AN ABSTRACT OF THE DISSERTATION OF

Eric L. Sauers for the degree of Doctor of Philosophy in Human Performance presented on June 05, 2000. Title: Characterization of Glenohumeral Joint Laxity and Stiffness Using Instrumented Arthrometry.

Abstract approved: Redacted for Privacy

Paul A. Borsa

The purpose of this study was to characterize glenohumeral joint laxity and stiffness using instrumented arthrometry. To evaluate the validity of an instrumented measurement system we compared cutaneous and bone-pinned measures of laxity and stiffness that replicate previously reported *in vivo* methodology. Characterization of capsular laxity was achieved through determination of the sagittal plane translational area at increasing levels of quantified force. Finally, a method for increasing the objectivity of the standard manual laxity examination was developed for the orthopaedic clinician to quantify humeral head translation and capsular volume *in vivo*. We hypothesized that: 1) cutaneous measures could accurately predict bone-pinned measures, 2) capsular laxity would increase with increasing levels of applied force, and 3) manual cutaneous, manual bone-pinned, and force-displacement bone-pinned measures of translation would be equal.

Thirty fresh frozen cadaveric shoulder specimens (mean age = 70 ± 14 years) were tested. The shoulders were thawed and mounted to a custom-made shoulder-testing

apparatus. Displacement was measured using an electromagnetic tracking system. Sensors were secured cutaneously and with bone-pins to the scapula and humerus. Force-displacement testing was performed using a load applicator and manual displacement testing utilized the anterior/posterior drawer and inferior sulcus tests.

A comparison of cutaneous and bone-pinned measures of laxity and stiffness revealed good to excellent criterion validity ($r = 0.68$ to 0.79). Examination of displacement measures at increasing levels of force revealed increasing capsular laxity with symmetric directional compliance. No significant difference was observed between anterior and posterior translation (0.4 mm, $p = .55$), with significant differences between inferior and anterior (4.6 mm, $p<.0001$) and between inferior and posterior (5.1 mm, $p<.0001$). A comparison of manual cutaneous to bone-pinned manual and kinetic measures of translation revealed a significant difference between methods ($p = .0024$) and between directions ($p<.0001$) with no significant interaction ($p = .0948$). Estimations of the force required to achieve clinical end-point suggest that greater force is required in the anterior (173 N) direction compared to posterior (123 N) and inferior (121 N).

We have developed two new methods to measure glenohumeral joint kinematics and reported new information regarding normal kinematics of the glenohumeral joint.

Characterization of Glenohumeral Joint Laxity and Stiffness Using Instrumented Arthrometry

by

Eric L. Sauers

A DISSERTATION

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Presented June 05, 2000
Commencement June 2001

Doctor of Philosophy dissertation of Eric L. Sauers presented on June 05, 2000

APPROVED:

Redacted for Privacy

Major Professor, representing Human Performance

Redacted for Privacy

Head of Department of Exercise and Sport Science

Redacted for Privacy

Dean of Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my entire dissertation to any reader upon request.

Redacted for Privacy

Eric L. Sauers, Author

ACKNOWLEDGMENTS

I wish to thank the following people for their assistance with this project and for their guidance and support of my personal and professional development:

To Jamie, for without whom none of this would have been possible.

Dr. Paul Borsa – my advisor, mentor, and friend, who treated me like a colleague and gave me the freedom to develop my own scientific skills and the support to call on him to see me through when I needed guidance.

Dr. Derald Herling – whose engineering expertise, problem solving skills, and enthusiasm were essential to the process. Our 'problem solving' sessions were one of the most enjoyable parts of this process.

Dr. Waleed Manzour –whose orthopaedic knowledge, surgical skills, and friendship, made this project not only possible, but enjoyable. I will never forget our trips to Portland and the fun that we had together.

The administration and staff of the Oregon Health Sciences Orthopaedic Biomechanics Research Laboratory, specifically Joel Gillard, who were always willing to lend support and without whose assistance and collaboration this project never would have been conducted.

Iain Hunter – who utilized his biomechanics and software programming expertise to develop the 'shoulder program' used to collect and reduce the data for this study.

The students, Tricia Lane, Elizabeth 'Liz' Swank, Andrea Elsasser, and Cord Killinger, for their tireless energy and enthusiasm and assistance collecting the data.

The faculty and staff of the Department of Recreational Sports and Student Health Services for the unfailing support I was given at all times.

CONTRIBUTION OF AUTHORS

Dr. Paul Borsa and Dr. Derald Herling were involved in the design, analysis, and writing of each manuscript. Dr. Waleed Manzour assisted in data collection for the study and interpretation of data.

TABLE OF CONTENTS

TABLE OF CONTENTS, CONTINUED

LIST OF FIGURES

LIST OF TABLES

DEDICATION

This dissertation is dedicated to my family whose lifelong love, support, guidance, and encouragement, have made it possible for me to realize my goals and dreams and to Jamie whose love, compassion, encouragement, and selflessness, have made this journey possible and challenged me to be a better man.

Characterization of Glenohumeral Joint Laxity and Stiffness
Using Instrumented Arthrometry

CHAPTER ONE

Introduction

The human shoulder complex consists of four articulations functioning collectively to allow mobility of the arm to position the hand in space (Culham and Peat, 1993). The majority of motion obtained by the shoulder complex is achieved at the glenohumeral joint (Freedman and Munro, 1966). The glenohumeral joint is the articulation of the humeral head and the glenoid fossa of the scapula. Proper shoulder function is dependent upon the static and dynamic restraining mechanisms of glenohumeral joint stability working in concert to maintain the humeral head centered within the glenoid fossa (Matsen et al., 1991; Lippit and Matsen, 1993; Bigliani et al., 1996). Glenohumeral joint stability is therefore described according to the spatial relationship between the humeral head and the glenoid fossa (Speer, 1995).

LAXITY AND STIFFNESS

The humeral head spins, rotates, and glides, or translates, on the face of the glenoid during arm elevation and rotation (Hart and Carmichael, 1985). Small magnitudes of humeral head translation are normal and have been recorded both with active (Weulker et al., 1994) and passive (Harryman et al., 1990) humeral elevation. This obligate translation of the humeral head on the glenoid is physiologic and in fact necessary in order to achieve the large degrees of freedom afforded the highly mobile shoulder. Laxity is defined as the ability of the humeral head to be passively translated

on the glenoid fossa (Matsen et al., 1991). The magnitude of force required to translate the humeral head a given amount is described as glenohumeral joint stiffness (McQuade et al., 1999). Stiffness is determined from the slope of the linear portion of the force-displacement curve and is an important clinical variable for assessing joint stability (Wright, 1973; Woo et al., 1990). Capsular volume is defined as the intra-articular capacity through which the humeral head can be translated. True measurement of three-dimensional capsular volume is not practical. However, for the purposes of this study capsular laxity is reported from calculating the sagittal translational area, a single measure of the area through which the humeral head can be translated in the anterior, posterior, and inferior directions (Harryman et al., 1992). In this report, the term capsular volume is used to describe theoretical changes in the intra-articular capacity of the glenohumeral joint, whereas use of the term capsular laxity denotes a measured variable representative of the global sagittal plane translational area.

Translation can occur in any direction as the humeral head moves on the glenoid face during humeral elevation and rotation. Clinically, the most important directions of translation to evaluate are anterior, posterior, and inferior (Gerber and Ganz, 1984). These examinations are based on the observation that instability of the glenohumeral joint occurs in the anterior, posterior, and inferior directions (Silliman and Hawkins, 1993). In healthy shoulders a wide spectrum of laxity and stiffness have been demonstrated (Harryman et al., 1992; McFarland et al., 1996a; Borsa et al., 1999; McQuade et al., 1999; Sauers, 1999; Borsa et al., 2000a; Borsa et al., 2000b). An evaluation of 102 healthy shoulders (Sauers, 1999) produced an average range of anterior-posterior laxity of 20.3 mm (8.4 mm to 37.0 mm). Similarly, stiffness in the same population exhibited a

wide range of normal (8.0 N/mm to 55.0 N/mm) (Borsa et al, 2000b). Individuals with bilaterally healthy shoulders have been shown to exhibit side-to-side symmetry of both laxity and stiffness (Borsa et al., 2000b). Laxity has been shown to exhibit directional symmetry within shoulders, whereas joint stiffness has been shown to be greater in the posterior direction compared to anterior (Borsa et al., 2000b).

JOINT STABILITY

Numerous factors collectively limit the magnitude of glenohumeral joint translation. Both active and passive stabilizing mechanisms serve to maintain normal glenohumeral joint mechanics (Soslowsky et al., 1997). The active scapular stabilizing and rotator cuff muscles function in a balance to maintain a centered relationship between the humeral head and the glenoid fossa (Lippit and Matsen, 1993). This dynamic stability mechanism is crucial to stability of the glenohumeral joint during the mid-ranges of arm movement (Wuelker et al., 1998).

At the extremes of motion glenohumeral joint stability is provided via passive bony and soft-tissue restraints. There is an inherent lack of bony stability at the glenohumeral joint. The surface area of the glenoid fossa is one-third to one-fourth that of the humeral head (Lippit and Matsen, 1993; Bigliani et al., 1996). This relationship has been likened to that of a golf ball on a tee. However, the bony geometry of the glenohumeral joint still plays an important roll in passive stability (Saha, 1971; Kibler, 1998). Genetic and pathologic changes in bone geometry have been associated with a reduction in glenohumeral joint stability (Warner, 1993; Wirth and Rockwood, 1993).

The soft-tissue components that contribute to passive glenohumeral joint stability have received substantial attention in the clinical and research literature (Lew et al., 1993). To compensate for the relatively shallow glenoid fossa a fibrocartilage ring, called the glenoid labrum, encompasses the entire glenoid rim (Warner, 1993). The glenoid labrum effectively deepens the glenoid concavity by as much as 50% (Howell and Galinat, 1989). By deepening the glenoid socket and providing a soft-tissue rim around the glenoid the labrum serves to limit glenohumeral joint translation (Pagnani et al., 1995).

The glenohumeral joint capsule extends from the labrum and glenoid rim to the neck of the humerus (Turkel et al., 1981). The capsule envelops the entire humeral head and creates a sealed space within the glenohumeral joint which has been referred to as a "soft-tissue socket" (Friedman, 1993). We refer to the space created by the joint capsule as capsular volume and the global amount of measurable translation within that space as capsular laxity. The capsule is reinforced by the ligaments of the glenohumeral joint which can be observed as functional thickenings of the capsule (O'Brien et al., 1995). The glenohumeral joint ligaments function collectively with the labrum and capsule to maintain a centered humeral head and limit excessive translation (Warner, 1993). Capsular volume is a major determinant of the amount of glenohumeral joint laxity and stiffness present within a given shoulder. Large differences in capsular volume exist between individuals that are thought to account for the large ranges of observed laxity and stiffness (O'Driscoll, 1993). A large, redundant joint capsule resulting in excessive capsular volume allows greater passive humeral head translation to occur (O'Driscoll, 1993). Therefore, increased capsular volume is thought to be associated with an increase

in joint laxity and a concurrent decrease in joint stiffness. Conversely, decreased capsular volume is thought to be associated with decreased joint laxity and increased joint stiffness.

As long as the dynamic musculature of the shoulder complex is able to maintain the humeral head centered within the glenoid the joint will remain stable (Speer and Garrett, 1993). However, if genetic or pathologic alterations have significantly diminished the contribution from the passive joint restraints the dynamic stabilizing muscles may not be able to compensate and maintain proper humeroscapular balance (O'Driscoll, 1993). For example, an individual with significantly increased capsular volume may suffer from symptoms associated with excess humeral head translation that cannot be effectively reduced via dynamic muscular stabilization.

PATHOLOGIC CHANGES IN CAPSULAR VOLUME

Pathologic alterations in capsular volume are hypothesized to result in concurrent changes in glenohumeral joint laxity and stiffness. Symptoms such as pain and dysfunction are associated with both increased and decreased capsular volume. Two examples of common pathologies at the glenohumeral joint associated with changes in capsular volume are instability (Speer, 1995) and adhesive capsulitis or frozen shoulder (Zuckerman and Cuomo, 1993).

Instability of the glenohumeral joint has been defined as, "loss of shoulder function as the result of excessive translation of the humeral head on the glenoid fossa", and is associated with pain (Friedman, 1993). Matsen et al. (1991) defined instability as, "a clinical condition in which unwanted translation of the head on the glenoid

compromises the comfort and function of the shoulder". In sports medicine practice glenohumeral joint instability is most frequently associated with a traumatic episode such as a fall on the outstretched arm (Zarins et al., 1993) or a microtraumatic / repetitive event, such as the overhead throw in baseball (Kvitne and Jobe, 1993).

Traumatic instability of the glenohumeral joint is the result of high forces applied to the capsuloligamentous restraints (Stefko et al., 1997). Resulting humeral head subluxation or dislocation causes tensile overload to these soft-tissue restraints (Soslowsky et al., 2000). Frequently, the anterioinferior glenoid labrum will become detached from its origin on the glenoid rim (Caspari and Geissler, 1993). This labral avulsion is referred to as a Bankart lesion (Bankart, 1923). Mid-substance stretching and tearing of the capsuloligamentous restraints has also been observed (Stefko, 1997; Soslowsky et al., 2000). Labral detachment and capsuloligamentous elongation both contribute to increased capsular volume (Caspari and Geissler, 1993; Tibone et al., 1998). Increased capsular volume following a traumatic dislocation or subluxation is thought to result in increased laxity, decreased stiffness and subsequent glenohumeral joint instability.

Atraumatic instability in the overhead athlete is thought to result from chronic tension on the anterior capsuloligamentous restraints (Jobe et al., 1996). For example, the pitcher in baseball places the arm in repetitive abduction and external rotation. This position places the anterior band of the inferior glenohumeral ligament complex under chronic strain. Attenuation of the capsuloligamentous restraints as a result of this chronic strain is thought to result in excessive anterior humeral head translation and subsequent symptoms of rotator cuff tendinitis and impingement (Glousman and Jobe, 1996).

Increased anterior laxity and decreased anterior stiffness in the overhead athlete has yet to be proven experimentally, but remains a prevalent theory of shoulder dysfunction in this population (Jobe et al., 1996).

The etiology of adhesive capsulitis, or frozen shoulder, is controversial (Zuckerman and Cuomo, 1993). However, one thing that remains unchallenged is the classic reduction in shoulder range of motion associated with this phenomenon (Zuckerman and Cuomo, 1993). A prevailing theory that explains this reduced motion is a reduction in capsular volume associated with some disease process (Neviaser, 1945). The reduction in capsular volume in turn limits humeral head translation and rotation, thereby limiting total humeral motion, specifically elevation and external rotation (Bruckner and Nye, 1981).

Recently, the posterior joint capsule in overhead athletes has received significant attention (Barber et al., 2000; Ticker et al., 2000). Contracture of the posterior joint capsule has been proposed as a major contributor to loss of internal humeral rotation and posterior superior internal impingement in the overhead athlete (Morgan, 2000; Ticker et al., 2000). The tight posterior capsule results in superior migration of the humeral head and subsequent contact with the posterior superior glenoid labrum and posterior rotator cuff tendons (Morgan et al., 1998; Ticker et al., 2000). This pathologic alteration in capsular volume is associated with Type II SLAP lesions and rotator cuff tears in the overhead athlete (Burkhart and Morgan, 1998).

The primary goal of surgical intervention for shoulder instability is to restore normal arthromechanics of the glenohumeral joint (Glousman and Jobe, 1996). In the presence of excessive capsular volume, such as occurs with glenohumeral joint

instability, the orthopaedic surgeon seeks to restore the normal anatomy by reducing capsular volume (Friedman, 1993; Tibone et al., 1998; Vangsness, 2000). In a patient who has suffered a Bankart lesion the labrum is re-attached to the glenoid rim using suture anchors (Barber, 2000). Associated capsuloligamentous stretching or tearing is addressed with a capsular plication procedure whereby attempts are made to reduce the capsular volume back to its pre-injury level (Friedman, 1993; Glousman and Jobe, 1996). Patients with congenital hypermobility and instability as the result of excessive capsular volume are treated with a variety of surgical procedures all with the same goal of decreasing capsular volume and reducing unwanted translation of the humeral head (O'Driscoll, 1993; Tibone et al., 1998).

Conversely, the patient with adhesive capsulitis is treated with a procedure aimed at increasing capsular volume (Iannotti et al., 2000). Surgical release of the glenohumeral joint capsule is reported to dramatically restore lost shoulder range of motion (Heis et al., 2000; Iannotti et al., 2000). The underlying mechanism attributed to this drastic increase in motion is the restoration of normal capsular volume.

Similarly, surgical release of the posterior capsule in the overhead athlete has been recently reported (Abrams, 2000; Ticker et al., 2000). Authors have reported significant increases in internal rotation and reduction in superior migration of the humeral head and decreased contact with the posterior superior glenoid following this procedure (Morgan, 2000; Ticker et al., 2000). Increased motion and reduction in contact symptoms is attributed to increased posterior capsular mobility.

Although a wide range of capsular volume is present between individuals, an optimal magnitude appears necessary within a given individual for normal shoulder

function to occur. Excessive capsular volume is associated with instability and increased humeral head translation. This is often treated with surgical procedures aimed at reducing excessive, pathologic capsular volume. Conversely, decreased capsular volume is thought to result in excessive restriction of humeral head motion resulting in pain and dysfunction. The goals of surgical intervention in the presence of decreased capsular volume are to restore normal motion through capsular lengthening procedures. Despite the critical importance of capsular volume, laxity, and stiffness, these variables remain difficult to objectively assess and little quantitative data exist to support the many theories regarding normal and pathologic stability.

STABILITY ASSESSMENT

A variety of methods exist to assess stability of the glenohumeral joint. Static stability assessment is based on standard manual laxity stress tests performed by the clinician (McFarland et al., 1996b). The anterior-posterior drawer, the load and shift, and the inferior sulcus, are all commonly used manual laxity stress tests (Gerber and Ganz, 1984; Hawkins and Mohtadi, 1991; Silliman and Hawkins, 1993). During these tests the clinician stabilizes the scapula and applies a manual force to the humeral head in order to assess its subsequent degree of translation on the glenoid fossa (McFarland et al., 1996b). Additional evaluative procedures involve imaging techniques such as radiography (Engebretsen & Craig, 1993; Ellenbecker et al., 2000), computed tomography (Pollock and Bigliani, 1993), and magnetic resonance imaging (Rofi et al, 1997, Kiss et al., 1997, Beaulieu et al., 1999), and hospital procedures such as evaluation under anesthesia (Cofield et al., 1993; Oliashirazi et al., 1999), and arthroscopy (Caspari and Giessler,

1993). Recently, attempts to increase the objectivity of the laxity examination through the use of instrumentation have started to emerge. However, quantitative research regarding normal and pathologic laxity and stiffness of the glenohumeral joint still remains scarce. A primary confounding factor is the lack of a reliable, objective, and clinically available means by which to quantify glenohumeral joint laxity and stiffness (Rodkey et al., 1993; Levy et al., 1999).

Manual Assessment

The most common means of evaluating glenohumeral joint laxity and stiffness is the manual laxity examination (McFarland et al., 1996b). During clinical examination of the glenohumeral joint the clinician uses the manual laxity examination in order to assess the magnitude of humeral head translation and subsequent end-feel of the joint (Rodkey et al., 1993; McQuade et al., 1999). The end-feel corresponds to the capsuloligamentous structures becoming taut and resisting further humeral head translation (Hawkins et al., 1996). Subjectively, a soft or mushy end-feel is associated with capsuloligamentous disruption and a hard or firm end-feel is associated with normal capsuloligamentous tissue (Markolf et al., 1978). The end-feel and magnitude of translation are compared between sides (right and left) within subjects in the anterior, posteriors, and inferior directions. Changes in the end-feel or the amount of translation are noted along with the patient's history and other physical findings to make a clinical diagnosis (Lintner et al., 1996).

Recently, the value of the manual laxity examination has come into question. Investigators have reported poor reproducibility (Levy et al., 1999) and poor diagnostic

value of the manual laxity examination (Lippitt et al., 1994). Poor reproducibility has been attributed to a number of factors including: examiner experience, inconsistent force application, inconsistent humeral centering, and inconsistent patient positioning (Rodkey et al., 1993; Levy et al., 1999). Furthermore, muscular tension around the shoulder during examination may significantly alter the magnitude of observed translation and clinical end-feel (Cofield et al., 1993; Oliashirazi et al., 1999).

Harryman et al. (1992) sought to increase the reliability of the manual laxity examination and describe the normal magnitude of translation in the healthy shoulder. Electromagnetic tracking sensors were pinned percutaneously to the scapula and humerus of 8 subjects *in vivo* who then underwent a manual laxity examination (Harryman et al., 1992). The results showed high reproducibility within trials and significant variability in the magnitude of translation between subjects. In this study Harryman et al. (1992) described a method to calculate a semicircular shaped area in the sagittal plane within which the humeral head can be translated. This value was referred to as the "sagittal plane laxity factor" (Harryman et al., 1992). This numeric characterization of laxity is useful for describing the global sagittal translational area, or capsular laxity, of a given glenohumeral joint. To calculate the sagittal translational area the mean displacement value for anterior (A), posterior (P), and inferior (I) translation of each subject is determined and placed into the following formula (Harryman et al., 1992):

$$\text{Capsular laxity} = \text{Sagittal translational area} = \pi / 4 \, (A \bullet I + P \bullet I)$$

The clinical potential for measuring capsular laxity is significant. Side-to-side comparisons of capsular laxity measured using the sagittal translational area could be used to develop diagnostic criteria for patients with hyper- and hypomobility of the

glenohumeral joint. Increasing the objectivity of the manual laxity examination through the addition of instrumentation to quantify translation would have widespread clinical and research applications from diagnostics to surgical outcomes.

A subsequent study to the one conducted by Harryman et al., (1992) was conducted by Lippitt et al., (1994) to compare three groups of patients: healthy shoulders, traumatic glenohumeral instability, and atraumatic multidirectional glenohumeral instability. A significant overlap in translation between the three groups was found and the investigators concluded that the instrumented manual laxity examination could not reliably differentiate between them (Lippitt et al., 1994). However, because of the invasive nature of the study, only one shoulder from each subject was examined. Because of the wide variability in capsular volume previously discussed, it is imperative to make side-to-side comparisons within subjects when performing the manual laxity examination. Based on previous reports of side-to-side symmetry of both laxity and stiffness in healthy shoulders (Borsa et al., 1999; Borsa et al., 2000b) it is logical to hypothesize that side-to-side comparisons in those patients with glenohumeral instability may have yielded valuable information.

Arthrometric Assessment

The concept of instrumented joint arthrometry to objectively characterize joint mechanics is widespread. Reports exist at the ankle (Kovaleski et al., 1999), the knee [patello-femoral (Fithian et al., 1995) and tibio-femoral (Strand et al., 1995) joints] and the glenohumeral joint (Jorgensen and Bak, 1995; Borsa et al., 1999; Pizzari et al., 1999; Borsa et al., 2000a; Borsa et al., 2000b). Instrumented arthrometry involves the

measurement of joint displacement relative to an applied force in a noninvasive, inexpensive, and objective manner through the use of specialized instrumentation (Markolf et al., 1978). Instrumented arthrometry at the knee has enabled researchers to quantify both laxity and stiffness in various populations (Kochan et al., 1984; Markolf et al., 1984; Markolf et al., 1989; Giannoti et al., 1996). Furthermore, side-to-side comparisons of laxity and stiffness parameters obtained using instrumented knee arthrometry have proven effective for predicting injury status (Markolf et al., 1984) and the efficacy of various surgical interventions (Markolf et al., 1989). Daniel et al. (1985a) reported their findings from an *ex vivo* study demonstrating the effects of unilateral disruption of the anterior cruciate ligament (ACL) on side-to-side comparisons of laxity. It was noted that 92% of subjects with both ACL's in tact had an arthrometric difference in laxity of no more than 2.0 mm, whereas 96% of patients with unilateral ACL disruption had an arthrometric side-to-side laxity difference of more than 2.0 mm (Daniel et al., 1985a). Daniel et al. (1985b) confirmed these findings *in vivo* where an arthrometric evaluation of anterior knee laxity revealed that all patients tested whose injured knee had $\geq$ 3.0 mm of increased anterior laxity compared to the normal knee had a confirmed ACL tear. These studies highlight the diagnostic value of side-to-side comparisons of joint laxity using instrumented measures. Investigators have also performed a series of studies at the knee to evaluate joint stiffness in healthy subjects (Markolf et al., 1978), subjects with ACL defficiency (Markolf et al., 1984), following ACL reconstruction (Kochan et al., 1984; Markolf et al., 1989), and in cadavera (Markolf et al., 1976; Shoemaker et al., 1985). From this research, investigators ultimately

concluded that stiffness was of significant diagnostic value at the knee (Markolf et al., 1984).

Based on the significant contributions of previous research at the knee several investigators have attempted to utilize a variety of methods to quantify glenohumeral joint mechanics. Studies reported by Harryman et al. (1992) and Lippit et al. (1994) using an instrumented manual laxity examination were the first *in vivo* studies to attempt to objectively characterize the magnitude of glenohumeral joint laxity in healthy shoulders. To date, these studies are widely cited and have been considered the gold standard in the research literature when discussing normative glenohumeral joint laxity.

In 1995, Jorgensen and Bak reported on the use of a knee laxity tester to measure anterior and posterior translation at the glenohumeral joint in healthy shoulders. Very small magnitudes of anterior-posterior translation were reported that were vastly different from those of Harryman et al. (1992) Another attempt to use a knee ligament arthrometer to quantify anterior-posterior translation in healthy subjects was reported by Pizzari et al. in 1999. The laxity findings of Pizzari et al. (1999) were comparable to those of Harryman et al. (1992) and side-to-side symmetry of laxity was also reported. In 1999 McQuade et al., published the first *in vivo* report of glenohumeral joint stiffness. A load cell and an electromagnetic tracking system were used to quantify force-displacement during a manual laxity examination. Unfortunately, these investigators (McQuade et al., 1999) failed to report their laxity data and did not perform a bilateral examination so no side-to-side comparisons were available. The end range stiffness values reported by McQuade et al. (1999) were very small (< 3 N/mm) which is difficult to account for based on previous research at the knee and recent research at the glenohumeral joint.

While attempts to quantify glenohumeral joint laxity and stiffness have started to emerge they are still relatively few and incomplete. Investigators are seeking to find clinical methods whereby laxity and stiffness can be evaluated more objectively. Previous investigations to quantify glenohumeral joint laxity and stiffness using instrumented techniques have suffered from several shortcomings: failure to compare bilaterally, failure to quantify force, failure to measure inferior laxity, and failure to control trunk / accessory motion. As was the case at the knee, investigators have started with evaluations of healthy shoulders and will presumably begin to investigate populations with various shoulder pathologies.

Instrumented Measurement System

An instrumented measurement system that measures *in vivo* sagittal plane glenohumeral joint laxity and stiffness has been developed at Oregon State University in a collaborative effort between members of the Department of Exercise and Sport Science and the Department of Mechanical Engineering. The instrumented measurement system consists of a test chair to position the subject and stabilize the trunk and arm. A load cell is used to quantify force and linear displacement transducers (LDTs) have been used to measure scapular and humeral motion. Recently, the LDTs were replaced with more sophisticated and easier to apply electromagnetic spatial tracking sensors. The sensors are secured cutaneously with adhesive tape to record displacement of the scapula and humerus. To date, two *in vivo* studies using the instrumented measurement system have been conducted to evaluate the functionality and reliability of the device and establish normative data for laxity and stiffness.

In Vivo Research

A pilot study of 40 shoulders (20 subjects) was conducted to determine functionality and between trial reliability of the instrumented measurement system (Borsa et al., 1999). The average between trial intraclass correlation (ICC) value for laxity was .94 (.90 to .97). Measures of glenohumeral joint laxity revealed bilateral symmetry between right and left shoulders within subjects. However, posterior translation was significantly less than anterior translation. The observed directional asymmetry was thought to be a result of the compliant back support, not a true capsular asymmetry. Thus, several design modifications were implemented as a result of this study including a more rigid back support to prevent excessive posterior displacement of the trunk during posterior laxity testing.

Next, a study was done to determine between session and between examiner reliability of the instrumented measurement system and establish normative data for glenohumeral joint laxity and stiffness (Sauers, 1999). Normative data were obtained from 102 shoulders (51 subjects). This large population of healthy shoulders exhibited bilateral symmetry of laxity and stiffness between right and left shoulders and symmetry between the anterior and posterior directions within shoulders (Borsa et al., 2000b). A subset of 50 shoulders (25 subjects) was evaluated to determine reliability of the measures which were shown to be within 1 mm between sessions and between examiners (Sauers et al., 2000). This study was the first to report gender differences in laxity and stiffness of the glenohumeral joint (Borsa et al., 2000a). Females exhibited significantly increased anterior translation with an associated decrease in anterior joint stiffness compared to males.

Measurement Validity

The instrumented measurement system utilizes non-invasive, cutaneous sensor application to quantify underlying bony translation. However, the soft-tissues overlying bone may be a source of error variance when cutaneous methods are utilized to quantify bone motion. Therefore, it is necessary to establish the accuracy of the cutaneous measurement system. The *in vivo* laxity values obtained using the instrumented measurement system closely approximate those obtained by Harryman et al. (1992), using percutaneous pins during a manual laxity examination. These comparative data lend some support to the accuracy of the measures obtained using the non-invasive, cutaneous methods. However, in order to establish the validity of the system a more direct comparison is warranted. The *in vivo* methods reported by Harryman et al. (1992) are not suitable for use with a large sample size due to the invasive nature of the procedure and inherent risks therein. Therefore, we utilized fresh frozen cadaver shoulder specimens to compare the non-invasive, cutaneous measures of laxity and stiffness with measures obtained using direct bone-pinning of the scapula and humerus. By reproducing the exact shoulder position and testing procedures as previously reported for *in vivo* testing we have been able to determine the validity of the instrumented measurement system.

Capsular Laxity and the Sagittal Translational Area

Capsular laxity is an important measure of the sagittal translational area of the humeral head. Capsular laxity can be quantified using the sagittal plane laxity factor previously described by Harryman et al. (1992). Measures of anterior, posterior, and

inferior translation are placed into a formula to calculate a semi-circular shaped area. *In vivo* calculation of capsular laxity may assist the orthopaedic clinician in determining the presence or absence of shoulder pathology. Following injury to the shoulder such as a truamatic dislocation of the glenohumeral joint the capsular volume is theorized to increase. This increase in capsular volume would allow excessive and symptomatic humeral head translation. Measuring capsular laxity *in vivo* may be confounded by the possibility of muscular tension during examination which may limit the observed translation.

Utilizing an instrumented measurement system to calculate the sagittal translational area relative to known force values in cadaver shoulder specimens has several advantages over the *in vivo* bone-pinned manual examination previously reported (Harryman et al., 1992). First, a method is utilized that replicates current *in vivo* measurement methods that are safe and easy to perform. Second, direct bone-pinning ensures accurate measures of capsular volume can be obtained. Third, the possible measurement error associated with muscular tension observed *in vivo* is controlled. Finally, the mechanical properties of the joint in response to measured increasing force levels can be observed. We determined capsular laxity of the glenohumeral joint using bone-pinned measurement methods at four increasing levels of quantified force in order to characterize the intra-articular space through which the humeral head could be translated.

Instrumented Manual Assessment

The manual laxity assessment is a major component of the standard physical examination of the shoulder (Hawkins and Bokor, 1990; McFarland et al., 1996b). The load and shift and inferior sulcus tests are manual tests frequently used to assess humeral translation (Gerber and Ganz, 1984; McFarland et al., 1996c). Recently, the manual laxity examination has been shown to exhibit poor reproducibility (Levy et al., 1999; Ellenbecker et al., 2000). Laxity tests are subjective in nature and rely on clinician "feel" to describe the magnitude of observed humeral translation in response to a manually applied force (Hawkins et al., 1996; Levy et al., 1999; Oliashirazi et al., 1999). A significant problem is the inability to precisely quantify humeral translation in response to applied loads. Current subjective grading systems utilize a four part categorical scale to attempt to define how far the humeral head translates on the glenoid (Hawkins and Bokor, 1990; McFarland et al., 1996c). However, examiners have difficulty agreeing on the observed translation even with such a crude scale and suggestions to simplify the classification system have been reported (McFarland et al., 1996a; Levy et al., 1999).

Another reported problem observed with the manual laxity examination is the lack of precise measurement of the applied force (Levy et al., 1999; McQuade et al., 1999). Authors have suggested a wide range of applied forces necessary to reach clinical end point during laxity examination. Some of the reports have been based on actual kinetic measures (Jorgensen and Bak, 1995; Borsa et al., 1999; Krarup et al., 1999; McQuade et al., 1999; Pizzari et al., 1999; Borsa et al., 2000a; Borsa et al., 2000b; Ellenbecker et al., 2000) while others appear to be subjective estimations (Gerber and Ganz, 1984; Hawkins et al., 1996; Oliashirazi et al., 1999).

In the last decade several attempts to quantify *in vivo* force-displacement at the shoulder, similar to those at the knee, have been reported in the orthopaedic literature. Harryman et al., (1992), and later Lippitt et al., (1994), were the first to report the addition of electromagnetic sensors to the manual laxity examination. This valid, reproducible, and objective measurement method yielded valuable information regarding normal and pathologic laxity at the glenohumeral joint, however the invasive methodology is not clinically applicable. We have developed a non-invasive technique to increase the objectivity of the manual laxity examination through the use of cutaneously applied instrumentation. However, the accuracy of this method has yet to be determined. If non-invasive cutaneous instrumentation and methods could be developed for use in conjunction with the manual laxity examination the objectivity, precision, and accuracy, of these tests could be greatly enhanced. This in turn could yield valuable data regarding normal and pathologic laxity at the shoulder.

SUMMARY

The healthy glenohumeral joint requires some humeral head translation to occur in order for the shoulder to achieve the large ranges of motion necessary for normal function. The passive soft-tissue restraints of the glenoid labrum and capsuloligamentous structures provide end-range stability at the glenohumeral joint by preventing excessive humeral head translation. In the presence of shoulder pathology such as instability or adhesive capsulitis, excessive or diminished humeral head translation results in symptoms of pain and dysfunction. Surgical intervention techniques address the

underlying increase or decrease in capsular volume to restore normal glenohumeral joint arthromechanics.

Traditionally, the manual laxity examination as well as other diagnostic measures have been employed to evaluate the magnitude of humeral head translation on the glenoid. Poor reproducibility, lack of quantified force, inconsistent positioning, and other problems have reduced the efficacy of these examination methods and led to attempts at more objective measures of glenohumeral joint laxity and stiffness. An instrumented shoulder arthrometer has been developed that objectively measures sagittal plane glenohumeral joint laxity and stiffness. The instrumented shoulder arthrometer utilizes non-invasive, cutaneous sensors applied to the scapula and humerus to quantify glenohumeral joint mechanics.

The general purpose of this study was to characterize glenohumeral joint laxity and stiffness in 30 fresh frozen cadaver shoulder specimens using instrumented arthrometry. The specific aims of this study were to: 1) evaluate the validity of the instrumented shoulder arthrometer using cutaneous and bone-pinned measures of laxity and stiffness that replicate previously reported *in vivo* methodology, 2) characterize capsular laxity through determination of the sagittal plane translational area at increasing levels of quantified force, and 3) develop a simple method for increasing the objectivity of the standard manual laxity examination for the orthopaedic clinician to quantify humeral head translation *in vivo*.

CHAPTER TWO

Validity of an Instrumented Measurement Technique for Determining Glenohumeral Joint Laxity and Stiffness

Eric L. Sauers, Paul A. Borsa, Derald E. Herling, and Waleed F. Manzour

To be submitted to *American Journal of Sports Medicine*
July, 2000

ABSTRACT

We have developed a non-invasive, instrumented measurement technique to objectively quantify *in vivo* force-displacement at the shoulder. The purpose of this study was to determine the criterion validity of the non-invasive, cutaneous measurement technique for quantifying glenohumeral joint laxity and stiffness. Thirty fresh frozen cadaver shoulders were tested in a custom-made shoulder-testing apparatus designed to replicate an *in vivo* instrumented testing system for measuring force-displacement at the shoulder. Force data were obtained using a full bridge thin beam load cell and displacement data were obtained using an electromagnetic spatial tracking system. Sensors were first applied to the scapula and humerus cutaneously using adhesive tape. A slow progressive force from 0-200 N was applied to the joint and force-displacement data were collected in the anterior, posterior, and inferior directions. Testing was then repeated with the sensors secured to the underlying scapula and humerus using perctuaneous bone-pinning. The two measurement techniques were then compared using Pearson-product moment correlations and simple linear regression. Correlation coefficients were found to be good for laxity in all directions (anterior = 0.71, posterior = 0.69, inferior = 0.68), excellent for anterior stiffness (0.79), and good for posterior (0.68) and inferior (0.71) stiffness. Minimal differences were observed between the cutaneous and bone-pinned measurement techniques for laxity (anterior = 1.5±4.0 mm, posterior = 0.4±4.0 mm, inferior = 5.4±7.6 mm) and stiffness (anterior = 5.4±12.3 N/mm, posterior = 12.1±20.0 N/mm, inferior = 5.4±7.6 N/mm). Based on the findings of this investigation we believe that this non-invasive, cutaneous measurement technique is a valid method for objectively evaluating *in vivo* glenohumeral joint stiffness.

INTRODUCTION

Physiologic translation of the humeral head is necessary in order to achieve the large degrees of freedom afforded the highly mobile shoulder (Harryman et al., 1990; Lippitt and Matsen, 1993; Wuelker et al., 1994). Passive translation of the humeral head in response to an applied force is termed laxity (Matsen et al., 1991; Speer, 1995; McFarland et al., 1996a). Significant magnitudes of laxity have been recorded in the healthy shoulder (Harryman et al., 1992; Borsa et al., 1999; Sauers, 1999; Borsa et al., 2000b). The force required to translate the humeral head a given amount is described as glenohumeral joint stiffness (McQuade et al., 1999; Borsa et al., 2000a; Borsa et al., 2000b). Stiffness is determined from the slope of the linear portion of the force-displacement curve and is an important clinical variable for assessing joint stability (Wright, 1973; Woo et al., 1990; Markolf et al., 1984; McQuade et al., 1999; Borsa et al., 2000a; Borsa et al., 2000b).

To assess the integrity of the static capsuloligamentous restraints that limit excessive humeral head translation, the clinician utilizes the manual laxity examination (McFarland et al., 1996c). The anterior-posterior drawer, the load and shift, and the inferior sulcus, are all commonly used manual laxity stress tests (Gerber and Ganz, 1984; Hawkins and Mohtadi, 1991; Silliman and Hawkins, 1993). During these tests the clinician stabilizes the scapula and applies a manual force to the humeral head in order to assess the subsequent magnitude of laxity and end-feel of the joint (Rodkey et al., 1993; McFarland et al., 1996c; McQuade et al., 1999). The end-feel corresponds to the capsuloligamentous structures becoming taut and resisting further humeral head translation (Hawkins et al., 1996). Subjectively, a soft or mushy end-feel is associated

with capsuloligamentous disruption and a hard or firm end-feel is associated with normal capsuloligamentous tissue (Markolf et al., 1978). Pathologic changes in the magnitude of translation and end-feel are noted along with the patient's history and other physical findings to make clinical diagnoses such as shoulder instability and adhesive capsulitis or frozen shoulder (Warner et al., 1990; Lintner et al., 1996; McFarland et al., 1996b).

Recently, the value of the manual laxity examination has come into question. Investigators have reported poor reproducibility (McFarland et al., 1996c; Levy et al., 1999; Ellenbecker et al., 2000) and poor diagnostic value of the manual laxity examination (Lippitt et al., 1994). Poor reproducibility has been attributed to a number of factors including: examiner experience, inconsistent force application, inconsistent humeral centering, and inconsistent patient positioning (Rodkey et al., 1993; McFarland et al., 1996c; Levy et al., 1999; Ellenbecker et al., 2000). To increase the objectivity of the laxity assessment investigators have used custom force-displacement systems (Borsa et al., 1999; Borsa et al., 2000a; Borsa et al., 2000b), knee arthrometers (Jorgensen and Bak, 1995; Pizzari et al., 1999), and instrumented manual tests (Harryman et al., 1992; Lippitt et al., 1994; McQuade et al., 1999), as well as a variety of imaging techniques (Beaulieu et al., 1999; Krarup et al., 1999; Ellenbecker et al., 2000), to quantify humeral translation. Despite significant advances in the understanding of shoulder mechanics over the past decade, quantitative research regarding normal and pathologic laxity and stiffness of the glenohumeral joint still remains scarce. A primary confounding factor is the lack of an objective, reliable, valid, and clinically available means by which to quantify glenohumeral joint laxity and stiffness (Rodkey et al., 1993; Borsa et al., 1999; Levy et al., 1999; Sauers, 1999; Borsa et al., 2000a; Borsa et al., 2000b).

The concept of instrumented arthrometry to objectively characterize joint mechanics is widespread. The majority of reports on the use of instrumented arthrometry exist at the tibio-femoral joint (Markolf et al., 1976; Markolf et al., 1978; Kochan et al., 1984; Markolf et al., 1984; Daniel et al., 1985a; Daniel et al., 1985b; Markolf et al., 1989; Strand et al., 1995; Giannoti et al., 1996). However, in recent years studies using instrumented devices have been reported at the ankle (Kovaleski et al., 1999), the patello-femoral joint (Fithian et al., 1995) and the glenohumeral joint (Jorgensen and Bak, 1995; Borsa et al., 1999; Pizzari et al., 1999; Borsa et al., 1999; Sauers, 1999; Borsa et al., 2000a; Borsa et al., 2000b). The use of instrumented arthrometry involves the measurement of joint displacement relative to an applied force in a noninvasive, inexpensive, and objective manner through the use of specialized instrumentation (Markolf et al., 1978). Instrumented arthrometry at the knee has enabled researchers to quantify both laxity and stiffness in various populations such as; healthy (Markolf et al., 1978) ligament injured (Markolf et al., 1984; Daniel et al., 1985a; Daniel et al., 1985b; Shoemaker and Markolf, 1985; Markolf and Amstutz, 1987; Bach et al., 1990; Neuschwander et al., 1990; Strand et al., 1995) and surgically repaired (Kochan et al., 1984; Markolf et al., 1989; Giannotti et al., 1996). Furthermore, side-to-side comparisons of laxity and stiffness parameters obtained using instrumented knee arthrometry have proven effective for predicting injury status (Markolf et al., 1984; Daniel et al., 1985a; Daniel et al., 1985b) and the efficacy of various surgical interventions (Markolf et al., 1989). A reliable and valid, non-invasive technique for quantifying *in vivo* force-displacement characteristics at the glenohumeral joint could

have significant merit for predicting injury status and evaluating surgical procedures aimed at restoring normal capsular volume.

An instrumented measurement technique that utilizes non-invasive, cutaneously applied sensors to quantify underlying scapular and humeral translation at the glenohumeral joint has recently been developed (Borsa et al., 1999; Sauers et al., 1999; Borsa et al., 2000a; Borsa et al., 2000b) (Figure 2.1). The reproducibility of this technique has been investigated *in vivo* and a high degree of precision has been observed between trials (0.2 mm), between sessions (0.5 mm), and between examiners (0.9 mm) (Sauers et al., 1999). However, the soft-tissues overlying the scapula and humerus may be a source of error variance when cutaneous measurement techniques are utilized to quantify underlying bone motion. To further establish the value of this cutaneous measurement technique for use as a laboratory or clinical tool it is necessary to determine the validity, or accuracy, of the obtained measures. Therefore, the purpose of this study was to reproduce the previously reported *in vivo* testing procedures using fresh frozen cadaver shoulder specimens to compare non-invasive, cutaneous measures of laxity and stiffness with measures obtained using direct bone-pinning of the scapula and humerus.

MATERIALS AND PROCEDURES

Specimen Preparation and Testing Apparatus

Thirty fresh frozen human cadaveric shoulder specimens (mean age = 70 ± 14 years) were tested. The average age of the specimens tested was very similar to other reported biomechanical investigations of the shoulder (Ferrari, 1990; Branch et al., 1995; O'Brien et al., 1995; Steinbeck et al., 1998; Tibone et al., 1998). For each specimen the

scapula, distal clavicle, humerus, proximal radius and ulna, and all overlying soft-tissues including ligament, muscle, fat, and skin, were retained. The shoulders were stored in a freezer at -20° C. Before testing, each specimen was thawed for 24 hours at room temperature. The scapula was placed in a medial border fixture and drilled with a three-hole mounting template. The mounting template was designed to ensure anatomic mounting of the shoulders with the medial border of the scapula placed vertically (Warner, 1993; Sobush et al., 1996). The specimen was then mounted to a custom-made shoulder-testing apparatus. The testing position duplicated the position of testing for previously reported *in vivo* laxity and stiffness data collection (Borsa et al., 1999; Sauers, 1999; Borsa et al., 2000a; Borsa et al., 2000b). During anterior and posterior translation testing the humerus was positioned in 20° of abduction in the scapular plane and neutral rotation (Figure 2.2). During inferior translation testing the humerus was placed in 0° of abduction and neutral rotation with the elbow held in 90° of flexion.

Instrumentation

Displacement force was applied and recorded using a custom load applicator. The load applicator consists of a full bridge thin beam load cell (Omega Engineering, Inc., Stamford, CT, model #LC105-50) that has a range from zero to 222 N. A plastic handle is mounted to the end of the load cell for the examiner to grasp and a metal hook is attached to the opposite end for securing the load applicator to an arm cuff. The 2" x 18" arm cuff was secured tightly around the proximal humerus as high in the axillary fold as possible (anterior and posterior trials) or around the proximal forearm (inferior trials).

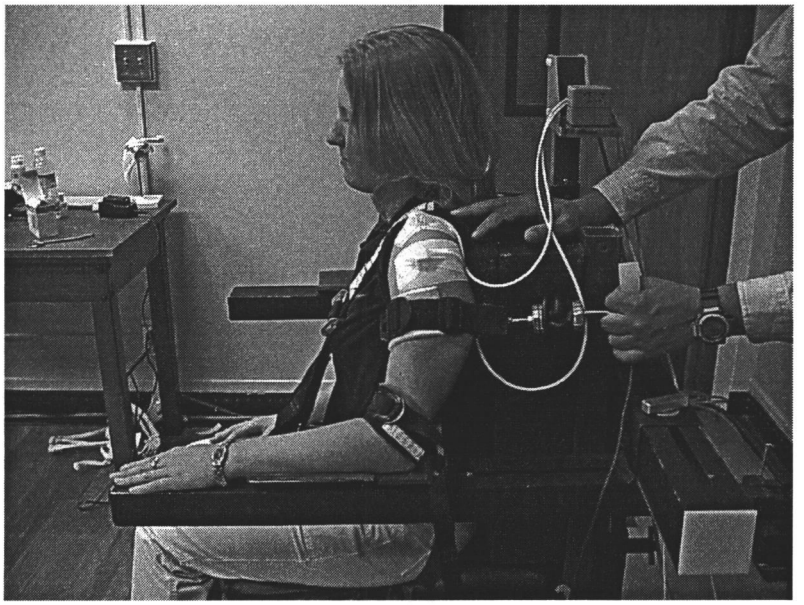

Figure 2.1: *In vivo* cutaneous measurement system.

Figure 2.2: Custom shoulder-testing apparatus with specimen mounted and positioned to replicate previously established *in vivo* force-displacement protocol.

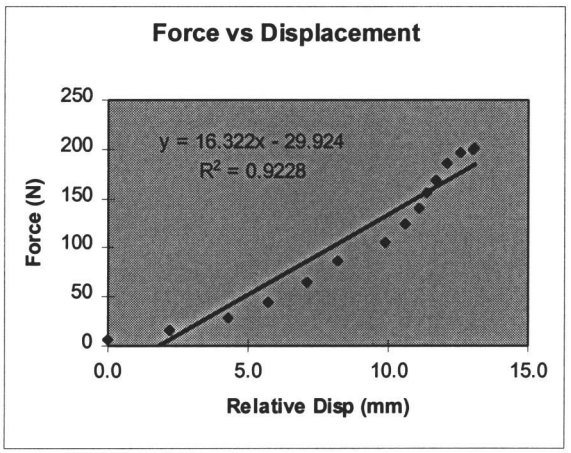

Figure 2.3: Force-displacement curve obtained from cutaneous testing technique.

Displacement was measured using an electromagnetic spatial tracking system (Polhemus Navigation Sciences, Colchester, VT). The electromagnetic transmitter was oriented and secured to the shoulder-testing apparatus. Electromagnetic sensors were secured to the scapula and humerus to record their respective displacements. Scapular displacement was minimal due to the rigid mounting of the specimens, however all observed scapular displacement was subtracted from the observed humeral displacement as an error artifact. Therefore, only measures of humeral displacement were considered in the data analysis with no error introduced from confounding scapular movement. Kinetic data were collected and reduced using custom software to obtain standard force-displacement curves (Figure 2.3).

Testing Protocol

With the shoulder specimen mounted and positioned the electromagnetic sensors were secured cutaneously using self-adhesive tape (Cover-roll® Stretch, Beirsdorff, Inc., Norwalk, CT). The scapular sensor was placed directly over the superior aspect of the acromion process to record errant scapular displacement. For anterior and posterior trials the humeral sensor was located over the lateral aspect of the proximal humerus at the region of the greater tuberosity. During inferior trials the humeral sensor was placed over the lateral humeral epicondyle. This change in sensor placement during inferior force-displacement trials was based on pilot testing which revealed poor cutaneous sensor displacement in the inferior direction when the sensor was placed proximally.

Data collection consisted of three repeated trials to measure translation in the anterior, posterior, and inferior directions. Prior to force-displacement testing the humeral head was manually centered in the glenoid fossa. Next, a progressive force (5.0±3.1 mm/second) from 0-200 N was applied to the joint using the hand held load applicator. Immediately following the cutaneous data collection the sensors were secured directly to the humerus and scapula using 0.093" percutaneous bone-pins. The sensors were left secured in place with the self-adhesive tape and the bone-pins were drilled through sensor holes into the underlying scapula and humerus. This procedure ensured that the cutaneous and bone-pinned data were obtained with the sensors secured in identical locations. Additionally, the use of two bone-pins to secure each sensor ensured the elimination of any unwanted sensor rotation. Data collection was then repeated using the same testing protocol as for the non-invasive, cutaneous technique.

Statistical Analysis

Glenohumeral joint laxity was determined from the mean of the three force-displacement trials in each direction of translation (anterior, posterior, and inferior) at the 200 N force value for each measurement method (cutaneous and bone-pinned). Glenohumeral joint stiffness was calculated in each direction from the slope of the linear portion of the force-displacement curves and the mean of the three trials for each method was used for comparison. Pearson-product moment correlation coefficients and simple linear regression equations were used to compare cutaneous with bone-pinned measurements of laxity and stiffness in each direction. For the purposes of this study, correlation coefficients were interpreted as follows: below 0.50 was poor, 0.50 to 0.75 was good, and above 0.75 was excellent (Portney and Watkins, 1993). Analysis of variance for repeated measures was used to obtain intraclass correlation coefficients (ICC) to determine the between trial reliability of the laxity and stiffness measures across methods and directions. Data were analyzed using Statview® 4.5 statistical software for Macintosh (Abacus Concepts, Inc., Berkeley, CA).

RESULTS

The average glenohumeral joint laxity and stiffness values for each measurement method in each direction of translation are presented in Table 2.1. Table 2.2 lists the results for validity comparing the non-invasive cutaneous measurement technique with percutaneous bone-pinned measurements. Figures 2.4 and 2.5 display the scatterplots for each direction of translation comparing the cutaneous and bone-pinned measures.

Reliability coefficients obtained using the ICC(2,k) formula (Shrout and Fleiss, 1979) were excellent (laxity = 0.99, stiffness =0.95) (Portney and Watkins, 1993).

	Cutaneous	Bone-Pinned	Average Difference
ANTERIOR: Laxity	11.8±5.7	10.3±4.2	1.5 ± 4.0 mm
ANTERIOR: Stiffness	36.8±19.9	31.4±16.0	5.4 ± 12.3 N/mm
POSTERIOR: Laxity	8.6±4.8	9.0±5.2	0.4 ± 4.0 mm
POSTERIOR: Stiffness	53.3±24.9	44.0±28.1	12.1 ± 20.0 N/mm
INFERIOR: Laxity	20.2±7.7	15.5±6.3	4.4 ± 5.8 mm
INFERIOR: Stiffness	15.9±9.0	21.3±12.3	5.4 ± 7.6 N/mm

Table 2.1: Average laxity (mm) and stiffness (N/mm) values reported with the average absolute difference between measurement techniques. All values are reported ± 1 SD.

Direction	r	Regression Equation	SEest	r2
Anterior	0.71	y = 4.1 + .53x	3	0.5
Posterior	0.69	y = 2.7 + .73x	3.9	0.47
Inferior	0.68	y = 4.4 + .56x	4.8	0.46

Table 2.2: Laxity - Correlation coefficient (r), regression equation, standard error of the estimate (SEest), and coefficient of determination (r2), for comparison of cutaneous and bone-pinned laxity data in each direction of translation.

Direction	r	Regression Equation	SEest	r2
Anterior	0.79	y = 8.1 + .63x	10.1	0.62
Posterior	0.68	y = 5.5 + .67x	18.6	0.46
Inferior	0.71	y = -2.0 + 1.5x	7	0.71

Table 2.3: Stiffness - Correlation coefficient (r), regression equation, standard error of the estimate (SEest), and coefficient of determination (r2), for comparison of cutaneous and bone-pinned stiffness data in each direction of translation.

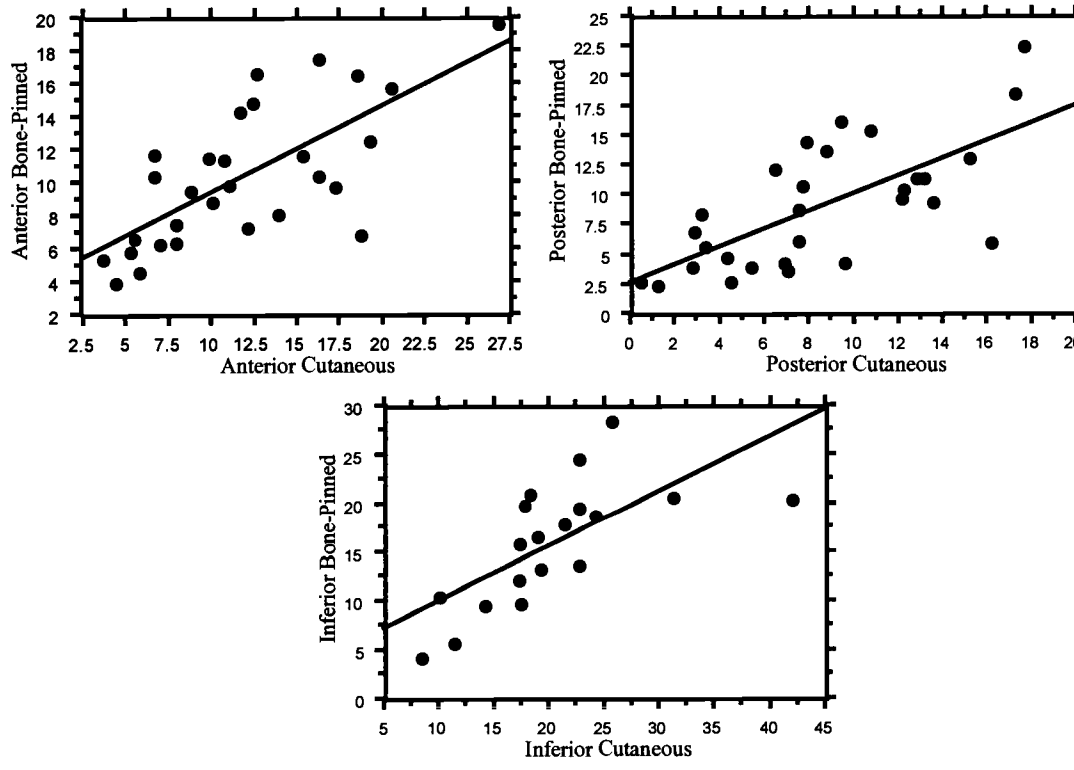

Figure 2.4: Laxity - Scatterplots of anterior, posterior, and inferior glenohumeral joint laxity comparing cutaneous with bone-pinned measurement techniques.

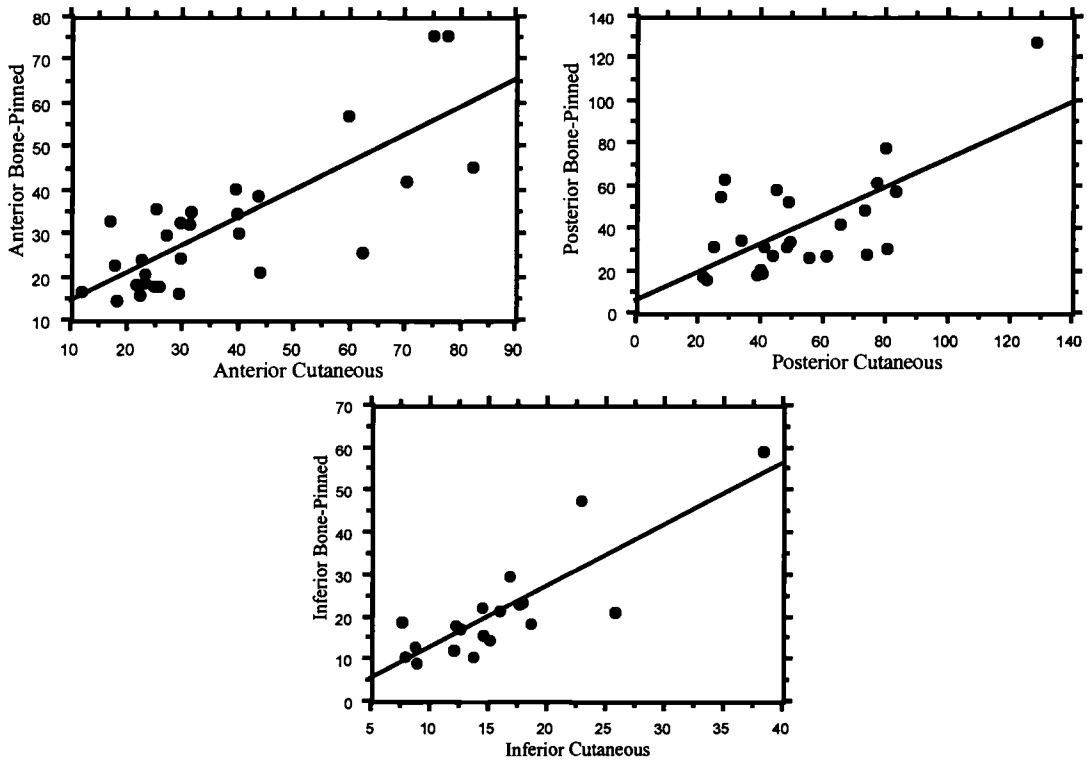

Figure 2.5: Stiffness - Scatterplots of anterior, posterior, and inferior glenohumeral joint stiffness comparing cutaneous with bone-pinned measurement techniques.

DISCUSSION

An *ex vivo* comparison of cutaneous to bone-pinned measures of anterior, posterior, and inferior glenohumeral joint laxity and stiffness using identical testing procedures was performed. The non-invasive, cutaneous measurement technique demonstrated good criterion validity for laxity in all three directions of translation. The Pearson's r values for laxity ranged from 0.68 to 0.71 and the average difference in laxity observed between measurement techniques was 0.4 to 4.4 mm. The cutaneous measurement technique demonstrated excellent criterion validity for stiffness in the

anterior direction (r=0.79) and good criterion validity for stiffness in the posterior (r=0.68) and inferior (r=0.71) direction. The average difference in stiffness between measurement techniques was 5.4 to 12.1 N/mm. The standard error of the estimate (SEest) quantifies the prediction accuracy of the cutaneous method by providing a standard deviation of the degree to which the cutaneous measures vary from the bone-pinned measures (Safrit and Wood, 1989). The SEest for laxity in all three directions ranged from 3.0 to 4.8 mm and from 7.0 to 18.6 N/mm for stiffness. These data indicate that the two different measurement methods are measuring similar changes in glenohumeral joint laxity and stiffness in the anterior, posterior, and inferior directions. Reliability coefficients revealed excellent reproducibility of the laxity and stiffness measures obtained between trials. The calculated regression equations for laxity (Table 2.2) and stiffness (Table 2.3) will enable future *in vivo* investigations of these variables to be performed using a correction factor in each direction that will increase the accuracy of the obtained measures.

Several possible sources of error may account for the observed differences between the cutaneous and bone-pinned measures. Consistent humeral head centering prior to testing is critical for obtaining similar measurements between testing sessions. Small magnitudes of change in the humeral head starting position between measurement sessions can account for significant alterations in obtained laxity and stiffness measures. Despite careful attempts to manually center the humeral head on the glenoid fossa between testing sessions no objective means to ensure appropriate humeral centering was utilized. The custom software utilized in this study determined the zero displacement starting point according to the sensor position at the start of each test session. Therefore,

alterations in actual humeral head start position between cutaneous and bone-pinned measurement sessions were not accounted for. For example, if the humeral head was located 2 mm more anterior on the glenoid at the start of the bone-pinned data collection session compared to the previously collected cutaneous values the end-range laxity value would be reduced by 2 mm with a corresponding change in joint stiffness. A simple and accurate method for ensuring consistent humeral head centering, and therefore a more consistent zero reference starting position, may have led to increased agreement between the two measurement methods.

A second possible source of error may have come from humeral sensor rotation during the cutaneous trials. The arm cuff was wrapped circumeferentially around the proximal humerus during the anterior and posterior test sessions. If the applied displacement force was slightly off-center some rotation of the arm cuff and adjacent skin and subcutaneous soft-tissues was observed. During the bone-pinned trials this rotation did not affect sensor movement due to the rigid two-pin fixation into the underlying humerus. However, small alterations in sensor translation due to skin and subcutaneous tissue rotation were observed on occasion during the cutaneous testing sessions. This rotation error could be accounted for in a more sophisticated evaluation of the 3-D sensor movements, but this investigation only examined linear sensor displacement.

Sensor rotation did not occur during the inferior cutaneous test sessions that utilized a prominent bony landmark, the lateral humeral epicondyle, with very little underlying soft-tissue. During inferior trials it was noted that linear force application was more difficult to achieve compared to the anterior and posterior trials. This was attributed simply to the increased distance between the applied force and the

glenohumeral joint. Fluctuations in the accuracy of the examiners' ability to apply a purely linear displacement force between measurement techniques may have contributed to small variations between measurements of inferior laxity and stiffness.

A valid concern when extrapolating *ex vivo* glenohumeral joint laxity and stiffness findings to *in vivo* application is the influence of resting muscle tone and/or muscle guarding (Karduna et al., 1996; Wuelker et al., 1998). Cadaveric research removes this variable as a source of error variance, however it is of genuine concern during *in vivo* testing and could adversely impact the mechanical properties of the glenohumeral joint (Cofield et al., 1993; Oliashirazi et al., 1993; Ellenbecker et al., 2000). Early *in vivo* pilot work performed on subjects with healthy shoulders revealed concerns associated with muscle guarding. During these early experiments the displacement force was applied with a rigid bar that resulted in contact discomfort at the proximal humerus and subsequent muscular tension about the shoulder. This problem was alleviated when an arm cuff was implemented in place of the rigid bar. To date, over 100 subjects (> 200 shoulders) have been evaluated with the cutaneous measurement technique utilizing the arm cuff. Every subject has been questioned regarding contact discomfort, joint discomfort, and muscular tension. No subject has reported any substantial contact or joint discomfort that has resulted in increased muscular tension or muscle guarding. However, subjects with shoulder pathology may experience greater muscle gaurding during the examination (Cofield et al., 1993; Oliashirazi et al., 1993; Ellenbecker et al., 2000). This proposed source of error remains to be evaluated experimentally.

It is reasonable to hypothesize that measurable and diagnostic differences in laxity and stiffness exist in those patients with shoulder pathology such as instability or adhesive capsulitis / frozen shoulder (Warner et al., 1990; Zuckerman and Cuomo, 1993; Lippitt et al., 1994; Tibone et al., 1998). Objective measures of laxity and stiffness may enable more objective evaluations of surgical procedures aimed at correcting hyper- or hypomobility of the capsuloligamentous restraints (Rodkey et al., 1993; Tibone et al., 1998). Presumably, optimal magnitudes of capsular volume within an individual could be determined based on a bilateral examination of laxity and stiffness in healthy and pathologic shoulders (Warner et al., 1990; Cofield et al., 1993; Oliashirazi et al., 1994; McFarland et al., 1996b). In turn, surgical procedures to increase or decrease capsular volume such as the anterior capsulolabral repair, thermal capsulorraphy, or capsular release could be more objectively performed and evaluated (Friedman, 1993; Glousman and Jobe, 1996; Tibone et al., 1998; Iannotti et al., 2000; Vangsness, 2000).

In recent years several attempts to objectively quantify glenohumeral joint laxity and stiffness *in vivo* have been reported. The *in vivo* bone-pinning studies reported by Harryman et al. (1992) and Lippitt et al. (1994) represent reliable and valid measures of laxity. However, the invasive nature of the measurement technique utilized by these investigators does not lend itself to widespread application. Because the applied force was not measured during the laxity testing these investigators were unable to calculate joint stiffness, a potentially important clinical variable (Wright, 1973; Markolf et al., 1984; McQuade et al., 1999; Borsa et al., 2000a). Furthermore, side-to-side comparisons were not performed on patients with shoulder instability (Lippitt et al., 1994) which may have hindered the ability to detect diagnostic changes in the magnitude of laxity in the

unstable shoulder (Warner et al., 1990). Other investigators have utilized various knee arthrometers to measure glenohumeral translation (Pizzari et al., 1999; Jorgensen and Bak, 1995). Unfortunately, no reports of the validity of these methods exist from which to determine the accuracy of the reported measures. McQuade et al. (1999) recently reported on a non-invasive, cutaneous method to quantify glenohumeral joint force-displacement data. Unfortunately, no validity data have been reported to describe the accuracy of this potentially valuable measurement technique.

This report represents the first step in developing the validity of a non-invasive, cutaneous measurement technique for objective quantification of glenohumeral joint laxity and stiffness. Currently, the cutaneous measurement technique reported herein is a valuable laboratory tool that with future research and development holds promise for more widespread clinical application. Based on the findings of this investigation we believe that the cutaneous measurement technique is a valid method for objectively evaluating *in vivo* glenohumeral joint laxity and stiffness. This instrumented cutaneous technique exhibited a high degree of precision and excellent to good criterion validity. Future investigations should seek to validate this technique *in vivo* and in subjects with documented shoulder instability.

REFERENCES

Bach BR, Warren RF, Flynn WM, et al. Arthrometric evaluation of knees that have a torn anterior cruciate ligament. *J Bone Joint Surg.* 1990;72-A:1299-1306.

Beaulieu CF, Hodge DK, Bergman AG, Butts K, Daniel BL, Napper CL, Darrow RD, Dumoulin CL, Herfkens RJ. Glenohumeral relationships during physiologic shoulder motion and stress testing: Initial experience with open MR imaging and active imaging-plane registration. *Radiology.* 1999;212(3):700-705.

Borsa PA, Sauers EL, Herling DE. In vivo assessment of AP laxity in healthy shoulders using an instrumented arthrometer. *Journal of Sport Rehabilitation* 1999;8:1-14.

Borsa PA, Sauers EL, Herling DE. Patterns of glenohumeral joint laxity and stiffness in healthy males and females. *Med Sci Sports Exerc.* 2000a (In Press).

Borsa PA, Sauers EL, Herling DE. Patterns of glenohumeral joint laxity and stiffness in healthy shoulders. *Med Sci Sports Exerc.* 2000b;32(suppl):S123. Abstract.

Branch TP, Lawton RL, Lobst CA, Hutton WC. The role of glenohumeral capsular ligaments in internal and external rotation of the humerus. *Am J Sports Med.* 1995;23(5):632-637.

Cofield RH, Nessler JP, Weinstabl R. Diagnosis of shoulder instability by examination under anesthesia. *Clin Orthop Rel Res.* 1993;291:45-53.

Daniel DM, Malcom LL, Lossee G, Stone ML, Sachs R, Burks R. Instrumented measurement of anterior laxity of the knee. *J Bone Joint Surg.* 1985a;67:720-726.

Daniel D, Stone ML, Sachs R, Lawrence M. Instrumented measurement of anterior laxity in patients with acute anterior cruciate ligament disruption. *Am J Sports Med.* 1985b;13:401-407.

Ellenbecker TS, Mattalino AJ, Elam E, Caplinger R. Quantification of anterior translation of the humeral head in the throwing shoulder: Manual assessment versus stress radiography. *Am J Sports Med.* 2000;28(2):161-166.

Ferrari DA. Capsular ligaments of the shoulder: Anatomical and functional study of the anterior superior capsule. *Am J Sports Med.* 1990;18(1):20-24.

Fithian DC, Mishra DK, Balen PF, Stone ML, Daniel DM. Instrumented measurement of patellar mobility. *Am J Sports Med.* 1995;23(5):607-615.

Friedman RJ. Glenohumeral capsulorrhaphy. In: Matsen FA, Fu FH, Hawkins RJ, eds. The Shoulder: A Balance of Mobility and Stability. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:445-458.

Gerber C, Ganz R. Clinical assessment of instability of the shoulder with special reference to anterior and posterior drawer tests. *J. Bone Joint Surg.* 1984;66B: 551-556.

Giannotti BF, Fanelli GC, Barrett TA, Edson C. The predictive value of intraoperative KT-1000 arthrometer measurements in single incision anterior cruciate ligament reconstruction. *Arthroscopy.* 1996;12(6):660-666.

Glousman RE, Jobe FW. Anterior shoulder instability, impingement, and rotator cuff tear: Anterior and multidirectional glenohumeral instability. In: Jobe FW (Ed). *Operative Techniques in Upper Extremity Sports Injuries.* St Louis: Mosby;1996:191-209.

Harryman DT, Sidles JA, Clark JM, McQuade KJ, Gibb TD, Matsen III FA. Translation of the humeral head on the glenoid with passive glenohumeral motion. *J Bone Joint Surg.* 1990;72-A(9):1334-1343.

Harryman DT, Sidles JA, Harris BS, Matsen FA: Laxity of normal glenohumeral joint: A quantitative in vivo assessment. *J Shoulder Elbow Surg.* 1992;1(2):66-76

Hawkins RJ, Mohtadi GH. Clinical Evaluation of shoulder instability. *Clin J Sports Med.* 1991;1: 59-64.

Hawkins RJ, Schutte JP, Janda DH, Huckell GH: Translation of the glenohumeral joint with the patient under anesthesia. *J Shoulder Elbow Surg.* 1996;5:286-292.

Iannotti JP, Williams GR, Ramsey ML, Holloway GB, Schenk TJ. Arthroscopic capsular release for the management of the post-operative stiff and painful shoulder. In: Program and abstracts of the 16th open meeting of the American Shoulder and Elbow Surgeons; March 18, 2000; Orlando, FL. Abstract 39.

Jorgensen Uffe, Bak K: Shoulder instability: Assessment of anterior-posterior translation with a knee laxity tester. *Acta Orthop Scand.* 1995;66(5):398-400.

Karduna AR, Williams GR, Williams JL, Iannotti JP. Kinematics of the glenohumeral joint: Influences of muscle forces, ligamentous constraints, and articular geometry. *J Orthop Res.* 1996;14:986-993.

Kochan A, Markolf KL, More RC. Anterior-posterior stiffness and laxity of the knee after major ligament reconstruction. *J Bone Joint Surg.* 1984;66(9):1460-1465.

Kovaleski JE, Gurchiek LR, Heitman RJ, Hollis JM, Pearsall AW 4th. Instrumented measurement of anteroposterior and inversion-eversion laxity of the normal ankle joint complex. *Foot Ankle Int.* 1999;20(12):808-814.

Krarup AL, Court-Payen M, Skjoldbye B, Lautsen GS. Ultrasonic measurement of the anterior translation in the shoulder joint. *J Shoulder Elbow Surg.* 1999;8:136-141.

Levy AS, Lintner S, Kentner, Speer KP. Intra- and interobserver reproducibility of the shoulder laxity examination. *Am J Sports Med.* 1999;27(4):460-463.

Lintner SA, Levy A, Kenter K, Speer K. Glenohumeral translation in the asymptomatic athlete's shoulder and its relationship to other clinically measurable anthropometric variables. *Am J Sports Med.* 1996;24(6):716-720.

Lippitt SB, Harris SL Harryman DT, Sidles J, Matsen FA. In vivo quantification of the laxity of normal and unstable glenohumeral joints. *J Shoulder Elbow Surg.* 1994;3:215-223.

Lippitt S, Matsen F. Mechanisms of glenohumeral joint stability. *Clin Orthop Rel Res.* 1993;291:20-28.

Markolf KL, Amstutz HC. The clinical relevance of instrumented testing for ACL insufficiency: Experience with the UCLA clinical knee testing apparatus. *Clin Orthop Rel Res.* 1987;223:198-207.

Markolf KL, Graff-Radford A, Amstutz HC. In vivo knee stability: A quantitative assessment using an instrumented clinical testing apparatus. *J Bone Joint Surg.* 1978;60A(5):664-674.

Markolf KL, Kochan A, Amstutz HC. Measurement of knee stiffness and laxity in patients with documented absence of the anterior cruciate ligament. *J Bone Joint Surg.* 66A;1984:242-253.

Markolf KL, Mensch JS, Amstutz HC. Stiffness and laxity of the knee – the contributions of the supporting structures: A quantitative *in vitro* study. *J Bone Joint Surg.* 1976;58(5):583-593.

Markolf KL, Pattee GA, Strum GM, Gallick GS, Sherman OH, Dorey VN, Dorey FJ. Instrumented measurements of laxity in patients who have a gore-tex cruciate-ligament substitute. *J Bone Joint Surg.* 1989;71A:887-893.

Matsen III FA, Harryman II DT, Sidles JA. Mechanics of glenohumeral instability. *Clin Sports Med.* 1991;10(4):783-788.

McFarland EG, Campbell G, McDowell J. Posterior shoulder laxity in asymptomatic athletes. *Am J Sports Med.* 1996a;24(4)468-471.

McFarland EG, Shaffer B, Glousman RE, Conway JE, Jobe FW. Anterior shoulder instability, impingement, and rotator cuff tear: Clinical and diagnostic evaluation. In: Jobe FW (Ed). *Operative Techniques in Upper Extremity Sports Injuries.* St Louis: Mosby;1996b:177-190.

McFarland EG, Torpey BM, Curl LA. Evaluation of shoulder laxity. *Sports Med.* 1996c;22:264-272.

McQuade JK, Shelley I, Cvitkovic J. Patterns of stiffness during clinical examination of the glenohumeral joint. *Clin Biomech.* 1999;14:620-627

Neuschwander DC, Drez D, Paine RM, Young JC. Comparison of anterior laxity measurements in anterior cruciate deficient knees with two instrumented testing devices. *Orthopedics.* 1990;13(3):299-302.

O'Brien SJ, Schwartz RS, Warren R, Torzilli PA. Capsular restraints to anterior-posterior motion of the abducted shoulder: A biomechanical study. *J Shoulder Elbow Surg.* 1995;4:298-308.

Oliashirazi A, Mansat P, Cofield RH, Rowland CM. Examination under anesthesia for evaluation of anterior shoulder instability. *Am J Sports Med.* 1999;27(4):464-468.

Pizzari T, Kolt GS, Remedios L. Measurement of anterior-to-posterior translation of the glenohumeral joint using the KT-1000. *J Orthop Sports Phys Ther.* 1999;29(10):602-608.

Portney L, Watkins M. *Foundations of Clinical Research: Applications to Practice.* Norwalk, CT: Appleton & Lange; 1993.

Rodkey WG, Noble JS, Hintermeister RA. Laboratory methods of evaluating the shoulder: Strength, range of motion, and stability. In: Matsen FA, Fu FH, Hawkins RJ, eds. *The Shoulder: A Balance of Mobility and Stability.* Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:551-582.

Safrit MJ, Wood TM. *Measurement Concepts in Physical Education and Exercise Science.* Champaign, IL: Human Kinetics; 1989.

Sauers EL. *In vivo assessment of glenohumeral joint laxity using an instrumented arthrometer: Reliability and correlation to range of motion and generalized joint laxity,* Corvallis, OR: Oregon State University; 1999. Thesis.

Shoemaker SC, Markolf KL. Effects of joint load on the stiffness and laxity of ligament-deficient knees. *J Bone Joint Surg.* 1985;67(1):136-146.

Shrout PE, Fleiss JL. Intraclass correlations: Uses in assessing rater reliability. *Psych Bull.* 1979;86:420-428.

Silliman JF, Hawkins RJ. Classification and physical diagnosis of instability of theshoulder. *Clin Orthop Rel Res* 1993;291:7-19.

Sobush DC, Simoneau GG, Dietz KE, Levene JA, Grossman RE, Smith WB. The lennie test for measuring scapular position in healthy young adult females: A reliability and validity study. *J Orthop Sports Phys Ther.* 1996;23(1):39-50.

Speer KP. Anatomy and pathomechanics of shoulder instability. *Clin Sports Med.* 1995;14(4):751-760.

Steinbeck J, Liljenqvist U, Jerosch J. The anatomy of the glenohumeral ligamentous complex and its contribution to anterior shoulder stability. *Am J Sports Med.* 1998;7:122-126.

Strand T, Solheim E. Clinical tests versus KT-1000 instrumented laxity test in acute anterior cruciate ligament tears. *Int J Sports Med.* 1995;16:51-53.

Tibone JE, McMahon PJ, Shrader TA, Sandusky MD, Lee T. Glenohumeral joint translation after arthroscopic, nonablative, thermal capsuloplasty with a laser. *Am J Sports Med.* 1998;26(4):495-498.

Vangsness CT. Shrink-wrap capsulorrhahpy: The laser and other thermal delivery techniques. In: Instructional Course Lecture. *Arthroscopic evaluation and treatment of shoulder instability.* American Academy of Orthopaedic Surgeons. 2000;191.

Warner JP, Micheli LJ, Arslanian LE, Kennedy J, Kennedy R. Patterns of flexibility, laxity, and strength in normal shoulders and shoulders with instability and impingement. *Am J Sports Med.* 1990;18(4):366-374.

Woo SLY, Young EP, Kwan MK. Fundamental studies in knee ligament mechanics. In: Daniel D, Akeson W, O'Connor J, eds. Knee ligament: structure, function, injury, and repair. New York: Raven Press, 1990:115-134.

Wright V. Stiffness: A review of its measurement and physiologic importance. *Physiotherapy.* 1973;59(4):107-111.

Wuelker N, Korell M, Thren K. Dynamic glenohumeral joint stability. *J Should Elbow Surg.* 1998;7:43-52.

Wuelker N, Schmotzer H, Thren K, Korell M. Translation of the glenohumeral joint with simulated active elevation. *Clin Orthop Rel Res.* 1994;309:193-200.

Zuckerman JD, Cuomo F. Frozen shoulder. In: Matsen FA, Fu FH, Hawkins RJ, eds. The Shoulder: A Balance of Mobility and Stability. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:253-268.

CHAPTER THREE

Characterization of Capsular Laxity and Glenohumeral Joint Compliance Using a Valid and Reproducible Cadaveric Model

Eric L. Sauers, Paul A. Borsa, Derald E. Herling, and Waleed F. Manzour

To be submitted to *Journal of Bone and Joint Surgery*
July, 2000

ABSTRACT

A variety of shoulder pathologies such as instability and posterior capsular contracture are the result of changes in capsular volume with symptomatic alterations in the magnitude of humeral translation. However, few studies exist from which to determine the normal magnitudes of translation and capsular volume at the glenohumeral joint. The purpose of this experiment was to determine the force-displacement characteristics of anterior, posterior, and inferior translation, and global capsular laxity using a valid and reproducible cadaveric model to provide further insight into the sagittal translational area of the normal glenohumeral joint. Twenty fresh frozen cadaver shoulders were tested in a custom-made shoulder-testing apparatus in 20° of abduction and neutral rotation in the scapular plane. Anterior, posterior, and inferior translation at four levels of increasing force (89, 134, 178, and 200 N) were recorded using a load cell and electromagnetic spatial tracking system. Analysis of variance showed a significant increase in capsular laxity with increasing force application ($p=.0017$). A 3 (direction) x 4 (force level) factorial ANOVA revealed significant differences in translation between directions ($p<.0001$) and between force levels ($p=.0003$). At the maximum force level (200 N) large magnitudes of translation were observed (anterior = 10.4±4.0 mm, posterior = 9.9±5.0 mm, inferior = 15.0±5.6 mm, capsular volume = 237±136 mm^2). Similar compliance in each direction was observed between force levels. This study provides valuable normative information regarding physiologic capsular laxity with special reference to the individual components of anterior, posterior, and inferior translation, at increasing levels of applied force.

INTRODUCTION

Small magnitudes of humeral head translation have been recorded both with active (Weulker et al., 1994) and passive (Harryman et al., 1990) humeral elevation. This obligate translation of the humeral head on the glenoid is physiologic and, in fact, necessary in order to achieve the large degrees of freedom afforded the highly mobile shoulder. Laxity is defined as the ability of the humeral head to be passively translated on the glenoid fossa in response to applied force (Matsen et al., 1991; Speer, 1995). Soft-tissue restraints at the glenohumeral joint such as the joint capsule, capsular ligaments, and glenoid labrum, restrict excessive translation of the humeral head on the glenoid surface and maintain stability of the joint at the extremes of humeral motion (O'Brien et al., 1990; O'Connell et al., 1990; Lew et al., 1993; Warner et al., 1992; Warner, 1993; O'Brien et al., 1995). Wide variations in the intra-articular capacity have been observed between shoulders and are considered normal (Harryman et al., 1992; Lippitt et al., 1994; Borsa et al., 1999; Sauers, 1999; Borsa et al., 2000a). These wide variations may result in significant differences in the observed laxity during the physical examination, but are not considered pathologic unless they are correlated with the presence of symptoms (Warner et al., 1990; Matsen et al., 1991; Harryman et al., 1992; Friedman, 1993; Speer, 1995; McFarland 1996a; Lintner et al., 1996). Changes in laxity as the result of attenuated or contracted capsular restraints leading to alterations of intra-articular capacity and symptoms such as pain, sensations of subluxation, or loss of motion, are considered pathologic (Zuckerman and Cuomo, 1993; Speer, 1995; Glousman and Jobe, 1996; Morgan, 2000; Ticker et al., 2000).

Capsular volume is defined as the intra-articular capacity through which the humeral head can be translated. True measurement of three-dimensional capsular volume is not practical. However, for the purposes of this study capsular laxity is reported from calculating the sagittal translational area, a single measure of the area through which the humeral head can be translated in the anterior, posterior, and inferior directions (Harryman et al., 1992). In this report, the term capsular volume is used to describe theoretical changes in the intra-articular capacity of the glenohumeral joint, whereas use of the term capsular laxity denotes a measured variable representative of the global sagittal plane translational area.

Following injury to the shoulder such as a traumatic subluxation or dislocation of the glenohumeral joint the capsular volume is theorized to increase (Caspari and Geissler, 1993; Soslowsky et al., 2000). Atraumatic and multidirectional instability are also associated with increased capsular volume (Kvitne and Jobe, 1993; O'Driscoll, 1993). These increases in capsular volume can result in excessive and symptomatic humeral head translation (Kvitne and Jobe, 1993; O'Driscoll, 1993; Glousman and Jobe, 1996). Similarly, contracture of the posterior joint capsule has been theorized to result in increased superior migration of the humeral head resulting in internal impingement (Morgan et al., 1998; Abrams, 2000; Morgan, 2000; Ticker et al., 2000). Determining the optimal intervention in the presence of shoulder symptoms necessitates that the total capsular laxity as well as the contributing components of anterior, posterior, and inferior laxity be determined and carefully considered.

Numerous surgical procedures share the common goal of restoring normal capsuloligamentous mechanics and intra-articular capacity (O'Driscoll, 1993; Glousman

and Jobe, 1996; Tibone et al., 1998; Abrams, 2000; Heis et al., 2000; Iannotti et al., 2000; Ticker et al., 2000; Vangsness, 2000). Different procedures are directed towards different areas of the capsule to decrease, or in some cases, increase the length of the capsuloligamentous restraints. Such procedures are thought to alter the magnitude of available humeral translation on the glenoid by tensioning or lengthening the static soft-tissue restraints that serve to limit humeral motion. Procedures to restore normal arthrokinematics of the shoulder are dependent upon the underlying pathology. The treatments for anterior instability (Glousman and Jobe, 1996; Tibone et al., 1998), congenital hyperlaxity (O'Driscoll, 1993; Vangsness, 2000), and contracted posterior capsule (Abrams, 2000; Morgan, 2000; Ticker et al., 2000), are each directed towards specific areas of the capsule. Therefore, it becomes imperative to define the global intra-articular capacity while still taking into consideration the contributions from anterior, posterior, and inferior translation, to determine the correct surgical intervention technique and magnitude of capsular alteration to restore normal arthrokinematics at the glenohumeral joint.

The purpose of this experiment was to determine the force-displacement characteristics of anterior, posterior, and inferior translation, and the global capsular laxity using a valid and reproducible cadaveric model to provide further insight into the sagittal translational area of the normal glenohumeral joint. In turn, future studies to determine the effects of pathologic capsular tension and surgical intervention strategies to restore normal capsular volume can be evaluated more objectively and compared across studies using identical experimental procedures.

MATERIALS AND PROCEDURES

Specimen Preparation and Testing Apparatus

Twenty fresh frozen human cadaveric shoulder specimens (mean age = 71 ± 14 years) were tested. The average age of the specimens tested was very similar to other reported biomechanical investigations of the shoulder (Ferrari, 1990; Branch et al., 1995; O'Brien et al., 1995; Steinbeck et al., 1998; Tibone et al., 1998). For each specimen the scapula, distal clavicle, humerus, proximal radius and ulna, and all overlying soft-tissues including ligament, muscle, fat, and skin, were retained. The shoulders were stored in a freezer at -20° C.

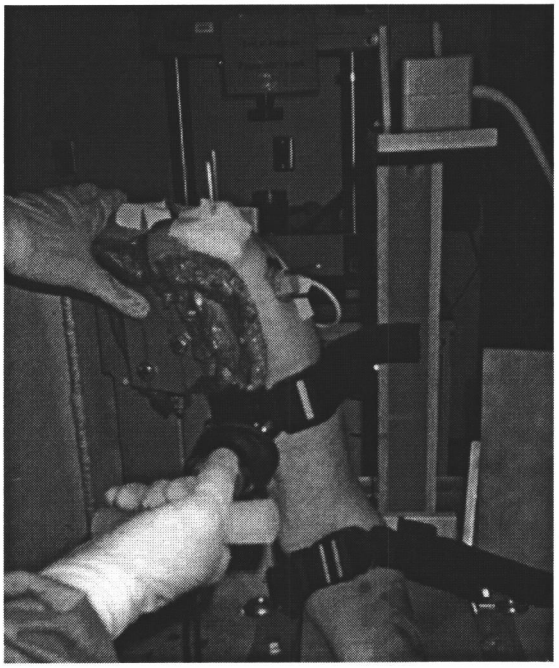

Figure 3.1: Shoulder specimen mounted for anterior-posterior testing.

Before testing, each specimen was thawed for 24 hours at room temperature. The scapula was placed in a medial border fixture and drilled with a three-hole mounting template. The mounting template was designed to ensure anatomic mounting of the shoulders with the medial border of the scapula placed vertically (Warner, 1993; Sobush et al., 1996). The specimen was then mounted to a custom-made shoulder-testing apparatus (Figure 3.1). The testing position duplicated the position of testing for previously reported *in vivo* force-displacement data collection (Borsa et al., 1999; Sauers, 1999; Borsa et al., 2000a; Borsa et al., 2000b). During anterior and posterior translation testing the humerus was secured in 20° of abduction in the scapular plane and neutral rotation (Figure 3.1). During inferior translation testing the humerus was placed in 0° of abduction and neutral rotation with the elbow held in 90° of flexion.

Instrumentation

Displacement force was applied and recorded using a custom load applicator. The load applicator consists of a full bridge thin beam load cell (Omega Engineering, Inc., Stamford, CT, model #LC105-50) that has a range from zero to 222 N. A plastic handle is mounted to the end of the load cell for the examiner to grasp and a metal hook is attached to the opposite end for securing the load applicator to an arm cuff. The 2" x 18" arm cuff was secured tightly around the proximal humerus as high in the axillary fold as possible (anterior and posterior trials) or around the proximal forearm (inferior trials).

Displacement was measured using an electromagnetic spatial tracking system (Polhemus Navigation Sciences, Colchester, VT). The electromagnetic transmitter was oriented and secured to the shoulder-testing apparatus. Electromagnetic sensors were

secured to the scapula and humerus to record their respective displacements. Scapular displacement was minimal due to the rigid mounting of the specimens, however all measured scapular displacement was subtracted from the measured humeral displacement as an error artifact. Therefore, only measures of humeral displacement were considered in the data analysis with no error introduced from confounding scapular movement. Data were collected and reduced using custom software to obtain standard force-displacement curves.

Testing Protocol

With the shoulder specimen mounted and positioned the electromagnetic sensors were affixed cutaneously using self-adhesive tape (Cover-roll® Stretch, Beirsdorff, Inc., Norwalk, CT) and then secured directly to the humerus and scapula using 0.093" percutaneous bone-pins. Two bone-pins were utilized to secure each sensor and ensure the elimination of any unwanted sensor rotation. The scapular sensor was placed directly over the superior aspect of the acromion process to record errant scapular displacement. For anterior and posterior trials the humeral sensor was located over the lateral aspect of the proximal humerus at the region of the greater tuberosity. During inferior trials the humeral sensor was placed over the lateral humeral epicondyle. This change in sensor placement during inferior force-displacement trials was based on pilot testing which revealed poor cutaneous sensor displacement in the inferior direction when the sensor was placed proximally.

Data collection consisted of three repeated trials to measure translation in the anterior, posterior, and inferior directions. Prior to force-displacement testing the

humeral head was manually centered in the glenoid fossa. Next, a progressive force (5.0±3.1 mm/second) from 0-200 N was applied to the joint using the hand held load applicator. Anterior and posterior displacement tests were conducted first and the specimen was then remounted to an inferior mounting bracket where inferior displacement testing followed using the same procedures.

Statistical Analysis

Glenohumeral joint laxity was determined from the mean of the three force-displacement trials in each direction of translation (anterior, posterior, and inferior) at four pre-selected force values (89, 134, 178, and 200 N). To calculate the sagittal translational area, or capsular laxity, the mean displacement value for anterior (A), posterior (P), and inferior (I) translation for each shoulder was placed into the following formula (Harryman et al., 1992):

Sagittal translational area = capsular laxity = π / 4 (A•I + P•I)

A comparison of capsular laxity at the four increasing levels of applied force was performed using a univariate analysis of variance (ANOVA). To provide information regarding the separate contributions to capsular laxity from anterior, posterior, and inferior translation a 3 (direction) x 4 (force level) factorial ANOVA was performed. The *a priori* alpha level for all analyses was set at 0.05. Data were analyzed using Statview® 4.5 statistical software for Macintosh (Abacus Concepts, Inc., Berkeley, CA).

RESULTS

Anterior, posterior, and inferior translation values and capsular laxity at each level of force are presented in Table 3.1. The capsular laxity ANOVA revealed significant differences in sagittal translational area recorded at increasing force levels (p=.0017). Figure 3.2 displays the linear increase in capsular laxity in response to increasing force application. The 3 (direction) x 4 (force level) factorial ANOVA revealed significant differences in translation between directions (p<.0001) and between force levels (p=.0003). Scheffe post-hoc analyses revealed no significant difference in translation between the anterior and posterior directions (0.4 mm, p = .55), however significant differences were observed between inferior and anterior (4.6 mm, p = <.0001) and inferior and posterior (5.1 mm, p<.0001) translation. Figure 3.3 displays the corresponding increase in translation at increasing levels of applied force for each direction. The corresponding compliance values for each direction of translation are presented in Table 3.2.

Force	Anterior	Posterior	Inferior	Capsular Laxity
89 N	7.2±3.0	7.0±4.0	11.0±4.5	123±75 sq-mm
134 N	8.7±3.3	8.3±4.5	12.9±4.6	172±99 sq-mm
178 N	9.9±3.7	9.4±4.8	14.4±5.3	217±126 sq-mm
200 N	10.4±4.0	9.9±5.0	15.0±5.6	237±136 sq-mm

Table 3.1: Translation and Capsular Laxity – The mean ± 1 SD values at each level of force for translation (mm) in each direction and global capsular laxity (mm^2).

Force Range	Anterior	Posterior	Inferior
0-89 N	7.2 mm (69%)	7.0 mm (71%)	11.0 mm (73%)
89-134 N	1.5 mm (14%)	1.3 mm (13%)	1.9 mm (13%)
134-178 N	1.2 mm (12%)	1.1 mm (11%)	1.5 mm (10%)
178-200 N	0.5 mm (5%)	0.5 mm (5%)	0.6 mm (4%)

Table 3.2: Glenohumeral joint compliance between each increasing level of force. Note the similarity in compliance between directions.

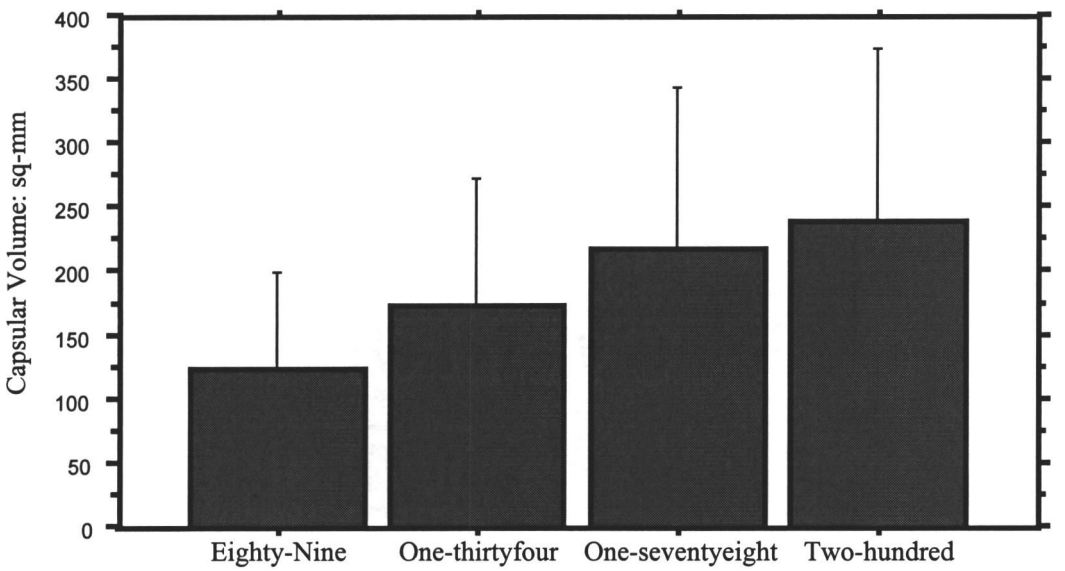

Figure 3.2: Bar plot for capsular laxity (mm^2) at increasing force levels (N). Error bars are +1 standard deviation.

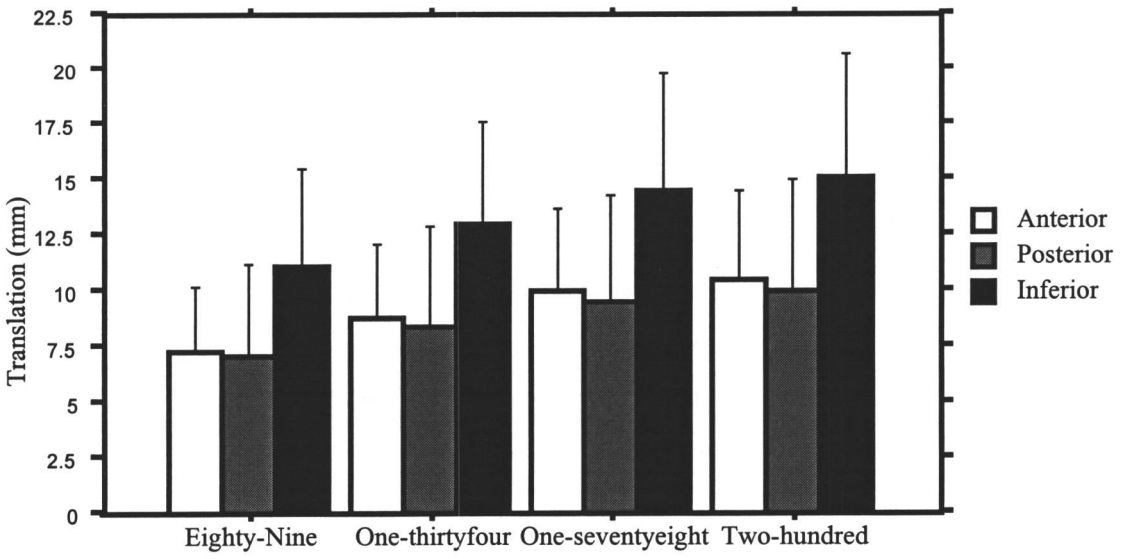

Figure 3.3: Bar plot for anterior, posterior, and inferior translation (mm) at increasing force levels (N). Error bars are +1 standard deviation.

DISCUSSION

The effect of changes in capsular volume on shoulder motion and function are not well understood (Tibone et al., 1998). Large variations in capsular volume and the individual magnitudes of translation in the anterior, posterior, and inferior directions have been described (Harryman et al., 1992; Lippitt et al., 1994; Borsa et al., 1999; Sauers, 1999; Borsa et al., 2000a). The most accurate measures of capsular laxity can be obtained using: 1) direct bone-pinning of the scapula and humerus to record force-displacement, 2) flaccid musculature to control measurement error induced from muscular tension, and 3) in tact musculature to provide passive restraint to translation (Harryman et al., 1992; Cofield et al., 1993; Rodkey et al., 1993; Lippitt et al., 1994; Debski et al., 1999; Oliashirazi et al., 1999). These conditions are most readily met through the use of cadaver shoulder specimens. We have determined capsular laxity

using a valid and reproducible measurement protocol of direct bone-pinning of the scapula and humerus to record force-displacement characteristics in cadaver shoulders with in tact rotator cuff and overlying musculature.

Recently, the importance of the rotator cuff and overlying musculature to provide passive restraint to anterior-posterior translation in response to applied loads has been reported (Debski et al., 1999). The majority of previous investigations performed using cadaver shoulders to evaluate force-displacement characteristics have dissected down to the capsuloligamentous restraints, thereby eliminating this important passive restraining mechanism. Despite the age of the specimens tested we observed large magnitudes of translation and global capsular volume with significant variability between shoulders. These findings highlight previously reported *in vivo* findings that large magnitudes of humeral translation are not necessarily pathologic and significant variability in the magnitude of translation exists between shoulders (Warner et al., 1990; Harryman et al., 1992; Lippitt et al., 1994; Lintner et al., 1996; McFarland et al., 1996c; Borsa et al., 1999; Sauers, 1999; Borsa et al., 2000a).

In response to increasing levels of applied force, the humeral head will continue to translate over the glenoid surface until the static soft-tissue restraints become taut and resist further displacement (Warner et al., 1992; Lew et al., 1993; Woo et al., 1993). The vertical and horizontal distance of the glenoid has been shown to be 35 mm and 25 mm, respectively (Maki and Gruen, 1988; Warner, 1993; Woo et al., 1993). Therefore, the humeral head is able to translate significant distances before tension is developed in the soft-tissue restraints (Lew et al., 1993; O'Brien et al., 1995). In the position of relative adduction and neutral rotation utilized in this study the capsuloligamentous restraints

would be at their most lax position allowing maximal translation to occur before becoming taut and resisting further displacement (O'Brien et al., 1990; O'Connell et al., 1990; Woo et al., 1993; O'Brien et al., 1995). We recorded force-displacement characteristics of the glenohumeral joint at displacement forces up to 200 N. Displacement was highly reproducible between trials indicating that non-recoverable deformation was not occurring during the three repeated applications of 0-200 N of force.

Capsular laxity was shown to increase significantly with increasing levels of applied force. Capsular laxity was shown to increase nearly two-fold between the 89 to 200 N displacement force levels. At 200 N the capsular laxity averaged 237±136 mm^2. This is approximately 68% of the available sagittal translational area if the humeral head were able to translate across the entire horizontal distance and inferior half of the vertical distance of the glenoid surface [$\pi/4$ (12.5 x 17.5 + 12.5 x 17.5) = 344 mm^2] (Maki and Gruen, 1988; Warner, 1993; Woo et al., 1993). This comparison suggests that on average the center of the humeral head was not translating over the rim of the glenoid in any direction even at the 200 N force level. This is supported subjectively by the observation that most shoulders were felt to translate up to the glenoid rim in each direction (Hawkins grade I) but never over the rim (Hawkins and Bokor, 1990). Between trials the humeral head reduced back to the starting position when the force was removed to within 0.3 mm. Evaluation of the average displacement at 200 N in each direction of translation provides further support to the observation that humeral head translation was less than the glenoid diameter. Based on previous reports of the average vertical and horizontal distance of the glenoid surface (Maki and Gruen, 1988; Warner, 1993; Woo et al., 1993; O'Brien et al., 1995) it can be assumed that >12.5 mm of translation in the anterior and posterior

directions and >17.5 mm of translation in the inferior direction are required to displace the center of the humeral head over the rim of the glenoid. The average maximum displacement values observed in this study were slightly less than would be required to displace the center of the humeral head over the rim of the glenoid (anterior = 10.4 mm, posterior = 9.9 mm, inferior = 15.0 mm). These displacement values represent translation equal to approximately 81% of the horizontal surface of the glenoid in the anterior and posterior directions and approximately 86% of the vertical surface of the glenoid in the inferior direction.

O'Brien et al. (1995) evaluated anterior and posterior translation of the humeral head at 90° of abduction and neutral rotation. These investigators reported on the close relationship between the average glenoid diameter and the average magnitude of anterior/posterior translation. The mean sagittal width of the glenoid surface averaged 28.4 mm compared to an average total anterior/posterior translation of 26±6.2 mm. The contributions from anterior (12.24±3.32 mm) and posterior (13.04±5.5 mm) translation were very symmetric. O'Brien et al. (1995) felt that this was because the ligaments were not under tension and the humeral head was allowed to translate over the entire glenoid surface until it contacted the anterior and posterior attachments of the inferior glenohumeral ligament on the glenoid rim.

Hawkins et al. (1996) assessed translation of the glenohumeral joint radiographically using manual laxity testing with the patient under anesthesia. Healthy shoulders were evaluated and translation in the anterior and posterior directions was reported as a percentage of the diameter of the glenoid from anterior to posterior and in the inferior direction as a percentage of the diameter of the glenoid from superior to

inferior. The geometric center of the humeral head was determined and radiographs under flouroscopic control were taken during loading and at the clinical end feel. The load and shift test was used to assess anterior-posterior translation and inferior translation was evaluated by applying enough longitudinal stress to reach a clinical end feel. Radiographic evaluation revealed anterior translation of only 17%, posterior of 26%, and inferior of 29%. These values are substantially lower than what we calculated using average glenoid diameter values from previously reported findings. A comparison of the observed displacement relative to actual glenoid diameter values in each cadaver shoulder would be valuable in the future.

Glenohumeral joint compliance is defined as the difference in translation between force levels in the same loading cycle (Borsa et al., 2000a). The findings of this study demonstrate nearly identical glenohumeral joint compliance in each direction of translation (Table 2.3). On average, approximately 71% of the observed displacement occurred between 0-89 N of force. Approximately 12% of the total amount of displacement was observed over each of the next two force ranges (89-134 N and 134-178N). Finally, over the last range of measured force (178-200 N) only 5% of the total translation was observed. It is not surprising that the magnitude of observed displacement decreased at the increasing force levels. The magnitude of applied increase in force between the four force levels was not equal. The measured ranges of force decreased in order from 89 N, 45 N, 45 N, to 22 N. Therefore, symmetrical magnitudes of displacement should not be expected. However, with the percentage of applied force normalized the compliance level is, in fact found to be decreasing over the last two force ranges. This finding supports the hypothesis that at forces greater than 134 N the

humeral head is no longer translating as freely on the glenoid surface. Several factors could be at work to explain this observation including joint geometry, labral resistance, and/or capsuloligamentous tension (Lew et al., 1993; Warner, 1993; Woo et al., 1993). We suspect that greater force is required to displace the humeral head as it begins to move up the glenoid rim and contact the capsuloligamentous insertions (Soslowski et al., 1993; O'Brien et al., 1995). Future research should seek to utilize this testing model to determine the contribution of these stabilizing mechanisms to the force-displacement characteristics of the glenohumeral joint.

The methods and procedures reported herein were meticulously modeled after previously developed *in vivo* testing apparatus, instrumentation, and procedures (Borsa et al., 1999; Sauers, 1999; Borsa et al., 2000a; Borsa et al., 2000b). We have reported glenohumeral joint compliance determined *in vivo* (Sauers, 1999; Borsa et al., 2000a). Unfortunately, only 134 N of force was applied and no inferior displacement testing was performed. However, valuable comparisons can still be made between anterior and posterior glenohumeral joint compliance at the 0-89 N and 89-134 N force levels. Similarly to that which was observed in the cadaver shoulders, the majority of displacement occurred during the first 89 N of applied force (anterior = 9.4 mm = 79%, posterior = 9.9 mm = 84%). A similar reduction in glenohumeral joint compliance, greater than expected from the reduction in force range, was also observed between the 89-134 N force range (anterior = 2.5 mm = 21%, posterior = 1.9 mm = 16%). These findings confirm that very similar force-displacement characteristics exist between data obtained from shoulders *in vivo* and fresh frozen cadaver shoulders. Future investigations should continue to use similar methods and procedures *in vivo* and *ex vivo*

to confirm the similarity in force-displacement characteristics we have observed. To our knowledge, the *ex vivo* biomechanical model reported herein is the first attempt to replicate precisely current *in vivo* testing methods and procedures to simultaneously describe force-displacement characteristics of the human shoulder.

In this study we observed directional symmetry between anterior and posterior laxity (difference = 0.5 mm, p=0.55) However, inferior laxity was significantly greater than both anterior (4.6 mm, p<.0001) and posterior (5.1 mm, p<.0001) laxity. We have previously reported *in vivo* findings of directional symmetry (p=0.26) between anterior (11.9 mm) and posterior (11.8 mm) translation (Sauers, 1999). Harryman et al. (1992), and later Lippitt et al. (1994), each recorded anterior, posterior, and inferior laxity of the healthy shoulder *in vivo*. Both studies were conducted at the same institution and utilized percutaneously bone-pinned sensors and an electromagnetic tracking system to record humeral displacement in response to manually applied forces. Both studies report stressing the joint to clinical end feel, however no objective measurement of force was utilized. Harryman et al. (1992) found anterior (7.8 mm) and posterior (7.9) translation to be within 0.1mm. Inferior translation was slightly greater (10.6 mm) than anterior and posterior translation. Similarly, Lippitt et al. (1994) reported directional symmetry between anterior (8.1 mm) and posterior (7.5 mm) translation. Again, inferior laxity (11.2 mm) was found to be greater than both anterior and posterior translation. Each of these four studies, using similar instrumentation and arm position have found directional symmetry between anterior and posterior laxity. Three of the four studies evaluated inferior laxity as well and found it to be consistently greater than both anterior and posterior translation. Inferior laxity reported from these studies is between 36% and 48%

greater than anterior and posterior laxity. Interestingly, the glenoid surface is approximately 30% greater in the vertical direction compared to the horizontal direction. Therefore, the available translation appears to be related to the vertical and horizontal distance of the glenoid surface.

Although a wide range of capsular volume and directional laxity are present between individuals, an optimal magnitude appears necessary within a given individual for normal shoulder function to occur. Excessive capsular volume is associated with instability as the result of symptomatic humeral head translation (Glousman and Jobe, 1996; Tibone et al., 1998; Vangsness, 2000). This is often treated with surgical procedures aimed at reducing excessive, pathologic capsular volume (Jobe et al., 1996; Tibone et a., 1998; Vangsness, 2000). Conversely, decreased capsular volume is thought to result in excessive restriction of humeral head motion resulting in pain and dysfunction (Abrams, 2000; Iannotti et al., 2000; Morgan, 2000; Ticker et al., 2000). The goals of surgical intervention in the presence of decreased capsular volume are to restore normal motion through capsular lengthening procedures (Abrams, 2000; Iannotti et al., 2000; Morgan, 2000; Ticker et al., 2000). Despite the critical importance of global capsular laxity and separate anterior, posterior, and inferior translation, these variables remain difficult to objectively assess and little quantitative data exists to support the many theories regarding normal and pathologic stability.

We have reported valuable information regarding physiologic capsular laxity with special reference to the individual components of anterior, posterior, and inferior laxity, at increasing levels of applied force. This information may assist the surgeon seeking to restore normal arthrokinematics to the injured shoulder in the presence of suspected

increased or diminished capsular volume. Furthermore, we have developed a valid and reproducible biomechanical model for evaluating force-displacement characteristics at the glenohumeral joint that mimics *in vivo* methods and procedures. Future studies using this model should evaluate the effects of various lesions and surgical intervention techniques on the force-displacement characteristics of the human shoulder.

REFERENCES

Abrams J. Posterior-superior glenohumeral impingement in overhead athletes. In: Instructional Course Lecture. *Arthroscopic evaluation and treatment of shoulder instability.* American Academy of Orthopaedic Surgeons. 2000;191.

Borsa PA, Sauers EL, Herling DE. In vivo assessment of AP laxity in healthy shoulders using an instrumented arthrometer. *Journal of Sport Rehabilitation* 1999;8:1-14.

Borsa PA, Sauers EL, Herling DE. Patterns of glenohumeral joint laxity and stiffness in healthy males and females. *Med Sci Sports Exerc.* 2000a (In Press).

Borsa PA, Sauers EL, Herling DE. Patterns of glenohumeral joint laxity and stiffness in healthy shoulders. *Med Sci Sports Exerc.* 2000b;32(suppl):S123. Abstract

Branch TP, Lawton RL, Lobst CA, Hutton WC. The role of glenohumeral capsular ligaments in internal and external rotation of the humerus. *Am J Sports Med.* 1995;23(5):632-637.

Caspari RB, Geissler WB. Arthroscopic manifestations of shoulder subluxation and dislocation. *Clin Orthop Rel Res.* 1993;291:54-66.

Cofield RH, Nessler JP, Weinstabl R. Diagnosis of shoulder instability by examination under anesthesia. *Clin Orthop Rel Res.* 1993;291:45-53.

Debski RE, Sakane M, Woo SLY, Wong K, Fu FH, Warner JJP. Contribution of the passive properties of the rotator cuff to glenohumeral stability during anterior-posterior loading. *J Shoulder Elbow Surg.* 1999;8:324-329.

Ferrari DA. Capsular ligaments of the shoulder: Anatomical and functional study of the anterior superior capsule. *Am J Sports Med.* 1990;18(1):20-24.

Glousman RE, Jobe FW. Anterior shoulder instability, impingement, and rotator cuff tear: Anterior and multidirectional glenohumeral instability. In: Jobe FW (Ed). *Operative Techniques in Upper Extremity Sports Injuries*. St Louis: Mosby;1996:191-209.

Harryman DT, Sidles JA, Clark JM, McQuade KJ, Gibb TD, Matsen III FA. Translation of the humeral head on the glenoid with passive glenohumeral motion. *J Bone Joint Surg*. 1990;72-A(9):1334-1343.

Harryman DT, Sidles JA, Harris BS, Matsen FA: Laxity of normal glenohumeral joint: A quantitative in vivo assessment. *J Shoulder Elbow Surg*. 1992;1(2):66-76

Hawkins RJ, Bokor DJ. Clinical evaluation of shoulder problems. In: Rockwood CA, Matsen FA, eds. The Shoulder. Philadelphia, WB Saunders; 1990:149-117.

Hawkins RJ, Schutte JP, Janda DH, Huckell GH: Translation of the glenohumeral joint with the patient under anesthesia. *J Shoulder Elbow Surg*. 1996;5:286-292.

Heis FT, Osbahr D, Speer KP. Arthroscopic release of the diabetic frozen shoulder: An outcome study. In: Program and abstracts of the 16th open meeting of the American Shoulder and Elbow Surgeons; March 18, 2000; Orlando, FL. Abstract 38.

Iannotti JP, Williams GR, Ramsey ML, Holloway GB, Schenk TJ. Arthroscopic capsular release for the management of the post-operative stiff and painful shoulder. In: Program and abstracts of the 16th open meeting of the American Shoulder and Elbow Surgeons; March 18, 2000; Orlando, FL. Abstract 39.

Jobe CM, Pink MM, Jobe FW, Shaffer B. Anterior shoulder instability, impingement, and rotator cuff tear: Theories and concepts. In: Jobe FW (Ed). *Operative Techniques in Upper Extremity Sports Injuries*. St Louis: Mosby;1996:164-176.

Kvitne RS, Jobe FW. The diagnosis and treatment of anterior instability in the throwing athlete. *Clin Orthop Rel Res*. 1993;291:107-123.

Lew WD, Lewis JL, Craig EV. Stabilization by capsule, ligaments, and labrum: Stability at the extremes of motion. In: Matsen FA, Fu FH, Hawkins RJ, eds. The Shoulder: A Balance of Mobility and Stability. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:69-90.

Lintner SA, Levy A, Kenter K, Speer K. Glenohumeral translation in the asymptomatic athlete's shoulder and its relationship to other clinically measurable anthropometric variables. *Am J Sports Med*. 1996;24(6):716-720.

Lippitt S, Matsen F. Mechanisms of glenohumeral joint stability. *Clin Orthop Rel Res*. 1993;291:20-28.

Maki S, Gruen T. Anthropometric studies of the glenohumeral joint. *Trans Orthop Res Soc.* 1988;13:162.

Matsen III FA, Harryman II DT, Sidles JA. Mechanics of glenohumeral instability. *Clin Sports Med.* 1991;10(4):783-788.

McFarland EG, Campbell G, McDowell J. Posterior shoulder laxity in asymptomatic athletes. *Am J Sports Med.* 1996a;24(4)468-471.

McFarland EG, Torpey BM, Curl LA. Evaluation of shoulder laxity. *Sports Med.* 1996c;22:264-272.

Morgan CD. SLAP lesions in the overhead athlete: Current concepts. In: Instructional Course Lecture. *Arthroscopic evaluation and treatment of shoulder instability.* American Academy of Orthopaedic Surgeons. 2000;191.

Morgan CD, Burkhart SS, Palmeri M, Gillespie M. Type II slap lesions: Three subtypes and their relationships to superior instability and rotator cuff tears. *Arthroscopy.* 1998;14:553-565.

O'Brien SJ, Neves MC, Arnoczky SP, Rozbruck R, Dicarlo EF, Warren RF, Schwartz R, Wickiewicz TL. The anatomy and histology of the inferior glenohumeral ligament complex of the shoulder. *Am J Sports Med.* 1990;18(5):449-456.

O'Brien SJ, Schwartz RS, Warren R, Torzilli PA. Capsular restraints to anterior-posterior motion of the abducted shoulder: A biomechanical study. *J Shoulder Elbow Surg.* 1995;4:298-308.

O'Connell PW, Nuber GW, Mileski RA, Lautenschlager E. The contribution of the glenohumeral ligaments to anterior stability of the shoulder joint. *Am J Sports Med.* 1990;18(6):579-583.

O'Driscoll SW. Atraumatic instability: Pathology and pathogenesis. In: Matsen FA, Fu FH, Hawkins RJ, eds. The Shoulder: A Balance of Mobility and Stability. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:305-316.

Oliashirazi A, Mansat P, Cofield RH, Rowland CM. Examination under anesthesia for evaluation of anterior shoulder instability. *Am J Sports Med.* 1999;27(4):464-468.

Rodkey WG, Noble JS, Hintermeister RA. Laboratory methods of evaluating the shoulder: Strength, range of motion, and stability. In: Matsen FA, Fu FH, Hawkins RJ, eds. *The Shoulder: A Balance of Mobility and Stability.* Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:551-582.

Sauers EL. *In vivo assessment of glenohumeral joint laxity using an instrumented arthrometer: Reliability and correlation to range of motion and generalized joint laxity,* Corvallis, OR: Oregon State University; 1999. Thesis.

Sobush DC, Simoneau GG, Dietz KE, Levene JA, Grossman RE, Smith WB. The lennie test for measuring scapular position in healthy young adult females: A reliability and validity study. *J Orthop Sports Phys Ther.* 1996;23(1):39-50.

Soslowsky LJ, Flatow EL, Bigliani LU, Mow VC. Stabilization of the glenohumeral joint by articular contact and by contact in the subacromial space In: Matsen FA, Fu FH, Hawkins RJ, eds. The Shoulder: A Balance of Mobility and Stability. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:107-124.

Soslowsky LJ, Malicky DM, Mouro C, Bey MJ, Frisancho J, Lindholm S, Kuhn J. Total and non-recoverable strain fields of the glenohumeral joint capsule under shoulder subluxation. In: Program and abstracts of the 16th open meeting of the American Shoulder and Elbow Surgeons; March 18, 2000; Orlando, FL. Abstract 32.

Speer KP. Anatomy and pathomechanics of shoulder instability. *Clin Sports Med.* 1995;14(4):751-760.

Steinbeck J, Liljenqvist U, Jerosch J. The anatomy of the glenohumeral ligamentous complex and its contribution to anterior shoulder stability. *Am J Sports Med.* 1998;7:122-126.

Tibone JE, McMahon PJ, Shrader TA, Sandusky MD, Lee T. Glenohumeral joint translation after arthroscopic, nonablative, thermal capsuloplasty with a laser. *Am J Sports Med.* 1998;26(4):495-498.

Ticker JB, Beim GM, Warner JP. Recognition and treatment of refractory posterior capsular contracture of the shoulder. *Arthroscopy.* 16(1);2000:27-34.

Vangsness CT. Shrink-wrap capsulorrhahpy: The laser and other thermal delivery techniques. In: Instructional Course Lecture. *Arthroscopic evaluation and treatment of shoulder instability.* American Academy of Orthopaedic Surgeons. 2000;191.

Warner JP. The gross anatomy of the the joint surfaces, ligaments, labrum, and capsule. In: Matsen FA, Fu FH, Hawkins RJ, eds. The Shoulder: A Balance of Mobility and Stability. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:7-27.

Warner JP, Deng XH, Warren RF, Torzilli PA. Static capsuloligamentous restraints to superior-inferior translation of the glenohumeral joint. *Am J Sports Med.* 1992;20(6):675-685.

Warner JP, Micheli LJ, Arslanian LE, Kennedy J, Kennedy R. Patterns of flexibility, laxity, and strength in normal shoulders and shoulders with instability and impingement. *Am J Sports Med.* 1990;18(4):366-374.

Woo SLY, McMahon PJ, Debski RE, Fu FH, Blomstrom GL. Factors limiting and defining shoulder motion: What keeps it form going farther?. In: Matsen FA, Fu FH, Hawkins RJ, eds. The Shoulder: A Balance of Mobility and Stability. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:141-158.

Wuelker N, Schmotzer H, Thren K, Korell M. Translation of the glenohumeral joint with simulated active elevation. *Clin Orthop Rel Res.* 1994;309:193-200.

Zuckerman JD, Cuomo F. Frozen shoulder. In: Matsen FA, Fu FH, Hawkins RJ, eds. The Shoulder: A Balance of Mobility and Stability. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:253-268.

CHAPTER FOUR

The Use of an Instrumented Manual Laxity Examination to Quantify Humeral Translation at the Shoulder

Eric L. Sauers, Paul A. Borsa, Derald E. Herling, and Waleed F. Manzour

To be submitted to *Journal of Shoulder and Elbow Surgery*
July, 2000

ABSTRACT

The manual laxity assessment is a major component of the standard physical examination of the shoulder. We have developed a non-invasive technique to increase the objectivity of the manual laxity examination through the use of cutaneously applied instrumentation. However, the accuracy of this method has yet to be determined. Therefore, the purpose of this study was to compare three different measurement methods (manual cutaneous, manual bone-pinned, and kinetic bone-pinned) used to quantify anterior, posterior, and inferior, translation at the shoulder. Our specific aims were to: 1) compare the three measurement methods, and 2) estimate the magnitude of force used to reach clinical end-point during manual laxity tests. Thirty fresh frozen cadaver shoulder specimens were tested. Standard manual laxity tests were performed and displacement was recorded using electromagnetic sensors applied both cutaneously and with percutaneous bone-pins to the scapula and humerus. Force-displacement (kinetic) data were also obtained. A 3(method) x 3(direction) factorial ANOVA revealed a significant difference between methods ($p=.0024$) and between directions ($p<.0001$) with no significant interaction effect ($p. = 0948$). A comparison of the bone-pinned force-displacement data and bone-pinned manual data showed that more force was necessary to reach clinical end-point in the anterior direction (173±45 N) compared to posterior (123±62 N; $p = .0071$) and inferior (121±58 N; $p = .0038$). The findings of this study indicate that non-invasive, cutaneous instrumentation can be added to the traditional manual laxity examination to increase the accuracy and reproducibility of measures of humeral translation. Furthermore, we have demonstrated that more force is required to achieve clinical end-point in the anterior direction compared to posterior and inferior.

INTRODUCTION

The manual laxity assessment is a major component of the standard physical examination of the shoulder (Hawkins and Bokor, 1990; McFarland et al., 1996b). The load and shift and inferior sulcus tests are manual tests frequently used to assess humeral translation (Gerber and Ganz, 1984; McFarland et al., 1996c). Laxity is a physiologic variable required for normal shoulder function (Harryman et al., 1990; Wuelker et al., 1994; Speer, 1995). In recent years it has become clear that large magnitudes of humeral translation are not necessarily pathologic. A wide spectrum of laxity is present in healthy shoulders with conflicting reports regarding observed side-to-side and directional symmetry of translation (Warner et al., 1990; Lintner et al., 1996; McFarland et al., 1996a; Borsa et al., 1999; Sauers, 1999; Borsa et al., 2000a; Borsa et al., 2000b).

Recently, the manual laxity examination has been shown to exhibit poor reproducibility (Levy et al., 1999; Ellenbecker et al., 2000). Laxity tests are subjective in nature and rely on clinician "feel" to describe the magnitude of observed humeral translation in response to a manually applied force (Hawkins et al., 1996; Levy et al., 1999; Oliashirazi et al., 1999). Difficulty in reproducibly quantifying the observed humeral translation, large magnitudes of translation in asymptomatic shoulders, and reports of significant overlap in the magnitude of translation between healthy and unstable shoulders have brought into question the value of the manual laxity examination (Warner et al., 1990; Lippitt et al., 1994; Lintner et al., 1996; McFarland et al., 1996a; Levy et al., 1999; Ellenbecker et al., 2000). A significant problem is the inability to precisely quantify humeral translation in response to applied loads. Current subjective grading systems utilize a four part categorical scale to attempt to define how far the

humeral head translates on the glenoid (Hawkins and Bokor, 1990; McFarland et al., 1996c). However, examiners have difficulty agreeing on the observed translation even with such a crude scale and suggestions to simplify the classification system have been reported (McFarland et al., 1996a; Levy et al., 1999).

Another reported problem observed with the manual laxity examination is the lack of precise measurement of the applied force (Levy et al., 1999; McQuade et al., 1999). Authors have suggested a wide range of applied forces necessary to reach clinical end point during laxity examination. Some of the reports have been based on actual kinetic measures (Jorgensen and Bak, 1995; Borsa et al., 1999; Krarup et al., 1999; McQuade et al., 1999; Pizzari et al., 1999; Borsa et al., 2000a; Borsa et al., 2000b; Ellenbecker et al., 2000) while others appear to be subjective estimations (Gerber and Ganz, 1984; Hawkins et al., 1996; Oliashirazi et al., 1999).

In the last decade several attempts to quantify *in vivo* force-displacement at the shoulder, similar to those at the knee, have been reported in the orthopaedic literature. Investigators have used custom force-displacement systems (Borsa et al., 1999; Borsa et al., 2000a; Borsa et al., 2000b), knee arthrometers (Jorgensen and Bak, 1995; Pizzari et al., 1999), and instrumented manual tests (Harryman et al., 1992; Lippitt et al., 1994; McQuade et al., 1999), as well as a variety of imaging techniques (Beaulieu et al., 1999; Krarup et al., 1999; Ellenbecker et al., 2000), to quantify humeral translation. Harryman et al., (1992), and later Lippitt et al., (1994), were the first to report the addition of electromagnetic sensors to the manual laxity examination. This valid, reproducible, and objective measurement method yielded valuable information regarding normal and pathologic laxity at the glenohumeral joint, however the invasive methodology is not

clinically applicable. If similar, non-invasive cutaneous instrumentation and methods could be developed for use in conjunction with the manual laxity examination the objectivity, precision, and accuracy, of these tests could be greatly enhanced. This in turn could yield valuable data regarding normal and pathologic laxity at the shoulder.

We have developed a non-invasive technique to increase the objectivity of the manual laxity examination through the use of cutaneously applied instrumentation. However, the accuracy of this method has yet to be determined. Therefore, the purpose of this study was to compare three different measurement methods used to quantify anterior, posterior, and inferior, translation at the shoulder. Our specific aims were to: 1) compare manual cutaneous, manual bone-pinned, and kinetic (force-displacement) bone-pinned, measures of translation in the anterior, posterior, and inferior, directions and 2) estimate the magnitude of force used to reach clinical end-point by comparing manual bone-pinned and kinetic bone-pinned measures of translation.

MATERIALS AND PROCEDURES

Specimen Preparation and Testing Apparatus

Thirty fresh frozen human cadaveric shoulder specimens (mean age = 70 ± 14 years) were tested. The average age of the specimens tested was very similar to other reported biomechanical investigations of the shoulder (Ferrari, 1990; Branch et al., 1995; O'Brien et al., 1995; Steinbeck et al., 1998; Tibone et al., 1998). For each specimen the scapula, distal clavicle, humerus, proximal radius and ulna, and all overlying soft-tissues including ligament, muscle, fat, and skin, were retained. The shoulders were stored in a

freezer at -20° C. Before testing, each specimen was thawed for 24 hours at room temperature. The scapula was placed in a medial border fixture and drilled with a three-hole mounting template. The mounting template was designed to ensure anatomic mounting of the shoulders with the medial border of the scapula placed vertically (Warner, 1993; Sobush et al., 1996). The specimen was then mounted to a custom-made shoulder-testing apparatus. The testing position duplicated the position of testing for previously reported *in vivo* laxity and stiffness data collection (Borsa et al., 1999; Sauers, 1999; Borsa et al., 2000a; Borsa et al., 2000b). During anterior and posterior translation testing the humerus was positioned in 20° of abduction in the scapular plane and neutral rotation. During inferior translation testing the humerus was placed in 0° of abduction and neutral rotation with the elbow held in 90° of flexion.

Instrumentation

During kinetic testing the displacement force was applied and recorded using a custom load applicator. The load applicator consists of a full bridge thin beam load cell (Omega Engineering, Inc., Stamford, CT, model #LC105-50) that has a range from zero to 222 N. A plastic handle is mounted to the end of the load cell for the examiner to grasp and a metal hook is attached to the opposite end for securing the load applicator to an arm cuff. The 2" x 18" arm cuff was secured tightly around the proximal humerus as high in the axillary fold as possible (anterior and posterior trials) or around the proximal forearm (inferior trials).

For both manual and kinetic data collection the observed displacement was measured using an electromagnetic spatial tracking system (Polhemus Navigation

Sciences, Colchester, VT). The electromagnetic transmitter was oriented and secured to the shoulder-testing apparatus. Electromagnetic sensors were secured to the scapula and humerus to record their respective displacements. Scapular displacement was minimal due to the rigid mounting of the specimens, however all observed scapular displacement was subtracted from the observed humeral displacement as an error artifact. Therefore, only measures of humeral displacement were considered in the data analysis with no error introduced from confounding scapular movement. Data were collected and reduced using custom software to obtain standard force-displacement curves (kinetic method) and displacement-time curves (manual methods).

Testing Protocol

Once the shoulder specimen was mounted and positioned the electromagnetic sensors were secured cutaneously using self-adhesive tape (Cover-roll® Stretch, Beirsdorff, Inc., Norwalk, CT). The scapular sensor was placed directly over the superior aspect of the acromion process to record errant scapular displacement. For anterior and posterior trials the humeral sensor was located over the lateral aspect of the proximal humerus at the region of the greater tuberosity. During inferior trials the humeral sensor was placed over the lateral humeral epicondyle. This change in humeral sensor placement during inferior trials was based on pilot testing which revealed poor cutaneous sensor displacement in the inferior direction when the sensor was placed proximally. The scapular sensor was left in place throughout the various testing procedures. Anterior and posterior measures were obtained first followed by inferior measures.

Data collection for each method consisted of three repeated trials to measure translation in the anterior, posterior, and inferior directions. The manual laxity tests were performed by an experienced orthopaedic surgeon (WFM). The load and shift test was utilized to evaluate anterior and posterior laxity (Figure 4.1) and the sulcus test was utilized to evaluate inferior laxity. Each of the manual laxity tests was performed to clinical end-point. The cutaneous manual laxity tests were performed first. Immediately following the cutaneous data collection the sensors were secured directly to the humerus and scapula using 0.093" percutaneous bone-pins. The sensors were left secured in place with the self-adhesive tape and the bone-pins were drilled through sensor holes into the underlying scapula and humerus. This procedure ensured that the cutaneous and bone-pinned data were obtained with the sensors secured in identical locations. Data collection then continued in random order with both manual bone-pinned and kinetic (force-displacement) bone-pinned measurement methods. Manual bone-pinned data collection utilized the same testing protocol as for the non-invasive, cutaneous technique.

With the sensors bone-pinned into the underlying scapula and humerus, force-displacement data were obtained. The load applicator and arm cuff were applied to record the magnitude of applied force. Prior to force-displacement testing the humeral head was manually centered in the glenoid fossa. Next, a progressive force (5.0±3.1 mm/second) from 0-200 N was applied to the joint and standard force-displacement curves were obtained.

Figure 4.1: Shoulder specimen mounted for anterior-posterior manual testing.

Statistical Analysis

Glenohumeral joint laxity for each method (manual cutaneous, manual bone-pinned and force-displacement bone-pinned) was determined from the mean of the three displacement trials in each direction of translation (anterior, posterior, and inferior). The maximum displacement value for each trial was used for the manual tests and the displacement value at 200 N of force was used for the kinetic tests. A 3 (method) x 3 (direction) factorial ANOVA was used to evaluate statistically significant main effects for laxity using each method and laxity in each direction of translation. Scheffe post-hoc analyses were used to reveal significant differences between translation for each method and direction. The level of statistical significance was set at 0.05.

To estimate the magnitude of force utilized during the manual laxity tests the force-displacement bone-pinned data were compared to the manual bone-pinned data. The force-displacement laxity value closest to the maximum manual bone-pinned

displacement value was determined. The corresponding force and displacement values were then compared to the clinical end-point value determined from the manual bone-pinned data to estimate the magnitude of force necessary to achieve clinical end-point. Planned comparisons in the form of multiple paired t-tests were performed to identify significant differences between the estimated force necessary to reach clinical end-point in each direction. To control for inflated alpha levels resulting from repeated comparisons, we adjusted the alpha of 0.05 by the number of comparisons per dependent variable ($c = 2$). Thus our adjusted alpha level was set at 0.025 (0.05/2). Data were reduced and analyzed using Statview® 4.5 statistical software for Macintosh (Abacus Concepts, Inc., Berkeley, CA).

RESULTS

The average laxity values obtained using each measurement method are provided in Table 4.1. Analysis of variance revealed statistically significant mean (±SD) differences in laxity between measurement methods [$F(2,238) = 6.2$; $p = .0024$] and between directions of translation [$F(2,238) = 41.1$; $p = <.0001$]. No statistically significant interaction effect for translation between measurement methods and directions was observed [$F(4,238) = 2.0$; $p = .0948$] (Figures 4.2 and 4.3). Sheffe post-hoc analyses revealed significant differences between force-displacement bone-pinned measures and manual cutaneous measures ($p = .0367$) and between manual cutaneous and manual bone-pinned measures ($p = .0017$) (Table 4.2). Scheffe post hoc analyses also revealed significant differences between each direction of translation ($p <.0001$) (Table 4.3).

Laxity (mm)	Bone-pinned	Manual Cutaneous	Manual Bone-pinned
Anterior	10.3±4.2	13.1±5.6	11.1±4.4
Posterior	9.0±5.2	8.5±4.7	7.5±4.1
Inferior	15.5±6.3	17.6±4.7	12.8±4.3

Table 4.1: Average laxity (±SD) recorded with each measurement method.

Methods	Mean Difference	Critical Difference	P-value
Bone-pin, ManCut	2.0 mm	1.88 mm	0.0367
Bone-pin, ManBone	0.7 mm	1.86 mm	0.6357
ManCut, ManBone	2.7 mm	1.83 mm	0.0017

Table 4.2: Scheffe post-hoc comparisons between measurement methods.

Directions	Mean Difference	Critical Difference	P-Value
Anterior, Posterior	3.2 mm	1.82 mm	<.0001
Anterior, Inferior	3.8 mm	1.88 mm	<.0001
Posterior, Inferior	6.9 mm	1.88 mm	<.0001

Table 4.3: Scheffe post-hoc comparisons between directions of translation.

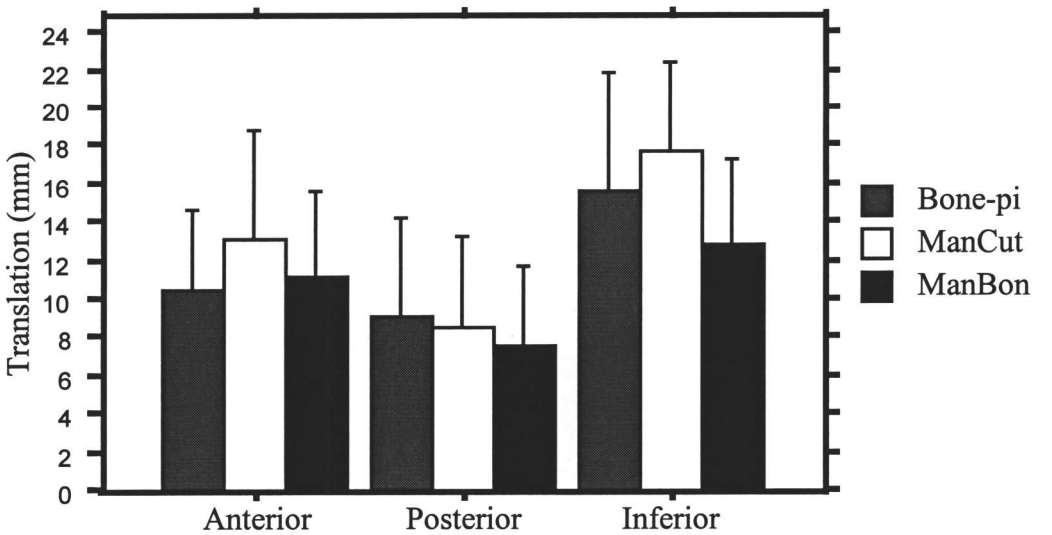

Figure 4.2: Interaction bar plot (method x direction) for translation (±SD) (ManCut = manual cutaneous; ManBone = manual bone-pin).

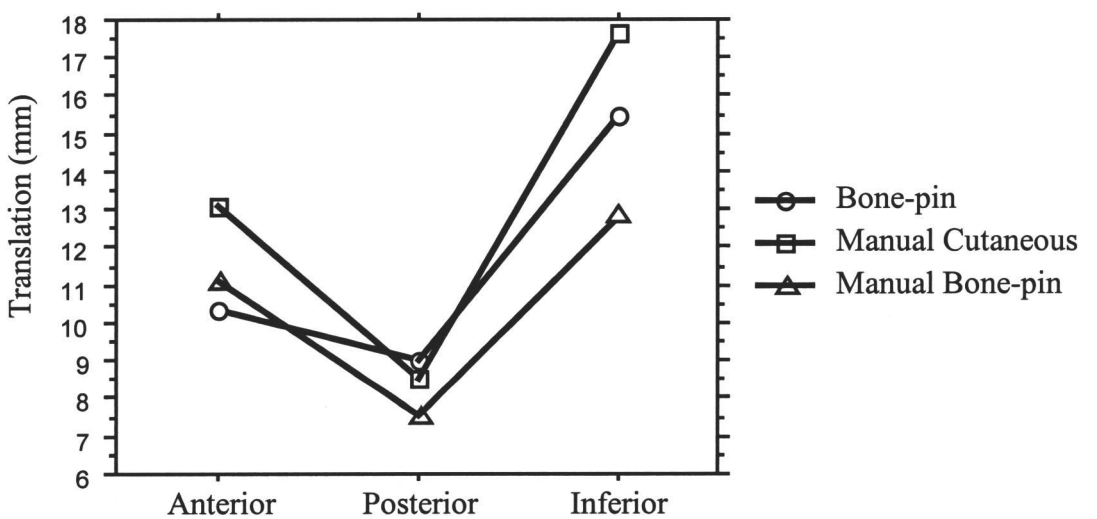

Figure 4.3: Interaction line plot for laxity.

The average estimated force to reach clinical end-point varied according to the direction of translation (Table 4.4). Planned comparisons revealed significant differences in the magnitude of force necessary to reach clinical end-point (Table 4.5). Figure 4.4 shows the reproducibility of the obtained laxity measures for each measurement method.

	Mean	SD	SE	Minimum	Maximum
Anterior	173	45	8.6	59	200
Posterior	123	62	11.9	26	200
Inferior	121	58	13.8	29	200

Table 4.4: Descriptive data for estimated force applied to reach clinical end-point. All values are reported in Newtons (N).

	Mean Difference	t-value	P-value
Anterior, Posterior	50 N	2.9	0.0071
Anterior, Inferior	53 N	3.4	0.0038
Posterior, Inferior	2 N	0.08	0.935

Table 4.5: Planned comparisons between directions for estimated force applied to reach clinical end-point.

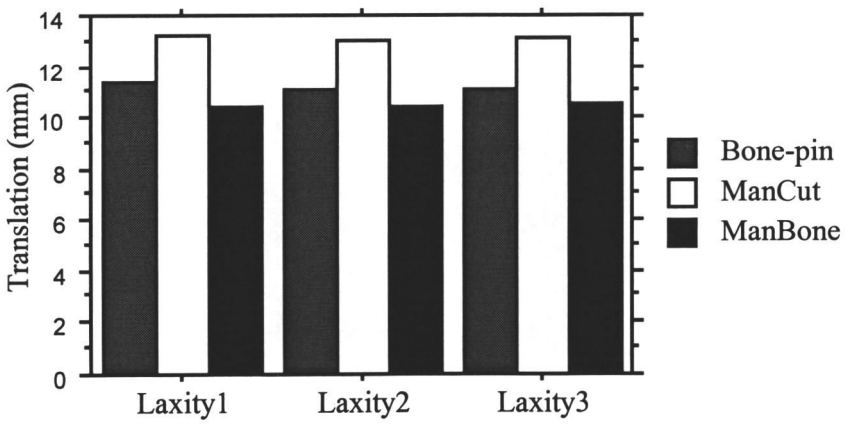

Figure 4.4: Bar plot displaying the reproducibility of laxity measurements obtained between trials for each measurement method.

DISCUSSION

Measurement Method

Our results revealed significant differences between the three different measurement methods utilized to quantify humeral translation. No significant difference was observed between the manual bone-pinned and kinetic bone-pinned measures. This finding indicates that these invasive techniques are, in fact, valid measures of glenohumeral joint laxity. The non-invasive, manual cutaneous method was significantly different from both of the invasive bone-pinned methods.

Small differences were observed in the magnitude of recorded anterior, posterior, and inferior translation between the three different measurement methods (Figures 4.2 and 4.3). Clinically, the magnitudes of observed differences between measurement methods may not be significant (<3 mm). However, with future refinement of the testing protocol, and special attention to sensor rotation observed during the cutaneous trials we believe that these differences can be minimized.

A review of the actual manual techniques performed yields what we believe to be the primary reasons for the observed differences between the cutaneous and bone-pinned manual methods. During the anterior and posterior measurements the examiner grasped the proximal humerus and cupped the humeral sensor between their thumb and index finger (Figure 4.1). Linear application of force from the examiners hand to the humerus was critical to obtaining accurate cutaneous measures. Flexion or extension of the examiners wrist resulted in rotation of the soft-tissues overlying the humerus. During the cutaneous measurement sessions this could cause unwanted rotation, and subsequent

translation, of the humeral sensor. Because two bone-pins were used to secure the sensor during the manual bone-pinned sessions this unwanted rotation did not alter the position of the humeral sensor. Due to constraints imposed by our testing apparatus and space the examiner always grasped the humerus with their thumb anterior and fingers posterior. It was apparent that a pure translation force, with no cutaneous rotation, was easier to achieve while the examiner was pushing (posterior trials) versus pulling (anterior trials). Therefore, greater error introduced from sensor rotation during the cutaneous trials was observed in the anterior direction. This is manifested as an increase in the mean anterior translation recorded from the manual cutaneous measurement method (Table 4.1). With care, we feel the examiner can control this unwanted cutaneous sensor rotation and increase the accuracy of the cutaneous manual method.

The discrepancy between inferior translation measures obtained with the different measurement methods is attributed to the difficulty in applying a purely linear displacement force. Small differences in the magnitude of inferior translation were recorded if the manual displacement force was directed somewhat anterior-posterior, or medial-lateral. Overall, the differences in translation recorded between measurement methods was small and we offer these observations to explain the recorded differences and for consideration during future experimental designs.

Our data demonstrate that each measurement method was highly reproducible between measurement trials. A previous *in vivo* study has demonstrated a high degree of precision using force-displacement cutaneous instrumentation (Sauers, 1999). Muscular tension did not appear to adversely effect the reproducibility of the obtained measures *in vivo* (Sauers, 1999). Further study is needed to determine the between session, and

between examiner reproducibility of the non-invasive cutaneous manual laxity examination.

Overall, significant differences in the magnitude of translation were observed between directions. Conflicting reports exist regarding the symmetry of translation recorded in different directions in the healthy (non-injured) shoulder (Harryman et al., 1992; Borsa et al., 1999; Borsa et al., 2000a; Borsa et al., 2000b). Using similar methods and procedures to evaluate anterior and posterior translation of the healthy shoulder *in vivo* we have reported directional symmetry in some populations of study (Borsa et al., 1999; Borsa et al., 2000b), whereas another population exhibited directional asymmetry (Borsa et al., 2000a). Certain populations, such as overhead athletes, may be expected to have greater anterior than posterior laxity (Kvitne and Jobe, 1993; Jobe et al., 1996; Ellenbecker et al., 2000). However, in the healthy shoulder the symmetry of directional translation appears to be shoulder specific. Further studies to characterize the magnitude of translation in each direction need to be conducted in overhead athletes and in shoulders with specific pathologies such as a Bankart lesion or posterior capsular contracture.

In this study the testing position, methods, and procedures, were designed to duplicate current *in vivo* measurement techniques (Borsa et al., 1999; Sauers, 1999; Borsa et al., 2000a; Borsa et al., 2000b). Unlike the traditional load and shift, and inferior sulcus tests, these procedures employ external mechanical constraints to reduce accessory motion of the trunk, scapula, and forearm. By minimizing accessory motion in these areas we have found that the manual laxity examination can be performed *in vivo* with greater ease. This is attributed to greater subject relaxation and decreased muscular tension. So, this *ex vivo* study attempted to replicate these test positions. However, this

limits the findings of this study to these test positions where external mechanical methods are employed to reduce accessory motion. Therefore, this study does not determine the value of the addition of cutaneous instrumentation to the manual laxity examination performed clinically with the patient seated or supine with no mechanical stabilization of the scapula or forearm. The methods and procedures employed in this study, and currently under investigation *in vivo*, are valuable from a research perspective, but further study to determine the clinical applicability of this technique needs to be conducted.

Force Estimation

Our results show that more force was necessary in the anterior direction compared to posterior and inferior to reach clinical end-point during the manual assessment (Table 4.4 and 4.5). To demonstrate the method by which we estimated the force during the manual exam, Figure 4.5 shows the displacement-time curve from a manual bone-pinned posterior laxity test (average translation = 6.1 mm). A review of the corresponding force-displacement curve obtained from the kinetic test shows that the corresponding laxity value (6.0 mm) was obtained at only 67 N of applied force (Figure 4.6). Therefore, for this specimen, it was estimated that 67 N was required to reach clinical end-point in the posterior direction. Figure 4.7 reveals that during an anterior manual bone-pinned test session the average translation recorded at clinical end-point was 18.3 mm. However, the corresponding force-displacement curve shows that even at the 200 N displacement force only 12.8 mm of anterior translation has been obtained (Figure 4.8). Therefore, for this shoulder more force was necessary to obtain clinical end-point and a force-displacement curve similar to Figure 4.6. Greater than 200 N of force would have been necessary to

achieve the magnitude of translation recorded using the manual method for 14 shoulders in the anterior direction compared to only 4 and 3 shoulders in the posterior and inferior directions, respectively.

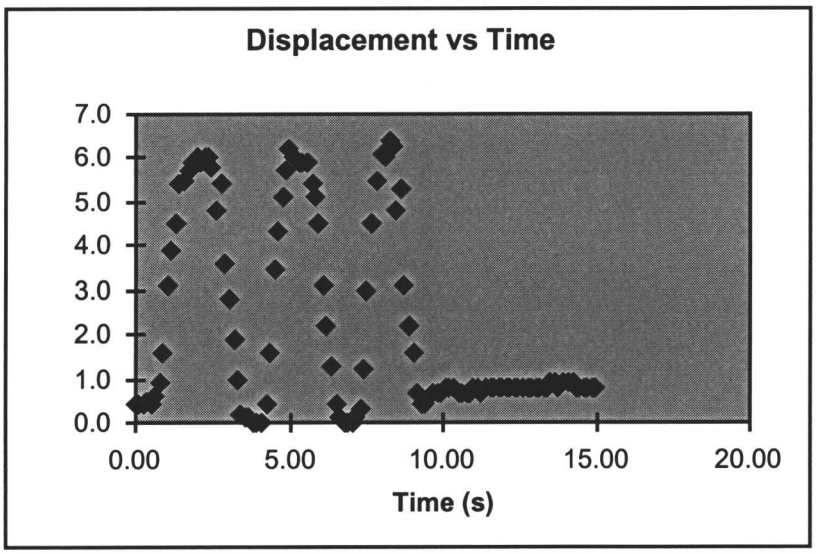

Figure 4.5: Displacement-time curve for posterior translation (6.1 mm) obtained from a manual bone-pinned test session. Note the reproducibility between trials.

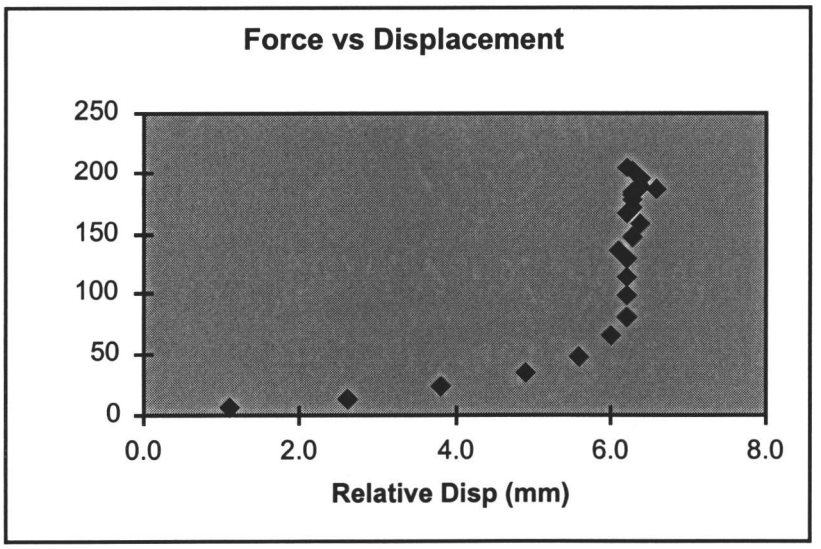

Figure 4.6: Posterior force-displacement curve from the same shoulder as Figure 4.5. Note that maximal translation (end-point) is obtained at approximately 67 N (6.0 mm).

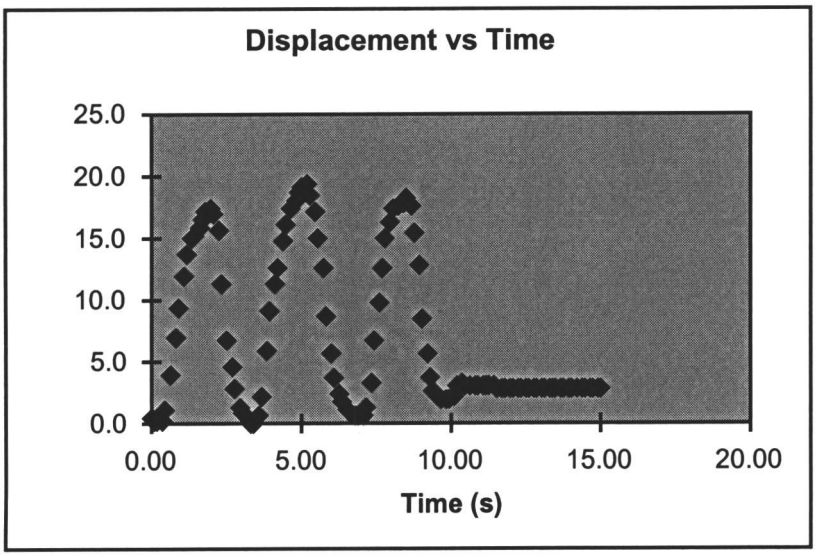

Figure 4.7: Anterior displacement-time curve showing clinical end-point at an average of 18.3 mm.

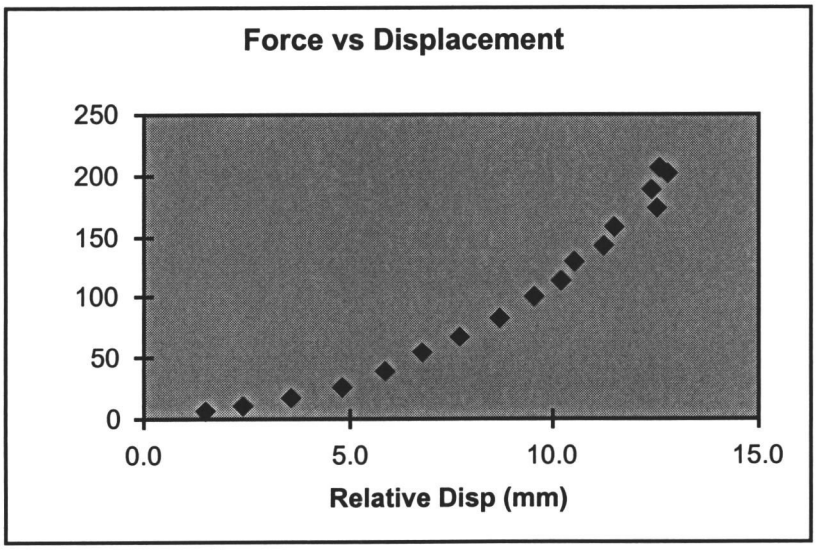

Figure 4.8: Anterior force-displacement curve for same shoulder as Figure 4.7. Translation is still on the rise at the termination of force application.

Our findings indicate that greater force is necessary to reach clinical end-point in the anterior direction compared to the posterior and inferior directions, which were remarkably similar. This may be attributed to several factors including; glenoid retroversion (Warner, 1993), the passive restraining properties of the anterior glenohumeral ligaments and subscapularis (Turkel et al., 1981), the relatively thin posterior capsule (O'Brien et al., 1990; Debski et al., 1999), and the lax inferior glenohumeral ligament in the position of relative adduction utilized in this study (Warner et al., 1992). Interestingly, this finding is in contrast to that of Lippitt and Matsen (1993) who reported a nearly two-fold increase in the average maximum translating force in the inferior direction compared to symmetric values for anterior and posterior force.

One problem of the manual laxity examination is the inability to quantify the force used to displace the humerus (Rodkey et al., 1993; Levy et al., 1999; McQuade et al., 1999). Several estimates of the force used to obtain clinical end-point during the manual laxity examination have been reported. In their classic paper on clinical assessment of instability of the shoulder Gerber and Ganz (1984) state that "...a force comparable to that used at the knee in Lachman's test" is used to assess anterior displacement.

Other investigators using the manual laxity examination to quantify humeral displacement have also attempted to estimate the magnitude of applied force. Oliashirzai et al. (1999) report that during the manual laxity examination with the patient under anesthesia only 1 to 3 kg (9.8 to 29.4 N) of displacement force, depending on the size of the shoulder, is necessary to reach clinical end-point. However, no objective means to determine this force range are reported and in a discussion of the limitations of the study

the authors admit, "the force is not precisely measured..." (Oliashirazi et al., 1999). Hawkins et al. (1996) also evaluated humeral translation using the manual laxity examination with the patient under anesthesia. These investigators note that, "The humeral head was stressed with adequate load to achieve translation to its end point" (Hawkins et al., 1996). With respect to the magnitude of applied force Hawkins et al. (1996) state, "On the basis of our appreciation of KT-1000 measurements in the knee, the force required to achieve this end point would be approximately 20 pounds". This equates to an 89 N force level, but appears to be a subjective estimation.

Ellenbecker et al. (2000) compared the manual laxity assessment to stress radiography performed using a 15 daN (150 N) anterior force to displace the humerus. The manual tests were performed to "endfeel" however the small magnitudes of translation obtained using the stress radiography suggest that the displacement force utilized was insufficient to reach end-point. Further support of this assumption is provided by the fact that essentially no correlation in the amount of recorded translation was observed between the manual assessment and the stress radiography (Ellenbecker et al., 2000). Krarup et al. (1999) were able to detect diagnostic side-to-side differences in anterior translation using a 90 N displacement force and ultrasonic measurement of humeral displacement. However, no mention with respect to clinical end-point was made.

Several investigators have also attempted to utilize more objective measures of force-displacement at the glenohumeral joint. Jorgensen and Bak (1995) used a Donjoy® Knee Laxity Tester to apply an 89 N anterior and posterior force to record subsequent humeral translation. Large variations in AP-translation were noted between subjects with

healthy shoulders and those with some form of instability, however the authors do not report whether or not clinical end-point was achieved (Jorgensen and Bak, 1995). Pizzari et al. (1999) used a modified knee ligament arthrometer (KT-1000, MEDmetric Corporation, SanDiego) to assess anterior and posterior humeral translation. During this investigation a 67 N force was used to displace the humerus. No mention was made as to whether or not clinical end-point was obtained, however Pizzari et al. (1999) stated in their discussion that, "Increasing the level of force at the shoulder could achieve a more valid reflection of the total AP translation of the humeral head...".

McQuade et al. (1999) utilized a palm-held button load cell and an electromagnetic tracking system to quantify *in vivo* anterior and posterior humeral translation in multiple degrees of abduction and rotation. These investigators found that, independent of shoulder position, approximately 101-113 N of force was required to reach clinical end-point (McQuade et al., 1999). Unfortunately, the validity of this non-invasive measurement method has yet to be reported.

We have previously reported the use of force-displacement techniques to quantify glenohumeral joint laxity *in vivo* (Borsa et al., 1999; Sauers, 1999; Borsa et al., 2000a; Borsa et al., 2000b). A load cell and linear displacement transducers were used to record force and displacement in the anterior and posterior directions of healthy shoulders. Displacement forces ranged from 0-134 N. Even at the maximum displacement force of 134 N many of the shoulders demonstrated force-displacement curves that were linear and still on the rise. Therefore, we have concluded that, for most shoulders, greater than 134 N of force was necessary to achieve clinical end-point using these procedures (Borsa

et al., 1999; Sauers, 1999). Subsequently, the study reported here was conducted using 0-200 N of applied force.

CONCLUSIONS

This report evaluates the findings from three different methods used for determining glenohumeral joint translation. We have developed an instrumented manual laxity examination for quantifying glenohumeral joint translation in a non-invasive manner. The findings of this study indicate that non-invasive, cutaneous instrumentation can be added to the traditional manual laxity examination to increase the objectivity, accuracy, and reproducibility, of measures of humeral translation in the anterior, posterior, and inferior directions. This new method could prove useful when assessing glenohumeral joint kinematics relative to injury state and surgical intervention.

Optimal assessment of shoulder laxity requires that clinical end-point be obtained in order to determine the true magnitude of available humeral translation. It is important to quantify the magnitude of force used to obtain measures of humeral translation. We have utilized valid bone-pinned measures of humeral translation obtained using the manual assessment and kinetic methods to estimate the magnitude of force required to reach clinical end-point during the manual laxity examination. Based on the findings of this study it appears that more force is required to achieve clinical end-point in the anterior direction compared to posterior and inferior. It is important to consider the findings of this investigation when manually assessing glenohumeral joint laxity.

REFERENCES

Beaulieu CF, Hodge DK, Bergman AG, Butts K, Daniel BL, Napper CL, Darrow RD, Dumoulin CL, Herfkens RJ. Glenohumeral relationships during physiologic shoulder motion and stress testing: Initial experience with open MR imaging and active imaging-plane registration. *Radiology.* 1999;212(3):700-705.

Borsa PA, Sauers EL, Herling DE. In vivo assessment of AP laxity in healthy shoulders using an instrumented arthrometer. *Journal of Sport Rehabilitation* 1999;8:1-14.

Borsa PA, Sauers EL, Herling DE. Patterns of glenohumeral joint laxity and stiffness in healthy males and females. *Med Sci Sports Exerc.* 2000a (In Press).

Borsa PA, Sauers EL, Herling DE. Patterns of glenohumeral joint laxity and stiffness in healthy shoulders. *Med Sci Sports Exerc.* 2000b;32(suppl):S123. Abstract.

Branch TP, Lawton RL, Lobst CA, Hutton WC. The role of glenohumeral capsular ligaments in internal and external rotation of the humerus. *Am J Sports Med.* 1995;23(5):632-637.

Debski RE, Sakane M, Woo SLY, Wong K, Fu FH, Warner JJP. Contribution of the passive properties of the rotator cuff to glenohumeral stability during anterior-posterior loading. *J Shoulder Elbow Surg.* 1999;8:324-329.

Ellenbecker TS, Mattalino AJ, Elam E, Caplinger R. Quantification of anterior translation of the humeral head in the throwing shoulder: Manual assessment versus stress radiography. *Am J Sports Med.* 2000;28(2):161-166.

Ferrari DA. Capsular ligaments of the shoulder: Anatomical and functional study of the anterior superior capsule. *Am J Sports Med.* 1990;18(1):20-24.

Gerber C, Ganz R. Clinical assessment of instability of the shoulder with special reference to anterior and posterior drawer tests. *J. Bone Joint Surg.* 1984;66B: 551-556.

Harryman DT, Sidles JA, Clark JM, McQuade KJ, Gibb TD, Matsen III FA. Translation of the humeral head on the glenoid with passive glenohumeral motion. *J Bone Joint Surg.* 1990;72-A(9):1334-1343.

Harryman DT, Sidles JA, Harris BS, Matsen FA: Laxity of normal glenohumeral joint: A quantitative in vivo assessment. *J Shoulder Elbow Surg.* 1992;1(2):66-76

Hawkins RJ, Bokor DJ. Clinical evaluation of shoulder problems. In: Rockwood CA, Matsen FA, eds. The Shoulder. Philadelphia, WB Saunders; 1990:149-117.

Hawkins RJ, Schutte JP, Janda DH, Huckell GH: Translation of the glenohumeral joint with the patient under anesthesia. *J Shoulder Elbow Surg.* 1996;5:286-292.

Jobe CM, Pink MM, Jobe FW, Shaffer B. Anterior shoulder instability, impingement, and rotator cuff tear: Theories and concepts. In: Jobe FW (Ed). *Operative Techniques in Upper Extremity Sports Injuries*. St Louis: Mosby;1996:164-176.

Jorgensen Uffe, Bak K: Shoulder instability: Assessment of anterior-posterior translation with a knee laxity tester. *Acta Orthop Scand.* 1995;66(5):398-400.

Krarup AL, Court-Payen M, Skjoldbye B, Lautsen GS. Ultrasonic measurement of the anterior translation in the shoulder joint. *J Shoulder Elbow Surg.* 1999;8:136-141.

Kvitne RS, Jobe FW. The diagnosis and treatment of anterior instability in the throwing athlete. *Clin Orthop Rel Res.* 1993;291:107-123.

Levy AS, Lintner S, Kentner, Speer KP. Intra- and interobserver reproducibility of the shoulder laxity examination. *Am J Sports Med.* 1999;27(4):460-463.

Lintner SA, Levy A, Kenter K, Speer K. Glenohumeral translation in the asymptomatic athlete's shoulder and its relationship to other clinically measurable anthropometric variables. *Am J Sports Med.* 1996;24(6):716-720.

Lippitt SB, Harris SL Harryman DT, Sidles J, Matsen FA. In vivo quantification of the laxity of normal and unstable glenohumeral joints. *J Shoulder Elbow Surg.* 1994;3:215-223.

Lippitt S, Matsen F. Mechanisms of glenohumeral joint stability. *Clin Orthop Rel Res.* 1993;291:20-28.

McFarland EG, Campbell G, McDowell J. Posterior shoulder laxity in asymptomatic athletes. *Am J Sports Med.* 1996a;24(4)468-471.

McFarland EG, Shaffer B, Glousman RE, Conway JE, Jobe FW. Anterior shoulder instability, impingement, and rotator cuff tear: Clinical and diagnostic evaluation. In: Jobe FW (Ed). *Operative Techniques in Upper Extremity Sports Injuries*. St Louis: Mosby;1996b:177-190.

McFarland EG, Torpey BM, Curl LA. Evaluation of shoulder laxity. *Sports Med.* 1996c;22:264-272.

McQuade JK, Shelley I, Cvitkovic J. Patterns of stiffness during clinical examination of the glenohumeral joint. *Clin Biomech.* 1999;14:620-627.

O'Brien SJ, Neves MC, Arnoczky SP, Rozbruck R, Dicarlo EF, Warren RF, Schwartz R, Wickiewicz TL. The anatomy and histology of the inferior glenohumeral ligament complex of the shoulder. *Am J Sports Med.* 1990;18(5):449-456.

O'Brien SJ, Schwartz RS, Warren R, Torzilli PA. Capsular restraints to anterior-posterior motion of the abducted shoulder: A biomechanical study. *J Shoulder Elbow Surg.* 1995;4:298-308.

Oliashirazi A, Mansat P, Cofield RH, Rowland CM. Examination under anesthesia for evaluation of anterior shoulder instability. *Am J Sports Med.* 1999;27(4):464-468.

Pizzari T, Kolt GS, Remedios L. Measurement of anterior-to-posterior translation of the glenohumeral joint using the KT-1000. *J Orthop Sports Phys Ther.* 1999;29(10):602-608.

Rodkey WG, Noble JS, Hintermeister RA. Laboratory methods of evaluating the shoulder: Strength, range of motion, and stability. In: Matsen FA, Fu FH, Hawkins RJ, eds. *The Shoulder: A Balance of Mobility and Stability.* Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:551-582.

Sauers EL. *In vivo assessment of glenohumeral joint laxity using an instrumented arthrometer: Reliability and correlation to range of motion and generalized joint laxity,* Corvallis, OR: Oregon State University; 1999. Thesis.

Sobush DC, Simoneau GG, Dietz KE, Levene JA, Grossman RE, Smith WB. The lennie test for measuring scapular position in healthy young adult females: A reliability and validity study. *J Orthop Sports Phys Ther.* 1996;23(1):39-50.

Speer KP. Anatomy and pathomechanics of shoulder instability. *Clin Sports Med.* 1995;14(4):751-760.

Steinbeck J, Liljenqvist U, Jerosch J. The anatomy of the glenohumeral ligamentous complex and its contribution to anterior shoulder stability. *Am J Sports Med.* 1998;7:122-126.

Tibone JE, McMahon PJ, Shrader TA, Sandusky MD, Lee T. Glenohumeral joint translation after arthroscopic, nonablative, thermal capsuloplasty with a laser. *Am J Sports Med.* 1998;26(4):495-498.

Turkel SJ, Panio MW, Marshal JL, Girgis FG. Stabilizing mechanisms preventing anterior dislocation of the glenohumeral joint. *J Bone Joint Surg.* 1981;63A:1208-1217.

Warner JP. The gross anatomy of the the joint surfaces, ligaments, labrum, and capsule. In: Matsen FA, Fu FH, Hawkins RJ, eds. The Shoulder: A Balance of Mobility and Stability. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:7-27.

Warner JP, Deng XH, Warren RF, Torzilli PA. Static capsuloligamentous restraints to superior-inferior translation of the glenohumeral joint. *Am J Sports Med.* 1992;20(6):675-685.

Warner JP, Micheli LJ, Arslanian LE, Kennedy J, Kennedy R. Patterns of flexibility, laxity, and strength in normal shoulders and shoulders with instability and impingement. *Am J Sports Med.* 1990;18(4):366-374.

Wuelker N, Schmotzer H, Thren K, Korell M. Translation of the glenohumeral joint with simulated active elevation. *Clin Orthop Rel Res.* 1994;309:193-200.

CHAPTER FIVE

Summary

INTRODUCTION

The healthy glenohumeral joint requires some humeral head translation to occur in order for the shoulder to achieve the large ranges of motion necessary for normal function (Harryman et al., 1990; Wuelker et al., 1994). The passive soft-tissue restraints of the glenoid labrum and capsuloligamentous structures provide end-range stability at the glenohumeral joint by preventing excessive humeral head translation (Lew et al., 1993). In the presence of shoulder pathology such as instability or adhesive capsulitis, excessive or diminished humeral head translation results in symptoms of pain and dysfunction. Surgical intervention techniques address the underlying increase or decrease in capsular volume to restore normal glenohumeral joint arthromechanics.

Traditionally, the manual laxity examination, as well as other diagnostic measures, have been employed to evaluate the magnitude of humeral head translation on the glenoid. Poor reproducibility, lack of quantified force, inconsistent positioning, and other problems have reduced the efficacy of these examination methods (Rodkey et al., 1993; Levy et al., 1999; Ellenbecker et al., 2000). Recently, attempts to increase the objectivity of the laxity examination through the use of force and displacement instrumentation have started to emerge. However, quantitative research regarding normal and pathologic laxity and stiffness of the glenohumeral joint still remains scarce. A primary confounding factor is the lack of a reliable, objective, and clinically available

means by which to quantify glenohumeral joint laxity and stiffness (Rodkey et al., 1993; Levy et al., 1999; Ellenbecker et al., 2000).

An instrumented measurement system that measures *in vivo* sagittal plane glenohumeral joint laxity and stiffness has been developed at Oregon State University in a collaborative effort between members of the Department of Exercise and Sport Science and the Department of Mechanical Engineering (Borsa et al., 1999; Sauers, 1999; Borsa et al., 2000a; Borsa et al., 2000b). The instrumented measurement system consists of a test chair to position the subject and stabilize the trunk and arm. A load cell is used to quantify force and linear displacement transducers (LDTs) have been used to measure scapular and humeral motion. Recently, the LDTs were replaced with more sophisticated and easier to apply electromagnetic spatial tracking sensors. The sensors are secured cutaneously with adhesive tape to record displacement of the scapula and humerus. To date, two *in vivo* studies using the instrumented measurement system have been conducted to evaluate the functionality and reliability of the device and establish normative data for laxity and stiffness (Borsa et al., 1999; Sauers, 1999; Borsa et al., 2000a; Borsa et al., 2000b).

The purpose of this study was to characterize glenohumeral joint laxity and stiffness in 30 fresh frozen cadaver shoulder specimens using instrumented arthrometry. To evaluate the validity of the instrumented shoulder arthrometer cutaneous and bone-pinned measures of laxity and stiffness that replicate previously reported *in vivo* methodology were obtained. Characterization of capsular laxity was achieved through determination of the sagittal plane translational area at increasing levels of quantified force. Finally, a simple method for increasing the objectivity of the standard manual

laxity examination was developed for the orthopaedic clinician to quantify humeral head translation *in vivo*.

FORCE-DISPLACEMENT METHOD

Reliable and valid quantification of glenohumeral joint laxity and stiffness in the clinical and laboratory settings is highly desirable (Warner et al., 1990; Rodkey et al., 1993; Borsa et al., 1999; Lintner et al., 1999; Sauers, 1999; Borsa et al., 2000a; Ellenbecker et al., 2000). The manual laxity examination has been shown to exhibit poor reproducibility (MdFarland et al., 1996c; Levy et al., 1999; Ellenbecker et al., 2000) and remains subjective with no objective measurement of translation or applied force (Rodkey et al., 1993; McFarland et al., 1996b; McQuade et al., 1999; Ellenbecker et al., 2000). In an effort to increase the objectivity of the laxity exmination a non-invasive, cutaneous measurement technique was developed (Borsa et al., 1999; Sauers, 1999; Borsa et al., 2000a; Borsa et al., 2000b). Previous research has established the reproducibility of laxity measures obtained using this methodology *in vivo* to be < 1 mm between sessions and between examiners (Sauers, 1999). However, due to concerns regarding soft-tissue error variance when using cutaneous measures to predict bony displacement it is imperative to establish the criterion validity of this new measurement technique.

An *ex vivo* comparison of cutaneous to bone-pinned measures of anterior, posterior, and inferior glenohumeral joint laxity and stiffness using identical testing procedures was performed. The non-invasive, cutaneous measurement technique demonstrated good criterion validity for laxity in all three directions of translation. The

Pearson's r values for laxity ranged from 0.68 to 0.71 and the average differences in laxity observed between measurement techniques was 0.4 to 4.4 mm. The cutaneous measurement technique demonstrated excellent criterion validity for stiffness in the anterior direction (r=0.79) and good criterion validity for stiffness in the posterior (r=0.68) and inferior (r=0.71) direction. The average difference in stiffness between measurement techniques was 5.4 to 12.1 N/mm.

The standard error of the estimate (SEest) quantifies the prediction accuracy of the cutaneous method by providing a standard deviation of the degree to which the cutaneous measures vary from the bone-pinned measures (Safrit and Wood, 1989). The SEest for laxity in all three directions ranged from 3.0 to 4.8 mm and from 7.0 to 18.6 N/mm for stiffness. These data indicate that the two different measurement methods are measuring similar changes in glenohumeral joint laxity and stiffness in the anterior, posterior, and inferior directions. Reliability coefficients revealed excellent reproducibility of the laxity and stiffness measures obtained between trials. The calculated regression equations for laxity (Table 1.2) and stiffness (Table 1.3) will enable future *in vivo* investigations of these variables to be performed using a correction factor in each direction that will increase the accuracy of the obtained measures.

This report represents the first step in developing the validity of a non-invasive, cutaneous measurement technique for objective quantification of glenohumeral joint laxity and stiffness. Currently, the cutaneous measurement technique reported herein is a valuable laboratory tool that with future research and development holds promise for more widespread clinical application. Based on the findings of this investigation we feel that the cutaneous measurement technique is a viable method for objectively evaluating

in vivo glenohumeral joint laxity and stiffness. This instrumented cutaneous technique has been found to exhibit a high degree of precision and excellent to good criterion validity. Future investigations should seek to validate this technique *in vivo* and in subjects with documented shoulder instability.

CHARACTERIZATION OF CAPSULAR LAXITY

The effect of changes in capsular volume on shoulder motion and function are not well understood (Tibone et al., 1998). Large variations in capsular volume and the individual magnitudes of translation in the anterior, posterior, and inferior directions have been described (Harryman et al., 1992; Lippitt et al., 1994; Borsa et al., 1999; Sauers, 1999; Borsa et al., 2000a). The most accurate measures of capsular laxity can be obtained using: 1) direct bone-pinning of the scapula and humerus to record force-displacement, 2) flaccid musculature to control measurement error induced from muscular tension, and 3) in tact musculature to provide passive restraint to translation (Harryman et al., 1992; Cofield et al., 1993; Rodkey et al., 1993; Lippitt et al., 1994; Debski et al., 1999; Oliashirazi et al., 1999). These conditions are most readily met through the use of cadaver shoulder specimens. We have determined capsular laxity using a valid and reproducible measurement protocol of direct bone-pinning of the scapula and humerus to record force-displacement characteristics in cadaver shoulders with in tact rotator cuff and overlying musculature.

We have reported valuable information regarding physiologic capsular laxity with special reference to the individual components of anterior, posterior, and inferior laxity, at increasing levels of applied force. This information may assist the surgeon seeking to

restore normal arthrokinematics to the injured shoulder in the presence of suspected increased or diminished capsular volume. Furthermore, a valid and reproducible biomechanical model for evaluating force-displacement characteristics at the glenohumeral joint that mimics *in vivo* methods and procedures has been developed. Future studies using these models should evaluate the effects of various lesions and surgical intervention techniques on the force-displacement characteristics of the human shoulder.

INSTRUMENTED MANUAL ASSESSMENT

We have developed an instrumented manual laxity examination for quantifying glenohumeral joint translation in a non-invasive manner. This report evaluates the findings from three different methods used for determining glenohumeral joint translation. The findings of this study indicate that non-invasive, cutaneous instrumentation can be added to the traditional manual laxity examination to increase the objectivity, accuracy, and reproducibility, of measures of humeral translation in the anterior, posterior, and inferior directions. This new method could prove useful when assessing glenohumeral joint kinematics relative to injury state and surgical intervention.

Our results revealed significant differences between the three different measurement methods utilized to quantify humeral translation. No significant difference was observed between the manual bone-pinned and kinetic bone-pinned measures. This finding indicates that these invasive techniques are in fact valid measures of glenohumeral joint laxity. The non-invasive, manual cutaneous method was significantly different from both of the invasive bone-pinned methods.

Small differences were observed in the magnitude of recorded anterior, posterior, and inferior translation between the three different measurement methods (Figures 4.2 and 4.3). Clinically, the magnitudes of observed differences between measurement methods may not be significant (<3 mm). However, with future refinement of the testing protocol, and special attention to sensor rotation observed during the cutaneous trials we feel that these differences can be minimized.

Our findings indicate that greater force is necessary to reach clinical end-point in the anterior direction compared to the posterior and inferior directions, which were remarkably similar. This may be attributed to several factors including; glenoid retroversion (Warner, 1993), the passive restraining properties of the anterior glenohumeral ligaments and subscapularis (Turkel et al., 1981), the relatively thin posterior capsule (O'Brien et al., 1990; Debski et al., 1999), and the lax inferior glenohumeral ligament in the position of relative adduction utilized in this study (Warner et al., 1992).

Optimal assessment of shoulder laxity requires that clinical end-point be obtained in order to determine the true magnitude of available humeral translation. It is important to quantify the magnitude of force used to obtain measures of humeral translation. We have utilized valid bone-pinned measures of humeral translation obtained using the manual assessment and kinetic methods to estimate the magnitude of force required to reach clinical end-point during the manual laxity examination. Based on the findings of this study it appears that more force is required to achieve clinical end-point in the anterior direction compared to posterior and inferior. It is important to consider the findings of this investigation when manually assessing glenohumeral joint laxity.

GENERAL CONCLUSIONS

Large magnitudes of humeral translation were observed in each direction of laxity. Non-invasive, cutaneous measurements appear to slightly overestimate underlying humeral displacement. This overestimation is attributed to cutaneous sensor rotation with resultant translation. During both the force-displacement method and instrumented manual method we observed small magnitudes of cutaneous sensor rotation which was thought to adversely impact the magnitude of measured translation. Future software programming could account for this problem and correct for any adverse rotation within the calculations of displacement or warn the examiner with an audible signal that unwanted sensor rotation is occurring. We feel that with the development of future testing systems that will involve a more rigid sensor housing, similar to the KT-1000 used at the knee, sensor rotation will not be a significant problem.

Another problem that was observed throughout these experiments was the application of a purely linear displacement force. Non-linear force application during anterior and posterior displacement trials was thought to attribute to the problem of cutaneous sensor rotation. Furthermore, small differences in the linearity of force application may have resulted in small changes in the magnitude of observed displacement. This could explain a significant amount of the variation observed between measurement methods. In fact, the majority of difference observed between methods in the inferior direction is thought to be the result of alterations in the linearity of the applied force.

To increase the agreement between measurement methods and between recorded values between sessions and between examiners it is imperative that some form of

constant zero referencing system be incorporated into the software. This has proven to be a significant obstacle in obtaining precise and accurate measurements of glenohumeral joint laxity and stiffness. To overcome this problem some investigators have utilized small magnitudes of compressive force to concentrically reduce the humeral head into the center of the glenoid fossa (Tibone et al., 1998; Debski et al., 1999). However, the effect of this method on increasing between method, between session, or between examiner, reproducibility has not been reported. Future design and development of instrumentation to quantify glenohumeral joint laxity and stiffness should take into consideration the effect of consistent humeral starting position.

To the best of our knowledge, the *ex vivo* instrumentation and methodology developed and utilized for this study is the first to replicate current *in vivo* instrumentation and methodology. This allows for closer comparison of experimental findings between studies performed using both techniques. Invasive studies that involve selective cutting of stabilizing mechanisms or surgical interventions can be evaluated using the *ex vivo* biomechanical testing system to further define normal glenohumeral joint kinematics. These findings can in turn be used to develop *in vivo* experiments to evaluate the effects of injury and surgery on glenohumeral joint stability.

FUTURE RESEARCH DIRECTIONS

This study represents the second phase in the development of a reliable and valid measurement system for quantifying glenohumeral joint laxity and stiffness. Future research and development efforts should focus on the development of a smaller, more rigid, and portable measurement system that can quantify glenohumeral joint laxity and

stiffness in multiple positions of elevation and rotation. To date, we have only evaluated healthy (non-injured) shoulders to establish normative laxity and stiffness data. Future studies should evaluate these measures in subjects with diagnosed shoulder instability. Side-to-side comparisons of laxity and stiffness may prove diagnostic of patients with unilateral shoulder instability. Identifying pathologic alterations in capsular laxity will aid the physician in diagnosing instability and determining the optimal surgical procedure to restore normal stability to the shoulder. The instrumentation and methods reported herein could be utilized to optimal parameters for capsular lengthening and shortening procedures. Prospective studies should be designed to evaluate the efficacy of various surgical intervention techniques designed to reduce capsular volume.

Investigations should also seek to more clearly define gender differences in laxity and stiffness. Currently, little is known regarding the possibility of increased risk for injury in the presence of acquired changes in glenohumeral joint kinematics. Studies should seek to determine if females are at greater risk for shoulder injuries such as instability or impingement as a function of increased laxity and decreased stiffness. Similarly, overhead athletes who are theorized to acquire increased anterior laxity and posterior capsular contracture should be evaluated using instrumented measurement techniques. These data could in turn be used to screen overhead athletes for any increased risk of shoulder injury. Objective study of glenohumeral joint laxity and stiffness is in its infancy and future characterization of normal and pathologic variations in these variables will ultimately influence the diagnosis and treatment of shoulder pathology.

BIBLIOGRAPHY

Abrams J. Posterior-superior glenohumeral impingement in overhead athletes. In: Instructional Course Lecture. *Arthroscopic evaluation and treatment of shoulder instability.* American Academy of Orthopaedic Surgeons. 2000;191.

Bach BR, Warren RF, Flynn WM, et al. Arthrometric evaluation of knees that have a torn anterior cruciate ligament. *J Bone Joint Surg.* 1990;72-A:1299-1306.

Bankart AS. The pathology and treatment of recurrent dislocation of the joint. *Br J Surg.* 1938;26:23-29.

Barber FA. Suture anchors 2000: Permanent versus bioabsorbable and technical pearls for their use. In: Instructional Course Lecture. *Arthroscopic evaluation and treatment of shoulder instability.* American Academy of Orthopaedic Surgeons. 2000;191.

Barber FA, Morgan CD, Burkhart SS, Jobe CML. Labrum/biceps/cuff dysfunction in the throwing athlete. *Arthroscopy.* 15(8):2000;852-857.

Beaulieu CF, Hodge DK, Bergman AG, Butts K, Daniel BL, Napper CL, Darrow RD, Dumoulin CL, Herfkens RJ. Glenohumeral relationships during physiologic shoulder motion and stress testing: Initial experience with open MR imaging and active imaging-plane registration. *Radiology.* 1999;212(3):700-705.

Bigliani LU, Kelkar R, Flatow EL, Pollock RG, Mow VC. Glenohumeral stability: Biomechanical properties of pasive and active stabilizers. *Clin Orthop Rel Res.* 1996;330:13-30.

Borsa PA, Sauers EL, Herling DE. In vivo assessment of AP laxity in healthy shoulders using an instrumented arthrometer. *Journal of Sport Rehabilitation* 1999;8:1-14.

Borsa PA, Sauers EL, Herling DE. Patterns of glenohumeral joint laxity and stiffness in healthy males and females. *Med Sci Sports Exerc.* 2000a (In Press).

Borsa PA, Sauers EL, Herling DE. Patterns of glenohumeral joint laxity and stiffness in healthy shoulders. *Med Sci Sports Exerc.* 2000b;32(suppl):S123. Abstract.

Branch TP, Lawton RL, Lobst CA, Hutton WC. The role of glenohumeral capsular ligaments in internal and external rotation of the humerus. *Am J Sports Med.* 1995;23(5):632-637.

Bruckner FE, Nye CJ. A prospective study of adhesive capsulitis of the shoulder (frozen shoulder) in a high risk population. *Q J Med.* 1981;50:191-204.

Burkhart SS, Morgan CD. The peel-back mechanism: Its role in producing and extending posterior type II slap lesions and its effect on slap repair rehabilitation. *Arthroscopy.* 1998:14:637-640.

Caspari RB, Geissler WB. Arthroscopic manifestations of shoulder subluxation and dislocation. *Clin Orthop Rel Res.* 1993;291:54-66.

Cofield RH, Nessler JP, Weinstabl R. Diagnosis of shoulder instability by examination under anesthesia. *Clin Orthop Rel Res.* 1993;291:45-53.

Culham E, Peat M. Functional anatomy of the shoulder complex. *J Orthop Sports Phys Ther.* 1993;18(1):342-350.

Daniel DM, Malcom LL, Lossee G, Stone ML, Sachs R, Burks R. Instrumented measurement of anterior laxity of the knee. *J Bone Joint Surg.* 1985a;67:720-726.

Daniel D, Stone ML, Sachs R, Lawrence M. Instrumented measurement of anterior laxity in patients with acute anterior cruciate ligament disruption. *Am J Sports Med.* 1985b;13:401-407.

Debski RE, Sakane M, Woo SLY, Wong K, Fu FH, Warner JJP. Contribution of the passive properties of the rotator cuff to glenohumeral stability during anterior-posterior loading. *J Shoulder Elbow Surg.* 1999;8:324-329.

Ellenbecker TS, Mattalino AJ, Elam E, Caplinger R. Quantification of anterior translation of the humeral head in the throwing shoulder: Manual assessment versus stress radiography. *Am J Sports Med.* 2000;28(2):161-166.

Engebretsen L, Craig EV. Radiologic features of shoulder instability. *Clin Orthop Rel Res.* 1993;291:29-44.

Ferrari DA. Capsular ligaments of the shoulder: Anatomical and functional study of the anterior superior capsule. *Am J Sports Med.* 1990;18(1):20-24.

Fithian DC, Mishra DK, Balen PF, Stone ML, Daniel DM. Instrumented measurement of patellar mobility. *Am J Sports Med.* 1995;23(5):607-615.

Freedman L, Munro RR. Abduction of the arm in the scapular plane: Scapular and glenohumeral movements. *J Bone Joint Surg.* 1966;48A(8):1503-1510.

Friedman RJ. Glenohumeral capsulorrhaphy. In: Matsen FA, Fu FH, Hawkins RJ, eds. The Shoulder: A Balance of Mobility and Stability. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:445-458.

Gerber C, Ganz R. Clinical assessment of instability of the shoulder with special reference to anterior and posterior drawer tests. *J. Bone Joint Surg.* 1984;66B: 551-556.

Giannotti BF, Fanelli GC, Barrett TA, Edson C. The predictive value of intraoperative KT-1000 arthrometer measurements in single incision anterior cruciate ligament reconstruction. *Arthroscopy.* 1996;12(6):660-666.

Glousman RE, Jobe FW. Anterior shoulder instability, impingement, and rotator cuff tear: Anterior and multidirectional glenohumeral instability. In: Jobe FW (Ed). *Operative Techniques in Upper Extremity Sports Injuries.* St Louis: Mosby;1996:191-209.

Harryman DT, Sidles JA, Clark JM, McQuade KJ, Gibb TD, Matsen III FA. Translation of the humeral head on the glenoid with passive glenohumeral motion. *J Bone Joint Surg.* 1990;72-A(9):1334-1343.

Harryman DT, Sidles JA, Harris BS, Matsen FA: Laxity of normal glenohumeral joint: A quantitative in vivo assessment. *J Shoulder Elbow Surg.* 1992;1(2):66-76

Hart DL, Carmichael SW. Biomechanics of the shoulder. *J Orthop Sports Phys Ther.* 1985;6(4):229-234.

Hawkins RJ, Bokor DJ. Clinical evaluation of shoulder problems. In: Rockwood CA, Matsen FA, eds. The Shoulder. Philadelphia, WB Saunders; 1990:149-117.

Hawkins RJ, Mohtadi GH. Clinical Evaluation of shoulder instability. *Clin J Sports Med.* 1991;1: 59-64.

Hawkins RJ, Schutte JP, Janda DH, Huckell GH: Translation of the glenohumeral joint with the patient under anesthesia. *J Shoulder Elbow Surg.* 1996;5:286-292.

Heis FT, Osbahr D, Speer KP. Arthroscopic release of the diabetic frozen shoulder: An outcome study. In: Program and abstracts of the 16th open meeting of the American Shoulder and Elbow Surgeons; March 18, 2000; Orlando, FL. Abstract 38.

Howell SM, Galinat BJ. The glenoid-labral socket: A constrained articular surface. *Clin Orthop.* 1989;243:122-125.

Iannotti JP, Williams GR, Ramsey ML, Holloway GB, Schenk TJ. Arthroscopic capsular release for the management of the post-operative stiff and painful shoulder. In: Program and abstracts of the 16th open meeting of the American Shoulder and Elbow Surgeons; March 18, 2000; Orlando, FL. Abstract 39.

Jobe CM, Pink MM, Jobe FW, Shaffer B. Anterior shoulder instability, impingement, and rotator cuff tear: Theories and concepts. In: Jobe FW (Ed). *Operative Techniques in Upper Extremity Sports Injuries.* St Louis: Mosby;1996:164-176.

Jorgensen Uffe, Bak K: Shoulder instability: Assessment of anterior-posterior translation with a knee laxity tester. *Acta Orthop Scand.* 1995;66(5):398-400.

Karduna AR, Williams GR, Williams JL, Iannotti JP. Kinematics of the glenohumeral joint: Influences of muscle forces, ligamentous constraints, and articular geometry. *J Orthop Res*. 1996;14:986-993.

Kibler WB. The role of the scapula in athletic shoulder function. *Am J Sports Med.* 1998;26:325-337.

Kiss J, McNally EG, Carr AJ. Measurment of the anteroposterior translation of the humeral head using MRI. *Int Orthop.* 1997;21:77-82.

Kochan A, Markolf KL, More RC. Anterior-posterior stiffness and laxity of the knee after major ligament reconstruction. *J Bone Joint Surg.* 1984;66(9):1460-1465.

Kovaleski JE, Gurchiek LR, Heitman RJ, Hollis JM, Pearsall AW 4th. Instrumented measurement of anteroposterior and inversion-eversion laxity of the normal ankle joint complex. *Foot Ankle Int.* 1999;20(12):808-814.

Krarup AL, Court-Payen M, Skjoldbye B, Lautsen GS. Ultrasonic measurement of the anterior translation in the shoulder joint. *J Shoulder Elbow Surg.* 1999;8:136-141.

Kvitne RS, Jobe FW. The diagnosis and treatment of anterior instability in the throwing athlete. *Clin Orthop Rel Res.* 1993;291:107-123.

Levy AS, Lintner S, Kentner, Speer KP. Intra- and interobserver reproducibility of the shoulder laxity examination. *Am J Sports Med.* 1999;27(4):460-463.

Lew WD, Lewis JL, Craig EV. Stabilization by capsule, ligaments, and labrum: Stability at the extremes of motion. In: Matsen FA, Fu FH, Hawkins RJ, eds. The Shoulder: A Balance of Mobility and Stability. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:69-90.

Lintner SA, Levy A, Kenter K, Speer K. Glenohumeral translation in the asymptomatic athlete's shoulder and its relationship to other clinically measurable anthropometric variables. *Am J Sports Med.* 1996;24(6):716-720.

Lippitt SB, Harris SL Harryman DT, Sidles J, Matsen FA. In vivo quantification of the laxity of normal and unstable glenohumeral joints. *J Shoulder Elbow Surg.* 1994;3:215-223.

Lippitt S, Matsen F. Mechanisms of glenohumeral joint stability. *Clin Orthop Rel Res.* 1993;291:20-28.

Maki S, Gruen T. Anthropometric studies of the glenohumeral joint. *Trans Orthop Res Soc.* 1988;13:162.

Markolf KL, Amstutz HC. The clinical relevance of instrumented testing for ACL insufficiency: Experience with the UCLA clinical knee testing apparatus. *Clin Orthop Rel Res.* 1987;223:198-207.

Markolf KL, Graff-Radford A, Amstutz HC. In vivo knee stability: A quantitative assessment using an instrumented clinical testing apparatus. *J Bone Joint Surg.* 1978;60A(5):664-674.

Markolf KL, Kochan A, Amstutz HC. Measurement of knee stiffness and laxity in patients with documented absence of the anterior cruciate ligament. *J Bone Joint Surg.* 66A;1984:242-253.

Markolf KL, Mensch JS, Amstutz HC. Stiffness and laxity of the knee – the contributions of the supporting structures: A quantitative *in vitro* study. *J Bone Joint Surg.* 1976;58(5):583-593.

Markolf KL, Pattee GA, Strum GM, Gallick GS, Sherman OH, Dorey VN, Dorey FJ. Instrumented measurements of laxity in patients who have a gore-tex cruciate-ligament substitute. *J Bone Joint Surg.* 1989;71A:887-893.

Matsen III FA, Harryman II DT, Sidles JA. Mechanics of glenohumeral instability. *Clin Sports Med.* 1991;10(4):783-788.

McFarland EG, Campbell G, McDowell J. Posterior shoulder laxity in asymptomatic athletes. *Am J Sports Med.* 1996a;24(4)468-471.

McFarland EG, Shaffer B, Glousman RE, Conway JE, Jobe FW. Anterior shoulder instability, impingement, and rotator cuff tear: Clinical and diagnostic evaluation. In: Jobe FW (Ed). *Operative Techniques in Upper Extremity Sports Injuries*. St Louis: Mosby;1996b:177-190.

McFarland EG, Torpey BM, Curl LA. Evaluation of shoulder laxity. *Sports Med.* 1996c;22:264-272.

McQuade JK, Shelley I, Cvitkovic J. Patterns of stiffness during clinical examination of the glenohumeral joint. *Clin Biomech.* 1999;14:620-627.

Morgan CD. SLAP lesions in the overhead athlete: Current concepts. In: Instructional Course Lecture. *Arthroscopic evaluation and treatment of shoulder instability.* American Academy of Orthopaedic Surgeons. 2000;191.

Morgan CD, Burkhart SS, Palmeri M, Gillespie M. Type II slap lesions: Three subtypes and their relationships to superior instability and rotator cuff tears. *Arthroscopy.* 1998;14:553-565.

Neuschwander DC, Drez D, Paine RM, Young JC. Comparison of anterior laxity measurements in anterior cruciate deficient knees with two instrumented testing devices. *Orthopedics.* 1990;13(3):299-302.

Neviaser JS. Adhesive capsulitis of the shoulder: Study of pathological findings in periarthritis of the shoulder. *J Bone Joint Surg.* 1945:27;211-222.

O'Brien SJ, Neves MC, Arnoczky SP, Rozbruck R, Dicarlo EF, Warren RF, Schwartz R, Wickiewicz TL. The anatomy and histology of the inferior glenohumeral ligament complex of the shoulder. *Am J Sports Med.* 1990;18(5):449-456.

O'Brien SJ, Schwartz RS, Warren R, Torzilli PA. Capsular restraints to anterior-posterior motion of the abducted shoulder: A biomechanical study. *J Shoulder Elbow Surg.* 1995;4:298-308.

O'Connell PW, Nuber GW, Mileski RA, Lautenschlager E. The contribution of the glenohumeral ligaments to anterior stability of the shoulder joint. *Am J Sports Med.* 1990;18(6):579-583.

O'Driscoll SW. Atraumatic instability: Pathology and pathogenesis. In: Matsen FA, Fu FH, Hawkins RJ, eds. The Shoulder: A Balance of Mobility and Stability. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:305-316.

Oliashirazi A, Mansat P, Cofield RH, Rowland CM. Examination under anesthesia for evaluation of anterior shoulder instability. *Am J Sports Med.* 1999;27(4):464-468.

Pagnani MJ, Deng XH, Warren RF, Torzilli PA, Altcheck DW. Effect of lesions of the superior portion of the glenoid labrum on glenohumeral translation. *J Bone Joint Surg.* 1995;77-A(7):1003-1010.

Pizzari T, Kolt GS, Remedios L. Measurement of anterior-to-posterior translation of the glenohumeral joint using the KT-1000. *J Orthop Sports Phys Ther.* 1999;29(10):602-608.

Portney L, Watkins M. *Foundations of Clinical Research: Applications to Practice.* Norwalk, CT: Appleton & Lange; 1993.

Rafi M, Firooznia H, Golimbu C. MR imaging of glenohumeral instability. *MR Clin North Am.* 1997;5(4):787-809.

Rodkey WG, Noble JS, Hintermeister RA. Laboratory methods of evaluating the shoulder: Strength, range of motion, and stability. In: Matsen FA, Fu FH, Hawkins RJ, eds. *The Shoulder: A Balance of Mobility and Stability.* Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:551-582.

Safrit MJ, Wood TM. *Measurement Concepts in Physical Education and Exercise Science.* Champaign, IL: Human Kinetics; 1989.

Saha AK. Dynamic stability of the glenohumeral joint. *Acta Orthop Scandina.* 1971;42:491-505.

Sauers EL. *In vivo assessment of glenohumeral joint laxity using an instrumented arthrometer: Reliability and correlation to range of motion and generalized joint laxity,* Corvallis, OR: Oregon State University; 1999. Thesis.

Sauers EL, Borsa PA, Herling DE. Reliability of an instrumented shoulder arthrometer for measuring sagittal plane glenohumeral laxity. *J Athletic Train.* 2000 (Manuscript in progress).

Shoemaker SC, Markolf KL. Effects of joint load on the stiffness and laxity of ligament-deficient knees. *J Bone Joint Surg.* 1985;67(1):136-146.

Shrout PE, Fleiss JL. Intraclass correlations: Uses in assessing rater reliability. *Psych Bull.* 1979;86:420-428.

Silliman JF, Hawkins RJ. Classification and physical diagnosis of instability of the shoulder. *Clin Orthop Rel Res* 1993;291:7-19.

Sobush DC, Simoneau GG, Dietz KE, Levene JA, Grossman RE, Smith WB. The lennie test for measuring scapular position in healthy young adult females: A reliability and validity study. *J Orthop Sports Phys Ther.* 1996;23(1):39-50.

Soslowsky LJ, Flatow EL, Bigliani LU, Mow VC. Stabilization of the glenohumeral joint by articular contact and by contact in the subacromial space In: Matsen FA, Fu FH, Hawkins RJ, eds. The Shoulder: A Balance of Mobility and Stability. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:107-124.

Soslowsky LJ, Malicky DM, Blasier RB. Active and passive factors in inferior glenohumeral stabilization: A biomechanical model. *J Shoulder Elbow Surg.* 1997;6:371-379.

Soslowsky LJ, Malicky DM, Mouro C, Bey MJ, Frisancho J, Lindholm S, Kuhn J. Total and non-recoverable strain fields of the glenohumeral joint capsule under shoulder subluxation. In: Program and abstracts of the 16th open meeting of the American Shoulder and Elbow Surgeons; March 18, 2000; Orlando, FL. Abstract 32.

Speer KP. Anatomy and pathomechanics of shoulder instability. *Clin Sports Med.* 1995;14(4):751-760.

Speer KP, Garrett WE. Muscular control of motion and stability about the pectoral girdle. In: Matsen FA, Fu FH, Hawkins RJ, eds. The Shoulder: A Balance of Mobility and Stability. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:159-172.

Stefko JM, Tibone JE, Cawley PW, ElAttrache NE, McMahon PJ. Strain of the anterior band of the inferior glenohumeral ligament during capsule failure. *J Shoulder Elbow Surg.* 1997;6:473-479.

Steinbeck J, Liljenqvist U, Jerosch J. The anatomy of the glenohumeral ligamentous complex and its contribution to anterior shoulder stability. *Am J Sports Med.* 1998;7:122-126.

Strand T, Solheim E. Clinical tests versus KT-1000 instrumented laxity test in acute anterior cruciate ligament tears. *Int J Sports Med.* 1995;16:51-53.

Tibone JE, McMahon PJ, Shrader TA, Sandusky MD, Lee T. Glenohumeral joint translation after arthroscopic, nonablative, thermal capsuloplasty with a laser. *Am J Sports Med.* 1998;26(4):495-498.

Ticker JB, Beim GM, Warner JP. Recognition and treatment of refractory posterior capsular contracture of the shoulder. *Arthroscopy.* 16(1);2000:27-34.

Turkel SJ, Panio MW, Marshal JL, Girgis FG. Stabilizing mechanisms preventing anterior dislocation of the glenohumeral joint. *J Bone Joint Surg.* 1981;63A:1208-1217.

Vangsness CT. Shrink-wrap capsulorrhahpy: The laser and other thermal delivery techniques. In: Instructional Course Lecture. *Arthroscopic evaluation and treatment of shoulder instability.* American Academy of Orthopaedic Surgeons. 2000;191.

Warner JP. The gross anatomy of the the joint surfaces, ligaments, labrum, and capsule. In: Matsen FA, Fu FH, Hawkins RJ, eds. The Shoulder: A Balance of Mobility and Stability. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:7-27.

Warner JP, Deng XH, Warren RF, Torzilli PA. Static capsuloligamentous restraints to superior-inferior translation of the glenohumeral joint. *Am J Sports Med.* 1992;20(6):675-685.

Warner JP, Micheli LJ, Arslanian LE, Kennedy J, Kennedy R. Patterns of flexibility, laxity, and strength in normal shoulders and shoulders with instability and impingement. *Am J Sports Med.* 1990;18(4):366-374.

Wirth MA, Rockwood Jr, CA. Traumatic glenohumeral instability: Pathology and pathogenesis. In: Matsen FA, Fu FH, Hawkins RJ, eds. The Shoulder: A Balance of Mobility and Stability. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:279-304.

Woo SLY, McMahon PJ, Debski RE, Fu FH, Blomstrom GL. Factors limiting and defining shoulder motion: What keeps it form going farther?. In: Matsen FA, Fu FH, Hawkins RJ, eds. The Shoulder: A Balance of Mobility and Stability. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:141-158.

Woo SLY, Young EP, Kwan MK. Fundamental studies in knee ligament mechanics. In: Daniel D, Akeson W, O'Connor J, eds. Knee ligament: structure, function, injury, and repair. New York: Raven Press, 1990:115-134.

Wright V. Stiffness: A review of its measurement and physiologic importance. *Physiotherapy.* 1973;59(4):107-111.

Wuelker N, Korell M, Thren K. Dynamic glenohumeral joint stability. *J Should Elbow Surg.* 1998;7:43-52.

Wuelker N, Schmotzer H, Thren K, Korell M. Translation of the glenohumeral joint with simulated active elevation. *Clin Orthop Rel Res.* 1994;309:193-200.

Zarins B, McMahon MS, Rowe CR. Diagnosis and treatment of anterior instability of the shoulder. *Clin Orthop Rel Res.* 1993;291:75-84.

Zuckerman JD, Cuomo F. Frozen shoulder. In: Matsen FA, Fu FH, Hawkins RJ, eds. The Shoulder: A Balance of Mobility and Stability. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1993:253-268.