# Evaluation of regression-based 3-D shoulder rhythms

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## ARTICLE INFO

## ABSTRACT

The movements of the humerus, the clavicle, and the scapula are not completely independent. The coupled pattern of movement of these bones is called the shoulder rhythm. To date, multiple studies have focused on providing regression-based 3-D shoulder rhythms, in which the orientations of the clavicle and the scapula are estimated by the orientation of the humerus. In this study, six existing regression-based shoulder rhythms were evaluated by an independent dataset in terms of their predictability. The datasets include the measured orientations of the humerus, the clavicle, and the scapula of 14 participants over 118 different upper arm postures. The predicted orientations of the clavicle and the scapula were derived from applying those regression-based shoulder rhythms to the humerus orientation. The results indicated that none of those regression-based shoulder rhythms provides consistently more accurate results than the others. For all the joint angles and all the shoulder rhythms, the RMSE are all greater than 5°. Among those shoulder rhythms, the scapula lateral/medial rotation has the strongest correlation between the predicted and the measured angles, while the other thoracoclavicular and thoracoscapular bone orientation angles only showed a weak to moderate correlation. Since the regression-based shoulder rhythm has been adopted for shoulder biomechanical models to estimate shoulder muscle activities and structure loads, there needs to be further investigation on how the predicted error from the shoulder rhythm affects the output of the biomechanical model.

## 1. Introduction

In the past decades, complex musculoskeletal shoulder biomechanical models have been proposed (Dickerson et al., 2007; Holzbaur et al., 2005; Karlsson and Peterson, 1992; Makhsous, 1999; van der Helm, 1994). These models are useful for estimating structural loads on musculoskeletal elements within the shoulder region and have been used to assess several of these, including arm elevation (Karlsson and Peterson, 1992), reaching (Dickerson et al., 2008), pushing (Steele et al., 2013), and wheelchair propulsion (Veeger et al., 2002).

Within a shoulder biomechanical model, it is important to accurately determine the relative orientations among the bony elements for calculating the magnitude and the direction of the moment arm of each muscle. This is essential in estimating the muscle activity level with the optimization-based method. However, the in vivo measurement of clavicle and scapula orientation in dynamic movements can be difficult when using skin-fixed

markers due to the soft tissue overlying the bones (Karduna et al., 2001; Prinold et al., 2011). As the movement of the clavicle, the scapula, and the humerus are related to each other (a.k.a. shoulder rhythm) (Inman et al., 1944), some studies (de Groot and Brand, 2001; Grewal and Dickerson, 2013; Hogfors et al., 1987; Makhsous, 1999; Xu et al., 2014) attempted to use the orientation of the humerus relative to the thorax to predict the orientations of the clavicle and the scapula by applying a regression method as a surrogate for direct measurement.

Different experimental approaches were used to develop currently available shoulder rhythm descriptions. For the Göteborg shoulder rhythm (Hogfors et al., 1991), tiny tantalum balls were inserted subcutaneously into the clavicle, the scapula, and the humerus in three participants. The orientation of the bones was measured by X-ray photometry during a set of no-load arm movements with the arm elevation angle mainly between 60° and 110°. Those bone orientation data were later used to build nonlinear regression equations of shoulder rhythm, first for a limited range of motion of the humerus (Karlsson and Peterson, 1992), and then in a more general range of motion of humerus (Makhsous, 1999). This shoulder rhythm was later used to build a shoulder

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biomechanical model (Dickerson et al., 2007). For the Dutch approach (de Groot and Brand, 2001), the shoulder rhythm was systematically examined over 23 different static humerus positions with 20 N adduction and abduction forces. For each posture, the orientation of the bones was measured with a spatial digitizer. Besides the orientation of the humerus, this study also included some individual factors such as gender and anthropometric data, as predictors of the orientations of the clavicle and the scapula. Among the factors evaluated, humerus orientation, and the initial orientation of the clavicle and the scapula, were significant predictors of subsequent scapula orientation. This model was further validated by an independent dataset of arm elevation in the elevation plane of 30°. The Dutch shoulder rhythm was later partially used to build an upper extremity model in SIMM (MusculoGraphics Inc., Santa Rosa, CA, USA) (Holzbaur et al., 2005). The Waterloo shoulder rhythm (Grewal and Dickerson, 2013) was proposed to extend the capabilities of the Dutch shoulder rhythm, primarily through inclusion of axial humeral rotation. In the Waterloo shoulder rhythm, 39 static humerus postures with 45° interval in each degree of freedom of thoracohumeral joint were investigated. Similar to the Dutch shoulder rhythm, a spatial digitizer was used to measure the bony landmarks, from which the orientation of the bones was derived. In the Waterloo shoulder rhythm, some quadratic terms and interaction terms of humerus orientation were significant predictors of the orientation of the clavicle and the scapula. While this study indicated the Waterloo shoulder rhythm has a smaller estimation error compared with the Dutch shoulder rhythm, it was not further validated by an independent dataset. Most recently, the Liberty Mutual shoulder rhythm (Xu et al., 2014) was derived with more positions at smaller interval including 118 static humerus postures. Considering individual factors may not always be available, two types of shoulder rhythm were created. The first type included the orientation of the humerus, as well as age, gender, and a few anthropometric data as the predictors. The second type only included the orientation of the humerus without the individual factors. Similar to the Waterloo shoulder rhythm, the results indicated that the quadratic terms and interaction terms of the orientation of the humerus were significant. Most of the individual factors were significant when they were considered as the predictors. This shoulder rhythm was later validated by an independent dataset and estimation error on the independent dataset was close to that of the Dutch shoulder rhythm, but greater than that of the Waterloo shoulder rhythm.

The objective of this study was to compare the accuracy of the existing shoulder rhythms with the same independent dataset. The following shoulder rhythms are chosen for the comparisons: (1) the Göteborg shoulder rhythm (GSR) proposed in Makhsous (1999); (2) the Dutch shoulder rhythm without knowing initial orientation of clavicle and scapula ($DSR_{no\ int}$); (3) the Dutch shoulder rhythm with known initial orientation of clavicle and scapula ($DSR_{with\ int}$); (4) the Waterloo shoulder rhythm (WSR); (5) the Liberty Mutual shoulder rhythm without knowing individual factors ($LMSR_{no\ ind}$); and (6) the Liberty Mutual shoulder rhythm with known individual factors ($LMSR_{with\ ind}$).

## 2. Method

### 2.1. Participants

Fourteen participants (6 females and 8 males, age: 28.4 (9.0), height: 1.70 (0.09) m, weight: 74.2 (20.3) kg, all right-handed) from local communities, with no upper extremity musculoskeletal disorders, participated in this study. The experimental protocol procedures were approved by an appropriate institutional review board, and all the participants gave written informed consent.

### 2.2. Experiment protocol

The experiment protocol is similar to that in a previous study (Xu et al., 2014). Before the experiment, the marker clusters of a motion tracking system (Optotrak Certus System, Northern Digital, Canada) were taped on the thorax, upper arm and forearm, and also on a scapula locator that was used to measure the orientation of the scapula (Johnson et al., 1993; Meskers et al., 2007). The suprasternal notch (IJ), xiphoid process (PX), C7 vertebra, T8 vertebra, and sternoclavicular (SC) was digitized by a probe with respect to the thorax cluster in an upright posture, arms at sides. The right acromion process (ACR), lateral and medial epicondyle (EL and EM) were digitized with respect to the upper arm cluster. The ulnar styloid (US) was digitized with respect to the forearm cluster. The right acromioclavicular (AC) joint, and the three pins of the scapula locator, the acromial angle (AA), the root of the scapula spine (TS), and the inferior angle (AI) of the scapula, were digitized with respect to the cluster on the scapula locator when placed on the right scapula.

The orientation of the clavicle and the scapula during the reference posture, with upper arms along the body, elbow angle at 90° and forearms pointing forward horizontally (de Groot and Brand, 2001), was recorded first for creating the predictors of the Dutch shoulder rhythm. After the measurement of the reference posture, the participants were asked to sit in an external frame which was used to guide the participants to reach various upper arm postures in five planes of elevation (0–120° with 30° increment), six elevation angle (0–150° with 30° increment), and seven humerus axial rotation angles (−90° to 90° with 30° increment) for thoracohumeral joint. After eliminating unreachable postures determined in pilot testing, 118 static postures were evaluated in random
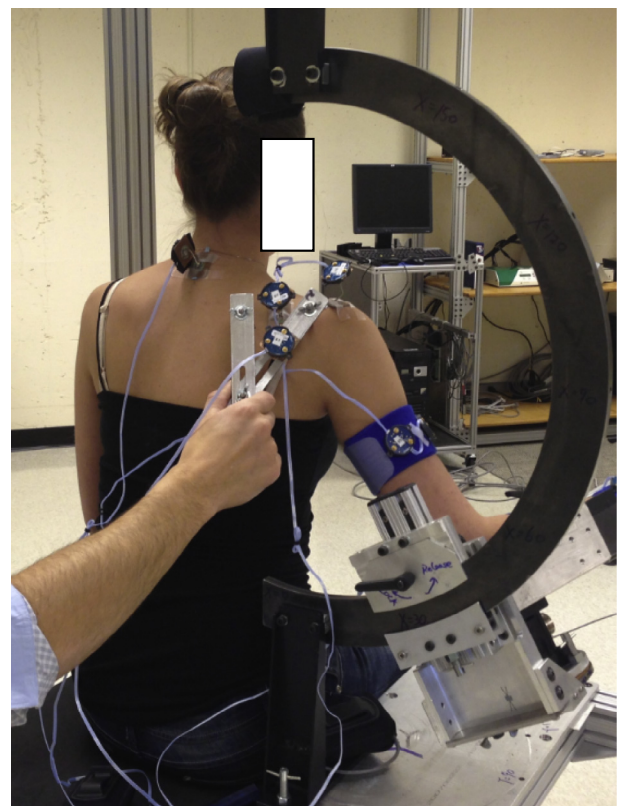


Fig. 1. Experimental setup. The participants sat within an external frame. The experimenter placed the scapula locator on participants' scapula. The shoulder posture shown is $\gamma_{TH1} = 0°$, $\beta_{TH} = -30°$, and $\gamma_{TH2} = -30°$.

order. For each arm posture, the three pins of the scapula locator were placed on the AA, TS, and AI of the scapula (Fig. 1).

## 2.3. Data analysis

The anatomical coordinate system of thorax, clavicle, scapula, and the humerus were generated from the bony landmarks using the recommendation of the International Society of Biomechanics (ISB) (Wu et al., 2005). For the humerus, the glenohumeral rotation center (GH) cannot be directly measured by a surface marker. Therefore, it was assumed it is on the line between ACR and the elbow joint center during the reference posture (de Leva, 1996). To avoid the error in upper arm cluster positioning due to axial rotation of the humerus (Cutti et al., 2005), the second option for calculating thoracohumeral bone orientation angles in the ISB recommendation was adopted (Wu et al., 2005), using the forearm orientation to estimate humerus axial rotation. The thoracoclavicular bone orientation angles (retraction/protraction – $\gamma_C$, elevation/depression – $\beta_C$), the thoracoscapular bone orientation angles (retraction/protraction – $\gamma_S$, lateral/medial rotation – $\beta_S$, anterior/posterior tilt – $\alpha_S$), and the thoracohumeral bone orientation angles (plane of elevation – $\gamma_{TH1}$, elevation – $\beta_{TH}$, axial rotation – $\gamma_{TH2}$) of each arm posture were then decomposed according to the ISB recommendation (Wu et al., 2005). Because the clavicle and thorax have one common axis, the axial rotation of the clavicle ($\alpha_C$) could not be derived.

## 2.4. Shoulder rhythms validation

In the GSR, the Euler angles sequence used to decompose the bone orientation angles are the same for all the angles, and the thoracoclavicular, the thoracoscapular, and the thoracohumeral bone orientation are referenced with respect to the coordinate system of the sternum which tilts down for 30° degrees compared with the thorax coordinate system (Hogfors et al., 1991, 1987; Makhsous, 1999). The nonlinear equations of the GSR were then adapted to estimate the clavicle and scapula orientation relative to the sternum. It should be noted that different bony landmarks of the scapula were used to create the anatomical coordinate system in the GSR compared with those in ISB recommendations. To ensure that the comparisons of the shoulder rhythm from all studies used the same definition of the anatomical coordinate system, the orientation of the scapula in the GSR was transformed to that in the ISB recommendation (Xu et al., 2012). For the clavicle, the different bony landmarks used in the GSR would result in different axial rotation angle of the clavicle ($\alpha_C$) but retraction/protraction ($\gamma_C$) and elevation/depression ($\beta_C$) would remain the same. Since the axial rotation angle of the clavicle cannot be derived in the current study, the anatomical coordinate system of the clavicle is not transformed in this study. After the transformation of the scapula anatomical coordinate system, the orientation of the clavicle and the scapula with respect to the thorax under the framework of ISB recommendation was derived and the thoracoclavicular and thoracoscapular joint angle was decomposed according to the ISB recommendation.

For the DSR$_{no int}$, since the initial orientation of clavicle and scapula was assumed to be unavailable, the average values for a population were used as the predictors. Those values were estimated using the equation of WSR (Grewal and Dickerson, 2013) by setting the $\gamma_{TH1}$, $\beta_{TH}$, and $\gamma_{TH2}$ to zero. This would result in that $\gamma_{S\ int} = 28.0°$, $\beta_{S\ int} = -1.0°$, $\alpha_{S\ int} = -11.2°$, $\gamma_{C\ int} = -13.3°$, and $\beta_{C\ int} = -2.5°$, under the framework of ISB recommendation. For DSR$_{with int}$, the measured initial orientation of clavicle and scapula for each participant as well as the thoracohumeral bone orientation angles were used as the predictors. In both DSR$_{no int}$ and DSR$_{with int}$, the definition of the anatomical coordinate systems of

the bones are slightly different than those in the ISB recommendation, with a 90° rotation along the Y-axis. Therefore, a corresponding rotation matrix was applied to derive the thoracoclavicular and thoracoscapular bone orientation angles under the framework of the ISB recommendation. The external force was set to zero for DSR$_{no int}$ and DSR$_{with int}$ for the evaluation.

For WSR and LMSR$_{no ind}$, the only predictors are the three thoracohumeral bone orientation angles. In WSR, a regression equation predicting clavicle axial rotation ($\alpha_C$) was also provided. This regression equation was based on the estimated $\alpha_C$ under the assumption that the rotations at the acromioclavicular joint should be minimized (van der Helm and Pronk, 1995). Since this rotation cannot be measured by the surface makers, this equation is not included for comparison in the current study. For LMSR$_{with ind}$, some anthropometric data were also used as the predictors. In this study, the average value (standard deviation) of those anthropometric data were thorax length ($L_t$, from T1–T12): 212 (31) mm, clavicle length ($L_c$, from SC–AC): 154 (23) mm, scapula length ($L_s$, from AA–AI): 189 (15) mm, and upper arm length ($L_{ua}$, from ACR–EL): 258 (17) mm.

Once the estimated thoracoclavicular and thoracoscapular bone orientation angles were derived from each shoulder rhythm, the estimated bone orientation angles were compared with the measured bone orientation angles. The mean error and its 95% confident interval, coefficient of determination ($r^2$) and the root-mean-square error (RMSE) were used to access the predictability of the models. A paired $t$-test was also performed between the estimated and measured bone orientation angles for each shoulder rhythm.

## 3. Results

For scapula retraction/protraction ($\gamma_S$), the $r^2$ of all shoulder rhythms ranged from 0.13 (GSR and DSR$_{no int}$) to 0.48 (DSR$_{with int}$) (Fig. 2). The mean error ranged from −11.90 (DSR$_{no int}$) to 2.31 (GSR), and the RMSE ranged from 9.89° (LMSR$_{with ind}$) to 15.93° (DSR$_{no int}$) (Table 1). For those shoulder rhythms that only used thoracohumeral bone orientation angles as the predictors, LMSR$_{no ind}$ has the greatest $r^2$ value of 0.23 and WSR had the smallest RMSE of 10.31.

For scapula lateral/medial rotation ($\beta_S$), the $r^2$ ranged from 0.48 (WSR) to 0.67 (LMSR$_{with ind}$). The mean error ranged from −4.28 (DSR$_{no int}$) to 14.01 (GSR), and the RMSE ranged from 7.03° (LMSR$_{with ind}$) to 16.38° (GSR). For those shoulder rhythms that only used thoracohumeral bone orientation angles as the predictors, LMSR$_{no ind}$ and GSR had the greatest $r^2$ value of 0.64 and 0.63, respectively, and LMSR$_{no ind}$ had the smallest RMSE, 7.26°.

For scapula anterior/posterior tilt ($\alpha_S$), the $r^2$ ranged from 0.01 (DSR$_{no int}$ and WSR) to 0.16 (DSR$_{with int}$). The mean error ranged from −3.83 (GSR) to 16.53 (WSR), and the RMSE ranged from 6.36° (LMSR$_{no ind}$) to 19.11° (WSR). For those shoulder rhythms that only used thoracohumeral bone orientation angles as the predictors, LMSR$_{no ind}$ has the greatest $r^2$ value, 0.12.

For clavicle retraction/protraction ($\gamma_C$), the $r^2$ of all shoulder rhythms ranged from 0.27 (GSR) to 0.46 (LMSR$_{no ind}$). The mean error ranged from −12.87 (WSR) to 17.82 (GSR), and the RMSE ranged from 7.11° (LMSR$_{no ind}$) to 21.37° (GSR). For clavicle elevation/depression ($\beta_C$), the $r^2$ of all shoulder rhythms ranged from 0.28 (WSR) to 0.46 (LMSR$_{no ind}$ and LMSR$_{with ind}$). The mean error ranged from −5.00 (GSR) to 11.44 (DSR$_{with int}$), and the RMSE ranged from 7.24° (LMSR$_{no ind}$) to 13.65° (GSR).

The results of the paired $t$-tests indicated that for all bone orientation angles over all shoulder rhythms, the estimated angle was significantly different ($p < 0.0001$) from the measured angle except for the scapula lateral/medial rotation ($\beta_S$) in LMSR$_{no ind}$.
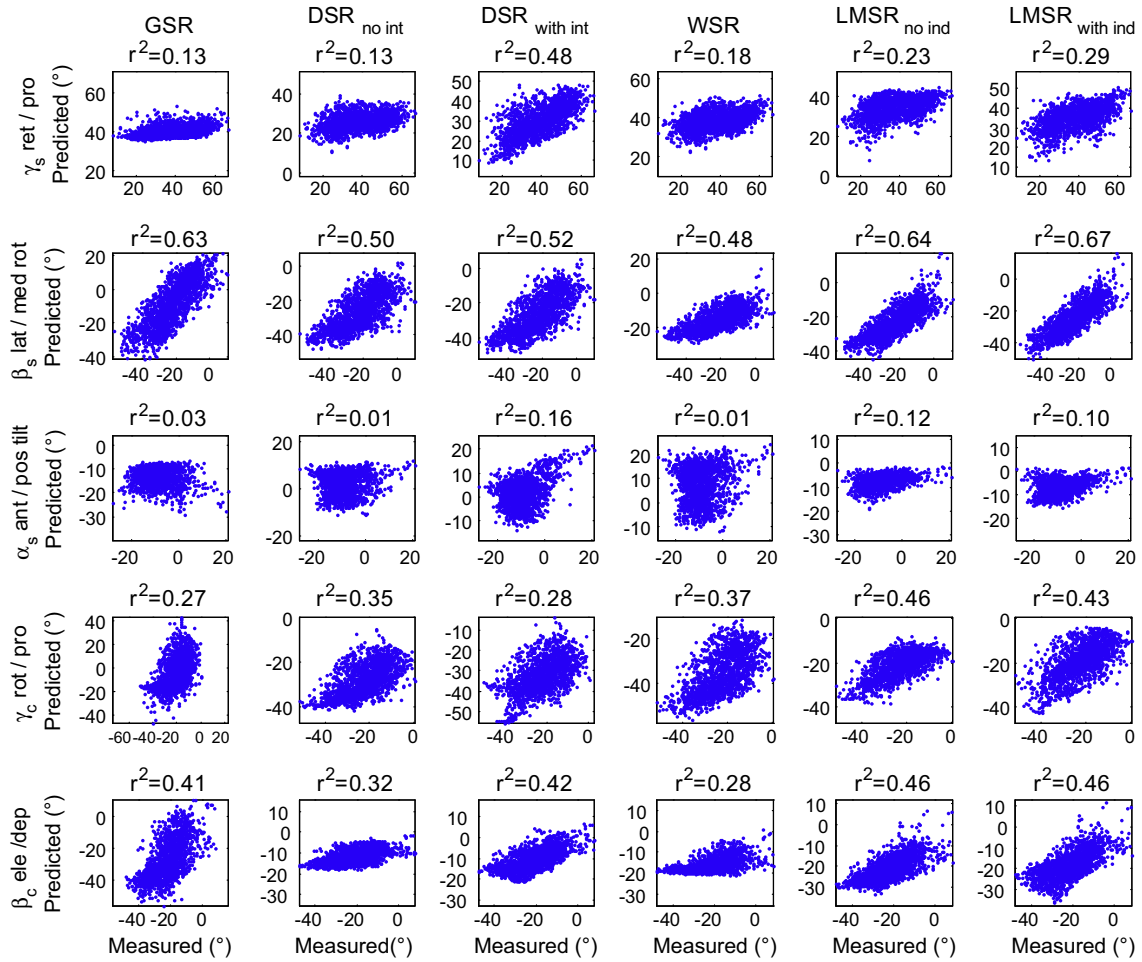
**Fig. 2.** The measured thoracoclavicular and thoracoscapular bone orientation angles and the predicted ones using various regression based shoulder rhythms. $\gamma_S$, $\beta_S$, and $\alpha_S$ are retraction/protraction, lateral/medial rotation, and anterior/posterior tilt for thoracoscapular joint. $\gamma_C$, and $\beta_C$ are retraction/protraction and elevation/depression of thoracoclavicular joint. $r^2$ and RMSE stand for coefficient of determination and root-mean-square error, respectively.

**Table 1**
The error of predicted thoracoclavicular and thoracoscapular bone orientation angles using regression-based shoulder rhythms. Mean Error, [Range], and RMSE stand for the average value of the predicted angles subtracted by the measured angles, 95% confident interval of Mean Error, and root-mean-square error, respectively.

| | GSR Mean error, [Range], RMSE (°) | DSR$_{no\ int}$ Mean error, [Range], RMSE (°) | DSR$_{with\ int}$ Mean error, [Range], RMSE (°) |
|---|---|---|---|
| $\gamma_S$ (scapula ret/protraction) | 2.31, [−15.61, 20.94], 10.89 | −11.90, [−30.39, 7.23], 15.93 | −8.19, [−23.41, 10.16], 11.58 |
| $\beta_S$ (scapula lat/med rotation) | 14.01, [−2.48, 29.81], 16.38 | −4.28, [−21.30, 12.41], 9.74 | −3.81, [−21.13, 12.84], 9.45 |
| $\alpha_S$ (scapula ant/pos tilt) | −3.83, [−23.79, 7.62], 8.97 | 11.04, [−5.48, 25.98], 13.48 | 10.78, [−2.37, 23.98], 12.83 |
| $\gamma_C$ (clavicle ret/protraction) | 17.82, [−2.43, 44.98], 21.37 | −5.23, [−19.39, 11.24], 9.29 | −9.49, [−26.13, 9.72], 12.91 |
| $\beta_C$ (clavicle elev/depression) | −5.00, [−23.58, 16.34], 11.16 | 10.03, [−6.60, 25.54], 13.00 | 11.44, [−2.17, 26.37], 13.65 |
| | WSR | LMSR$_{noind}$ | LMSR$_{with\ ind}$ |
| $\gamma_S$ (scapula ret/protraction) | 0.66, [−16.73, 18.70], 10.31 | −3.46, [−21.07, 14.16], 10.53 | −2.58, [−19.98, 14.70], 9.89 |
| $\beta_S$ (scapula lat/med rotation) | 7.52, [−9.08, 25.45], 11.62 | 0.01, [−14.10, 14.02], 7.26 | −1.04, [−14.76, 13.13], 7.03 |
| $\alpha_S$ (scapula ant/pos tilt) | 16.53, [−2.28, 34.25], 19.11 | 1.53, [−12.35, 12.26], 6.36 | 2.30, [−9.90, 15.41], 6.74 |
| $\gamma_C$ (clavicle ret/protraction) | −12.87, [−28.02, 4.86], 15.32 | 1.79, [−11.43, 15.28], 7.11 | 3.49, [−10.63, 19.91], 8.09 |
| $\beta_C$ (clavicle elev/depression) | 5.82, [−10.78, 22.37], 10.21 | 1.30, [−13.57, 14.50], 7.24 | 3.65, [−9.19, 18.61], 8.01 |

## 4. Discussion

This study evaluated regression-based 3-D shoulder rhythms proposed in multiple studies by comparing the predicted thoraco-clavicular and thoracoscapular bone orientation angles with measured values in an independent participant pool. In general, the predicted joint angle only weakly to moderately (Taylor, 1990) correlated with the measured joint angle, except for scapula lateral/medial rotation ($\beta_S$), which has a strong correlation between the predicted and the measured angles. For all the bone orientation angles, the average predicted errors are greater than 5° which is considered a clinically significant difference (McGinley et al., 2009). It seems none of those shoulder rhythms provides consistently more accurate results than the others. Each of them has a better predictability on one or more bone orientation angles than the others.

Among all thoracoclavicular and thoracoscapular bone orientation angles, scapula lateral/medial rotation ($\beta_S$) is best predicted by all the evaluated shoulder rhythms in terms of the coefficient of the determination ($r^2$ value). This is primarily because $\beta_S$ is mainly affected by the elevation of the humerus ($\beta_{TH}$), given that the coefficient of $\beta_{TH}$ is generally much greater than the coefficient of other predictors under the condition of no external load. However, even with a high $r^2$ value, the RMSE of $\beta_S$ still ranged approximately from 7° to 16° over all the shoulder rhythms. That indicates that great inter-participant variability of $\beta_S$ exists. In contrast, scapula anterior/posterior tilt ($\alpha_S$) is least predicted in terms of $r^2$ value. This is probably because the range of $\alpha_S$ is relatively small, and there is no dominant predictor for $\alpha_S$. Therefore, the variance contributed by the thoracohumeral bone orientation angles and other individual factors for $\alpha_S$ is less than the inter-participant variability.

By comparing the $r^2$ value and RMSE between $DSR_{no\ int}$ and $DSR_{with\ int}$, and those between $LMSR_{no\ ind}$ and $LMSR_{with\ ind}$, it shows that adding individual factors, such as initial orientation of the clavicle and scapula, age, and anthropometric data, provides only limited improvement in predictability. On one hand, while the individual factors evaluated in this study may significantly affect thoracoclavicular and thoracoscapular bone orientation angles statistically, such effect may be of little practical significance. On the other hand, the participants in this study are mainly young adults. The limited diversity in the studied group may conceal the effect of the individual factors.

The comparison of the evaluated shoulder rhythms is not totally unbiased. The results of the current study indicated that the mean error of the predicted bone orientation angles from $LMSR_{no\ ind}$ and $LMSR_{with\ ind}$ were smaller than the other regression-based shoulder rhythms. However, it should be noted that the current study shares the same protocol and equipment of the experiment from which $LMSR_{no\ ind}$ and $LMSR_{with\ ind}$ were derived (Xu et al., 2014). The orientation of the scapula in this protocol was measured by a scapula locator, while in the $DSR_{with\ int}$ and WSR shoulder rhythms, the orientation of the scapula was derived by separately digitizing the bony landmarks of the scapula through palpation. Though using a scapula locator can ensure that the relative position among the bony landmarks is constant, the overall orientation of the scapula may be compromised, as in some circumstances it may hard to fit the scapula locator on the scapula. In addition, the bony landmarks used for calculating the clavicle and scapula orientation were found by palpation and surface maker clusters in this protocol, while in the study deriving GSR (Hogfors et al., 1991), those orientations were acquired by the X-ray photometry, which should mitigate the effect of skin artifact on the surface markers. Since the systematic errors that contribute to experiment protocols can affect the mean error, the results of the current study could show some bias to that created with the same protocol. In contrast, the confidence intervals of mean error among the examined shoulder rhythms are similar to each other, as the confidence interval is affected more by the inter-participants variability than by the systematic errors.

There are several pertinent issues for future studies of shoulder rhythm. First, all these existing shoulder rhythms with the exception of DSR, do not address the effect of external loading of the upper extremities on the orientation of the clavicle and the scapula. Even though only one force magnitude, applied in two directions, was tested for DSR (de Groot and Brand, 2001), it was shown that force magnitude significantly affected some thoracoclavicular and thoracoscapular bone orientation angles. Overall, the effect of direction of force application still remains unclear. Second, all the existing shoulder rhythms, except GSR, used surface markers to acquire the orientation of the bony segments. Since surface markers could introduce significant error during body movement (Li et al., 2012), the shoulder rhythm derived in such way may contain systematic errors. Third, the regression-based shoulder rhythm has been adopted for shoulder biomechanical models. In a shoulder biomechanical model, the positions of origin and insertion of muscles, which is determined by the orientation of the bones, are key elements for estimating the structure loads. The predicted error of shoulder rhythm could alter muscle orientation, and in turn, alter the moment arm of muscles as well as wrapping path. Previous studies (Bolsterlee and Zadpoor, 2014; Hughes and An, 1997) have demonstrated that the error of muscle moment arms and the error of origin and insertion position would affect the estimated muscle activities through optimization-based shoulder models. Therefore, how sensitive the shoulder biomechanical model is to the regression error of shoulder rhythms needs to be further investigated.

## 5. Conclusion

In summary, this study evaluated six regression-based 3-D shoulder rhythms by comparing the predicted thoracoclavicular and thoracoscapular bone orientation angles with measured values. The results indicated that none of those shoulder rhythms provides consistently more accurate results than the others. For all the bone orientation angles and all the shoulder rhythms, the RMSE are all greater than 5°. Among those shoulder rhythms, the scapula lateral/medial rotation has the strongest correlation between the predicted and the measured angles, while the other thoracoclavicular and thoracoscapular bone orientation angles only showed a weak to moderate correlation.

## Conflict of interest

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 the manuscript entitled "Evaluation of regression-based 3-D shoulder rhythms".

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