ELSEVIER

Journal of Biomechanics 33 (2000) 1063–1068

JOURNAL OF BIOMECHANICS

www.elsevier.com/locate/jbiomech

Scapular kinematics: effects of altering the Euler angle sequence of rotations

Andrew R. Karduna[a,*], Phil W. McClure[b], Lori A. Michener[c]

[a]*Department of Rehabilitation Sciences, Biomechanics Laboratory, MCP Hahnemann University, 8th Floor, 219 N Broad Street, Philadelphia, PA 19107, USA*

[b]*Department of Physical Therapy, Beaver College, Glenside, PA 19038, USA*

[c]*Department of Physical Therapy, Virginia Commonwealth University, Medical College of Virginia, Richmond, VA 23298, USA*

Accepted 21 March 2000

Abstract

An analysis of Euler angle sequences is presented for the scapula. In vivo kinematics were collected with a magnetic tracking device on eight healthy volunteers. To ensure accurate representation of scapular motion, pins were rigidly drilled into the scapular spine. Three rotations of the scapula with respect to the thorax were recorded during humeral elevation in the scapular plane: posterior (or backward) tilting, upward (or lateral) rotation and external rotation (or retraction). Rotations using all six possible Euler angle sequences were calculated for which each angle was represented only once. The sequence proposed by an International Society of Biomechanics subcommittee on shoulder motion (external rotation, upward rotation, posterior tilting) is consistent with both research- and clinical-based two-dimensional representations of scapular motion. Results from the present study indicate that changing sequence results in significant alterations in the description of motion, with differences up to 50° noted for some angles. Therefore, in order to compare results across different laboratories, it is recommended that the proposed standard sequence be adopted. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Shoulder; Scapula; Kinematics; Euler angles

1. Introduction

A common method for describing three-dimensional joint motion is with the use of Euler angles, which represent three sequential rotations about anatomic axes. However, for a given motion, different rotational sequences can theoretically result in different angle calculations (Blankevoort et al., 1988; Woltring, 1991; Cole et al., 1993). Previous experimental results have been mixed, with large differences between sequences demonstrated for the knee (Woltring, 1994) and spine (Crawford et al., 1996; McGill et al., 1997), while only minimal differences were found in a study of the ankle (Areblad et al., 1990). Recently, the International Society of Biomechanics (ISB) formed a Committee for Standardization and Terminology that has begun the process of developing standards for reporting kinematics, in part to address issues related to the selection of Euler angle sequences (Wu and Cavanagh, 1995). Although there is an ISB sub-committee focusing on shoulder motion (van der Helm, 1996), there have been no published studies that have specifically addressed Euler angle sequences for in vivo scapular motion.

Motion of the scapula with respect to the thorax is typically based on the following Euler angle rotations: upward (or lateral) rotation (U), external rotation (or retraction) (E) and posterior (or backward) tilting (P) (Fig. 1). Due to its unusual anatomy, the proposal presented by Cole et al. for the selection of an appropriate sequence, which requires the identification of a unique longitudinal axis, is not applicable to the scapula (1993). This may help explain why at least four of the six possible Euler angle sequences have been reported in the literature (McQuade et al., 1995; van der Helm and Pronk, 1995; Johnson et al., 1998; Hébert et al., 2000). Additionally, the angular differences between sequences will be exaggerated if there are large rotations about more than one axis (Cole et al., 1993; Skalli et al., 1995). Unlike the motion of other bones, it is possible for all three scapular

* Corresponding author. Tel.: + 1-215-762-5057; fax: + 1-215-762-6075.

E-mail address: karduna@drexel.edu (A.R. Karduna).

0021-9290/00/$ - see front matter
PII: S0021-9290(00)00078-6

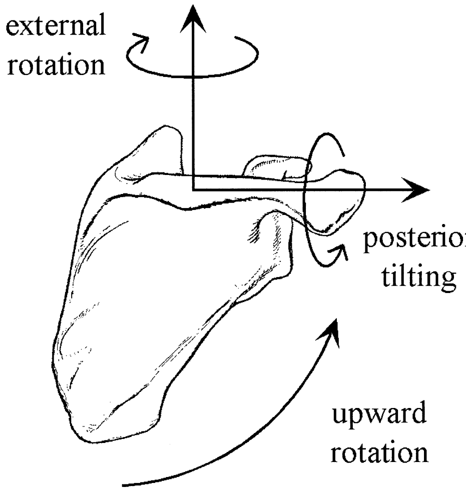

Fig. 1. Schematic representation of the Euler angles used in this study. In the neutral position, external rotation is about a superior/inferior axis, posterior tilting is about a medial/lateral axis and upward rotation is about an anterior/posterior axis.

rotations to exceed 50° (McQuade et al., 1995; de Groot, 1997).

When the motion of the scapula is considered planar, only upward rotation is typically measured (Poppen and Walker, 1976; Bagg and Forrest, 1988). Additionally, this is the only scapular rotation that can be easily assessed clinically (Youdas et al., 1994; Johnson et al., 1999). Upward rotation can be defined as rotation of the scapula about a horizontal axis perpendicular to the scapular plane. Consequently, in order to insure consistency with a two-dimensional description of scapular motion, the upward rotation axis must be constrained in the horizontal plane, yet free to rotate within this plane. The only Euler angle sequence that fulfills these conditions is the one proposed by the ISB subcommittee: external rotation, followed by upward rotation, followed by posterior tilting (van der Helm, 1996). The goal of the present study is to determine the alterations in scapular rotational patterns between this sequence and other possible sequences.

2. Materials and methods

Healthy volunteers were recruited for a companion study to compare skin- and bone-based kinematic measurements of scapular motion (Karduna et al., 2000). A total of eight subjects (five males and three females) with a mean age of 33 yr (range, 27–37 yr) participated. Approval for the experiment was obtained from this institution's internal review board. Shoulders with any current or history of pathology were excluded from the study.

A magnetic tracking device (Polhemus 3Space Fastrak, Colchester, VT) captured the motion of the scapula, humerus and thorax. This system consists of a transmitter that emits low-frequency magnetic fields sensed by multiple receivers and a digitizing stylus. An electronics unit uses this information to determine the position and orientation of the receivers and digitizer (An et al., 1988). The digitizer allows the user to collect the three-dimensional coordinates of its tip by clicking on a toggle switch. Similar studies using pins inserted into cadavers have documented an accuracy of approximately 0.5° for the magnetic tracking device (Harryman et al., 1990; Harryman et al., 1992). We have confirmed this in our laboratory setting.

A global coordinate system was established by mounting the transmitter on a plastic base and aligning it with the cardinal planes so that the transmitter axes coincided with the body's anterior–posterior, superior–inferior and medial–lateral axes. The first receiver was placed on the thorax at the level of T3 using double-sided tape. The second receiver was positioned on the humerus by mounting it on a molded cuff strapped to the distal humerus. The final receiver was attached to the scapula with pins. An orthopaedic surgeon drilled two 1.6 mm K-wires through the skin and into the lateral aspect of the scapular spine using a plastic alignment jig to keep the pins parallel. After manual examination of fixation, the pins were secured to the alignment jig with set screws and the receiver was attached to this jig. A pilot cadaver study indicated that skin tension and the mass of the receiver and cord would have a negligible effect on angle measurements.

The arbitrary axes defined by the magnetic tracking device were converted to embedded anatomic axes derived from digitized bony landmarks as described previously (Table 1) (Karduna et al., 2000). Landmark selection was based on the work of van der Helm and Pronk (1995). All landmarks were located with the digitizer except for the center of the humeral head, which was found mathematically rather than measuring directly. The humerus was actively moved into several mid-range positions (less than 90° of motion), and the center of the humeral head was defined as the point on the humerus that moved the least according to a least-squares algorithm (Sidles et al., 1989).

For each position, two rotational matrices were calculated, one represented the orientation of the humerus with respect to the thorax (R_{HT}) and one represented the orientation of the scapula with respect to the thorax (R_{ST}). Eq. (1) was used to solve for the commonly used humeral rotation sequence proposed by An et al. (1991). Eq. (2) was used to solve for all six possible scapular Euler angle sequences containing each rotation once (Cardan angles).

$$R_{\mathrm{HT}} = R(\phi)R(\theta)R(\psi) \tag{1}$$

where ϕ represents the plane of elevation, θ represents the amount of elevation and ψ represents humeral axial

Table 1
Definition of the coordinate axes derived from the position of the bony landmarks[a]

Thorax	Superior axis	Vector connecting T7–T1
	Lateral axis	Vector perpendicular to plane T1-T7-SN
	Anterior axis	Cross product of superior and lateral axes
Scapula	Lateral axis	Vector connecting root of scapular spine to AC joint
	Anterior axis	Vector perpendicular to plane AC-SP-IA
	Superior axis	Cross product of lateral and anterior axes
Humerus	Superior axis	Vector connecting midpoint of ME and LE to HH
	Anterior axis	Vector perpendicular to plane ME-LE-HH
	Lateral axis	Cross product of anterior and superior axes

[a]T1 — first thoracic vertebrae, T7 — seventh thoracic vertebrae, SN — sternal notch sternal notch, AC — acromioclavicular joint, SP — root of the scapular spine, IA — inferior angle ME — medial epicondyle, LE — lateral epicondyle, HH — center of the humeral head.

(internal/external) rotation

$$\begin{aligned} R_{\mathrm{ST}} &= R(\alpha_1)R(\beta_1)R(\gamma_1) = R(\alpha_2)R(\gamma_2)R(\beta_2) \\ &= R(\beta_3)R(\alpha_3)R(\gamma_3)R(\beta_4)R(\gamma_4)R(\alpha_4) \\ &= R(\gamma_5)R(\beta_5)R(\alpha_5) = R(\gamma_6)R(\alpha_6)R(\beta_6) \end{aligned} \quad (2)$$

where α_i represents posterior tilting, β_i represents upward rotation and γ_i represents external rotation for the ith sequence.

Humeral rotations were displayed in real time using LabView software (National Instruments, Austin, TX). Subjects were asked to stand directly in front of the transmitter with their eyes fixed forward. The experimental protocol consisted of active elevation of the arm in the scapular plane ($40 \pm 5^\circ$ anterior to the frontal plane) with the elbow in full extension. Subjects maximally elevated their arm in the scapular plane to a count of three and then lowered their arm along the same path for three consecutive trials with data collected continuously at a rate of approximately 10 Hz.

For each trial, scapular rotations were interpolated in five-degree increments of humerothoracic elevation and averaged over the three trials. Statistical tests were performed at the following elevation angles: minimum, 30, 60, 90, 120° and maximum. For each dependent variable (posterior tilting, upward rotation and external rotation) a two-way repeated measures analysis of variance (ANOVA) was performed with two within subject factors (elevation angle and sequence). If there were significant interactions between factors, one way ANOVAs were run for each elevation angle. For significant effects, contrasts were used to make planned comparisons between means. Contrasts are similar to post-hoc tests, but allow for the comparison of specific means. All sequences were compared with the proposed ISB standard (sequence EUP). Since these contrasts were not orthogonal, a Bonferroni correction factor was used to maintain a desired experiment-wise error rate of 5% (Sokal and Rohlf, 1981; Kirby, 1993).

3. Results

Altering the Euler angle sequence had a significant effect on posterior tilting, upward rotation, and external rotation ($p < 0.0001$). However, there were also significant interactions between sequence and humeral elevation for all rotations ($p < 0.0001$). Follow up one way ANOVAs revealed a significant effect of sequence on all rotations at all elevation angles ($p < 0.0001$), so the planned contrasts were performed.

Although all sequences demonstrated the same trend towards posterior tilting with humeral elevation, different patterns were observed (Fig. 2a). All sequences demonstrated significant differences for at least one humeral elevation angles when compared to the proposed standard (EUP) ($p < 0.05$, Table 2). While there was an increase in posterior tilting (when compared to the proposed standard) for sequence PUE at all humeral elevations, this increase was found for sequences UPE and UEP at all humeral elevations except maximum ($p < 0.05$). There was a decrease in posterior tilting for sequence PEU at maximum humeral elevation and for EPU from 90° to maximal humeral elevation.

For upward rotation, the general pattern of upward rotation with humeral elevation was similar for all six sequences (Fig. 2b). However, all sequences demonstrated significant differences for at least two humeral elevation angles when compared to the proposed standard (EUP) ($p < 0.05$, Table 2). There was an increase in upward rotation for sequence UEP from minimum to 120° of humeral elevation and for EPU for 120° and maximal humeral elevation. There was a decrease in upward rotation for sequence PUE at all humeral elevations except minimum, for PEU from 90° to maximal humeral elevation and for UPE from 30 to 120° of elevation.

Unlike the other two rotations, the same pattern of motion was not observed for external rotation (Fig. 2c). All sequences demonstrated significant differences for at least two humeral elevation angles when compared to the proposed standard (EUP) ($p < 0.05$, Table 2). There was an increase in external rotation for sequence UPE for 90 and 120° of humeral elevation, and for UEP between minimum and 120° of elevation. There was a decrease in external rotation between 60° and maximal humeral elevation for sequences PUE, PEU and EPU.

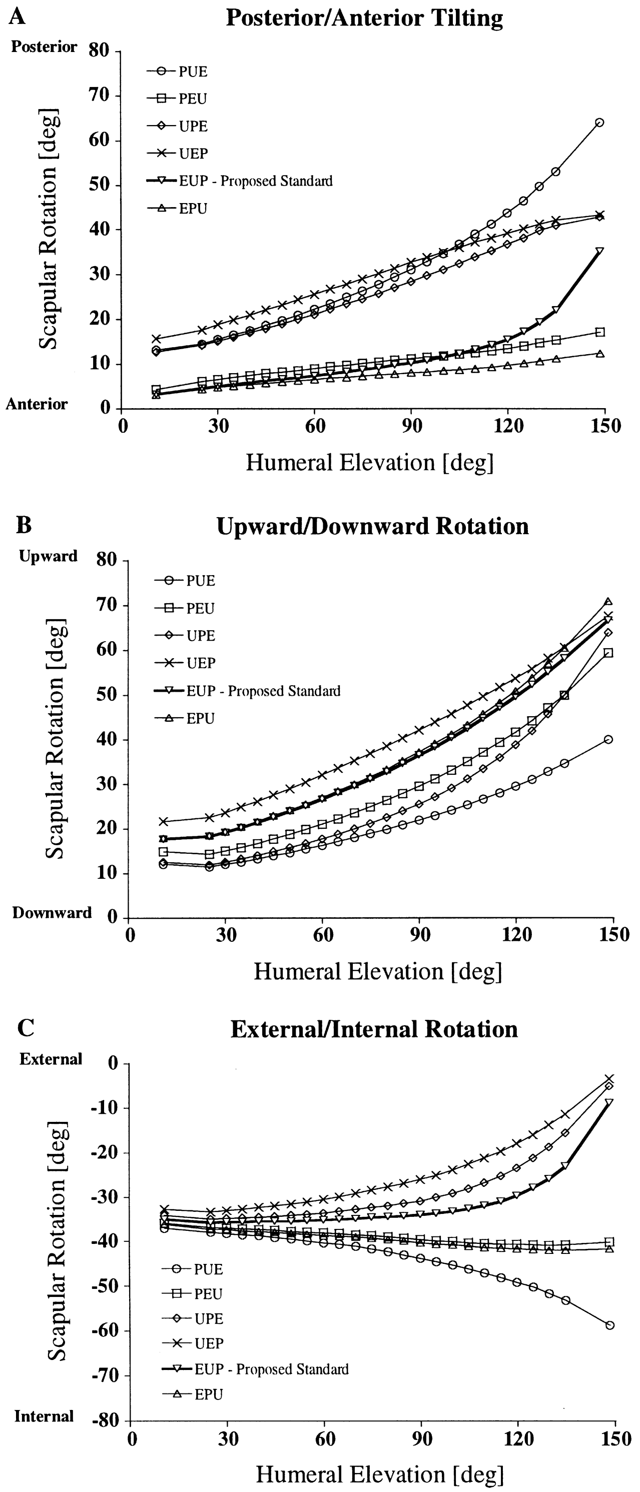

Fig. 2. Scapular rotations for all six Euler angle sequences considered in this study: (A) posterior/anterior tilting, (B) upward/downward rotation, (C) external/internal rotation. Each point represents the mean from eight subjects. The sequence EUP is the proposed ISB standard.

4. Discussion

Although Euler angles are used extensively in musculoskeletal biomechanics to represent three-dimensional orientations of bony segments, Woltring (1994) suggests that their sequence-dependent nature limits their usefulness. To our knowledge, only Hébert et al. (2000) have experimentally studied this issue with respect to the scapula. However, that investigation was performed by simulating rotations in an anatomical model. Our study represents the first comprehensive in vivo study of scapular Euler angles.

All sequences demonstrated a significant difference from the proposed standard for all three rotations. In general, the most similarity between sequences was found for upward rotation. Although the general pattern is consistent with reported two and three-dimensional studies (Freedman and Munro, 1966; Poppen and Walker, 1976; van der Helm and Pronk, 1995; Ludewig et al., 1996), the discrepancies in angles would result in different calculations for the relative contribution of glenohumeral and scapulothoracic motion.

For posterior tilting, there were two sequences (one of them being the proposed standard) that had a different shape than the others. These were the two sequences in which the largest rotation, upward rotation, was set as the second Euler angle. These results are in agreement with those of Woltring (1994), who found the greatest discrepancies between sequences for knee rotations when the second rotation was the largest. When the second Euler angle equals 90°, the first and third axes become aligned resulting in a gimbal lock singularity. However, in the present study the average maximum upward rotations for the sequences PUE and EUP were only 40 and 68°, respectively.

The most inconsistent results were observed for external rotation. Depending on which sequence was selected, the scapula appears to be either externally rotating, internally rotating or not rotating much at all. These results are very disconcerting because different conclusions about how the scapula is moving can be reached simply by the choice of sequences. This is the same problem that was encountered by Crawford et al. in their analysis of spinal motion (1996).

In a clinical setting, scapular motion is typically checked qualitatively by standing behind a patient while they elevate their arms. Under these conditions, upward rotation can be assessed by observing the movement of bony landmarks laterally, while anterior tilting (scapular tipping) and internal rotation (winging) can be assessed by watching the posteriorly directed motion of the inferior angle and medial border, respectively (Norkin and Levangie, 1992). While several investigators have proposed using available clinical tools for quantifying upward rotation angles (Doody et al., 1970; Youdas et al., 1994; Johnson et al., 1999), we are not aware of any proposed clinical measurements of posterior tilting or external rotation angles. In fact, Plafcan et al. (1997) suggest that “it is virtually impossible to separate the two phenomena for precise clinical measurement.” Therefore,

Table 2
Differences between indicated sequences and proposed standard sequence (EUP)

Scapular rotation	Humeral elevation	Euler angle sequence									
		Means					Standard deviations				
		PUE	PEU	UPE	UEP	EPU	PUE	PEU	UPE	UEP	EPU
Posterior Tilting	Minimum	9.8[a]	1.0	9.4[a]	12.4[a]	− 0.2	4.4	1.8	4.1	5.3	0.5
	30°	10.4[a]	1.4	9.9[a]	13.6[a]	− 0.4	4.4	2.3	4.0	5.4	0.5
	60°	14.7[a]	1.5	13.6[a]	18.0[a]	− 1.0	5.4	2.4	4.7	7.0	0.9
	90°	20.8[a]	0.8	18.1[a]	22.4[a]	− 2.3[a]	6.9	2.4	5.8	8.4	1.7
	120°	28.2[a]	− 2.1	21.1[a]	23.6[a]	− 5.9[a]	8.4	1.9	6.3	7.4	3.5
	Maximum	29.0[a]	− 18.0[a]	7.7	8.1	− 22.9[a]	12.8	12.0	12.8	13.1	13.9
Upward Rotation	Minimum	− 5.8	− 2.9	− 5.4	3.9[a]	0.1	4.9	4.9	4.6	2.0	0.2
	30°	− 7.3[a]	− 4.3	− 6.7[a]	4.4[a]	0.1	4.9	5.3	4.7	2.3	0.2
	60°	− 10.4[a]	− 5.6	− 9.0[a]	5.4[a]	0.3	5.7	5.1	5.2	3.1	0.4
	90°	− 14.6[a]	− 7.0[a]	− 11.0[a]	5.6[a]	0.6	7.5	5.2	6.1	3.2	0.5
	120°	− 20.1[a]	− 7.9[a]	− 10.8[a]	4.0[a]	1.2[a]	8.9	4.9	5.2	1.7	0.9
	Maximum	− 26.6[a]	− 7.4[a]	− 2.9	0.9	4.2[a]	11.2	5.3	6.3	0.9	3.0
External Rotation	Minimum	− 2.1	− 0.9	0.8	2.3[a]	− 1.2	2.0	1.9	1.1	1.5	2.2
	30°	− 2.7	− 1.5	0.8	2.6[a]	− 1.8	2.2	2.0	1.2	1.5	2.4
	60°	− 5.2[a]	− 3.0[a]	1.6	4.7[a]	− 3.5[a]	3.1	2.5	1.8	2.5	2.9
	90°	− 9.8[a]	− 5.7[a]	3.1[a]	8.0[a]	− 6.3[a]	4.6	3.5	2.4	4.0	4.0
	120°	− 19.6[a]	− 11.2[a]	6.2[a]	11.6[a]	− 12.1[a]	6.6	5.5	3.2	4.8	6.2
	Maximum	− 50.0[a]	− 31.5[a]	3.7	5.4	− 33.0[a]	17.1	15.8	6.4	8.7	16.5

[a] $p < 0.05$, $n = 8$.
All data are in degrees.

although the proposed ISB standard sequence can be justified based on theoretical consistency with two-dimensional upward rotation measurements, the results of our study do not invalidate the use of any of the other sequences.

Every effort was made to ensure an accurate representation of scapular motion; however, there are several possible sources of errors. Pin slippage was minimized by testing pin fixation manually to ensure that it was secure in the bone. Since it is possible that the motion of the skin could have slightly bent the pins, this effect was tested in a cadaver. Although errors were found to be negligible, active muscle contraction may have increased skin tension in-vivo. There may also be errors associated with the skin mounted humeral and thoracic receivers. Finally, although the definition of the axis systems was standardized, there could have been errors in digitizing the bony landmarks. However, for a given subject, the axis system was identical for all Euler angle sequences.

In conclusion, since it is consistent with both research- and clinical-based two-dimensional representations of scapular motion, we recommend the adoption of the proposed ISB sequence of Euler angle rotations: external rotation, followed by upward rotation, followed by posterior tilting. Results of the present study suggest that altering this sequence can dramatically change the described motion pattern. The adoption of a standard Euler angle sequence will allow researchers to compare work from different laboratories. Caution should be used in comparing the results of studies that use different sequences or that fail to report the sequence of rotation used.

Acknowledgements

This work was supported in part by a grant from the Orthopaedic Section of the American Physical Therapy Association. The authors would like to thank Brian Sennett, M.D. for performing the surgical insertion of the pins.

References

An, K.N., Browne, A.O., Korinek, S., Tanaka, S., Morrey, B.F., 1991. Three-dimensional kinematics of glenohumeral elevation. Journal of Orthopaedic Research 9, 143–149.

An, K.N., Jacobsen, M.C., Berglund, L.J., Chao, E.Y.S., 1988. Application of a magnetic tracking device to kinesiologic studies. Journal of Biomechanics 21, 613–620.

Areblad, M., Nigg, B.M., Ekstrand, J., Olsson, O., Ekström, H., 1990. Three-dimensional measurement of rearfoot motion during walking. Journal of Biomechanics 23, 933–940.

Bagg, S.D., Forrest, W.J., 1988. A biomechanical analysis of scapular rotation during arm abduction in the scapular plane. American Journal of Physical Medicine and Rehabilitation 67, 238–245.

Blankevoort, L., Huiskes, R., de Lange, A., 1988. The envelope of passive knee joint motion. Journal of Biomechanics 21, 705–720.

Cole, G.K., Nigg, B.M., Ronsky, J.L., Yeadon, M.R., 1993. Application of the joint coordinate system to three-dimensional joint attitude and movement representation: a standardization proposal. Journal of Biomechanical Engineering 115, 344–349.

Crawford, N.R., Yamaguchi, G.T., Dickman, C.A., 1996. Methods for determining spinal flexion/extension, lateral bending, and axial rotation from marker coordinate data: analysis and refinement. Human Movement Science 15, 55–78.

de Groot, J.H., 1997. The variability of shoulder motions recorded by means of palpation. Clinical Biomechanics 12, 461–472.

Doody, S.G., Waterland, J.C., Freedman, L., 1970. Scapulo-humeral goniometer. Archives of Physical Medicine and Rehabilitation 51, 711–713.

Freedman, L., Munro, R.R., 1966. Abduction of the arm in the scapular plane: scapular and glenohumeral movements. Journal of Bone and Joint Surgery 48A, 1503–1510.

Harryman, D.T., II, Sidles, J.A., Clark, J.M., McQuade, K.J., Gibb, T.D., Matsen, F.A., III. 1990. Translation of the humeral head on the glenoid with passive glenohumeral motion. Journal of Bone and Joint Surgery 72A, 1334–1343.

Harryman, D.T., II, Sidles, J.A., Harris, S.L., Matsen, F.A., III. 1992. The role of the rotator interval capsule in passive motion and stability of the shoulder. Journal of Bone and Joint Surgery 74A, 53–66.

Hébert, L.J., Moffet, H., McFadyen, B.J., St-Vincent, G., 2000. A method of measuring three-dimensional scapular attitudes using the optotrak probing system. Clinical Biomechanics 15, 1–8.

Johnson, G.R., Franklin, P., Price, C.I.M., Curless, R., Rodgers, H., 1998. A study of the motion of the shoulder complex in patients with hemiplegia. In Proceedings of the Fifth International Symposium on the 3-D Analysis of Human Movement, Chattanooga, Tennessee, pp. 30–33.

Johnson, M.P., McClure, P.W., Karduna, A.R., 1999. Use of a digital inclinometer to assess scapular upward rotation: A reliability and validity study. In Proceedings of the 23rd Annual Meeting of the American Society of Biomechanics, Pittsburgh, PA, pp. 56–57.

Karduna, A.R., McClure, P.W., Michener, L.A., Sennett, B., 2000. The accuracy of measuring dynamic three-dimensional scapular kinematics. Journal of Biomechanical Engineering (submitted for publication).

Kirby, K.N., 1993. Advanced Data Analysis with Systat. Van Nostrand Reinhold, New York, 475 pp.

Ludewig, P.M., Cook, T.M., Nawoczenski, D.A., 1996. Three-dimensional scapular orientation and muscle activity at selected positions of humeral elevation. Journal of Orthopaedic and Sports Physical Therapy 24, 57–65.

McGill, S.M., Cholewicki, J., Peach, J.P., 1997. Methodological considerations for using inductive sensors (3Space Isotrak) to monitor 3-D orthopaedic joint motion. Clinical Biomechanics 12, 190–194.

McQuade, K.J., Wei, S.H., Smidt, G.L., 1995. Effects of local muscle fatigue on three-dimensional scapulohumeral rhythm. Clinical Biomechanics 10, 144–148.

Norkin, C.C., Levangie, P.K., 1992. Joint Structure and Function: A Comprehensive Analysis. F. A. Davis Co, Philadelphia.

Plafcan, D.M., Turczany, P.J., Guenin, B.A., Kegerreis, S., Worrell, T.W., 1997. An objective measurement technique for posterior scapula displacement. Journal of Orthopaedic and Sports Physical Therapy 25, 336–341.

Poppen, N.K., Walker, P.S., 1976. Normal and abnormal motion of the shoulder. Journal of Bone and Joint Surgery 58A, 195–201.

Sidles, J.A., Garbini, J.L., Matsen, F.A., III. 1989. A general-purpose system for joint kinematic measurements. In 1989 Biomechanics Symposium, La Jolla, CA, pp. 93–96.

Skalli, W., Lavaste, F., Descrimes, J.L., 1995. Quantification of three-dimensional vertebral rotations in scoliosis: what are the true values?. Spine 20, 546–553.

Sokal, R.R., Rohlf, F.J., 1981. Biometry. W. H. Freeman and Co., New York, 859 pp.

van der Helm, F.C.T., 1996. A standardized protocol for motion recordings of the shoulder. In: Veeger, H.E.J., van der Helm, F.C.T., Rozing, R.M. (Eds.), Proceedings of the First Conference of the International Shoulder Group. Shaker Publishing, St Maartenslaan, pp. 7–12.

van der Helm, F.C.T., Pronk, G.M., 1995. Three-dimensional recording and description of motions of the shoulder mechanism. Journal of Biomechanical Engineering 117, 27–40.

Woltring, H.J., 1991. Representation and calculation of 3-D joint movement. Human Movement Science 10, 603–616.

Woltring, H.J., 1994. 3-D attitude representation of human joints: a standardization proposal. Journal of Biomechanics 27, 1399–1414.

Wu, G., Cavanagh, P.R., 1995. ISB recommendations for standardization in the reporting of kinematic data. Journal of Biomechanics 28, 1257–1261.

Youdas, J.W., Carey, J.R., Garrett, T.R., Suman, V.J., 1994. Reliability of goniometric measurements of active arm elevation in the scapula plane obtained in a clinical setting. Archives of Physical Medicine and Rehabilitation 75, 1137–1144.