The influence of handheld weight on the scapulohumeral rhythm

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Scapulohumeral rhythm (SHR) provides insight to neuromuscular control and fundamental biomechanics of the shoulder. This rhythm often is disrupted in pathologic shoulders. As the first step, we sought to quantify SHR in healthy subjects for diagnostic assessment of shoulder function. Ten healthy shoulders were studied. Three-dimensional models of the humerus and scapula were created from computed tomography scans. Dynamic shoulder motion was recorded by use of single-plane fluoroscopy during arm abduction with 0-kg and 3-kg handheld loads. Shoulder kinematics were quantified by use of model-based 3-dimensional–to–2-dimensional registration techniques. SHR decreased (more scapular motion) with increasing abduction. With a 3-kg load, scapulothoracic motion was significantly reduced through the range of 35° to 45° of glenohumeral motion. Muscular stabilization of the scapula increased with external loading, as shown by decreased SHR during early lifting. Dynamic scapular stabilization provides a critical platform for upper extremity activity. (J Shoulder Elbow Surg 2008;17:943-946.)

Inman et al[16] reported in 1944 that the ratio of glenohumeral (GH) motion to scapulothoracic (ST) motion, the scapulohumeral rhythm (SHR), was 2:1. More recent studies report varying ratios,[2,8-13,23,24,27-29] where humeral motion predominates at lower levels of arm elevation and scapular motion predominates at higher levels.[19] The changing SHR captures this biphasic pattern of scapular motion, providing an important parameter to characterize shoulder function during dynamic activity. Kibler[19] has suggested that the SHR often is disrupted in patients with symptoms and signs of shoulder impingement (subacromial or internal). A large percentage of patients with shoulder impingement have scapular dyskinesis and alterations in scapular position or in dynamic scapular motion.[19-21] Thus, it is necessary for shoulder surgeons and physical therapists to understand how SHR changes with shoulder dysfunction. Though previously studied by use of a variety of methods, we introduce a new method, using equipment available in most hospitals, and apply this method to quantify SHR in healthy subjects.

This study focused on scapular stabilization in the early phase of abduction with or without an external load. The specific goal was to determine in vivo the influence on the SHR of lifting a 3-kg handheld weight, an implement commonly used during functional assessment of the shoulder. We assumed that muscular stabilization of the scapula increases while lifting weights; thus, less scapular motion might be seen during early lifting, and the SHR would decrease.

We hypothesized that the SHR would not be a constant 2:1 ratio but would decrease (more scapular motion), along with abduction, in asymptomatic subjects. We also hypothesized that arm abduction with a 3-kg handheld weight would result in decreased scapular upward rotation and an increased SHR compared with arm abduction without a handheld weight, especially in the early phase of shoulder abduction.

MATERIALS AND METHODS

We studied 10 healthy shoulders in 10 subjects (8 men and 2 women; age range, 27-38 years; mean age, 31.5 years). All shoulders were asymptomatic, had no history of injury, and lacked any clinical or radiographic sign of pathology. All subjects provided informed consent to participate in this study.

The subject was positioned in front of a single-plane fluoroscope (AdvantxACT; GE Medical Systems, Milwaukee, WI), and motions were recorded during active abduction from the arm at the side to about 120° in the scapular plane. Before fluoroscopic examinations were performed, all subjects practiced several trials of abduction in the scapular plane so that they were comfortable performing this motion at a constant speed. One trial of abduction from the arm-at-the-side position required approximately 5 seconds (mean, 5.31 seconds; range, 3.50-6.77 seconds). The subjects

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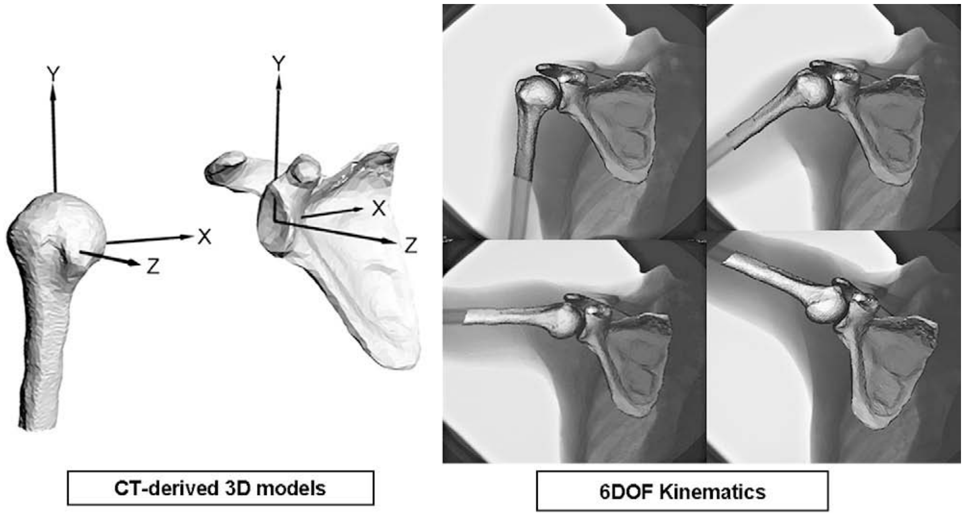

Figure 1 Six–degrees-of-freedom (*6DOF*) kinematics of the shoulder were determined from fluoroscopic image sequences and CT-derived bone models via 3D-to-2D registration.

performed two trials: one was done while holding a 3-kg weight, and the other was an unloaded trial. "Unloaded" means that no additional external load was added to the arm but the subject still was required to lift the mass of his or her arm against gravity.

Computed tomography (CT) scans (LightSpeed Plus; GE Medical Systems) of each shoulder were acquired by use of 1.25-mm-thick slices having a 0.75-mm gap.

Three-dimensional (3D) models of the scapula and proximal humerus were created from the CT images in 2 stages. The exterior cortical bone edges of the CT images were segmented by use of commercial software (SliceOmatic; TomoVision, Montreal, Quebec, Canada), and the resulting point clouds were converted into polygonal surface models (Geomagic Studio; Raindrop Geomagic, Research Triangle Park, NC). Anatomic coordinate systems were embedded in each bone model by use of commercial software (Rhinoceros; Robert McNeel & Associates, Seattle, WA). The scapular origin was defined as the center of the line connecting the most superior and inferior bony edges of the glenoid surface. The humeral origin was placed at the center of the humeral head, with a long axis parallel to the humeral shaft (Figure 1).

In vivo 3D motions of the scapula and humerus were determined by use of model-based 3D–to–2-dimensional (2D) registration (Figure 1).[5] A human operator manually positioned the humerus and scapula models into rough registration in each image, and then an automatic nonlinear least squares optimization routine was used to refine the registration based on minimizing the distance between bone edges in the image and the projected bone model.[26]

The measured 3D kinematics of the humerus and scapula were analyzed to determine scapular upward rotation and arm abduction relative to the ground. SHR was computed as the increment in GH angle (10°) divided by the increment in ST angle, and the SD for SHR was computed by use of the quotient rule for propagation of SDs. Motion data were grouped into 10° intervals and compared from 5° to 65° of GH motion by use of *t* tests with Bonferroni correction. The significance level was set at $P < .05$.

RESULTS

SHR varied with GH angle and loading condition (Table I). SHR was 2.0 at 25° of GH abduction in the unloaded condition, yielding an SHR of 2:1, as previously reported by Inman et al.[16] SHR was greater (less scapular motion) for the loaded case at all motion increments (Table I). SHR was 1.4:1 with a 0-kg load and 5.0:1 with a 3-kg load at 35° of GH abduction. SHR was 1.3:1 with a 0-kg load and 1.9:1 with a 3-kg load at 45° of GH abduction.

Scapular upward rotation with a 3-kg load was significantly decreased over the range of 40° to 70° of arm abduction (Figure 2). ST motion with a 3-kg load also was significantly reduced over the range of 35° to 45° of GH motion (Figure 3).

DISCUSSION

There is no argument that direct in vivo observation of dynamic joint motion could be clinically useful. Kinematic analyses of knee replacements during a wide variety of activities have been reported for the past 15 years by use of fluoroscopic imaging and 3D-to-2D registration techniques.[3-6,17] This type of measurement recently has been applied to the shoulder, by use of bi-plane and single-plane imaging techniques,[7,22] and quickly has established utility for observing aspects of shoulder motion that previously were difficult to measure accurately.

A limitation of single-plane fluoroscopic imaging, or any monocular vision technique, is that it provides poor sensitivity for out-of-plane translations. This study was concerned exclusively with bone rotations and translations parallel to the image plane (ie, scapular

Table I GH/ST ratio as a function of GH angle

GH angle	GH/ST ratio (mean ± SD)	
	0 kg	3 kg
15°	3.0 ± 4.2	3.7 ± 5.7
25°	2.0 ± 1.8	2.5 ± 2.5
35°	1.4 ± 1.1	5.0 ± 4.4
45°	1.3 ± 0.9	1.9 ± 1.4

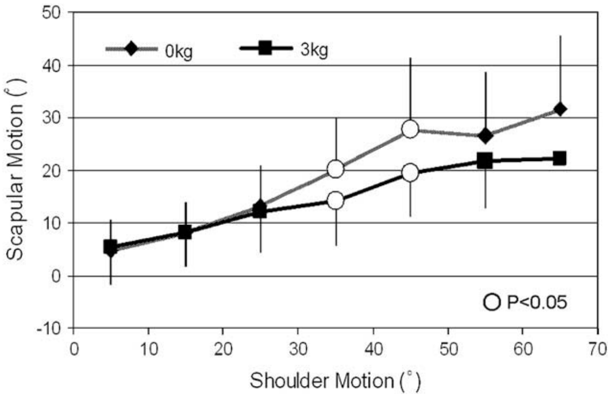

Figure 2 Scapular upward rotation with a 3-kg load was significantly decreased over the range of 40° to 70° of arm abduction (*ABD*). *Error bars* represent ± 1 SD.

plane), where measurement uncertainties are small compared with the large ranges of translation and rotation observed. This measurement technique has been used extensively to characterize knee motion, but few studies have reported shoulder kinematics using these measures.[7,22] For natural knees, Moro-oka et al[26] reported measurement precision of the model-based 3D-to-2D registration technique of approximately 0.5 mm for translations parallel to the image plane and 0.5° for rotations, and similar results should be achieved for shoulders.[5] This study reports a relatively small number of subjects, a limitation of using a radiographic technique in a young, healthy population.

SHR is important to understand shoulder and upper extremity function. It is indicative of correct neuromuscular stabilization of the scapula as the basis for dynamic upper extremity activity. Inman et al[16] characterized SHR as a fixed 2:1 ratio. We addressed the following 2 questions: (1) Is SHR consistently 2:1 over the arc of abduction? (2) Does external load affect shoulder kinematics, especially during early lifting?

Inman et al[16] characterized SHR as a fixed 2:1 ratio; however, our data and those of other investigators have suggested that the model of Inman et al is an oversimplification.[8,13,24,28] McClure et al[23] used a 3D

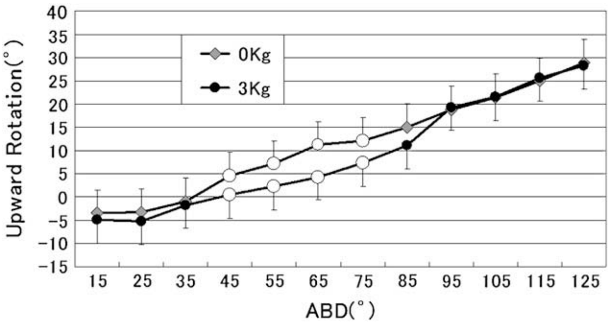

Figure 3 The SHR varied over the arc of motion and with handheld weight. ST motion was significantly reduced over the range of 35° to 45° of GH abduction in the scapular plane. *Error bars* represent ± 1 SD.

electromagnetic-based system and attached a motion sensor directly to the scapula bone with a bone pin drilled into the scapular spine. This invasive, but precise, report showed that the mean ratio of GH motion to ST motion was 1.7:1 for abduction in the scapular plane and suggested that the relation between scapular upward rotation and humeral abduction was not linear, with the scapula moving very little during the first 30° of abduction. Our data, using a noninvasive technique, support this observation. SHR was greatest (least scapular motion) at low GH abduction angles.

We asked subjects to perform abduction at a comfortable speed that allowed smooth abduction over the entire arc with and without the handheld weight. Several studies have reported that SHR changes significantly between slow and fast motions,[10,29] but de Groot et al[10] described the magnitude of velocity effects as negligibly small. We observed a peak in SHR at 35° of abduction that was not observed without the handheld weight. This might represent additional transient scapular stabilization as the shoulder begins to accelerate the handheld weight upward against gravity. These observations on abduction speed and conjecture regarding the effect of handheld load merit further systematic study.

The effect of external resistance on SHR has been studied previously.[24,25,27] Some authors have reported that external loads did not have a significant influence on SHR. However, McQuade and Smidt[24] reported that a large external resistance caused an increase in SHR during elevation of the arm in the scapular plane. Our observations agree, in part, with their findings, even though the magnitudes of external load differed.

Inman et al[16] termed the early phase of shoulder motion the "setting phase," indicating preparatory stabilization of the scapula to permit controlled humeral motion. Reduced scapular upward rotation in early abduction with a 3-kg handheld weight indicates a prolonged setting phase. Sensibly, this suggests that, with greater loads, the scapula is relatively more fixed to the torso early in the abduction arc to provide a stable fulcrum for the rotator cuff.[18] We emphasize the rotator cuff function because the rotator cuff muscles are believed to play an important role in initiating and stabilizing the shoulder in the early phase of abduction in the scapular plane.[1,14-16]

These observations are of practical clinical significance. It is simple to check a patient's shoulder function and scapular stability in the clinic, with observation of scapular motion during active abduction with external manual resistance. Scapular motion outside the observed values is indicative of scapular dyskinesis and merits more detailed exploration.

In summary, this study quantified the influence of lifting 3-kg handheld weights on SHR. Three-dimensional shoulder motions were determined from fluoroscopic image sequences and CT-derived bone models via 3D-to-2D registration. SHR increased with the addition of a 3-kg weight, indicative of increased muscular stabilization with increased shoulder loads. This study showed changing in vivo scapular movement over the abduction arc and with varying loads. We believe greater insight into neuromuscular coordination of the shoulder complex will assist shoulder surgeons and physical therapists in making better diagnoses.

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REFERENCES

1. Alpert SW, Pink MM, Jobe FW, McMahon PJ, Mathiyakom W. Electromyographic analysis of deltoid and rotator cuff function under varying loads and speeds. J Shoulder Elbow Surg 2000; 9:47-58.
2. Bagg SD, Forrest WJ. A biomechanical analysis of scapular rotation during arm abduction in the scapular plane. Am J Phys Med Rehabil 1988;67:238-45.
3. Banks SA, Fregly BJ, Boniforti F, Reinschmidt C, Romagnoli S. Comparing in vivo kinematics of unicondylar and bi-unicondylar knee replacements. Knee Surg Sports Traumatol Arthrosc 2005; 13:551-6.
4. Banks SA, Hodge WA. 2003 Hap Paul Award Paper of the International Society for Technology in Arthroplasty. Design and activity dependence of kinematics in fixed and mobile-bearing knee arthroplasties. J Arthroplasty 2004;19:809-16.
5. Banks SA, Hodge WA. Accurate measurement of three-dimensional knee replacement kinematics using single-plane fluoroscopy. IEEE Trans Biomed Eng 1996;43:638-49.
6. Banks SA, Hodge WA. Implant design affects knee arthroplasty kinematics during stair-stepping. Clin Orthop Relat Res 2004:187-93.
7. Bey MJ, Zauel R, Brock SK, Tashman S. Validation of a new model-based tracking technique for measuring three-dimensional, in vivo glenohumeral joint kinematics. J Biomech Eng 2006;128:604-9.
8. Borsa PA, Timmons MK, Sauers EL. Scapular-positioning patterns during humeral elevation in unimpaired shoulders. J Athl Train 2003;38:12-7.
9. de Groot JH. The scapulo-humeral rhythm: effects of 2-D roentgen projection. Clin Biomech (Bristol, Avon) 1999;14:63-8.
10. de Groot JH, Valstar ER, Arwert HJ. Velocity effects on the scapulo-humeral rhythm. Clin Biomech (Bristol, Avon) 1998;13:593-602.
11. de Groot JH, van Woensel W. van der Helm FC. Effect of different arm loads on the position of the scapula in abduction postures. Clin Biomech (Bristol, Avon) 1999;14:309-14.
12. Doody SG, Freedman L, Waterland JC. Shoulder movements during abduction in the scapular plane. Arch Phys Med Rehabil 1970;51:595-604.
13. Freedman L, Munro RR. Abduction of the arm in the scapular plane: scapular and glenohumeral movements. A roentgenographic study. J Bone Joint Surg Am 1966;48:1503-10.
14. Gerber C, Blumenthal S, Curt A, Welner CML. Effect of selective experimental suprascapular nerve block on abduction and external rotation strength of the shoulder. J Shoulder Elbow Surg 2007;16:815-20.
15. Howell SM, Imobersteg AM, Seger DH, Marone PJ. Clarification of the role of the supraspinatus muscle in shoulder function. J Bone Joint Surg Am 1986;68:398-404.
16. Inman VT, Saunders JBDM, Abbott LC. Observations on the function of the shoulder joint. J Bone Joint Surg 1944;26:1-30.
17. Kanisawa I, Banks AZ, Banks SA, Moriya H, Tsuchiya A. Weight-bearing knee kinematics in subjects with two types of anterior cruciate ligament reconstructions. Knee Surg Sports Traumatol Arthrosc 2003;11:16-22.
18. Kebaetse M, McClure P, Pratt NA. Thoracic position effect on shoulder range of motion, strength, and three-dimensional scapular kinematics. Arch Phys Med Rehabil 1999;80:945-50.
19. Kibler WB. Scapular involvement in impingement: signs and symptoms. Instr Course Lect 2006;55:35-43.
20. Kibler WB, McMullen J. Scapular dyskinesis and its relation to shoulder pain. J Am Acad Orthop Surg 2003;11:142-51.
21. Ludewig PM, Cook TM. Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. Phys Ther 2000;80:276-91.
22. Mahfouz M, Nicholson G, Komistek R, Hovis D, Kubo M. In vivo determination of the dynamics of normal, rotator cuff-deficient, total, and reverse replacement shoulders. J Bone Joint Surg Am 2005;87(Suppl 2):107-13.
23. McClure PW, Michener LA, Sennett BJ, Karduna AR. Direct 3-dimensional measurement of scapular kinematics during dynamic movements in vivo. J Shoulder Elbow Surg 2001;10:269-77.
24. McQuade KJ, Smidt GL. Dynamic scapulohumeral rhythm: the effects of external resistance during elevation of the arm in the scapular plane. J Orthop Sports Phys Ther 1998;27:125-33.
25. Michiels I, Grevenstein J. Kinematics of shoulder abduction in the scapular plane. On the influence of abduction velocity and external load. Clin Biomech (Bristol, Avon) 1995;10:137-43.
26. Moro-oka TA, Hamai S, Miura H, Shimoto T, Higaki H, Fregly BJ, et al. Can magnetic resonance imaging-derived bone models be used for accurate motion measurement with single-plane three-dimensional shape registration? J Orthop Res 2007;25:867-72.
27. Pascoal AG, van der Helm FF, Pezarat Correia P, Carita I. Effects of different arm external loads on the scapulo-humeral rhythm. Clin Biomech (Bristol, Avon) 2000;15(Suppl 1):S21-4.
28. Poppen NK, Walker PS. Normal and abnormal motion of the shoulder. J Bone Joint Surg Am 1976;58:195-201.
29. Sugamoto K, Harada T, Machida A, Inui H, Miyamoto T, Takeuchi E, et al. Scapulohumeral rhythm: relationship between motion velocity and rhythm. Clin Orthop Relat Res 2002:119-24.