, perceived shoulder angles. However, this study hypothesized better shoulder position sense with the active positioning protocol because active shoulder muscle contraction may reduce the displacement of the humeral head. Researchers have found that anterior translation of the humeral head was reduced such that it was in a more centered/normal location within the glenoid fossa with active shoulder abduction and rotation (Wuelker et al. 1998; Graichen et al. 2000; Hsu et al. 2000; Lee et al. 2000; von Eisenhart-Rothe et al. 2002; Kido et al. 2003). Thus, muscle receptors may provide better position sense concerning muscle length and joint angles during shoulder muscle contraction, which may partially explain the lack of position sense deficit in unstable shoulders with the active positioning protocol.

The accuracy of perception of shoulder abduction angles depended strongly on the shoulder abduction angle. Results show that both groups of subjects exhibited the
largest errors at 45° of abduction and the smallest errors at 90° of abduction (Fig. 13).
Although no study previously examined shoulder position sense with the same active
positioning protocol (with no position matching involved), other studies had found better
position sense when shoulder flexion/abduction angles approached 90° (Forwell and
Carnahan 1996; Jerosch et al. 1996). One explanation for the more accurate position
sense near 90° of abduction is that upper limb generates the largest gravitational torque at
90° and therefore requires greater muscle force from shoulder abductors to achieve the
position. As discussed earlier, better sensation of joint angles (due to more sensitive
muscle spindles) as well as a better stabilized humeral head (especially for unstable
shoulders) may contribute to the observed superior position sense at 90° due to the
necessary stronger muscle contractions. Moreover, less shoulder position error at 90° of
abduction may be also due to that individuals are more capable of aligning the upper limb
to earth fixed horizontal than other orientations. On the other hand, both groups of
subjects had the largest position errors at 45° of abduction where less abduction force is
needed and both active and passive shoulder stabilizers are least stretched. Thus, both
muscle receptors and joint receptors may be less sensitive in providing shoulder position
sense near 45° of abduction.

The accuracy of the perception of shoulder rotation angles did not depend on the
rotation angle (Fig. 17). However, unstable and intact shoulder subjects responded
slightly different to various target locations as the group x target interaction approached
significance (p = 0.09). For subjects with a history of anterior shoulder dislocation, 90°
of external rotation with 90° of abduction would be considered the most vulnerable
position among the 3 designated targets because compromised passive stabilizers may not
be able to properly restrain the humeral head within the glenoid fossa (Turkel et al. 1981; Itoi et al. 1996; Brenneke et al. 2000; von Eisenhart-Rothe et al. 2002). As a result, subjects with unstable shoulders may exhibit the largest errors at 90° of external rotation, which is supported by the findings of this investigation. Surprisingly, the errors for unstable shoulders were not significantly larger (averaged only 2.48° larger) than healthy controls at this critical position. One possible explanation is that enhanced muscle spindle sensitivity with the active positioning protocol may compensate for the position sense deficits caused by compromised joint receptors. In addition, as a protective mechanism while moving towards a vulnerable position, unstable shoulder subjects might tense their shoulder girdle muscles and further increase muscle spindle sensitivity to provided better shoulder stability and position sense near the end-range of rotation.

Unstable and intact shoulder subjects exhibited similar scapular orientations during shoulder abduction testing with the active positioning protocol (Fig. 16). Proper scapular motion during upper-limb movements is important in maintaining shoulder stability (Itoi et al. 1992; Matias and Pascoal 2006) as well as preventing injuries (e.g. shoulder impingement syndrome) (Ludewig and Cook 2000; Graichen et al. 2001; McClure et al. 2006). Previous studies have shown that subjects with stable shoulders progressively upward-rotated (about the A-P axis), posteriorly-tipped (about the M-L axis), and laterally-rotated (about the vertical axis) the scapula as humeral elevation increased (Ludewig et al. 1996; de Groot et al. 1999; Ludewig and Cook 2000; Fayad et al. 2006; Matias and Pascoal 2006; McClure et al. 2001, 2006; Bourne et al. 2007). The results of this investigation are consistent with previous studies and suggest that posttraumatic shoulder instability has no impact on scapular orientation. However, other
studies had found muscle activation (EMG) changes in scapular stabilizers (e.g., serratus anterior) and shoulder rotator cuff muscles (e.g., supraspinatus) in unstable shoulders, which may have an impact on scapular and humeral motion (Glousman et al. 1987; McMahon et al. 1996; Matias and Pascoal 2006; Hundza and Zehr 2007). It is important to note that EMG data should be interpreted with caution because the final acting force acting on the scapula could vary as the results of many contributing scapular movers and stabilizers. Moreover, previous studies have not directly compared scapula motions accompanying humeral motions in unstable shoulders with those of normal controls. Results of this investigation show unstable shoulder subjects can actively move the shoulder to the three target angles with similar scapular orientations to those used by healthy controls.

**Kinesthetically Guided Reaching**

Anterior shoulder instability had little effect on accuracy of kinesthetically guided reaching to visually specified targets in space (p > .32, Fig. 20). This study investigated reaching/pointing accuracy in terms of index fingertip location relative to the target in all three dimensions (anterior-posterior, medial-lateral, and vertical). Comparing the overall rms errors, unstable shoulder subjects were able to reach to the remembered targets as accurately as healthy controls, especially to the targets located in the sagittal and oblique planes. In addition, there were no overall reaching error differences between the two groups in any of the 3 dimensions (Fig. 21, 22, 23). Although unstable shoulder subjects may experience position sense deficits at the shoulder joint (based on the results of the passive positioning testing), these findings agree with the hypothesis that unstable
shoulder subjects may have sufficient kinesthetic information about their upper limb in order to point accurately to visually specified targets in space.

Despite the importance of proprioception in end-point reaching accuracy and inter-joint coordination during kinesthetically guided movements, it is important to note that even larger-fiber neuropathy patients who receive no proprioceptive information can position the hand in the vicinity of the target without visual guidance under some conditions (Gordon et al, 1995; Ghez et al. 1995). Moreover, end-point reaching accuracy could be greatly enhanced when a deafferented subject was provided with visual feedback during the movement and/or prior vision of the moving arm (Ghez et al. 1995). Although the unstable shoulder subjects of the current study did not receive visual feedback during reaching or vision of the moving arm prior to movement (except for the low target trials), compromised shoulder position sense due to dislocation would be much less severe than deafferented patients. Therefore, we were not surprised that reaching accuracy was similar in intact and unstable shoulder subjects.

Further analysis showed that kinesthetically guided reaching accuracy (in terms of the final index fingertip position) depended strongly on the target location (p < .01), and reaching accuracy to targets in different planes differed between groups (p < 0.03 for group x plane interaction). Subjects exhibited the smallest reaching errors in the sagittal plane (average: 8.6 cm) and the largest errors in the frontal plane (average: 13.4 cm) but the plane effect was most prominent in unstable subjects (Fig. 20). Although the group differences did not reach significance in all three planes, subjects with unstable shoulders exhibited similar reaching errors to healthy controls in both the sagittal and oblique planes but larger errors than controls in the frontal plane (0.1 cm, 0.4 cm, and 3.2 cm
No unstable shoulder subjects reported discomfort or difficulty while reaching to targets in the frontal plane. However, subconscious fear of shoulder dislocation while positioning the shoulder near end-range of external rotation with abduction (when reaching to the top and middle targets) or end-range of external rotation with the humerus near a vertical orientation (when reaching to the low target) may keep unstable shoulder subjects from reaching accurately to the targets located in the frontal plane.

Kinesthetically guided reaching accuracy also depended strongly on the height of targets \( p < .01 \). Both unstable and intact shoulder subjects exhibited the smallest errors while reaching to the low targets (corresponding to the height of each individual’s ASIS) (Fig. 20). Because the low targets were located much closer to the index finger at its resting position than the other two targets, subjects were able to view both the target and the hand at the same time before initiating the movement. When viewing the middle and top targets, subjects may be able to see the hand with peripheral vision (for the targets in the sagittal and oblique planes) or not being able to view the hand before reaching (for the targets in the frontal planes). Although it can not be determined if subjects quickly glanced at the hand before gazing at the middle and top targets, hand position information provided by the glance may not as accurate as when hand is in view with the target for a period of time. As reported by Rossetti et al. (1994), both visual and kinesthetic information can be efficiently combined by the CNS to plan a proper limb trajectory when the hand is visible prior to movement. Compared to reaching to the middle and high targets where initial hand location may not be accurately specified visually, subjects
can better identify the initial hand position and specify the spatial relationship between their index fingertip and the target while reaching to the low targets.

Unstable shoulder subjects point to the remembered location with precision by adopting a new reaching strategy with different upper-limb configurations to protect the injured shoulder near vulnerable/unstable positions. Results of the present study show subjects with unstable shoulders exhibited smaller shoulder rotation angles than healthy controls while reaching to visually specified targets in space (p < .02, Fig. 28). No previous studies have compared shoulder rotation angle between unstable and intact shoulders with a functional 3-D reaching task with unrestrained shoulder, elbow, wrist, and finger motion. In the present work, subjects with unstable shoulders averaged 12° smaller external rotation angles than subjects with intact shoulders. This discrepancy was consistent for all targets at different heights and in different planes (Fig. 28). The lack of shoulder external rotation was not due to physical restraints because all unstable shoulder subjects achieved more than 90° of shoulder external rotation and exhibited normal shoulder external rotation muscle strength in the screening test. Furthermore, no unstable shoulder subject reported discomfort or difficulty in the reaching test, and all subjects felt they had successfully reached to the remembered targets in space. Results of this investigation suggest that unstable shoulder subjects subconsciously adapted a new pointing strategy with less shoulder external rotation in order to protect the injured shoulder from recurrent injuries. Such adaptation did not rely totally on peripheral information during the movement because less shoulder external rotation was also observed when reaching to non-vulnerable positions in the sagittal and oblique planes.
Scapula Orientation in Kinesthetically Guided Reaching

Unstable and intact shoulder subjects exhibited similar scapular orientations (upward rotation, posterior tipping, lateral rotation) at various target locations in kinesthetically guided reaching test (Fig. 29, 30, 31). Proper scapula motion during upper-limb movements is thought to be important in maintaining shoulder stability (Itoi et al. 1992; Matias and Pascoal 2006) as well as preventing injuries (Ludewig and Cook 2000; Graichen et al. 2001; McClure et al. 2006). Scapular orientation changes have been observed in subjects with shoulder impingement syndrome (Warner et al. 1992; Ludewig and Cook 2000; Endo et al. 2001; McClure et al. 2006) and multi-directional shoulder instability (Ozaki 1989; Ogston and Ludewig 2007). However, no previous work compared scapular orientations between unstable and intact shoulder subjects during a functional reaching task with unrestrained shoulder, elbow, wrist, and finger motion. Results of this investigation show unstable shoulder subjects not only reached to the targets as accurately as healthy controls, but also exhibited similar scapular orientations to intact shoulder subjects at the end of the pointing movement. It has been suggested that pain, muscle weakness, and reduced range of motion observed in subjects with shoulder impingement syndrome or multidirectional shoulder instability may influence scapular orientations during upper limb movements (Ludewig and Cook 2000; Kibler and McMullen 2003; Ogston and Ludewig 2007). However, those factors may not have an impact on the present study because all participating subjects have normal shoulder muscle strength, range of motion, and can reach to all targets without pain.

It is important to note that variations in defining a local scapula coordinate system and the order of rotations used for analysis may vary in different studies. For recent
scapular orientation studies, scapula orientations were presented about a local scapula coordinate system which was established with 3-dimensional positions of 3 digitized scapular bony landmarks (Karduna et al. 2001; Wu et al. 2005; Bourne et al. 2007; Ogston and Ludewig 2007). Based on the definitions recommended by the International Society of Biomechanics (ISB) (Wu et al. 2005), the local scapula X_S axis represents the line connecting the acromial angle (most laterodorsal point of the scapula or posterior lateral acromion) and the root of the scapula spine (the midpoint of the triangular surface on the medial border of the scapula in line with the scapular spine). The local scapula Y_S axis represents a line perpendicular to the plane formed by the acromial angle, the root of the scapular spine, and the inferior angle (most caudal point of the scapula). The local scapula Z_S axis represents a line perpendicular to the X_S and Y_S axes. Scapular rotations were defined as upward-downward rotation (U-D rotation) about the Y_S axis, anterior-posterior tipping (A-P tipping) about the X_S axis, and medial-lateral rotation (M-L rotation) about the Z_S axis. However, there were variations among studies of this method as different bony landmarks were chosen to establish a local scapula coordinate system (Karduna et al. 2001; Ogston and Ludewig 2007). For the current investigation, a new local scapula coordinate system could not be established without the 3-D information of two other body landmarks. Therefore, scapular rotations were represented about the three axes fixed to the scapula: medial-laterally rotation (about the vertical axis), anterior-posterior tipping (about the M-L axis), and upward-downward rotation (about the A-P axis). Another consideration for comparing the results of different studies is the order of rotation. The scapular rotation sequence of the present study is M-L rotation, A-P tipping, and U-D rotation, which is different from the sequence of M-L rotation, U-D
rotation, and A-P tipping adopted by other 3-D scapula studies (Karduna et al. 2001; Wu et al. 2005; Bourne et al. 2007; Ogston and Ludewig 2007). Therefore, direct comparisons may not be made between the current and previous scapula orientation studies.

Target location greatly affected scapular orientation in a similar manner in both unstable and intact shoulder subjects. When subjects pointed to the targets located to the side of the body in the frontal plane and oblique plane, scapular orientations were consistent with previous studies that showed scapula upward rotated, posterior tipped, and laterally rotated as humeral elevation increased (Ludewig et al. 1996; de Groot et al. 1999; Ludewig and Cook 2000; Fayad et al. 2006; Matias and Pascoal 2006; McClure et al. 2006; Bourne et al. 2007). However, scapula angle changes between targets were less than what were observed in previous studies because less shoulder abduction was needed in the tasks studied here, especially when reaching towards the low (ASIS height) and middle (GHJ height) targets. Only a few studies have examined scapular orientation while reaching to targets in the sagittal plane and the reported results are not consistent, especially for scapular tipping (Fayad et al. 2006; McClure et al. 2006; Bourne et al. 2007). Results of the present investigation are consistent with the results of previous studies that scapula upward and medial rotators while reaching to target located in the sagittal plane.
CHAPTER VI: SUMMARY

Conclusions

The most significant finding of this study is that unstable shoulder subjects exhibited significantly larger errors in perception of shoulder joint angles than healthy controls in the classical reproduction of target shoulder rotation angles with imposed motion protocol but not in the active positioning and kinesthetically guided reaching protocols. For the imposed motion technique, results of this investigation agree with the findings of previous studies (Smith and Brunolli, 1989; Lephart et al. 1994; Zuckerman et al. 2003) and suggest that position sense is somewhat compromised in subjects with a history of anterior shoulder dislocation, especially for shoulder angles far from vulnerable positions which may elicit apprehension and increased muscle activity. Such deficits could be due to either compromised joint receptors (due to over-stretched joint capsule/ligament) or muscle receptors (due to shoulder rotator muscles length changes as the results of altered humeral head location). However, the reproduction of shoulder angles with imposed motion protocol does not resemble daily activities. Moreover, the clinical significance of the observed deficit is questionable because the group differences in the current investigation (1.8°) and previous studies (ranging from 1° to 2.3°) are relatively small. Compared to the imposed motion technique, being able to move the arm actively better resembles daily activities and therefore merits a much greater clinical and functional significance (Gandevia et al. 1992, Nyland et al. 1998, Aydin et al. 2001, Pötzl et al. 2004). Although compromised joint receptors may have a slight impact on shoulder position sense in unstable shoulders, it is suggested that joint receptors probably only make contributions to position sense near the end-range of motion (Clark and Burgess
1975; Grigg and Hoffman 1982; Grigg 1994; Borsa et al. 1994; Clark et al. 1985, 1986, 1989). With the functional active testing protocol, better muscle spindle sensitivity (closer to a level that the subject is accustomed to) and better muscle length information (due to a more centered humeral head) may compensate for the proprioceptive deficits caused by damaged joint receptors.

Results of this investigation suggest that impaired shoulder position sense may not be the main contributor to the high recurrence rate (30% for non-athletes and 92% for athletes) of shoulder dislocation (Wheller et al. 1989, Simonet et al. 1997). For individuals who experienced an anterior shoulder dislocation, over-stretched passive shoulder stabilizers may not be able to provide sufficient mechanical stabilization (static restraints) to maintain the humeral head within the glenoid cavity (Graichen et al. 2000, von Eisenhart-Rothe 2002). In addition, altered neuromuscular control over shoulder girdle muscles due to compromised position sense may contribute to recurrent injuries (Lephart et al. 1994, 1997; Simonet et al. 1997; Mahaffey and Smith 1999; Myers et al. 2006). However, results of this study show unstable shoulder subjects can perceive shoulder angles and reach to visually specified targets in space as accurately as healthy controls. When unstable shoulder subjects have awareness of the shoulder position (especially towards vulnerable positions such as the end range of external rotation), they should be able to engage appropriate muscle activities to stabilize the joint or implement alternative moving strategies to protect the shoulder from recurrent injuries. However, traumatic recurrent shoulder dislocations are often the results of unexpected fast acting forces acting on the humerus. A person would not have enough time to perceive a vulnerable shoulder position, and then generate appropriate muscle reaction to stabilize
the shoulder joint in response to the perturbation. Therefore, the present study suggests that compromised shoulder position perception may not be the main cause for the high recurrence rate of shoulder dislocation. Weaker shoulder girdle muscles and/or over-stretched static/dynamic shoulder stabilizers may contribute more to recurrent shoulder instability.

Another significant and unexpected finding of present study is that unstable shoulder subjects employed a different reaching strategy/upper limb configuration to point to the visually remembered targets with similar end-point accuracy as intact shoulder subjects. Although unstable shoulder subjects were physically capable of reaching to those targets with similar shoulder rotation as in healthy controls, they performed with significantly less shoulder external rotation, perhaps to protect the injured shoulder. Results also suggest that such adaptation did not only rely on peripheral information during the movement because less shoulder external rotation was also observed when reaching to non-vulnerable positions in the sagittal and oblique planes. It suggests that subjects might have acquired a new motor program in reaching during rehabilitation training and/or from experiences in daily activities.

Limitations and Suggestions

It should be noted that the majority of studies on shoulder position sense in unstable shoulder subjects were implemented with the custom designed apparatuses and varied considerably in terms of the subjects’ injury classification (i.e., direction of instability), injury history (i.e., the numbers of dislocation and the period since last injury), testing method (i.e., passive or active), testing position (i.e., supine or upright), movement direction (i.e., abduction, forward flexion, or rotation), movement patterns
(i.e., single or multi-joints movements), target location (i.e., mid-range or end-range of motion), and treatment history (i.e., rehabilitation or surgical repair). Variations in subject characteristics and testing methods can vary the results and impose difficulties in comparing results among different studies. The current study examined and compared several factors (e.g., dominant vs. non-dominant arms, passive vs. active testing, mid-range vs. end-range of motion, single vs. multi-joint movements) that might affect the results and found shoulder position sense discrepancy between unstable and intact shoulder subjects differed in several comparisons (i.e., passive vs. active testing, mid-range vs. end-range of motion, single vs. multi-joint movements). Therefore, special consideration is needed when comparing shoulder position sense studies with different subject characteristics and testing methods.

In addition to variations in defining local scapula rotation axes and computing scapula rotation angles, it is important to note that there are possible limitations in measuring scapula motion/orientation, especially during active movements. Variations in testing equipment, sensor location, and the extent and direction of humerus movements can potentially contribute to the discrepancy among studies. Moreover, when using the skin/surface receiver to examine scapular orientation, the possibility of receiver moving on the skin (or skin moving on the bony landmark) and the size of shoulder girdle muscles (e.g., deltoid) and subcutaneous fat may further contribute to inaccurate measurements. Karduna et al. (2001) compared scapular orientations measured by a similar electromagnetic system (Polhemus FASTRAK) against bone-fixed measurements and found small rms errors (2°) for scapular upward rotation but larger rms errors for posterior tipping (6.6°) and lateral rotation (9.4°) during humeral abduction (up to 120°).
in the scapular plane. Moreover, rms errors greatly increased once the humeral abduction angle exceeded 120° (Karduna et al. 2001). Considering the relatively small scapula rotation angle changes during humerus movements (especially for A-P tipping and M-L rotation), scapular orientation data measured by skin receivers may not accurately represent scapular movements in all scapular movement dimensions. However, there are potential limitations for bone pin measurements as well. Normal scapular movements may be altered due to discomfort or apprehension, and soft tissue tension during the movements may cause the pins to bend (Karduna et al. 2001; Bourne et al. 2007).

It is important to note that during the imposed position testing, subjects were asked to fully relax the testing arm on the manipulandum while being moved to various rotation angles. The primary investigator closely monitored for additional resistance and apprehension from the subjects while moving the device. However, it is unknown how much shoulder girdle muscle activation actually occurred, especially towards the end-range of external rotation where the GHJ is least stable. In addition to the information from joint and muscle receptors in response to capsule/ligament tension and muscle length changes, larger muscle activation or apprehension may further enhance muscle spindle sensitivity due to alpha-gamma-beta co-activation (McCloskey 1978; Gandevia et al. 1992; Kandel et al. 2000) and re-center the humeral head in the glenoid cavity, which may explain the lack of group difference near the end-range of shoulder external rotation. For active positioning and kinesthetically guided reaching, unstable shoulder subjects might also have engaged greater shoulder girdle muscle activation than healthy controls overall or near vulnerable positions to further increase muscle spindle sensitivity and
better stabilize the GHJ. Hence, examining the EMG activity of shoulder girdle muscles along with kinematics assessments may be beneficial in future studies.

The majority of the unstable shoulder subjects (9 out of 10) and intact shoulder subjects (13 out of 15) of the current investigation were at a similar fitness level and regularly participated in recreational or competitive activities. Although traumatic anterior shoulder dislocation is commonly caused by sports related injuries and the recurrence rate is especially high in athletes (92%, Wheeler et al. 1989), individuals who are at a lower fitness level could also experience anterior dislocation by accidents (such as falling). It is not clear whether a person’s fitness level would have an impact on shoulder perception as well as reaching accuracy. For the present study, one unstable shoulder subject and two intact shoulder subjects who did not engage in sport/physical activity on a regular basis did not show larger errors than other more active subjects in the same group. However, a larger number of inactive shoulder subjects may be beneficial to examine the impact of different fitness levels (both before and after the injury) on shoulder perception and reaching accuracy in future studies. Moreover, literature on knee and ankle instability have suggested that after the initial injury, some subjects (known as copers) are able to regain functional stability and resume pre-injury activities by engaging coordinated muscle activation to stabilize the unstable joint (Herrington and Fowler 2006; Hurd and Snyder-Mackler 2007; Brown et al. 2008). Although all unstable shoulder subjects of the present study exhibited similar shoulder perception and reaching accuracy to intact shoulder subjects and were able to return to pre-injury levels of activity, 7 of the 10 unstable shoulder subjects have experienced additional dislocations. This indicates that they were not able to generate proper
coordinated muscle activation to protect the injured shoulder and remained prone to recurrent injury. Thus, assuming that recurrent shoulder dislocations were preventable injuries, subjects with anterior shoulder instability did not cope particularly well in spite of their ability to use proprioceptive information appropriately in the present work both at the perceptual level and when making kinesthetically guided arm movements.
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