Knee Surg, Sports Traumatol, Arthrosc
(2001) 9 : 34–41

SHOULDER

DOI 10.1007/s001670000174

Eric L. Sauers
Paul A. Borsa
Derald E. Herling
Richard D. Stanley

Instrumented measurement of glenohumeral joint laxity: reliability and normative data

Received: 18 July 2000
Accepted: 15 October 2000
Published online: 9 January 2001

E. L. Sauers
Sports Health Care Department,
Arizona School of Health Sciences,
Phoenix, AZ 85017, USA

P. A. Borsa (✉)
Shoulder Kinematics Laboratory,
Division of Kinesiology,
401 Washtenaw Ave., 3060A CCRB,
University of Michigan, Ann Arbor,
MI 48109-2214, USA
e-mail: borsap@umich.edu,
Tel.: +1-734-6153765,
Fax: +1-734-9361925

D. E. Herling
Biomechanics Research Laboratory,
Departments of Mechanical Engineering
and Exercise and Sport Science,
Oregon State University, Corvallis,
OR 97331, USA

R. D. Stanley
Mid-Valley Orthopaedics, Albany,
OR 97321, USA

Abstract This study assessed shoulder laxity using an instrumented arthrometer. We compared anterior and posterior translations at various force levels to determine the reliability of our measurement technique and to provide normative data in healthy shoulders. Fifty shoulders were assessed for glenohumeral joint laxity in two directions (anterior and posterior) and at four force levels (67, 89, 111, and 134 N). The dependent measure was joint displacement. Laxity values were widely, yet normally, distributed in our group of healthy shoulders. Intraclass correlation coefficients revealed excellent between-trial reliability (0.92) and fair between-session (0.73) and between-examiner (0.74) reliability. The average standard error of measurement between trials (0.56 mm), sessions (1.5 mm), and examiners (1.7 mm) demonstrated an unprecedentedly high degree of precision for quantifying glenohumeral joint laxity. Paired *t* tests revealed no significant laxity differences between sides ($P>0.05$), indicating bilateral symmetry. A 2 (direction) × 4 (force) analysis of variance revealed significant differences in laxity between directions ($P<0.0001$) and force levels ($P<0.0001$). Our results show that our instrumented technique for quantifying glenohumeral joint laxity is precise and reproducible. Posterior translation was significantly greater than anterior, and a significant increase in translation was observed between increasing levels of force.

Keywords Assessment · Translation · Arthrometer · Reproducibility · Force displacement

Introduction

Translational laxity of the glenohumeral joint is commonly assessed during physical examination, especially in cases of suspected instability. Clinicians use information regarding the magnitude and direction of glenohumeral laxity to diagnose shoulder injury and make decisions regarding the need for surgery and/or rehabilitation [5, 12, 15, 27]. However, very little is known regarding the normal magnitudes of glenohumeral laxity in healthy and injured shoulders. Glenohumeral laxity assessment is most often performed using selected manual tests such as the anterior-posterior drawer, load and shift, and sulcus [12, 15, 23]. These manual tests are subjective in nature, and the clinician must rely on "feel" to determine the magnitude of the observed translation. Many studies have been carried out with regards to the validity and reliability of these tests [14, 18, 19, 20, 30, 37]. Investigators have reported poor reproducibility and diagnostic value of the manual laxity examination [18, 20]. Poor reproducibility has been attributed to a number of factors, including examiner experience and inconsistencies with respect to force application, humeral head centering, and patient positioning [18,

30]. Furthermore, muscular tension around the shoulder during examination may significantly alter the magnitude of observed translation and capsular end feel [5, 27]. Researchers suggest that a reliable, objective, and clinically available instrument to quantify glenohumeral joint translation is necessary to eliminate the shortcomings of these manual tests [11, 18, 19, 30].

A limited understanding of glenohumeral joint laxity coupled with the importance of this physiological variable in clinical decision making suggests that the normal amount of glenohumeral translation needs to be more objectively defined. Therefore the purpose of this study was to quantify anterior and posterior translations of the glenohumeral joint as a function of force in healthy shoulders using instrumented arthrometry. Our objectives were to compare anterior and posterior translations at various force levels in order to provide normative data and determine the between trial, between session (intrarater), and between examiner (interrater) reliability of our measurement technique.

Materials and methods

Experimental design and subjects

A repeated measures design was used to assess glenohumeral joint laxity in two directions (anterior and posterior) and at four force levels (67, 89, 111, 134 N). The dependent measure was joint displacement (translation) and was recorded in millimeters.

An a priori power analysis for a repeated measures analysis of variance (ANOVA) design was based on our previous study that yielded group differences (between force levels) of approximately 1 mm and an average standard deviation of 2.6 mm [3]. Using these values a calculated effect size of 0.4 was determined. Choosing an effect size of 0.4, α 0.05, and power 0.80, 50 shoulders were required to achieve appropriate statistical power for this investigation [35].

Twenty-five subjects (12 women, 13 men; mean age 21.9± 2.6 years) were recruited based on the absence of any subjective pain complaints about either shoulder, no significant history of shoulder pathology (i.e., required surgery or rehabilitation), and no history of long-term participation in overhead sports (e.g., swimming, tennis, baseball). While none of the subjects included in this study reported long-term involvement in overhead sports, the majority of the subjects did engage in regular physical activity and recreational sports of a wide variety. Both shoulders for each subject were randomly assessed, giving a total of 50 shoulders.

Approval was granted for this research study from the Institutional Review Board for the protection of human subjects. Each subject signed an informed consent document and completed an orthopedic shoulder history and demographic information questionnaire before participating in the study.

Instrumentation

Glenohumeral joint laxity was measured using an instrumented arthrometer (patent pending; Fig. 1). A custom-designed test chair equipped with nylon strapping was used as a base of support for testing. Displacement forces were applied to the glenohumeral joint using a custom force applicator. The force applicator consists of a plastic handle mounted to a load cell (Omega Engineering, Stamford, Conn., USA). A metal hook is attached at the opposite end for securing the force applicator to an arm cuff. A 3×18 in. arm cuff made of padded nylon is wrapped around the proximal humerus and secured with hook and loop fastening strips. The load cell was calibrated with a known force regularly to ensure accuracy.

Two linear displacement transducers (LDTs; Davis Instruments, Baltimore, Md., USA) were used to measure linear displacement of the humeral head and acromion process. The LDTs consist of an aluminum cylinder with a retractable, high-grade aluminum strip that can measure linear displacement to the nearest tenth of a millimeter. One LDT measured displacement of the acromion process of the scapula, and the other measured humeral head displacement. Custom-made LDT adapters were fabricated to interface the alu-

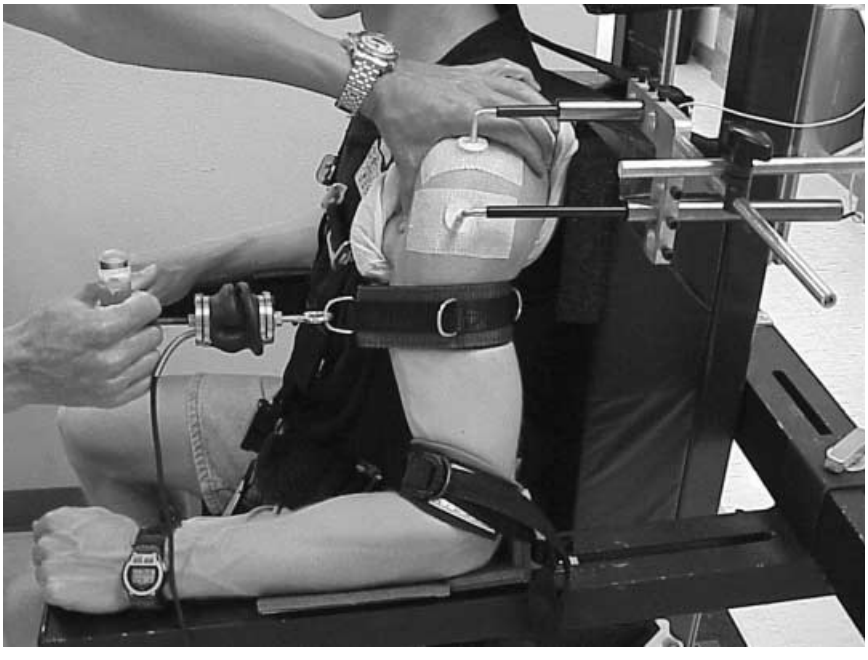

Fig. 1 Anterior trial using the instrumented shoulder arthrometer (patent pending)

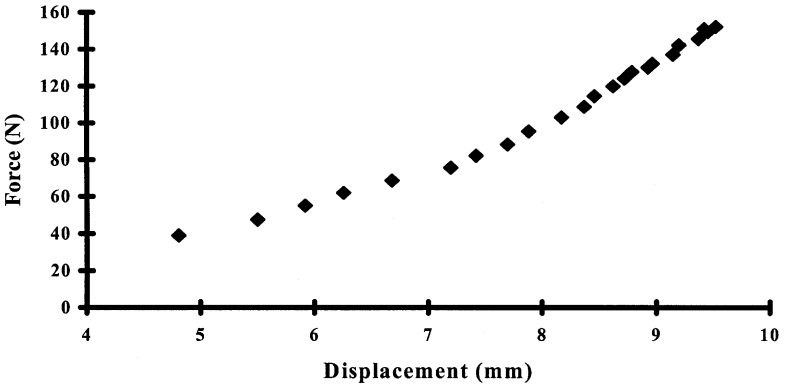

Fig. 2 Typical force-displacement curve from an anterior trial using the instrumented shoulder arthrometer (patent pending). Note: data points are not plotted at forces below 30 N

minum strips of the LDTs to the cutaneous attachment sites. One adapter was affixed to the skin surface over the acromion process, and the other was affixed to the skin surface over the lateral portion of the proximal humerus. The LDTs were calibrated regularly using a standard analog caliper. Scapulothoracic motion was accounted for by subtracting the recorded acromion process displacement from the recorded humeral head displacement. Therefore glenohumeral joint laxity was calculated from the following equation and rounded to the nearest tenth of a millimeter: true humeral head translation=$(X_1–X_2)–(Y_1–Y_2)$, where X is humeral head sensor, Y is scapular (acromion) sensor, $(X_1–X_2)$ is linear displacement of humeral head, X_1 is start position, X_2 is end-point, $(Y_1–Y_2)$ is linear displacement of scapula (acromion), Y_1 is the start position, and Y_2 is the end-point.

Voltage signals from the load cell and LDTs were fed to an analog to digital converter box. The converter box contains three circuit boards with a power supply (Davis Instruments) to relay signals to a host computer. Force and displacement values were visualized on the computer screen in real-time during test trials through the use of Labtech Notebookpro version 10.02 (Labtech, Andover, Mass., USA). Raw data were acquired from the test instruments that operate through the Labtech Notebookpro (Labtech). The raw data were reduced and converted to a spreadsheet format (Microsoft Visual Basic 6.0, Redmond, Wash., USA), and displayed graphically and numerically as force-displacement (Microsoft Excel 5.0; Fig. 2). From the force-displacement curves laxity values were recorded at 67, 89, 111, and 134 N of force.

Experimental procedures

Prior to testing each subject was examined by an orthopedic surgeon (R.D.S.) to rule out hyperlaxity and/or pathology (instability) of both glenohumeral joints. The load and shift and sulcus tests were used to evaluate anterior, posterior and inferior joint laxity, respectively [12, 15, 23]. Laxity was graded on a scale of 0 to 3+ (0, no humeral head translation; 1+, humeral head translates up to but not over the glenoid rim; 2+, humeral head translates over glenoid rim but spontaneously reduces; 3+, humeral head translates over glenoid rim without spontaneous reduction) [19, 22]. Based on the manual laxity test scores and the absence of any subjective pain complaints or history of injury, the subjects were found to have bilaterally healthy shoulders.

During each testing session anterior and posterior force-displacement data were obtained for both shoulders of each subject. Between-trial and between-session reliability tests were conducted by the primary author (E.L.S.). Between-examiner reliability tests were performed by E.L.S. and P.A.B. Subjects were seated and secured comfortably in the test chair with the adjustable padded straps. The order of testing for side (right or left) was randomly determined, and anterior trials always preceded posterior trials. The humerus was positioned and secured in 20° of elevation in the scapular plane and neutral rotation, measured using standard goniometry. This test position is similar to the position used by clinicians during standard manual examinations for shoulder laxity [12, 14, 15, 18, 19, 23]

The acromion process was located via palpation, and the acromion LDT attachment bar was affixed cutaneously to its superior aspect. The humeral head was then located via palpation to determine the position for placement of the humeral LDT. The humeral LDT attachment bar was then affixed over the lateral aspect of the proximal humerus adjacent to the acromion LDT. Each LDT attachment bar was secured to the skin surface with adhesive tape. The LDTs were then positioned parallel to the line of force application using a linkage system with 3 degrees of freedom. Once in place, the LDTs were secured to their corresponding attachment bars already affixed to the subject.

Next the arm cuff was secured firmly around the proximal humerus as high in the axillary fold as possible to closely approximate the point of force application with the humeral head. Using the real-time display of force-displacement the LDT positions were adjusted to within ±1 mm of 0 displacement to determine the start position. Once the start position was achieved a progressive force from 0 to 134 N was applied to the joint using the force applicator at an average displacement rate of 3.3±1.4 mm/s. The experimenter further stabilized the scapula with his thumb (coracoid process) and index finger (scapular spine) during each trial. The mean displacement from the three trials in each direction was recorded to the nearest tenth of a millimeter.

The second arthrometer test session was conducted by the first examiner no sooner than 24 h following the first to determine between session reliability. The second examiner (P.A.B.) randomly tested subjects immediately after either their first or second arthrometer test session to determine between-examiner reliability. Counterbalance was achieved by randomly selecting 12 subjects' data from his/her first test session and 13 subjects' data from his/her second test session. During laxity assessment the examiner was blinded to the test results between trials, sessions, and examiners.

Statistical procedures

Descriptive statistics were used to screen data for measures of central tendency, variance, and frequency and symmetry of distribution.

Reliability

Intraclass correlation ($ICC_{2,1}$) values, means, standard deviations, and standard error of the measurements (SEM) were calculated for glenohumeral joint laxity values (a) for each shoulder (right and

left), (c) in each direction, and (c) at each of the specified levels of force. Using an ANOVA for repeated measures, the mean square values were obtained for inclusion in ICC formulas. Estimated reliability of the mean of multiple (a) trials (between-trial reliability), (b) sessions (between-session reliability), and (c) examiners (between-examiner reliability) were calculated using the $ICC_{2,1}$ formula [9, 31]. All reliability coefficients were interpreted as follows; below 0.69 was poor, 0.70–0.79 was fair, 0.80–0.89 was good, and 0.90-1.00 was considered excellent [29].

Within- and between-subject comparisons

Paired *t* tests were used to analyze side-to-side differences for both anterior and posterior laxity at each force level. A 2 (direction) × 4 (force) factorial ANOVA was used to evaluate glenohumeral joint laxity for all 50 shoulders. This analysis was used to determine main effects for direction and force. In the presence of statistically significant main effects, Fisher's protected least significant difference post hoc analyses were performed to identify significant differences between each level of the independent variables. All data analyses were performed using Statview Version 4.5 (Statview, Albacus Concepts, Berkeley, Calif., USA). The level of statistical significance was set at α=0.05.

Results

Descriptive data

The normative laxity values were all calculated from tests performed by the primary author (E.L.S). Descriptive data and frequency distribution histograms for anterior and posterior laxity are displayed in Fig. 3 and Table 1.

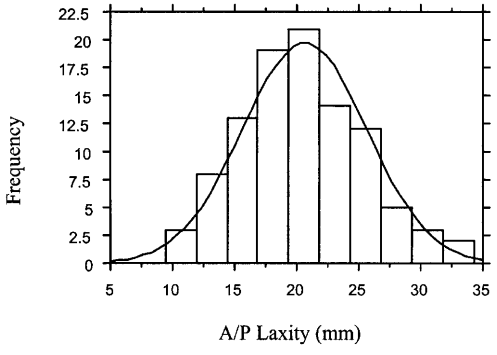

Fig. 3 Histogram depicting a normal distribution of anterior + posterior laxity over all levels of force

Table 1 Descriptive statistics for anterior and posterior laxity averaged over all levels of force

Descriptive statistics	Anterior laxity (mm)	Posterior laxity (mm)
Mean	9.5	11.1
Standard deviation	2.8	2.6
Minimum	4.3	4.7
Maximum	17.3	17.5
Variance	7.8	7.0
Range	13.0	12.8

Table 2 Mean reliability coefficients ($ICC_{2,1}$) and standard error of measurements (*SEM*)

	$ICC_{2,1}$	SEM (mm)
Between-trial	0.92 (0.77–0.96)	0.56 (0.45–0.73)
Between-session	0.73 (0.60–0.88)	1.5 (0.79–1.9)
Between-examiner	0.74 (0.66–0.81)	1.7 (1.3 –2.1)

Reliability

The between-trial $ICC_{2,1}$ values averaged over all sides, directions, and force levels indicates excellent reliability (Table 2). The between-session and between-examiner $ICC_{2,1}$ values averaged over all sides, directions, and force levels indicate fair reliability (Table 2). The mean and range of the SEM are also provided (Table 2).

Within- and between-subject comparisons

Paired *t* tests revealed no statistically significant differences in glenohumeral joint laxity between sides in either the anterior (t_{99}=0.14) or posterior (t_{99}=0.07) directions. Based on these findings the data were pooled for additional

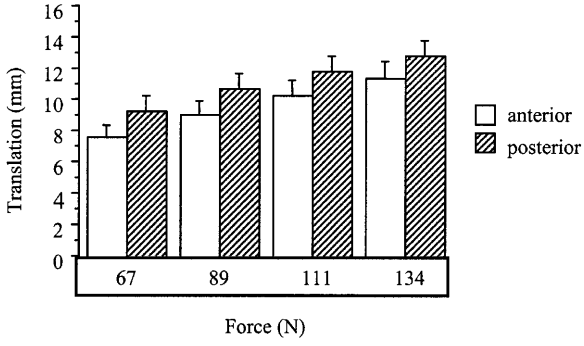

Fig. 4 Bar plots depicting mean (±SD) anterior and posterior translation (mm) at each force level. Posterior translation was significantly greater than anterior (P<0.01), and significant differences were revealed between each force level (P<0.01)

Table 3 Mean (±SD) values for anterior and posterior translation (mm) at observed force levels

Force level (N)	Anterior	Posterior
67	7.5±2.1	9.3±2.2
89	8.9±2.3	10.7±2.3
111	10.2±2.6	11.8±2.4
134	11.3±2.8	12.7±2.5

Table 4 Post hoc (Fisher's protected least significant difference) comparisons between each force level

Force (N)	Mean difference (mm)	Critical difference (mm)	*P*
67 vs. 89	–1.43	0.95	0.003
67 vs. 111	–2.60	0.95	<0.01
67 vs. 134	–3.63	0.95	<0.01
89 vs. 111	–1.17	0.95	0.015
89 vs. 134	–2.20	0.95	<0.0001
111 vs. 134	–1.03	0.95	0.033

analyses. A 2 (direction) × 4 (force) factorial ANOVA revealed significant mean differences between directions ($F_{1,192}$=23.64, P<0.01) and significant mean differences between force levels ($F_{3,192}$=21.23, P<0.01; Fig. 4, Table 3). Post hoc tests revealed that posterior translation was significantly greater than anterior translation, and significant differences were demonstrated between each force level (Table 4).

Discussion

Instrumented arthrometry involves the measurement of joint displacement as a function of applied force in a noninvasive, inexpensive, and objective manner using specialized instrumentation [1, 6, 7, 21]. Unlike the knee, reports of instrumented arthrometry at the glenohumeral joint are currently very limited in the orthopedic and sports medicine literature [3, 14, 16, 24, 28]. This report presents new information on the use of an instrumented arthrometer to assess the magnitude of glenohumeral laxity in healthy shoulders.

Determining the reliability and SEM of a test instrument is important and has practical significance as well. The ability to document instrument reliability and measurement error helps to validate research findings and demonstrates the precision of obtained measures [9, 28]. We used the ICC and SEM to demonstrate the reliability and precision of our test instrument. Our between-trial, between-session, and between-examiner reliability coefficients over each direction and force level were found to be fair to excellent (Table 2). Similar studies assessing glenohumeral laxity have also reported fair to excellent reliability of their respective technique/instrument [3, 14, 16, 28].

The SEM reflects the degree one may expect a test score to vary due to measurement error [9]. Deneger and Ball [9] liken the SEM to a confidence interval. The between-trial, between-session, and between-examiner SEM values determined during this investigation indicate that only a small degree of measurement error (range 0.56–1.7 mm) was present between repeated trials, sessions, and examiners. Overall, these data confirm that our instrumented shoulder arthrometer is very precise and reproducible and may be used as a viable method of assessing glenohumeral laxity.

Several possible sources of measurement error may have contributed to the observed measurement variance and fair reproducibility between sessions and examiners. The placement of the motion sensors did not change between trials, but were removed and reapplied between sides (right and left) and sessions (1 and 2). Care was taken to ensure consistent placement of the sensors, although a slight change in placement of only 1–2 mm could account for some of the observed error.

Glenohumeral joint laxity is dependent upon the capsuloligamentous structures that serve as the primary static stabilizers of the joint [15, 23, 32, 37]. These structures are known to exhibit viscoelastic (rate-dependent) mechanical behavior [33, 36]. A nonuniform rate of force application between trials may have produced variable displacement patterns. However, biomechanical testing at the shoulder and the knee have shown that slight variations in strain rates have only minimal impact on ligament structural and material properties [2, 8]. Care was taken throughout our investigation to utilize a consistent displacement rate of 3–4 mm/s. Slight variations in our displacement rates are not assumed to have significantly altered the force-displacement response and therefore are not believed to be a significant source of error variance.

Another source of error variance may be from muscular tension during testing. From our observations, the force-displacement curves were consistent between trials and subjects, indicating to us that the subjects' shoulders were not "tensing-up" during force application even though several subjects reported difficulty relaxing during test trials. Future studies may utilize electromyographic feedback during testing to determine whether significant muscular activity is present during testing.

Accessibility to viable bony landmarks was another possible source of error variance in our study. We used the humeral head and acromion process as our bony reference points. The bulk tissues surrounding the humeral head prevented our instrumentation from closely approximating this bony landmark. Therefore the inability to account for soft tissue compression during force application likely contributed to the observed measurement error.

The second aim of this study was to report baseline normative data in healthy shoulders. The descriptive values and frequency distribution histograms for anterior and posterior laxity show our data to be normally and equally distributed (Table 1, Fig. 3). These data support earlier reports revealing a wide range of laxity among healthy shoulders [14, 19, 20, 32]. Figure 3 shows a wide distribution of laxity with a normal bell-shaped curve. Interindividual laxity differences in healthy shoulders are reported to be a function of variability in articular geometry, joint volume, connective tissue morphology, low-level muscle tension, and other related factors [14, 23, 32, 37, 38]. Unfortunately, the relative contribution of each factor to the

Table 5 Summary of previous in vivo studies assessing glenohumeral laxity

Investigation	Instrumentation	Shoulders	Arm Position	Force (N)	Laxity values (mm)
Current study	LDT	50 healthy	20° abduction	67	A=7.5 (2.1) P=9.3 (2.2)
				89	A=8.9 (2.3) P=10.7 (2.3)
				111	A=10.2 (2.6) P=11.8 (2.4)
				134	A=11.3 (2.8) P=12.7 (2.5)
Borsa et al. [3]	LDT	50 healthy	20° abduction	67	A=6.1 (1.7) P=5.0 (2.7)
				89	A=7.4 (1.8) P=6.1 (3.0)
				111	A=8.7 (1.9) P=6.8 (3.7)
				134	A=9.7 (2.0) P=6.5 (4.1)
Krarup et al. [17]	Ultrasonography	20 healthy	0° abduction	89	A=1.9
Pazzari et al. [28]	knee arthrometer (KT-1000)	56 healthy	90° abduction	67	A/P combined=21.0 (4.9)
Jorgensen and Bak [16]	knee arthrometer (DonJoy)	10 healthy	0° abduction	89	A/P combined=2.1 (1.7)
Harryman et al. [14]	Electromagnetic spatial trackers	8 healthy	0° abduction	Not known	A=7.8 (4.0) P=7.9 (5.6)

total magnitude of glenohumeral joint laxity is not presently known.

Laxity is usually assessed in three directions; anterior, posterior, and inferior. According to the "circle concept" of shoulder stability, the amount of glenohumeral joint translation in each direction (anterior, posterior, and inferior) is equivalent [14]. Our data indicate that healthy shoulders have greater posterior translation than anterior, thus refuting the circle concept theory (Fig. 4). Our finding is in contrast to earlier studies citing directional symmetry in healthy shoulders [4, 14]. It should be noted that the posterior capsule is thinner than the anterior capsuloligamentous structures and therefore may provide less resistance to translation than the thicker anterior capsule and supporting glenohumeral ligaments [26]. Additionally, the subscapularis tendon is also reported to resist anterior translation when the humerus is below 90° of abduction [23]. The true clinical implications of asymmetric directional laxity are not known at this time, although it may be postulated that directional asymmetries may alter joint kinematics contributing to the development of chronic impairment.

There are several other published reports on the instrumented measurement of in vivo shoulder laxity; however, it is difficult to compare these findings to our data due to methodological differences between the studies. The methodological differences include variations in the applied force, position of the arm, and data acquisition and instrumentation procedures [3, 4, 10, 14, 16, 17, 24, 28]. The results of previous studies reporting on in vivo glenohumeral joint laxity are summarized in Table 5.

Our within-subject comparisons revealed no significant side-to-side difference in translation between the right (dominant) and left (nondominant) shoulders. Since all subjects were right-hand dominant, our side-to-side comparisons also demonstrate that no significant differences in translation exist between the dominant and nondominant shoulder. Our finding of bilateral symmetry in healthy shoulders is consistent with our previous investigation [3] as well as those of others [16, 28].

Jorgensen and Bak [16] and Pazarri et al. [28] used a commercial knee arthrometer adapted to the adducted shoulder to quantify anterior-to-posterior (AP) translations. In the study by Jorgensen and Bak [16] ten subjects with bilateral healthy shoulders were assessed for laxity using an 89-N displacement force. The mean AP translation values for both left and right shoulders were 2.1±1.7 mm with a side-to-side difference score of 0.6±0.5-mm. Pazzari et al. [28] reported the AP laxity range in 28 subjects with bilateral healthy shoulders to be 20.9±4.9 mm (dominant 20.2±5.0, nondominant 21.5±4.8 mm) using a force of 67 N. Subjects in this study were prone with the arm positioned in 90° abduction. Borsa et al. [3, 4], using a force applicator equipped with a load cell and linear displacement transducers, recorded force-displacement measures in the anterior and posterior directions of healthy shoulders. Displacement forces used in the study ranged from 0 to 134 N. The mean anterior and posterior laxity values reported by Borsa et al. [3, 4] ranged from 5.0±2.7 to 11.9±2.9 mm. The magnitude of translation shown by Jorgensen and Bak [16] is much less than the magnitudes reported by Borsa et al. [3, 4] and Pazzari et al. [28] as well as those obtained in this study (89-N load AP range=19.6±2.3 mm). The disparity in laxity values is difficult to account for, and underscores the need for standardized instrumentation to measure shoulder laxity.

Studies by Lintner et al. [19] and McFarland et al. [22] used manual laxity examinations and found significant side-to-side differences in asymptomatic shoulders of high school and collegiate athletes. Both studies used qualitative scores to grade the magnitude of glenohumeral translation, and made no reference to the force applied to the joint. This is in contrast to the studies reported above using instrumented devices related to force. These conflict-

ing reports between subjective and objective measures of laxity further support the need for an instrumented device to quantify glenohumeral laxity.

Side-to-side comparisons are commonly used during clinical assessment to evaluate the injured joint with the contralateral, noninjured joint. The difference score is then used to identify the presence of excessive laxity and/or pathology [1, 6, 7]. Knee arthrometers use side to side comparisons as predictive indicators of anterior cruciate ligament injury and clinical outcomes [13, 21, 25, 34]. The ability of an instrumented device to discriminate between healthy shoulders and shoulders with suspected pathology is desirable in clinical orthopedic practice. In order for the test to be a sensitive and specific indicator of pathology a low SEM is necessary when observing within-subject, side-to-side differences, especially when the differences are subtle [3]. It is conceivable that an arthrometer, similar to those used at the knee, could be developed for the glenohumeral joint and be used as an objective measure of capsuloligamentous insufficiency.

In our efforts to characterize the force-displacement response of the glenohumeral joint we observed laxity at four force levels (67, 89, 111, and 134 N). Our laxity data demonstrate a consistent and relatively linear relationship between force and displacement even at our highest force level (Fig. 4). This linear relationship between force and displacement demonstrates the compliant nature of the glenohumeral joint. Our mean values for anterior and posterior translation demonstrate a similar force-displacement response pattern with a gradual decline in displacement between the highest force levels (Fig. 4). This is an indication that the structures resisting translation are becoming more taut; however, a true clinical end-point is not discernable.

Several orthopedic surgeons have suggested that laxity is most accurately gauged at clinical end-point, which has been estimated to occur at about 89 N of force [12, 14, 15, 23]. A report by Gerber and Ganz [12] recommends using a force comparable to that used for the Lachman test at the knee. Oliashirzai et al. [27] report that during the manual laxity examination with the patient under anesthesia only 1–3 kg (9.8–29.4 N) of displacement force, depending on the size of the shoulder, is necessary to reach capsular end-point. Hawkins and Mohtadi [15] evaluated humeral translation using the AP drawer with the patient under anesthesia and noted that the force required to achieve capsular end-point would be approximately 20 lb (89 N). However, our force-displacement data suggest that forces higher than 134 N are necessary in order to reach the end-point of translation in the healthy shoulder.

Our laxity trials did not apply maximum displacement forces to the glenohumeral joint and therefore did not capture the absolute limits of glenohumeral translation. From a biomechanical perspective, we feel the forces applied to the joint could have been safely increased in the healthy shoulder to more thoroughly characterize force-displacement response.

Several limitations to our study should be noted. Our technique used linear motion sensors affixed to the skin surface leaving us without a viable bony landmark for the humerus. The inability to approximate the humeral head with our sensors due to overlying soft tissues may have affected the accuracy of our measures. Only by using an invasive approach would you be able to most accurately measure translation. Laxity was assessed in only one position (20° abduction). Most comprehensive assessments use a variety of positions to obtain a more global profile of the joint. Additionally, we were unable to account for the effects of muscle guarding on translation. Even though we required our subjects to maximally relax the limb during testing, some muscle guarding, however minor, was always present. Muscle guarding can only be completely controlled when the subject is under anesthesia [5, 27]. Lastly, we are unable to generalize our findings to a pathological group. In light of these limitations, we are still confident that a clinical device such as our own will provide practical measures of laxity in healthy shoulders.

Conclusions

This study objectively measured glenohumeral joint translations as a function of force in healthy shoulders. Our results show that our instrumented technique for quantifying glenohumeral joint laxity is precise and reproducible. A wide spectrum of laxity was shown to be present in healthy shoulders. Our results found no significant within-subject, side-to-side differences in laxity, although posterior laxity was found to be greater than anterior. Healthy shoulders also demonstrated good compliance with increasing force levels with no discernable end-point observed.

Future investigations should examine laxity at increasing levels of elevation and rotation to further characterize the normal magnitude of glenohumeral joint laxity. Also, in vivo studies should aim to examine laxity patterns in overhead athletes, in patients with documented shoulder pathologies, and following specific surgical techniques. This information will lead to greater understanding of normal and abnormal glenohumeral joint displacement and have application to injury prevention strategies, diagnoses, and treatment outcomes.

Acknowledgements This study was conducted in the Biomechanics Research Laboratory at Oregon State University, Corvallis, Oregon, with funding provided by the John C. Erkkila Endowment for Health and Human Performance.

References

1. Bach BR, Warren RF, Flynn WM, Kroll M, Wickiewiecz TL (1990) Arthrometric evaluation of knees that have a torn anterior cruciate ligament. J Bone Joint Surg Am 72:1299–1306
2. Bigliani LU, Pollock RG, Soslowsky LJ, Flatow EL, Pawluk RJ, Mow VC (1992) Tensile properties of the inferior glenohumeral ligament. J Orthop Res 10:187–197
3. Borsa PA, Sauers EL, Herling DE (1999) In vivo assessment of AP laxity in healthy shoulders using an instrumented arthrometer. J Sport Rehabil 8:1–14
4. Borsa PA, Sauers EL, Herling DE (2000) Glenohumeral joint laxity and stiffness in healthy shoulders. Med Sci Sports Exerc 32:S123
5. Cofield RH, Nessler JP, Weinstabl R (1993) Diagnosis of shoulder instability by examination under anesthesia. Clin Orthop 291:45–53
6. Daniel DM, Stone ML, Sachs R, Lawrence M (1985) Instrumented measurement of anterior laxity in patients with acute anterior cruciate ligament disruption. Am J Sports Med 13:401–407
7. Daniel DM, Malcom LL, Losse G, Stone ML, Sachs R, Burks R (1985) Instrumented measurement of anterior laxity of the knee. J Bone Joint Surg Am 67:720–725
8. Danto MI, Hacker SA, MacKenna DA, Joshi M, Li CK, Woo SLY (1991) Effect of strain rate on the mechanical properties of rabbit anterior cruciate ligament (ACL) and patellar tendon (PT). Trans Orthop Res Soc 16:233–241
9. Denegar CR, Ball DW (1993) Assessing reliability and precision of measurement: an introduction to intraclass correlation and standard error of measurement. J Sport Rehabil 2:35–42
10. Ellenbecker TS, Mattalino AJ, Elam E, Caplinger R (2000) Quantification of anterior translation of the humeral head in the throwing shoulder: manual assessment versus stress radiography. Am J Sports Med 28:161–167
11. Eriksson E (2000) How reliable are measurements with arthrometers? Knee Surg Sports Traumatol Arthrosc 8:131
12. Gerber C, Ganz R (1984) Clinical assessment of instability of the shoulder with special reference to anterior and posterior drawer tests. J. Bone Joint Surg Br 66:551–556
13. Giannotti BF, Fanelli GC, Barrett TA, Edson C (1996) The predictive value of intraoperative KT-1000 arthrometer measurements in single incision anterior cruciate ligament reconstruction. Arthroscopy 12:660–666
14. Harryman DT, Sidles JA, Harris BS, Matsen FA (1992) Laxity of normal glenohumeral joint: a quantitative in vivo assessment. J Shoulder Elbow Surg 1:66–76
15. Hawkins RJ, Mohtadi GH (1991) Clinical evaluation of shoulder instability. Clin J Sports Med 1:59–64
16. Jorgensen U, Bak K (1995) Shoulder instability: assessment of anterior-posterior translation with a knee laxity tester. Acta Orthop Scand 66:398–400
17. Krarup AL, Court-Payen M, Skjoldbye B, Lausten GS (1999) Ultrasonic measurement of the anterior translation in the shoulder joint. J Shoulder Elbow Surg 8:136–141
18. Levy AS, Lintner S, Kenter K, Speer KP (1999) Intra- and interobserver reproducibility of the shoulder laxity examination. Am J Sports Med 27: 460–463
19. Lintner SA, Levy A, Kenter K, Speer K (1996) Glenohumeral translation in the asymptomatic athlete's shoulder and its relationship to other clinically measurable anthropometric variables. Am J Sports Med 24:716–720
20. Lippitt SB, Harris SL, Harryman DT, Sidles J, Matsen FA (1994) In vivo quantification of the laxity of normal and unstable glenohumeral joints. J Shoulder Elbow Surg 3:215–223
21. Markolf KL, Amstutz HC (1987) The clinical relevance of instrumented testing for ACL insufficiency: experience with the UCLA clinical knee testing apparatus. Clin Orthop 223:198–207
22. McFarland EG, Campbell G, McDowell J (1996) Posterior shoulder laxity in asymptomatic athletes. Am J Sports Med 24:468–471
23. McFarland EG, Torpey BM, Curl LA (1996) Evaluation of shoulder laxity. Sports Med 22:264–272
24. McQuade KJ, Shelley I, Cvitkovic J (1999) Patterns of stiffness during clinical examination of the glenohumeral joint. Clin Biomech 14:620–627
25. Neuschwander DC, Drez D, Paine RM, Young JC (1990) Comparison of anterior laxity measurements in anterior cruciate deficient knees with two instrumented testing devices. Orthopedics 13:299–302
26. O'Brien SJ, Schwartz RS, Warren RF, Torzilli PA (1995) Capsular restraints to anterior-posterior motion of the abducted shoulder: a biomechanical study. J Shoulder Elbow Surg 4:298–308
27. Oliashirazi A, Mansat P, Cofield RH, Rowland CM (1999) Examination under anesthesia for evaluation of anterior shoulder instability. Am J Sports Med 27:464–468
28. Pizzari T, Kolt GS, Remedios L (1999) Measurement of anterior-to-posterior translation of the glenohumeral joint using the KT-1000. J Orthop Sports Phys Ther 29:602–608
29. Portney L, Watkins M (1993) Foundations of clinical research: application to practice. Appleton & Lang, Norwalk
30. Rodkey WG, Noble JS, Hintermeister RA (1993) 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. American Academy of Orthopaedic Surgeons, Rosemont, pp 551–582
31. Shrout PE, Fleiss JL (1979) Intraclass correlations. Uses in assessing rater reliability. Psychol Bull 86:420–428
32. Speer KP (1995) Anatomy and pathomechanics of shoulder instability. Clin Sports Med 14:751–760
33. Stefko JM, Tibone JE, Cawley PW, ElAttrache NE, McMahon PJ (1997) Strain of the anterior band of the inferior glenohumeral ligament during capsule failure. J Shoulder Elbow Surg 6:473–479
34. Strand T, Solheim E (1995) Clinical tests versus KT-1000 instrumented laxity test in acute anterior cruciate ligament tears. Int J Sports Med 16:51–53
35. Thomas JR, Nelson JK (1996) Research methods in physical activity, 3rd edn. Human Kinetics, Champaign
36. Ticker JB, Bigliani LU, Soslowsky LJ, Pawluk RJ, Flatow EL, Mow VC (1996) Inferior glenohumeral ligament: geometric and strain-rate dependent properties. J Shoulder Elbow Surg 5:269–279
37. Warner JJP, Micheli LJ, Arslanian LE, Kennedy J, Kennedy R (1990) Patterns of flexibility, laxity, and strength in normal shoulders and shoulders with instability and impingement. Am J Sports Med 18:366–375
38. Warner JJP, Deng X-H, Warren RF, Torzilli PA (1992) Static Capsuloligamentous restraints to superior-inferior translation of the glenohumeral joint. Am J Sports Med 20 (6):675–685