Journal of Biomechanics 47 (2014) 1206–1210

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

A regression-based 3-D shoulder rhythm

Xu Xu*, Jia-hua Lin, Raymond W. McGorry

Liberty Mutual Research Institute for Safety, 71 Frankland Road, Hopkinton, MA 01748, USA

ARTICLE INFO

Article history:
Accepted 18 January 2014

Keywords:
Humerus
Clavicle
Scapula
Kinematics
ISB recommendations

ABSTRACT

In biomechanical modeling of the shoulder, it is important to know the orientation of each bone in the shoulder girdle when estimating the loads on each musculoskeletal element. However, because of the soft tissue overlying the bones, it is difficult to accurately derive the orientation of the clavicle and scapula using surface markers during dynamic movement. The purpose of this study is to develop two regression models which predict the orientation of the clavicle and the scapula. The first regression model uses humerus orientation and individual factors such as age, gender, and anthropometry data as the predictors. The second regression model includes only the humerus orientation as the predictor. Thirty-eight participants performed 118 static postures covering the volume of the right hand reach. The orientation of the thorax, clavicle, scapula and humerus were measured with a motion tracking system. Regression analysis was performed on the Euler angles decomposed from the orientation of each bone from 26 randomly selected participants. The regression models were then validated with the remaining 12 participants. The results indicate that for the first model, the r^2 of the predicted orientation of the clavicle and the scapula ranged between 0.31 and 0.65, and the RMSE obtained from the validation dataset ranged from 6.92° to 10.39°. For the second model, the r^2 ranged between 0.19 and 0.57, and the RMSE obtained from the validation dataset ranged from 6.62° and 11.13°. The derived regression-based shoulder rhythm could be useful in future biomechanical modeling of the shoulder.

1. Introduction

The shoulder girdle includes three bones: the clavicle, the scapula, and the humerus. It has been observed that during movement the orientations of these shoulder bones are not completely independent (Hogfors et al., 1991; Inman et al., 1944). For example, when the arm is elevated in the sagittal plane, the clavicle elevates and the scapula rotates laterally (de Groot and Brand, 2001; Grewal and Dickerson, 2013; Hogfors et al., 1991). This pattern of movement of the bones comprising the shoulder girdle is called the shoulder rhythm.

During shoulder biomechanical modeling, it is important to know the orientation of each bone in the shoulder girdle when calculating the structural loads on each musculoskeletal element. The orientation of the clavicle and the scapula, however, can be difficult to determine with accuracy using non-invasive surface marker-based motion tracking methods, because of the soft tissue overlying the bones (Brochard et al., 2011; Karduna et al., 2001; Prinold et al., 2011; van Andel et al., 2009). Some previous studies (de Groot and Brand, 2001; Grewal and Dickerson, 2013; Hogfors et al., 1991), attempted to investigate regression-based shoulder rhythms in which the orientation of the clavicle and the scapula were predicted by the orientation of the humerus. Such shoulder rhythms were later used in shoulder biomechanical modeling (Dickerson et al., 2007; Holzbaur et al., 2005; Karlsson and Peterson, 1992).

However, the shoulder rhythms derived in these previous studies utilized a limited envelope of arm postures. In Hogfors et al. (1991), arm elevation angle was only evaluated within a range from approximately 60° to 110°. In the de Groot and Brand (2001) study, 23 different arm postures in four planes of elevation and six elevation angles were tested, but axial rotation of the humerus was not included. Extrapolating shoulder rhythms to an untested range may result in poor prediction of the orientation of the clavicle and scapula. In a very recent study, Grewal and Dickerson (2013) measured 39 static postures with three arm elevation planes, five elevation angles, and three humerus axial rotation angles. The sampling interval for each rotation was approximately 45°, which likely does not provide sufficient resolution to detect the nonlinear property of shoulder rhythm, if it exists.

The purpose of this study was to describe a 3-D shoulder rhythm using a larger envelope of arm postures and higher angular resolution than currently available in the literature. For each participant, 118 arm postures were examined with a 30° interval in each rotation axis. Two types of regression models were

---

* Corresponding author. Tel.: +1 508 497 0218.
E-mail address: Xu.Xu@libertymutual.com (X. Xu).

http://dx.doi.org/10.1016/j.jbiomech.2014.01.043
0021-9290

built to predict the 3-D orientation of clavicle and scapula. The first model used the humerus orientation and individual factors including age, gender, and anthropometry data as the predictors. However, the data regarding the individual factors may not always be available; the second model only used humerus orientation as the predictor. The regression models were then validated using an independent dataset.

2. Method

2.1. Participants and arm postures

Thirty-eight participants (19 females and 19 males, age: 32.3 (10.8), height: 1.72 (0.09) m, weight: 72.0 (16.6) kg, all right-handed) with no acute or chronic upper extremity musculoskeletal disorders were recruited from local communities. All participants gave written informed consent to participate in a protocol approved by the local Institutional Review Board. An external frame with three rotational degrees of freedom, consistent with the recommendation of the International Society of Biomechanics (ISB) (Wu et al., 2005), was used to standardize the arm postures. The frame provided five planes of elevation (0°, 30°, 60°, 90°, and 120°), six elevation angles (0°, 30°, 60°, 90°, 120° and 150°), and seven humerus axial rotation angles (−90°, −60°, −30°, 0°, 30°, 60°, and 90°) for the thoracohumeral joint. After eliminating unattainable postures found in the pilot test, 118 out of 210 static postures were tested (Table 1). Elbow angle was set to 90° for all the tested postures.

2.2. Apparatus

A scapula locator (Johnson et al., 1993; Meskers et al., 2007; van Andel et al., 2009) was customized to measure the orientation of the scapula under each arm posture. The scapula locator is a device with three adjustable pegs which were set to fit the acromial angle (AA), the root of the scapula spine (TS), and the inferior angle (AI) of the scapula for each participant prior to starting the protocol. A motion tracking system (Optotrak Certus System, Northern Digital, Canada) was used to collect 3-D kinematics of the right upper arm, right forearm, thorax, and scapula locator for each posture. Clusters of three markers were taped to each body segment and the scapula locator. Anatomical landmarks were digitized by a probe with the participants in an upright standing reference posture, arms at sides, and the scapula locator placed overlying the scapula. The suprasternal notch (IJ), xiphoid process (PX), C7 vertebra, T8 vertebra, and sternoclavicular (SC) joint were digitized with respect to the marker cluster taped on the thorax; the right acromion process (ACR), the lateral and medial epicondyle (EL and EM) were digitized with respect to the marker cluster taped on the upper arm; the ulnar styloid (US) was digitized with respect to the marker cluster taped on the forearm; and the three pegs of the scapula locator and acromioclavicular (AC) joint were digitized with respect to the marker cluster taped on the scapula locator.

2.3. Experiment procedure

Before the experiment, anthropometry data including body length, clavicle length, scapula length (the distance between AA and AI), and upper arm length (Hogfors et al., 1987) were measured by a digitizer (Table 2). During the protocol, the external frame was set to 118 arm postures for the right arm. The testing order of all arm postures was randomized first by the plane of elevation, and then by the elevation angle. Axial rotation angle was increased from the minimum reachable angle to the maximum for one block, and then decreased from maximum reachable angle to the minimum for the next block. For each arm posture, the participants were seated, fitting their upper arm and forearm into the external frame. An experimenter fit the three pegs of the scapula locator on the AA, TS, and AI of the scapula to measure the scapula orientation.

2.4. Data analysis

For each arm posture, the anatomical coordinate systems of thorax, clavicle, scapula, and humerus were generated from the measured bony landmarks based on the method recommended by the ISB (Wu et al., 2005). For the humerus, it was assumed that the glenohumeral rotation center (GH) was on the line between the

Table 2
Average anthropometry data for 38 participants.

Anthropometry data	Definition	Average (mm)	SD (mm)
Thorax length (L_t)	T1-T12	217	30
Clavicle length (L_c)	SC-AC	157	23
Scapula length (L_s)	AA-AI	183	15
Upper arm length (L_{ua})	ACR-EL	256	17

Note: SD = Standard deviation.

Table 1
The 118 static thoracohumeral joint angles tested in the current study. γ_{TH1_f}, β_{TH_f}, and γ_{TH1_f} are plane of elevation, elevation angle, and axial rotation defined by the frame, respectively. The lower case "*f*" stands for "frame-defined".

γ_{TH1_f}	β_{TH_f}	γ_{TH2_f}	γ_{TH1_f}	β_{TH_f}	γ_{TH2_f}	γ_{TH1_f}	β_{TH_f}	γ_{TH2_f}	γ_{TH1_f}	β_{TH_f}	γ_{TH2_f}	γ_{TH1_f}	β_{TH_f}	γ_{TH2_f}
0	0	−60	30	30	−90	60	30	−90	90	30	−90	120	30	−90
0	0	−30	30	30	−60	60	30	−60	90	30	−60	120	30	−60
0	0	0	30	30	−30	60	30	−30	90	30	−30	120	30	−30
0	0	30	30	30	0	60	30	0	90	30	0			
0	0	60	30	30	30	60	30	30				120	60	−90
									90	60	−90	120	60	−60
0	30	−90	30	60	−90	60	60	−90	90	60	−60	120	60	−30
0	30	−60	30	60	−60	60	60	−60	90	60	−30	120	60	0
0	30	−30	30	60	−30	60	60	−30	90	60	0			
0	30	0	30	60	0	60	60	0	90	60	30	120	90	−90
0	30	30	30	60	30	60	60	30				120	90	−60
									90	90	−90	120	90	−30
0	60	−90	30	90	−90	60	90	−90	90	90	−60	120	90	0
0	60	−60	30	90	−60	60	90	−60	90	90	−30			
0	60	−30	30	90	−30	60	90	−30	90	90	0	120	120	−90
0	60	0	30	90	0	60	90	0	90	90	30	120	120	−60
0	60	30	30	90	30	60	90	30				120	120	−30
			30	90	60				90	120	−90	120	120	0
0	90	−90				60	120	−90	90	120	−60	120	120	30
0	90	−60	30	120	−90	60	120	−60	90	120	−30			
0	90	−30	30	120	−60	60	120	−30	90	120	0	120	150	0
0	90	0	30	120	−30	60	120	0	90	120	30	120	150	30
0	90	30	30	120	0	60	120	30				120	150	60
0	90	60	30	120	30				90	150	−90	120	150	90
			30	120	60	60	150	−90	90	150	30			
0	120	−90				60	150	−60						
0	120	−60	30	150	−90	60	150	−30						
0	120	−30	30	150	−60	60	150	0						
0	120	0	30	150	−30	60	150	30						
0	120	30	30	150	0									

elbow joint center (mid-point of EL and EM) and ACR during the reference posture. The thoracoclavicular joint angle, the thoracoscapular joint angle, and the thoracohumeral joint angle of each arm posture were then decomposed using the Euler angle sequence recommended by the ISB (Wu et al., 2005) (Table 3). For the thoracohumeral joint angle, the second option of the ISB recommendation, using the forearm orientation to estimate axial rotation, was adopted. It should be noted since the clavicle and thorax share one common axis (vertical axis of the thorax), only two angles can be derived for the thoracoclavicular joint.

2.5. *Regression analysis*

The data of 26 participants (13 females and 13 males, age: 33.4 (11.6), height: 1.73 (0.10) m, weight: 71.5 (14.1) kg) were randomly selected to build the regression models. Two types of regression model were built. The first one included three thoracohumeral angles and individual factors including age, gender, and anthropometry data as the predictors. The second regression model included only the three thoracohumeral angles as the predictors. For each regression model, a two-step regression procedure similar to those performed in previous studies (de Groot and Brand, 2001; Grewal and Dickerson, 2013) was used to create the regression equation. In the first step, gender and frame-defined thoracohumeral angles were treated as nominal variables while age and anthropometry data were treated as continuous variables. A linear regression model was used to assess the influence of the independent variables. In the second step, the significant variables from the first step were treated as continuous variables to build the regression equation by stepwise regression. If the frame-defined thoracohumeral angles were found to be significant in the first step, the measured thoracohumeral angles, their quadratic terms, and the interaction terms would also be evaluated in the second step (Grewal and Dickerson, 2013). All the predictors were centered to reduce multicollinearity (Aiken et al., 1991). For the stepwise regression, the *p*-value required for a term to be entered in the model was 0.05, and the *p*-value for a term to be retained in the model was 0.10. The coefficient of determination (r^2) and the root-mean-square error (RMSE) were calculated to evaluate the predictability of the model.

2.6. *Model validation*

The dataset of the remaining twelve participants (6 females and 6 males, age: 30.1 (8.6), height: 1.69 (0.08) m, weight: 73.2 (21.8) kg) were used to validate the regression models. The r^2 and RMSE was used to quantify the quality of the regression models.

Table 3
The ISB-recommended Euler angle decomposition and their interpretation for clavicle, scapula, and humerus orientation with respect to the thorax. Parentheses indicate that axial rotation of clavicle cannot be derived in the current study since the clavicle and the thorax share a common vertical axis.

Joint	Euler decomposition order	Rotation description
Thoracoclavicular	Y X (Z)	Retraction/protraction (γ_C) Elevation/depression (β_C) (Axial rotation)
Thoracoscapular	Y X Z	Retraction/protraction (γ_S) Lateral/medial rotation (β_S) Anterior/posterior tilt (α_S)
Thoracohumeral	Y X Y	Plane of elevation (γ_{TH1}) Elevation (β_{TH}) Axial rotation (γ_{TH2})

3. Results

For the first model, including the individual factors, the first step of the regression analysis indicated that all the predictors contributed to all the thoracoclavicular and thoracoscapular joint angles, except for gender and age, which did not contribute to protraction/retraction of thoracoclavicular joint (Table 4). The second step further eliminated the thorax length as a predictor for all three thoracoscapular joints. The medial/lateral rotation of the thoracoscapular joints had the greatest r^2 value of 0.65 and the anterior/posterior tilt of the thoracoscapular joints had the least r^2 value of 0.31 (Fig. 1). The RMSE of the model ranged between 4.63° and 8.27°. For the validation dataset, the r^2 value ranged between 0.10 and 0.68, while the RMSE ranged from 6.92° and 10.39°.

For the second model, based only on the three thoracohumeral angles and excluding the individual factors, the first step of the regression analysis indicated that all predictors (linear and quadratic terms of the thoracohumeral joint angles) contributed to all the thoracoclavicular and thoracoscapular joint angles (Table 5). The medial/lateral rotation of the thoracoscapular joints had the greatest r^2 value of 0.57 and the anterior/posterior tilt of the thoracoscapular joints had the least r^2 value of 0.19 (Fig. 2). For the validation dataset, the r^2 value ranged between 0.10 and 0.68, The RMSE of the model ranged between 5.03° and 9.45°, while the RMSE obtained from the validation dataset ranged from 6.62° and 11.13°.

4. Discussion

The goal of this study was to build regression models, with and without individual factors, to predict the orientation of the clavicle and scapula based on the orientation of the humerus. The results can be integrated into existing shoulder biomechanical models used for calculating structural loads. In general, the findings in the current study are consistent with the literature (de Groot and Brand, 2001; Grewal and Dickerson, 2013; Hogfors et al., 1991). For example, the positive correlation between the elevation of the thoracohumeral joint and the retraction of the thoracoclavicular joint was observed in previous studies as well as in the current study. The model performances, as indicated by r^2, varied among difference joints. While the models can best explain the variance of medial/lateral rotation of the thoracoscapular joint, the explanatory ability for other joints is relatively limited. The value of the RMSE also suggests that error exists between measured and predicted joint angles.

There were also some differences between the current and previous studies. The RMSEs of the current models were in the similar range as measured in de Groot and Brand (2001), but greater than those in Grewal and Dickerson (2013), in general. The r^2 in the current study was also smaller than those in Grewal and Dickerson (2013). In addition, it was found that individual factors

Table 4
The regression equation of shoulder rhythm with individual factors.

Y	c1	c2	c3	c4	c5	c6	c7	c8	c9	c10	c11	c12	c13	c14	c15	Const.
γ_S	0.160	−0.013	0.041	−0.0013	−0.0015	−0.0002	−0.0022	−0.0006	0.0003	1.565	0.100	–	0.033	−0.026	−0.211	37.89
β_S	−0.076	0.332	−0.027	−0.0006	−0.0015	–	−0.0006	−0.0017	−0.0003	−2.651	−0.220	–	0.062	−0.099	0.143	−22.35
α_S	0.054	−0.037	−0.010	0.0002	0.0003	0.0002	–	0.0006	0.0008	2.432	−0.085	–	0.029	−0.064	−0.073	-7.50
γ_C	0.068	0.199	0.011	−0.0017	−0.0026	−0.0004	−0.0017	−0.0018	–	/	/	0.029	−0.080	–	−0.248	−17.42
β_C	−0.024	0.201	−0.033	–	–	0.0003	−0.0006	−0.0003	0.0006	−1.222	−0.233	−0.068	0.066	0.127	−0.048	−21.04

The equations are in the form $Y = c_1(\gamma_{TH1} - 46.97) + c_2(\beta_{TH} + 66.46) + c_3(\gamma_{TH2} + 37.64) + c_4(\gamma_{TH1} - 46.97)^2 + c_5(\beta_{TH} + 66.46)^2 + c_6(\gamma_{TH2} + 37.64)^2 + c_7(\gamma_{TH1} - 46.97)\ (\beta_{TH} + 66.46) + c_8(\gamma_{TH1} - 46.97)\ (\gamma_{TH2} + 37.64) + c_9(\beta_{TH} + 66.46)\ (\gamma_{TH2} + 37.64) + c_{10}\ \text{gender} + c_{11}(\text{age} - 33.31) + c_{12}(L_b - 218.9) + c_{13}(L_c - 157.8) + c_{14}(L_s - 182.1) + c_{15}(L_{ua} - 259.2) + \text{Const.}$ Gender is −1 for female and 1 for male. L_t, L_c, L_s, and L_{ua} are the length of body, clavicle, scapula, and upper arm, respectively, with a unit of millimeter. "/" indicates the term was eliminated in the first step of regression analysis, while a "–;" indicates the term was eliminated in the second step by the stepwise regression.

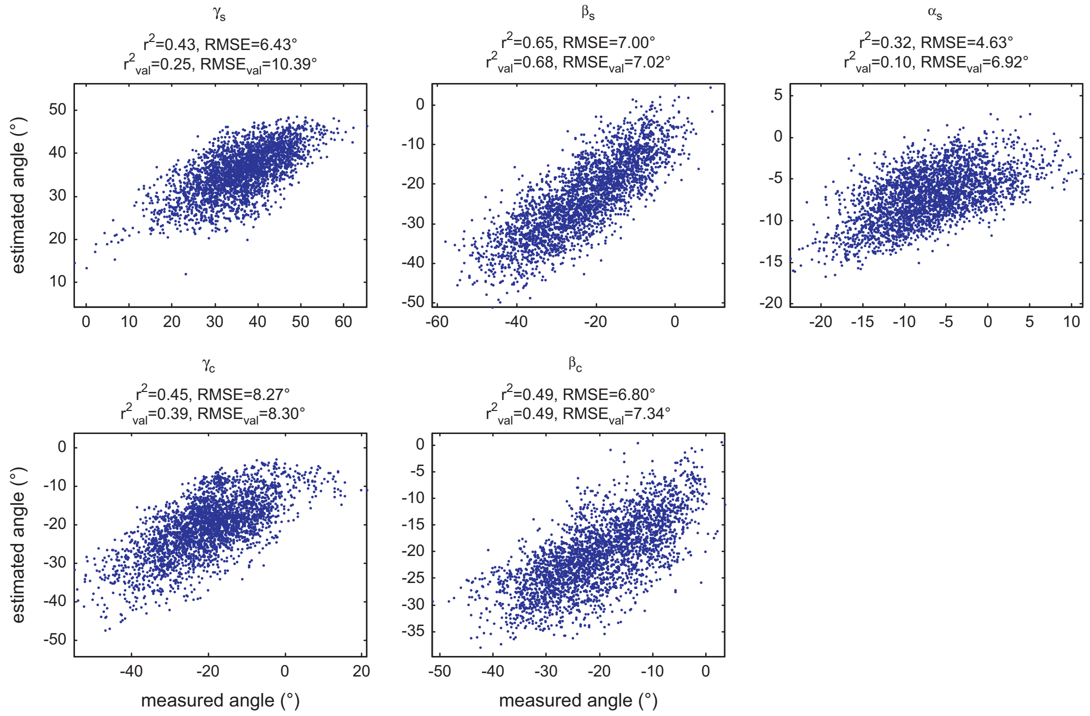

Fig. 1. Correlation between the measured and the predicted thoracoclavicular and thoracoscapular joint angles, with individual factors as inputs.

Table 5
The regression equation of shoulder rhythm without individual factors.

Y	c'_1	c'_2	c'_3	c'_4	c'_5	c'_6	c'_7	c'_8	c'_9	Const.
γ_S	0.163	–	0.039	−0.0016	−0.0018	−0.0003	−0.0023	−0.0009	0.0003	38.35
β_S	−0.065	0.322	−0.024	–	−0.0009	–	–	−0.0014	–	−23.20
α_S	0.060	−0.039	−0.011	–	–	0.0002	–	0.0005	0.0008	−7.11
γ_C	0.059	0.207	0.013	−0.0017	−0.0025	−0.0005	−0.0020	−0.0020	–	−17.42
β_C	−0.025	0.204	−0.031	–	–	0.0002	−0.0007	−0.0003	0.0007	−21.04

The equations are in the form $Y=c'_1\ (\gamma_{TH1}-46.97)+c'_2\ (\beta_{TH}+66.46)+c'_3\ (\gamma_{TH2}+37.64)+c'_4\ (\gamma_{TH1}-46.97)^2+c'_5\ (\beta_{TH}+66.46)^2+c'_6\ (\gamma_{TH2}+37.64)^2+c'_7\ (\gamma_{TH1}-46.97)(\beta_{TH}+66.46)+c'_8\ (\gamma_{TH1}-46.97)(\gamma_{TH2}+37.64)+c'_9\ (\beta_{TH}+66.46)(\gamma_{TH2}+37.64)+\text{Const.}$ "–" indicates the term is eliminated by the stepwise regression.

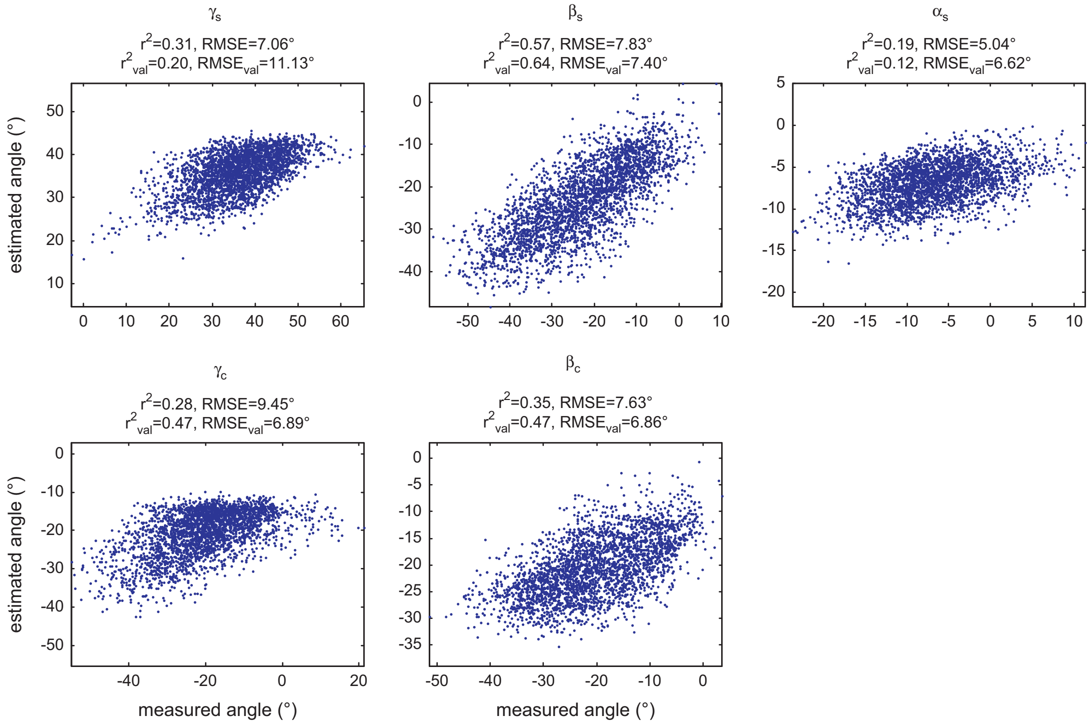

Fig. 2. Correlation between the measured and the predicted thoracoclavicular and thoracoscapular joint angles, without individual factors as inputs.

such as age, gender, and anthropometry data were significant predictors for most of the thoracoclavicular and thoracoscapular joint angles in the current study. Gender differences in thoracic anthropometry might account for some of the observed variance. The disproportionately smaller rib cages, and greater rib inclination angles in women than men (Bellemare et al., 2003) could affect scapular motion patterns. One could also speculate that the significant changes in scapular motion observed with age might be attributable to morphologic changes, such as increasing kyphosis (Gayzik et al., 2008). This finding conflicts with those of previous studies. In de Groot and Brand (2001), it was found that gender and anthropometry data were not significant predictors. In Grewal and Dickerson (2013), age, height, and weight were also excluded in the regression model due to lack of predictive power. One possible reason for those inconsistencies is likely due to participant selection. In the current study, the participants were recruited from the local community and had great diversity in terms of age and weight, while the participants in those previous studies were mainly young adults. Such great diversity may contribute to less model predictability and enlarge the effect of the individual factors.

There are limitations to the ability to generalize the results that need to be addressed. First, all the tested planes of elevation of the thoracohumeral joint were equal or greater than zero. The predictability of the current model for the postures with negative planes of elevation, such as those involved in pitching or throwing, remains unclear. Second, the effect of force exertion on shoulder rhythm was not examined. Results of a previous study (de Groot and Brand, 2001) indicated that abduction in the plane of elevation can alter the tilt and rotation angle of the scapula. In general, the current models can be used to describe the shoulder rhythms when the upper arm is in a positive elevation plane without substantial external load, such as those during office work or light-duty assembly tasks. However, caution needs to be taken when extrapolating the current model to untested thoracohumeral joint angles and/or force conditions.

Conflict of interest statement

All authors declare that there is no proprietary, financial, professional or other personal interest of any nature or kind in any product, service or company that could be construed as influencing the position presented in this manuscript.

Acknowledgments

The authors are also grateful to Dr. Chien-chi Chang and Dr. William Horrey for many useful comments and suggestions and Jacob Banks, Niall O'Brien, and Amanda Rivard for assistance in data collection.

References

Aiken, L.S., West, S.G., Reno, R.R., 1991. Multiple Regression: Testing and Interpreting Interactions. Thousand Oaks, CA, USA: Sage Publications, Inc.

Bellemare, F., Jeanneret, A., Couture, J., 2003. Sex differences in thoracic dimensions and configuration. Am. J. Respir. Crit. Care Med. 168, 305–312.

Brochard, S., Lempereur, M., Remy-Neris, O., 2011. Accuracy and reliability of three methods of recording scapular motion using reflective skin markers. Proc. Inst. Mech. Eng. Part H-J. Eng. Med. 225, 100–105.

de Groot, J.H., Brand, R., 2001. A three-dimensional regression model of the shoulder rhythm. Clin. Biomech. 16, 735–743.

Dickerson, C.R., Chaffin, D.B., Hughes, R.E., 2007. A mathematical musculoskeletal shoulder model for proactive ergonomic analysis. Comput. Methods Biomech. Biomed. Eng. 10, 389–400.

Gayzik, F.S., Yu, M.M., Danelson, K.A., Slice, D.E., Stitzel, J.D., 2008. Quantification of age-related shape change of the human rib cage through geometric morphometrics. J. Biomech. 41, 1545–1554.

Grewal, T.-J., Dickerson, C.R., 2013. A novel three-dimensional shoulder rhythm definition that includes overhead and axially rotated humeral postures. J. Biomech. 46, 608–611.

Hogfors, C., Peterson, B., Sigholm, G., Herberts, P., 1991. Biomechanical model of the human shoulder joint.2. The shoulder rhythm. J. Biomech. 24, 699–709.

Hogfors, C., Sigholm, G., Herberts, P., 1987. Biomechanical model of the human shoulder.1. Elements. J. Biomech. 20, 157–166.

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, 829–840.

Inman, V.T., Saunders, J.B., Abbott, L.C., 1944. Observations of the function of the shoulder joint. J. Bone Joint Surg., 1–30

Johnson, G.R., Stuart, P.R., Mitchell, S., 1993. A method for the measurement of 3-dimensional scapular movement. Clin. Biomech. 8, 269–273.

Karduna, A.R., McClure, P.W., Michener, L.A., Sennett, B., 2001. Dynamic measurements of three-dimensional scapular kinematics: a validation study. J. Biomech. Eng.-Trans. ASME 123, 184–190.

Karlsson, D., Peterson, B., 1992. Towards a model for force predictions in the human shoulder. J. Biomech. 25, 189–199.

Meskers, C.G.M., van de Sande, M.A.J., de Groot, J.H., 2007. Comparison between tripod and skin-fixed recording of scapular motion. J. Biomech. 40, 941–946.

Prinold, J.A.I., Shaheen, A.F., Bull, A.M.J., 2011. Skin-fixed scapula trackers: a comparison of two dynamic methods across a range of calibration positions. J. Biomech. 44, 2004–2007.

van Andel, C., van Hutten, K., Eversdijk, M., Veeger, D., Harlaar, J., 2009. Recording scapular motion using an acromion marker cluster. Gait Posture 29, 123–128.

Wu, G., van der Helm, F.C.T., Veeger, H.E.J., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A.R., McQuade, K., Wang, X.G., Werner, F.W., Buchholz, B., 2005. 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, 981–992.