Isometric Shoulder Girdle Strength of Healthy Young Adults

Brian A. Garner, PhD, *Department of Mechanical Engineering*
Joe Shim, PhD, *Department of Health, Human Performance, and Recreation*
Baylor University, Waco, Texas, 76798, USA

Corresponding Author:
Brian A. Garner, PhD
One Bear Place #97356
Waco, TX 76798-7356, USA
Telephone: (254) 710-4191
Fax: (254) 710-3839
Email: brian_garner@baylor.edu

Clinical Biomechanics
Word count: 4061

Abstract

Background: Shoulder girdle muscles are important for stabilizing the scapula and orienting the glenoid for upper extremity motion. However, data describing shoulder girdle strength and how it varies with position is lacking.

Methods: A series of experiments was conducted to measure isometric strength at three positions each for elevation, depression, protraction, and retraction of the shoulder girdle. Nineteen healthy men and women (ages 19 to 23 years) participated in the study. Subjects were seated in a custom apparatus and asked to push or pull with extended arms as forcefully as possible against force-sensing handles. Shoulder girdle elevation angle and protraction angle were recorded with a video system during the tests.

Findings: In each direction the force generated by the shoulder girdle varied significantly ($P<0.05$) and monotonically with position. The greatest forces in elevation (mean 1101 N, SD 370 N) and protraction (mean 1117 N, SD 471 N) occurred at the most depressed and retracted positions, respectively. Similarly, the greatest forces in depression (mean 810 N, SD 274 N) and retraction (mean 914 N, SD 362 N) occurred at the most elevated and protracted positions, respectively. Male subjects generated 38% to 81% greater force than female subjects, depending on direction. Shoulder girdle elevation and protraction strengths correlated significantly ($P<0.01$) with bodyweight ($r>0.71$) and with one-repetition maximum bench press strength ($r>0.83$).

Interpretation: Functional tasks such as bench press may be good indicators of shoulder girdle strength in some directions.

Keywords: shrug, elevation, depression, protraction, retraction, scapula, clavicle

Word count: 246

Introduction

Knowledge of the strength characteristics at a joint can be valuable for a variety of applications. Strength measured from an impaired individual can be compared against healthy strength characteristics to indicate the nature, locality, and severity of musculoskeletal injury (Mayer et al., 2001). Strength data may be used in engineering applications to design safe and effective products or devices (Peebles & Norris, 2003; Garner 2007). Finally, strength measurements may be used in research to investigate joint force variability in motor control (Christou et al., 2002), or to validate computer models representing musculoskeletal biomechanics (Garner & Pandy, 2001; Garner & Pandy, 2003; Holzbaur et al., 2005).

Joint strength is commonly characterized by measuring the external moment or force generated by the contributing muscles during maximal, voluntary effort (e.g., Winters & Kleweno, 1993). These measures typically vary with joint position and velocity, and reflect the complex interactions between joint geometry and muscle physiology. The geometric relationship between the muscle path and joint axis dictates the muscle's excursion (i.e., length variation over the range of joint motion) and its mechanical advantage at the joint (i.e., moment arm). In turn, the muscle excursion determines muscle fiber lengths and shortening velocities, which, along with physiological cross-sectional area and neuromuscular adaptations, dictate the capacity of a muscle to produce force (Zajac, 1989; Wilmore & Costill, 2004).

Although many studies have reported strength measurements at joints in the lower extremity, upper extremity, and back (e.g., Knapik et al., 1983; Graves et al., 1990), studies quantifying the strength of the shoulder girdle are lacking, despite the importance of this joint in upper-extremity motion. Muscles actuating the shoulder girdle are responsible for stabilizing the scapula and coordinating with glenohumeral movements to effect the wide-ranging, phased kinematics of the shoulder joint (Poppen & Walker, 1976). Proper strength ratios between the agonist and antagonist muscles of the shoulder girdle are believed important for proper alignment of glenoid forces and for reducing susceptibility to glenohumeral instability and overload rotator cuff injury (Kibler, 1998; Mayer et al., 2001; Wilk et al., 2002).

In the past, shoulder girdle strength has been assessed using basic exercises whose gross movements involve the shoulder girdle muscles (Rutherford & Corbin, 1994; Kibler, 1998). Examples include push-ups, pull-ups, scapular pinches, and seated lat pulls. While strength exhibited during functional tasks is important, it may not reflect the maximal capacity of muscles activating specific joints due to its dependence on motor coordination and the strength of other involved joints.

A few recent studies have sought to measure shoulder girdle strength more directly. Cools et al. (2002) measured isokinetic protraction and retraction strength of the shoulder girdle in the scapular plane. The study reported unilateral peak force and total work, but did not consider the role of joint position.

Wilk et al. (1999, 2002) reported the isometric strength of male professional baseball players for four directions of shoulder girdle movement. However, strength was reported at only one, unspecified position in each direction, and the measurement methods were not fully described. To our knowledge, no previous study has reported isometric shoulder girdle strength for male and female subjects as a function of position.

The purpose of this study was to 1) measure maximum isometric force generated by the shoulder girdle during elevation, depression, protraction, and retraction exercises, 2) assess how these forces vary with joint position in each direction, and 3) evaluate possible correlations between these strength measures and other subject-specific characteristics such as gender, bodyweight, and bench-press strength.

Methods

A series of experiments was performed to measure isometric force generated by the shoulder girdle at three positions each for four directions of shoulder girdle movement. The experiments were approved by the Baylor University Institutional Review Board, and all subjects signed informed consent. For purposes of this study, the four directions of shoulder girdle movement were defined as follows: *elevation* is pulling upwards, and *depression* is pushing downwards with the arms alongside the upright torso; *protraction* is pushing forwards, and *retraction* is pulling backwards with the arms positioned horizontally anterior to the upright torso.

Subjects

Nine female and ten male volunteers were recruited to participate in the study. All subjects were healthy, involved in regular physical activity, and had no recent (~5 years) history of joint disorder or injury to the arms, shoulders, neck, or back. Subject ages ranged from 19 to 23 years. The average height and mass of the female subjects was 164.0 (SD=11.3) cm and 64.4 (SD=9.7) kg, respectively. That of the male subjects was 176.5 (SD=8.5) cm and 82.4 (SD=20.1) kg, respectively.

Apparatus

A custom apparatus was constructed to facilitate the experiments (Figure 1). The apparatus consists of a stable base supporting an upright seat that is adjustable to accommodate users of different heights. Affixed to the top of the seat's vertical post is a horizontal member that extends laterally on either side and then forward. To this member is hinged a set of sturdy arm beams that rotate about an axis aligned approximately with the shoulder flexion and extension axis of a seated subject. The arm beams can be pinned at one of a number of angles ranging from vertically downward, to horizontally forward, to vertically upward. A grip assembly clamps onto and spans between the distal ends of the two arm beams.

The grip assembly contains two handles mounted via force-sensing load cells, and may be pinned at one of numerous positions along the proximal-distal length of the arm beams.

Strength measurements were conducted with a subject seated in the apparatus and grasping the grip handles with elbows fully extended. For elevation and depression trials the arm beams were pinned in the vertically downward position. For protraction and retraction trials the arm beams were pinned in the horizontally forward position. For each experimental trial the grip assembly was adjusted proximally or distally to a position which accommodated the user's arm length while maintaining the shoulder girdle position prescribed for the trial. For both elevation and depression trials forces were measured with the shoulder girdle in a depressed, neutral, and elevated position. For protraction and retraction trials forces were measured with the shoulder girdle in a retracted, neutral, and protracted position. Neutral positions were selected somewhat central to the other two positions in each direction, and near the natural, anatomical position. The actual position of the shoulder girdle during each trial was recorded by video as described below. Straps around the chest and lap were used to secure the subject in place without interfering with their strength performance.

Force and motion data were collected during the experimental trials. The load cells recorded forces applied to each handle as generated by the shoulder girdle and transmitted through the glenohumeral joint and extended arm. The SSM series load cells (Transducer Techniques, Temecula, CA, USA) were each rated to measure up to 2.2 kN (500 lb) of force in both tension and compression. A three-camera, video motion capture system (zFlo Motion, Inc., Quincy, MA, USA) recorded the three-dimensional positions of reflective markers adhesively attached to the subject's skin at the jugular notch (JN), acromioclavicular joint (AC), and seventh cervical vertebra (C7). The video and force data were collected at 60 Hz and 300 Hz, respectively.

Experimental Protocol

Each subject was asked to complete one familiarity session and three data collection sessions on separate, non-consecutive days. During the familiarity session the subjects practiced strength trials in each direction beginning with submaximal effort and building to maximal effort. Subjects were measured for anthropometry and for one-repetition maximum (1RM) bench press according to the standard assessment protocol of the National Strength and Conditioning Association (Baechle & Earle, 2000). Each subject's range of voluntary shoulder girdle motion in the elevation-depression direction and in the protraction-retraction direction was recorded using the motion capture system. Within this range three appropriate testing positions for each of the four directions of shoulder girdle motion were selected. Positions were selected for each subject so as to span a major portion of the range of motion in each direction, and to permit the subject to generate substantial force at each position. The respective positions selected for elevation and protraction were not necessarily the same as for depression and retraction, respectively.

During each of the three data collection sessions the subjects were asked to complete a total of twelve strength trials: three trials at different positions for each of the four testing directions. For each trial, subjects were instructed and observed to maintain extended elbows while exerting maximum force against the grip handles. Extended elbows configure the arm as a rigid link to prevent possible elbow weakness from confounding maximal shoulder girdle effort. The grip assembly pin locations were numbered so that the positions selected for each subject and each trial could be repeated over the three data collection sessions. Prior to the testing trials subjects were asked to warm up for several minutes on a hand-powered cycle ergometer with light resistance. Between trials subjects were given one to two minutes of rest while the apparatus was adjusted in preparation for the next trial. The order of the trials was varied over the three testing sessions to reduce the risk of bias.

Data Analysis

Five seconds of data were collected for each trial. Plots of measured positions and forces over this period were analyzed visually to identify a single time instant, following stabilization of shoulder girdle position, where maximum total force was generated. There was little difficulty identifying an appropriate time instant for each trial as the positions and forces settled to fairly constant values in most all cases. For the selected time instant, the elevation angle, protraction angle, and total force (sum of left and right sides) were recorded to represent the subject's performance for the trial. To nullify gravitational contributions, the magnitudes of elevation and depression forces were increased and decreased, respectively, by each subject's arm weight (both arms), assumed to be 11.2% of bodyweight based on data reported by Winter (1990) as derived from Dempster (1955).

The shoulder girdle elevation angle and protraction angle were computed for each trial based on the recorded positions of the anatomical markers JN, C7, and AC. The midpoint (MP) between JN and C7 was used as a reference to compute these angles as defined for this study. Elevation angle was defined as the angle of line MP-AC above the horizontal plane, and protraction angle was defined as the angle of line MP-AC anterior to the frontal plane (see Garner et al., in review, for more details).

A repeatability analysis was performed on the data collected over the three data-collection sessions as detailed in Garner et al. (in review). In short, the analysis showed Shrout and Fleiss (1977) interclass correlation coefficients ICC(2,1) of 0.79 to 0.95 (good to excellent) for force measurements, of 0.85 to 0.89 (very good) for elevation angle measurements during elevation and depression tests, and of 0.68 to 0.88 (good to very good) for protraction angle measurements during protraction and retraction tests.

To summarize recorded strength characteristics for the purposes of this study, the elevation angle, protraction angle, and shoulder girdle force recorded over the three days of testing were averaged for each subject and each strength test. The averages and standard deviations of these data were then computed for three groups: all female subjects, all male subjects, and all subjects combined. Simple t-tests were performed to compare male strength with female strength, and to compare agonist strength with antagonist strength. One-way ANOVA with repeated measures on shoulder girdle position, and two-by-three ANOVA (gender x position), was performed for shoulder girdle force. A *P*-value of less than 0.05 was used to determine significance.

Results

The observed average range of motion for all subjects was 32.5 degrees for elevation angle and 39.5 degrees for protraction angle (Table 1, Figure 2 range-of-motion lines). Elevation angle ranged on average from positions where the MP-AC line was just below horizontal by 4.6 degrees to a substantial angle of 27.9 degrees above horizontal. Average protraction angle was fairly symmetric about the frontal plane, ranging from 18.2 degrees posterior to the plane to 21.3 degrees anterior to the plane. Comparison of the sum of minimum and maximum elevation angles between female and male subjects indicated that the female range of motion (-2.4 to 29.5 degrees) was significantly more elevated than the male range of motion (-7.0 to 26.1 degrees). Comparison of the sum of minimum and maximum protraction angles indicated no significant differences between genders.

The measured forces in all directions were substantial, and in each direction varied significantly and monotonically with position, $F(2,36)>25.5$, $p<.01$ (Figure 2). Elevation forces were strongest in the most depressed positions measured and decreased as elevation angle increased. Conversely, depression forces were strongest in the most elevated positions measured and decreased as elevation angle decreased. Elevation forces averaged over all subjects varied over the range of measured positions from 976 N (219 lb) to 1182 N (266 lb), while the average depression forces varied from 521 N (117 lb) to 729 N (164 lb).

A similar pattern was seen for protraction and retraction forces (Figure 2B). The measured protraction forces were strongest in the most retracted positions measured and decreased as protraction angle increased. Retraction forces were strongest in the most protracted positions measured and decreased as protraction angle decreased. Subject averages of measured protraction forces varied over the range of measured positions from 951 N (214 lb) to 1117 N (251 lb), while average retraction forces varied from 595 N (114 lb) to 914 N (206 lb).

The monotonic strength trends observed on average for all subjects were similarly observed for each gender group. However, an independent t-test showed that the average of measured forces for the male group was significantly larger than for the female group on every test. Male strengths averaged over the three measured positions were greater than those of females by 57% for elevation, 38% for depression, 81% for protraction, and 78% for retraction (compare males and females in Figure 2).

The relative magnitudes of agonist and antagonist forces differed significantly over the measured range of motion for all subjects and for each gender group. Elevation forces averaged over the range of motion for all subjects were 70% greater than the average depression forces. For females this percentage was lower at 57%, and for males it was higher at 79%. For both gender groups the protraction forces averaged over the range of motion were about 37% greater than the average retraction forces.

Cross-correlation analysis on subject height, bodyweight, 1RM bench press, and the strength measurements in each of the four testing directions indicated strong and significant correlations between these variables (Table 2). The weakest and only non-significant (P=0.14) correlation was found between bodyweight and depression force (r=0.35). The strongest significant (P<0.01) correlation was found between elevation force and protraction force (r=0.92). The measures of strength in each direction correlated significantly (P<0.01) with the strength in every other direction with r>0.69. The 1RM bench press correlated significantly (P<0.01) with all other variables, and most closely correlated with elevation force and protraction force (r>0.83). Even when controlling for the influence of bodyweight on both bench press and protraction strength, the 1RM bench press correlated significantly with protraction force (r=0.62).

Discussion

For the purposes of this study the shoulder girdle positions were described by angles formed between anatomical planes and the line from point MP to AC (where MP was derived from points JN and C7). This description of shoulder girdle position deviates from the ISB recommendations for defining anatomical positions (Wu et al., 2005). The ISB recommendation relates the position and orientation of a clavicle-fixed coordinate system to that of a trunk-fixed coordinate system, and is intended to track motion of the clavicle relative to the trunk irrespective of trunk orientation. The more simplified angle definitions used in this study were adopted to represent the overall position of the shoulder girdle and to provide for neutral angles near zero. In addition, the definitions of angles in this study coincide with the directions of measured forces (which are perpendicular to the respective anatomical planes) and compensate for small anterior-posterior variations in trunk orientation.

We sought to measure forces generated in the shoulder girdle over a substantial portion of the range of motion in each direction. It proved difficult, however, to measure forces near the limits of motion in the agonist directions (directions of applied forces) because typically little force could be generated at those positions. For example, toward the most elevated shoulder girdle positions subjects found it difficult to generate substantial elevation forces. As a result, we measured forces at a range of positions somewhat narrower than the full range of motion in each direction. Based on our anecdotal experiences at the extreme positions, and the consistent monotonic strength patterns observed for all directions tested, we believe it is reasonable to assume that shoulder girdle strength drops off steeply toward the agonist limits of the ranges of motion in each direction (e.g., elevation strength falls off at maximum elevation angle).

Near the antagonist range-of-motion limits (opposite the directions of applied force) in each direction it was likewise difficult to measure strength due to unavoidable laxity in the testing apparatus and strapping. It was at these positions that subjects seemed to be strongest, and as subjects began to apply force their shoulder girdle positions tended to move slightly in the agonist directions and away from the antagonist limits. Tests in some directions proved more difficult than others. For elevation and protraction tests the subjects pressed themselves into the seat and seat back, respectively, and so laxity was minimal in these directions, and strength measurements could be made fairly near the antagonist limits. It was most difficult to secure the subject against the seat during depression tests. Although a padded board was strapped tightly around the subject's lap to hold them down, as they depressed against the handles appreciable depression movement was observed in the shoulder girdle. As a result, all the measurements of depression force tended to be at more depressed positions relative to the range of motion (Figure 2, depression).

The reported results involving depression strength may be somewhat distorted due to the more depressed positions at which depression strength was measured. For example, the 170% ratio of elevation-to-depression strength may be exaggerated because depression force magnitudes declined substantially at the most depressed position. More realistic comparisons could perhaps be obtained by considering the depression force averaged over only the two more elevated positions at which depression strength was measured. In such a case, the elevation-to-depression strength ratio becomes 156% (145% for females, 162% for males), which is closer to, but still higher than, the protraction-to-retraction strength ratios (~137%). In addition, correlations with depression strength (Table 2) increase somewhat (<10% in each case), but remain insignificant ($p=.124$) between depression strength and bodyweight.

It is interesting to consider how the relative strengths between genders might be interpreted if joint moments were reported rather than forces. Measurements of force are related to joint moments by way of an appropriate moment arm, such as the length of the clavicle. Although we did not measure clavicle length specifically, our recorded marker-to-marker distances from jugular notch to acromioclavicular joint (slightly longer than clavicle length) indicated that shoulder breadth in the male subjects (19.1 cm average) was significantly larger ($p<0.01$) than in the female subjects (16.6 cm average). Since longer moment arms result in greater joint moments for a given force, the ratios of male strength over female strength observed for force in this study would be even greater if reported as joint moments.

The 1RM bench press was found to correlate significantly with shoulder girdle strength in all four directions tested, but most closely with elevation and protraction strength (Table 2). Figure 3 shows elevation and protraction forces measured at neutral positions plotted against 1RM bench press strength for all subjects. The strong correlations observed between these variables lend credence to the historical practice of using functional tasks as indicators of shoulder girdle strength, despite the dependence of these tasks on motor coordination and the strength of other participating joints. It seems natural that bench press and protraction strength would show strong correlation (r=0.84) because they share a common direction of force. The strong correlation (r=0.83) between bench press and elevation strength seems less intuitive because of the orthogonal directions of force, but may coincidentally reflect a common characteristic of overall shoulder girdle strength (elevation and protraction strength correlated with r=0.92). However, the weaker correlation (r=0.58) between bench press and depression strength serves as a caution against using functional task performance universally as an indicator for all directions of shoulder girdle strength.

Although this study is unique, it seems appropriate to draw comparisons between our results and those of the two known previous studies that have directly measured shoulder girdle strength. Cools et al. (2002) measured unilateral, isokinetic protraction and retraction strength for a pool of healthy subjects (10 females, 9 males) very similar to our subject pool (9 females, 10 males). Their averaged peak forces summed over dominant and non-dominant sides at the slowest reported isokinetic speed (12.2 cm/sec, 4.8 inches/sec) are substantially lower than the average isometric forces we measured at the strongest positions over the range of motion. Their peak protraction force is 58% of our strongest force of 1117 N, and their peak retraction force is 66% of our strongest force of 914 N. It is natural that isokinetic forces would be less than isometric forces, but at the slow isokinetic speed reported by Cools it is likely that additional factors contribute to the differences. For example, they measured force in the scapular plane whereas we measured forces in the sagittal plane. Due to asymmetry, it may also be more difficult to apply full strength during unilateral experiments than when both arms can apply force together as in our study. Finally, isokinetic tests require time and displacement to ramp up to the isokinetic speed and generate force. Therefore, it may be difficult to record isokinetic forces at the most antagonist positions in each direction where our results indicate that maximum strength occurs (Cools did not report the shoulder girdle position where peak force was measured).

Wilk et al. (1999) used a hand-held dynamometer to record the isometric shoulder girdle strength of 65 professional baseball players. The athleticism of this population would suggest strength at least as great or greater than that of our male subjects. The Wilk data is reported in the form of unilateral torques, and does not specify a shoulder girdle position. For the sake of comparison, therefore, we here assume a neutral shoulder girdle position and a reasonable clavicle length of 15.4 cm (Garner & Pandy, 1999; to convert torques to forces). So doing, data reported for the baseball position players (not pitcher or catcher) is very comparable to that of our male subjects for all directions but depression. The sum of dominant and non-dominant forces measured by Wilk for elevation, protraction, and retraction are 86%, 75%, and 100%, respectively, of the corresponding average male forces we measured at neutral shoulder girdle positions. However, the depression force reported by Wilk is only 43% of our corresponding force (even at our more depressed "neutral" position). Since Wilk did not specifically describe his strength measurement methods, it is difficult to provide explanations for the stark difference in depression forces. However, it is doubtful that any measurement error would substantially *over-estimate* depression strength. And, the comparability of measured strength in the other directions is reassuring.

Conclusion

This study is the first to report direct measurements of female and male shoulder girdle strength as it varies with position in elevation, depression, protraction, and retraction. In each direction strength was found to decrease monotonically as the shoulder girdle was moved in the direction of applied force. Elevation and protraction forces were stronger than depression and retraction forces, respectively. Male subjects were on average stronger than female subjects, and strength tended to increase with bodyweight and bench press strength. Bench press performance seemed to be a good indicator of shoulder girdle elevation and protraction strengths. The subject-pool of this study involved healthy, college-aged females and males. Whether the observed strength patterns apply to other population groups such as the elderly, impaired, or specially-trained athletes remains a question for future study.

Acknowledgements

The authors express their sincere thanks to the following contributors: Drs. Lori Greenwood and Mike Greenwood for guidance and help with the experiments and familiarity sessions; Trent Zou and Micah Pravel for assistance with data collection and processing; and Baylor University for financial and facilities support.

References

Baechle, T.R. & Earle, R., (Eds), 2000. Essentials of strength training and conditioning / National Strength and Conditioning Association, 2nd ed. Human Kinetics, Champaign, Ill.

Christou, E.A., Grossman, M., Carlton, L.G., 2002. Modeling variability of force during isometric contractions of the quadriceps femoris. J. of Motor Behav. 34(1), 67-81.

Cools, A.M., Witvrouw, E.E., Danneels, L.A., Vanderstraeten, G.G., Cambier, D.C., 2002. Test-retest reproducibility of concentric strength values for shoulder girdle protraction and retraction using the Biodex isokinetic dynamometer. Isokinet. Exerc. Sci. 10(3), 129-136.

Dempster, W.T., 1955. Space requirements of the seated operator: Geometrical, kinematic, and mechanical aspects of the body with special reference to the limb. Wright Patterson Air Force Base Technical Report WADC-TR-55-159.

Garner, B.A., Shim, J., Wilson, S., accepted. An apparatus and protocol to measure shoulder girdle strength. J. Med. Devices.

Garner, B.A., 2007. Designing strength-proportional hydraulic resistance for an elbow flexion-extension exercise machine. J. Med. Devices. 1, 3-13.

Garner, B.A., Pandy, M.G., 2003. Estimation of musculotendon properties in the human upper limb. Ann. Biomed. Eng. 31, 207-220.

Garner, B.A., Pandy, M.G., 2001. A musculoskeletal model of the upper limb based on the visible human male dataset. Comput. Meth. Biomech. Biomed. Eng. 4(2), 93-126.

Garner, B.A., Pandy, M.G., 1999. A kinematic model of the upper limb based on the Visible Human Project (VHP) image dataset. Comput. Meth. Biomech. Biomed. Eng. 2(2), 107-124.

Graves, J.E., Pollock, M.L., Carpenter, D.M., Legget, S.H., Jones, A., MacMillan, M., Fulton, M., 1990. Quantitative assessment of full range-of-motion isometric lumbar extension strength. Spine. 15(4), 289-294.

Holzbaur, K.R.S., Murray, W.M., Delp, S.L., 2005. A model of the upper extremity for simulating musculoskeletal surgery and analyzing neuromuscular control. Ann. Biomed. Eng. 33(6), 829-840.

Kibler, W.B., 1998. The role of the scapula in athletic shoulder function. Am. J. Sports Med. 26(2), 325-337.

Knapik, J.J., Wright, J.E., Mawdsley, R.H., Braun, J., 1983. Isometric, isotonic, and isokinetic torque variations in four muscle groups through a range of joint motion. Phys. Ther. 63(6), 938-947.

Mayer, F., Horstmann, T., Baurle, W., Grau, S., Handel, M., Dickhuth, H.H., 2001. Diagnostics with isokinetic devices in shoulder measurements - potentials and limits. Isokinet. Exerc. Sci. 9(1), 19-25.

Peebles, L., Norris, B., 2003. Filling 'gaps' in strength data for design. Appl. Ergon. 34(1), 73-88.

Poppen, N.K., Walker, P.S., 1976. Normal and abnormal motion of the shoulder. J. Bone Joint Surg. 58-A(2), 195-201.

Rutherford, W.J., Corbin, C.B., 1994. Validation of criterion-referenced standards for tests of arm and shoulder girdle strength and endurance. Research quarterly for exercise and sport. 65(2), 110-119.

Wilk, K.E., Suarez, K., Reed, J., 1999. Scapular muscular strength values in professional baseball players. Phys Ther. 79(5) suppl, S81-82.

Wilk, K.E., Meister, K., Andrews, J.R., 2002. Current concepts in the rehabilitation of the overhead throwing athlete. Am. J. Sports Med. 30(1), 136-151.

Wilmore, J.H., Costill, D.L., 2004. Physiology of Sport and Exercise, 3rd ed. Human Kinetics, Champaign, Illinois.

Winter, D.A., 1990. Biomechanics and Motor Control of Human Movement, 2nd ed. John Wiley & Sons, Inc., New York.

Winters, J.M., Kleweno, D.G., 1993. Effect of Initial Upper Limb Alignment on Muscle Contributions to Isometric Strength Curves. J. Biomech. 26(2), 143-153.

Wu, G., van der Helm,Frans C.T., (DirkJan) Veeger, H.E.J., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A.R., McQuade, K., Wang, X., 2005/5. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion--Part II: shoulder, elbow, wrist and hand. J. Biomech. 38(5), 981-992.

Zajac, F.E., 1989. Muscle and tendon: Properties, models, scaling, and application to biomechanics and motor control. Crit. Rev. Biomed. Eng. 17(4), 359-411.

Captions

Table 1: Statistics on shoulder girdle range of motion for female subjects, male subjects, and all subjects combined. Minimum elevation angle corresponds to the most depressed position, and negative values indicate positions below the horizontal plane. Minimum protraction angle corresponds to the most retracted position, and negative values indicate positions behind the frontal plane. See text for more specific angle definitions.

Table 2: Pearson correlation coefficients (r) and corresponding measures of significance (*P*) between subject height, bodyweight, one-repetition maximum (1RM) bench press, and shoulder girdle strength in the directions of elevation, depression, protraction, and retraction. Correlations between all measures were significant ($P<0.05$) except between bodyweight and shoulder girdle depression force.

Figure 1: Custom apparatus designed to measure maximum isometric forces generated at the shoulder girdle. The apparatus consists of a stable base and seat, a pair of rotating arm beams, and an adjustable grip handle assembly. The arm beams rotate about an axis aligned with the shoulder flexion-extension axis, and can be pinned at any of a number of positions including vertically downward and horizontally forward (as shown). The grip assembly slides along the arm beams in the proximal-distal direction, and can be locked in place to accommodate different user arm lengths and different shoulder girdle positions. The seated user pulls or pushes on the force-sensing handles using force generated at the shoulder girdle and transmitted through extended arms.

Figure 2: Shoulder girdle elevation-depression forces (A) and protraction-retraction forces (B) plotted as a function of shoulder girdle position in each direction. Values shown are averaged (with standard deviation bars) across female subjects, male subjects, and all subjects combined. The voluntary range of motion (average, with standard deviation bars) in each direction is shown next to the abscissa axis for the female subjects (diamond) and male subjects (square). For comparison, average bench press strengths (with standard deviation bars) are also shown for each group (unfilled markers) near the right ordinate axis of graph B.

Figure 3: Graphs of elevation strength (A) and protraction strength (B) at shoulder girdle neutral positions versus one-repetition maximum (1RM) bench press strength for all subjects. Linear regression lines (with corresponding equations) computed over all subjects (solid lines) corroborate the strong correlations found between these measures (see text, Results and Discussion).

Table 1. Statistics on shoulder girdle range of motion for female subjects, male subjects, and all subjects combined. Minimum elevation angle corresponds to the most depressed position, and negative values indicate positions below the horizontal plane. Minimum protraction angle corresponds to the most retracted position, and negative values indicate positions behind the frontal plane. See text for more specific angle definitions.

	Elevation Angle (deg)			Protraction Angle (deg)		
Subject	Min	Max	ROM	Min	Max	ROM
Females	-2.4	29.5	32.0	-16.3	22.3	38.7
(SD)	*3.7*	*5.1*	*3.6*	*7.2*	*5.2*	*8.9*
Males	-7.0	26.2	33.2	-20.3	20.1	40.4
(SD)	*4.7*	*4.7*	*7.3*	*6.5*	*7.0*	*7.2*
All	-4.6	27.9	32.5	-18.2	21.3	39.5
(SD)	*4.7*	*5.1*	*5.5*	*7.0*	*6.0*	*7.9*

Table 2. Pearson correlation coefficients (r) and corresponding measures of significance (*P*) between subject height, bodyweight, one-repetition maximum (1RM) bench press, and shoulder girdle strength in the directions of elevation, depression, protraction, and retraction. Correlations between all measures were significant ($P<0.05$) except between bodyweight and shoulder girdle depression force.

	Height	Weight	Bench	Elevation	Depression	Protraction
Weight						
Correlation r	0.753	1.000				
Significance p	*0.000*					
1RM Bench Press						
Correlation r	0.750	0.782	1.000			
Significance p	*0.000*	*0.000*				
Elevation Force						
Correlation r	0.654	0.711	0.833	1.000		
Significance p	*0.002*	*0.001*	*0.000*			
Depression Force						
Correlation r	0.463	0.348	0.583	0.690	1.000	
Significance p	*0.046*	*0.144*	*0.009*	*0.001*		
Protraction Force						
Correlation r	0.661	0.730	0.836	0.919	0.699	1.000
Significance p	*0.002*	*0.000*	*0.000*	*0.000*	*0.001*	
Retraction Force						
Correlation r	0.605	0.511	0.653	0.891	0.766	0.788
Significance p	*0.006*	*0.025*	*0.002*	*0.000*	*0.000*	*0.000*

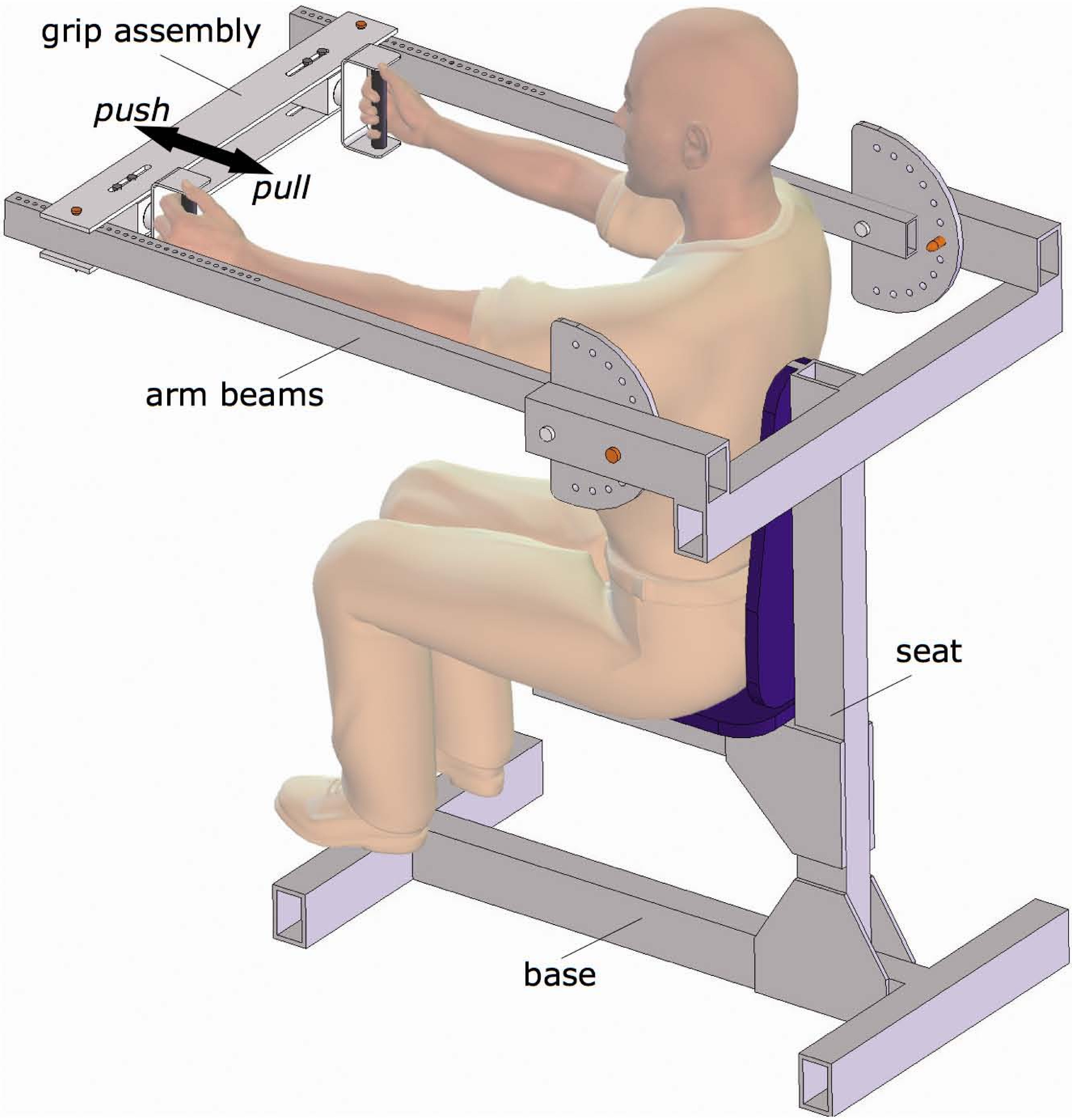

Figure 1. Custom apparatus designed to measure maximum isometric forces generated at the shoulder girdle. The apparatus consists of a stable base and seat, a pair of rotating arm beams, and an adjustable grip handle assembly. The arm beams rotate about an axis aligned with the shoulder flexion-extension axis, and can be pinned at any of a number of positions including vertically downward and horizontally forward (as shown). The grip assembly slides along the arm beams in the proximal-distal direction, and can be locked in place to accommodate different user arm lengths and different shoulder girdle positions. The seated user pulls or pushes on the force-sensing handles using force generated at the shoulder girdle and transmitted through extended arms.

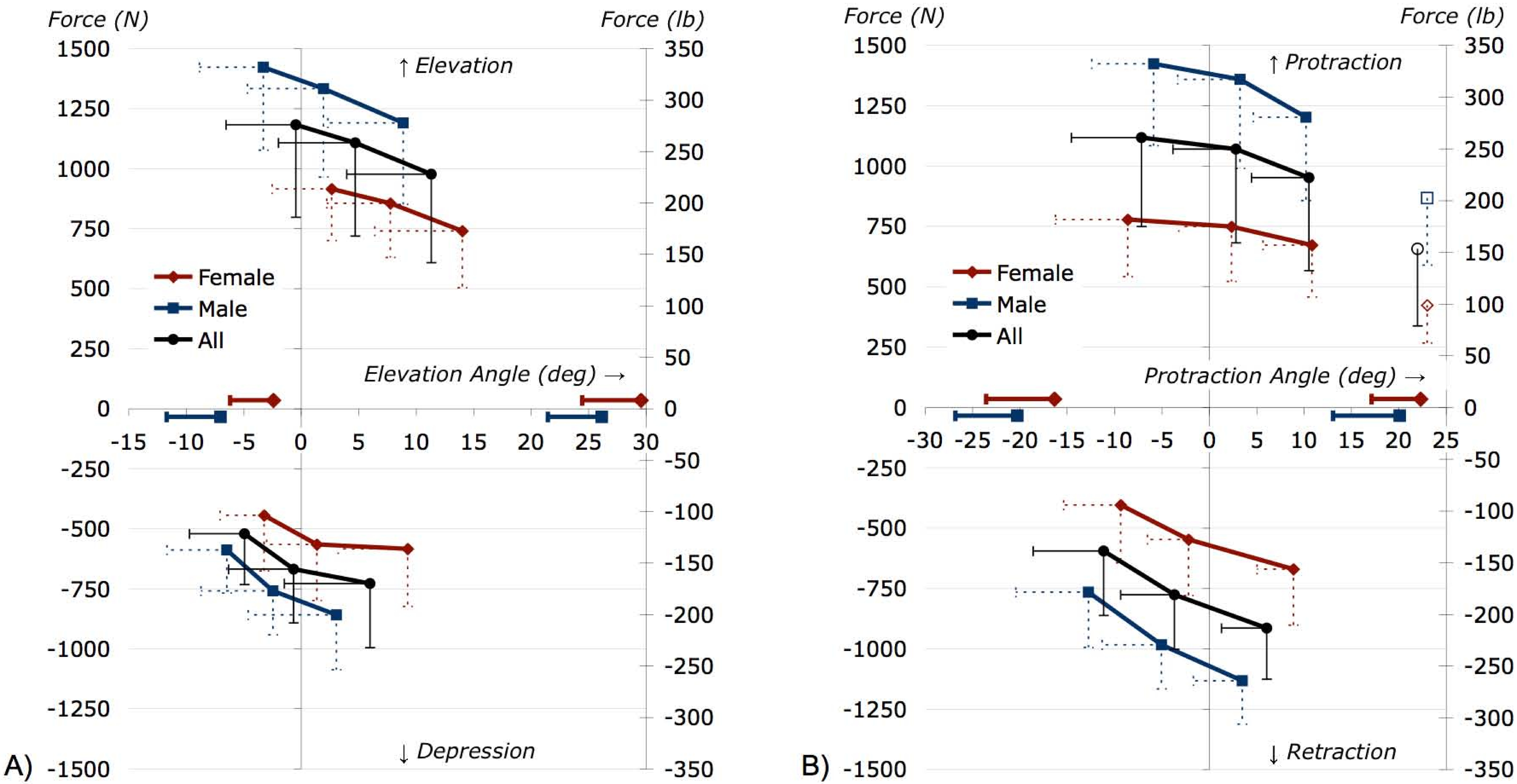

Figure 2. Shoulder girdle elevation-depression forces (A) and protraction-retraction forces (B) plotted as a function of shoulder girdle position in each direction. Values shown are averaged (with standard deviation bars) across female subjects, male subjects, and all subjects combined. The voluntary range of motion (average, with standard deviation bars) in each direction is shown next to the abscissa axis for the female subjects (diamond) and male subjects (square). For comparison, average bench press strengths (with standard deviation bars) are also shown for each group (unfilled markers) near the right ordinate axis of graph B.

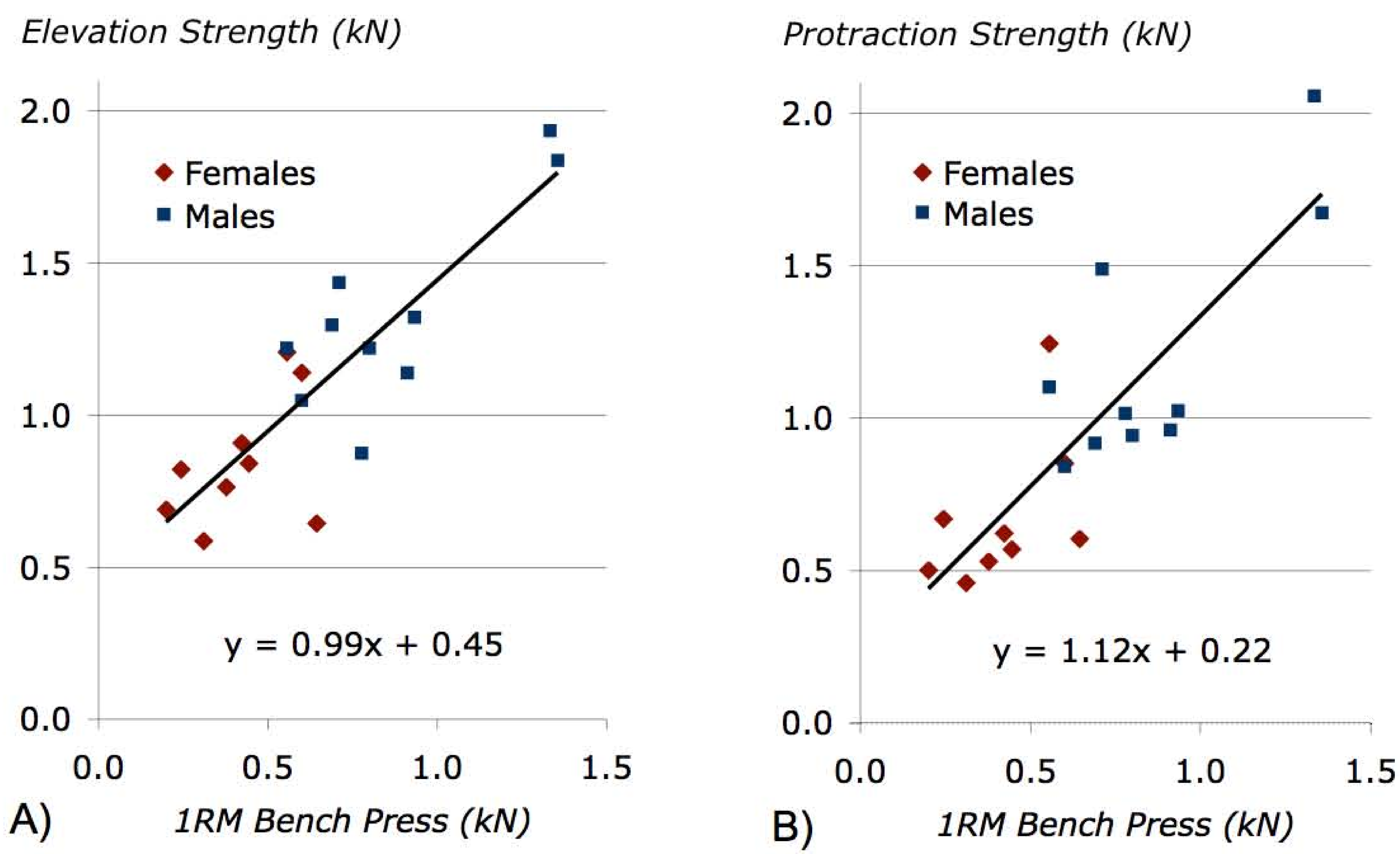

Figure 3. Graphs of elevation strength (A) and protraction strength (B) at neutral shoulder girdle positions versus one-repetition maximum (1RM) bench press strength for all subjects. Linear regression lines (with corresponding equations) computed over all subjects (solid lines) corroborate the strong correlations found between these measures (see text, Results and Discussion).