A Three-Dimensional regression model of the scapulo-humeral rhythm

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Abstract - During arm movements the scapula shows large displacements with respect to the skin and therefore it was not possible to record scapular motions by means customary motion analysis systems. In order to overcome the practical problems of scapular motion recording a 3-Dimensional regression model was developed including the initial position of the scapula and the orientations of the clavicle and the humerus, all with respect to the thorax orientation. The parameters of the model were estimated from 23 humeral positions in a wide range of humeral motion measured on 5 subjects. The model was successfully validated on 10 subjects.

INTRODUCTION

The range of motion of the human arm is a unique phenomenon, established by the constructional concepts of the shoulder. In the kinematic chain of thorax, clavicle, scapula and humerus the mechanical stability of the arm support is increased by the scapulo-thoracic gliding plane and the range of motion of the arm is increased by the shape of the gleno-humeral joint. The contribution of the length of the scapular link, the distance between the acromio-clavicular joint and the gleno-humeral joint of about 0.04m, in the kinematic chain is relatively small. The rotational contribution of the gleno-humeral joint is unique in the human body.

Recording of the scapular motions was not possible by means of conventional optical methods using skin fixed markers due to the fact that the scapular movement showed large skin displacements.

The close relation between scapular orientation and humerus was first quantified by means of 2-Dimensional (2-D) X-ray photogrammetry (Inman et al., 1944). The originally 2-D scapulo-humeral Rhythm, SH_{2-D}, was defined as the humeral rotation angle over the scapular rotation angle during a full abduction movement. The SH_{2-D} was later determined by several other authors (Saha, 1961; Freedman & Munro, 1966; Doody et al., 1970; Poppen & Walker, 1976; Bagg & Forrest, 1988).

By means of a spatial digitizer (Pronk & Van der Helm, 1991) the 3-Dimensional scapulo-humeral Rhythm or SH_{3-D} was described as measured from stationary postures (Pronk, 1988; Pronk, 1991). With a slightly different approach Johnson (1993) obtained comparable results. Van der Helm (1994), Van der Helm & Pronk (1995) and Groot (1997[a]) applied these methods, using different definitions for their kinematic descriptions.

The necessity of three dimensional description methods was confirmed by simulations of planar projections of a 3-D abduction recording. The effect of the use of different scapular ridges, determining the scapular angles, and the positioning of the subjects in the X-ray recording setting was simulated and all previously reported SH_{2-D}, ranging from $2.1 \leq SH_{2-D} \leq 3.3$ could be explained from the projection of one single SH_{3-D} recording (Groot, 1996,1997[b]).

A disadvantage of the methods based on palpation and subsequent digitization is the fact that the recordings are made during stationary postures. Movements are modeled by means of interpolation of the stationary recordings. A dynamic alternative was described by Högfors et al. (1991). The method is based on bi-planar X-ray recording of metal implants in the shoulder bones during a shoulder movement. However, the fact that implantation of metal markers is required is a major drawback for the application of this method on healthy subjects. Therefore the effect of movement on the SH_{2-D} was studied by means of a 2-D X-ray video recording of a cyclic arm movement in the scapular plane (Groot et al., 1997[c]). Relative to the humerus the scapular amplitude reduced with increasing arm motion frequency while the hysteresis of the humeral motion with respect to the scapular motion disappeared. However, these effects were estimated to be in the order of magnitude of the intra-individual variability and it was concluded that these effects could be disregarded for the description of 3-D motions from stationary recordings.

In this paper it is shown that there exists a relationship between the movement of the scapula and the humerus that can be described by the initial position of the scapula, the position of the clavicle and the position of the humerus with respect to the thorax. This regression model of the SH_{3-D} can be applied to estimate the scapular motions during motion recordings using skin-fixed markers. The position of the scapula determines the attachment-sites and moment arms of muscles in biomechanical studies. The model of the SH_{2-D} facilitates the studies on the causes of profession related shoulder complaints as the method of motion recording is simplified. In comparison with the 'healthy' $SH_{3\text{-}D}$ clinical disorders of the scapulo-humeral rhythm e.g. frozen shoulder, impingement, habitual gleno-humeral instability, can be quantified.

This study is part of an extensive study determining the relations between the shoulder muscle activities for different postures and during different tasks.

METHOD

Subjects and positions

The position of the shoulder mechanism of 10 subjects was measured while standing. 23 Standardized postures, established by fixation of the head, hips, feet and arms were measured (Figure 1).

The right arm of the subjects was suspended in a splint with the elbow in a 90° flexed position and connected to a 6 degrees of freedom (6-dof) AMTI-force transducer. The force transducer was orientated parallel with the local coordinate system of the humerus. The suspension was such that all forces and moments acting on the arm were reduced to a minimum, while the degrees of freedom perpendicular to the longitudinal axis of the humerus were both fixed. The suspension of the left arm was such that the subject was standing symmetrically and forces and moments (along the longitudinal body axis) exerted by the right arm on the fixed degrees of freedom could be counter-acted.

While exerting an abduction and adduction force of 20 N in the plane of elevation, the position of the skeletal landmarks of the thorax (Incisura Jugularis

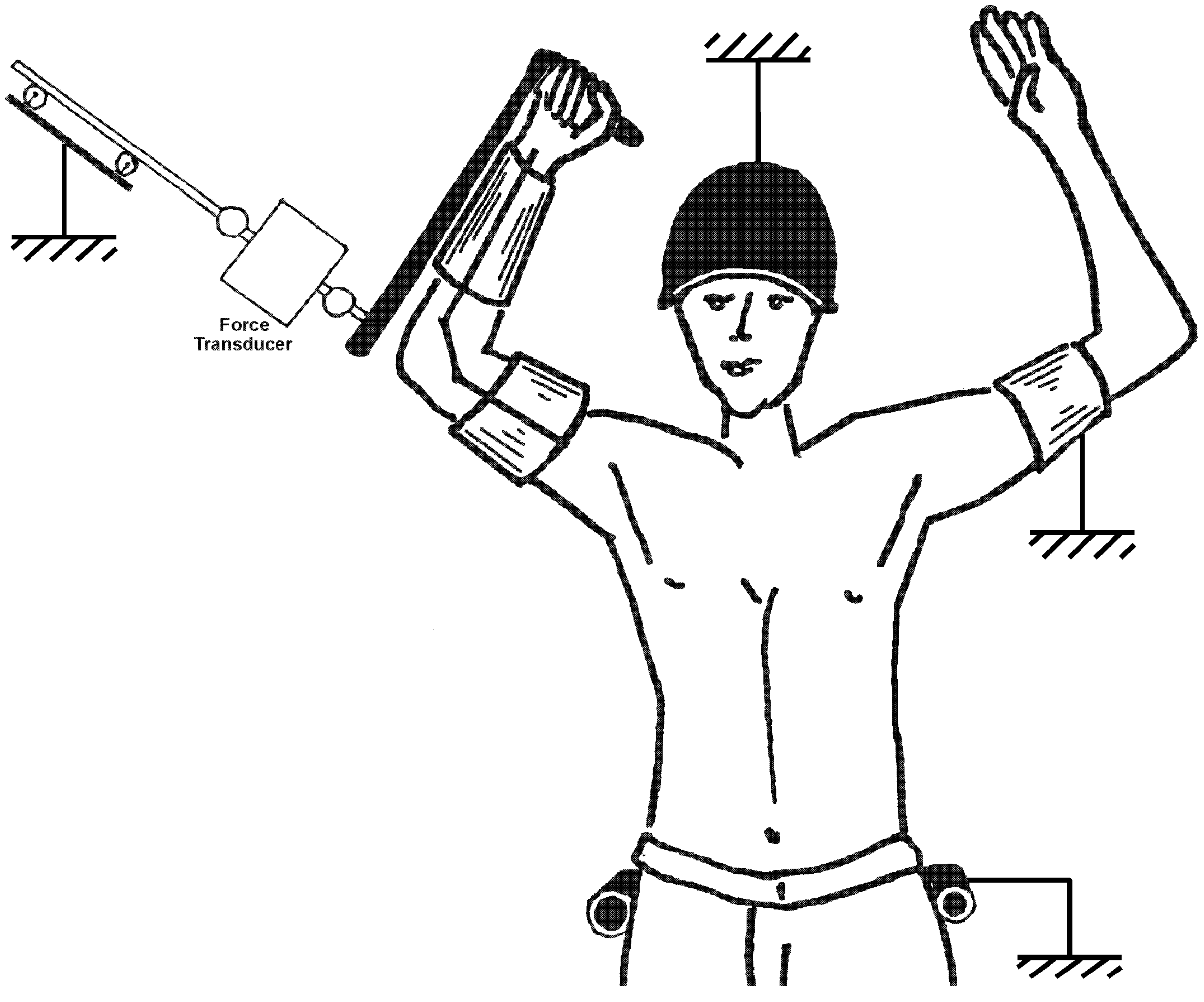

Figure 1- *Positioning of the subject during the stationary recordings of the scapulo-humeral rhythm. The positions of the head, hips and feet were standardized.*

The right arm was enclosed in a splint which was suspended on to a force transducer. The two degrees of freedom of the suspension perpendicular to the humerus were fixed. The subject experienced no gravitation forces on the arm.

The subject could exert a force in the ab-/adduction direction in the plane of elevation and in the direction perpendicular to the plane of elevation. All the other degrees of freedom were released.

The left arm was also suspended in order to obtain a symmetrical position of the subject.

[IJ], Processus Xiphoideus [PX], Processi Spinosii of the 7th cervical vertebra [C7] and the 8th thoracic vertebra [T8]), the clavicle (Sterno-Clavicular joint [SC] and the Acromio-Clavicular joint [AC]), the scapula (Angulus Acromialis [AA], Trigonum Spinae [TS] and Angulus Inferior [AI]) and the humerus (medial and lateral Epicondyles [Epi_M & Epi_L]) was recorded and transferred to Cardan-angles according to Groot (1997[a]) (Figure 2).

<u>clavicle:</u>
1. XC-axis from sternoclavicular skeletal landmark SC to the acromioclavicular skeletal landmark AC.
2. ZC-axis perpendicular to the XC and YG-axes.
3. YC-axis perpendicular to XC and ZC.
4. rotation order: YC: protraction ZC: elevation XC: axial rotation.

<u>scapula</u>:
1. XS-axis from the trigonum spinae landmark TS to the anglus acromialis landmark AA.
2. S-axis perpendicular to the plane defined by the XS-axis and the angulus inferior landmark AI.
3. YS-axis perpendicular to XS and ZS.
4. rotation order: YS: protraction ZS: elevation XS: spinal tilt.

<u>humerus</u>:
1. YH-axis from the midpoint between the epicondyles Epi_m and Epi_l to the glenohumeral centre of rotation GH which is estimated from the coordinates of AC, AA, TS and AI.
2. ZH-axis perpendicular to the YH-axis and the line connecting the epicondyles.
3. YH-axis perpendicular to XH and ZH.
4. rotation order: YG: elevation plane ZH: elevation XH: axial rotation.

The skeletal landmarks were also used to determine some anthropometric data of the shoulder mechanism relative to the body length $\mathbf{L}_{body}$ [m]: the length of the sternum $\mathbf{L}_T$ (IJ-PX, [mm]), the depth of the thorax $\mathbf{D}_T$ (PX-T8, [mm]), length of the clavicle $\mathbf{L}_C$ (SC-AC, [mm]) and the length of the scapular spine $\mathbf{L}_S$ (AA-TS, [mm]). The orientation of the bones at the initial position was determined while standing with the upper arm vertically along the body and the forearm horizontally forward. These orientations were also used as regression variables.
Afterwards, the subjects were divided into two groups such that both groups differed minimally on the anthropometric data. Group 1 (n=5 subjects) was used to estimate the parameters of the equations, group 2 (n=5 subjects) was used to determine the predictive validity of the model. A third data set that was used for validation of the model was obtained from a different experiment (Groot, 1997[a]) and described the elevation of the arm in a plane rotated 30° ventral from the frontal plane (30° scapular abduction).

Regression analysis
The regression analysis was performed with 18 variables: the anthropometric variables: L_{body} [m] and L_T, D_T, L_C & L_S relative to body length, sex: male & female, force direction: abduction & adduction, the clavicular initial orientation: C_y0, C_z0, the scapular initial position: S_y0, S_z0 & S_x and four humeral variables: H_Y, H_Y^2, H_z and $H_z{}^2{}_x$. (the definition of the local co-ordinate systems and the Cardan rotation order are given in Figure 2).
A multiple regression analysis was performed with a statistical software package NCSS. The minimal required number of regression variables was determined based on the R^2 and the RMSE of the various possible models.

RESULTS

The 10 subjects were divided into two groups, a parameter estimation group and a validation group.

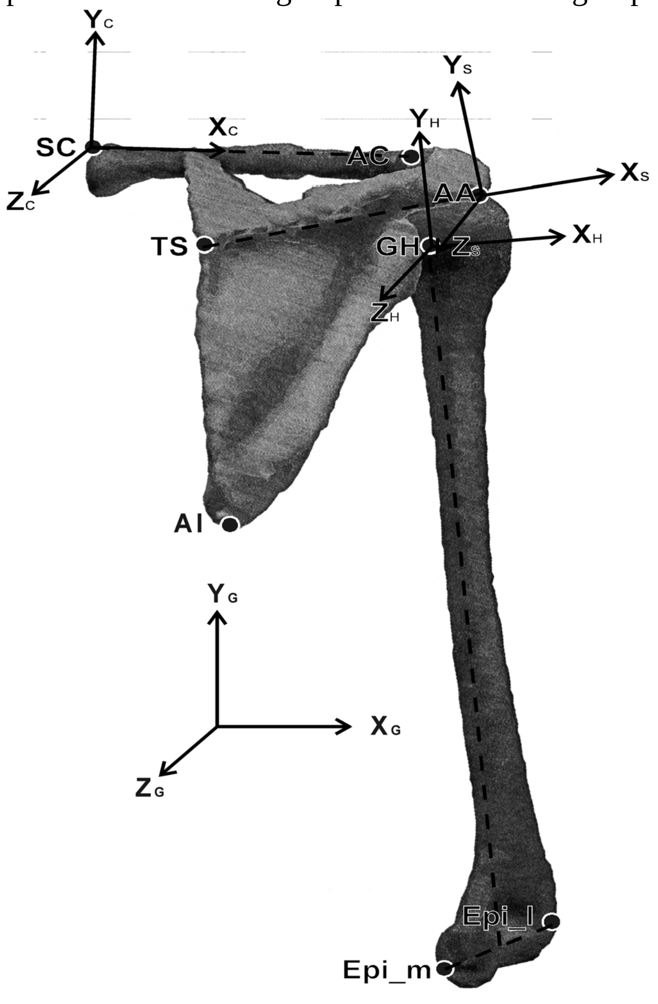

Figure 2- *Definition of the local co-ordinate systems of the shoulder (dorsal view) and the Cardan rotation order.*

Table 1- *The regression parameters for 5 subjects (group 1) and 230 arm positions. All regressors are significant (α ≤ 0.05). The RMSE is given for the estimation (group 1, n=5), validation (group 2, n=5) and validation on data of a different experiment (Groot, 1997[a]) obtained during elevation in the plane 30° ventrally rotated from the frontal plane (group 3, n=4).*

regressor	Protraction	Elevation	Spinal-tilt
offset	32.379	-7.494	-4.452
H_y^2 [$.10^{-4}$]	5.676	0*	0
H_z	0.104	0.215	0.143
S_y0	0.326	0	0*
S_x0	0	0	1.047
C_y	0.849	-0.307	-0.308
C_z	0.428	0.963	-0.197
L_{body}	0*	0	0
RMSE (group1)	4.7°	4.5°	4.5°
RMSE (group2)	5.4°	6.2°	6.2°
RMSE (group3)	6.3°	6.9°	4.6°

NB: The model could be enlarged with the 0-elements but the relative increase of the R^2 is negligibly small.*

The parameters of the resulting regression model are given in Table 1. Given an optimal value of R^2 (indicating the proportion of variance explained by the regression model) the smallest significant model (α ≤ .05) was chosen. The best possible variable to extend the model is marked with an asterisk.
The RMSE of the model is less than 5° which is low with respect to the inter-individual variance of 10° found during postural recordings of the arm in the scapular plane (Groot, 1997[a]).
All parameters of the regression equations are significant. The validity of the model was checked on the data of group 2, measured in the same experimental setting. The RMSE of the difference between estimated and measured data was about 6° for the scapular Cardan angles. This is in the order of the intra-individual variability.
The present measurements were performed in a setting where the arm was suspended. This suspension might have influenced the scapulo-humeral rhythm. Though most biomechanical, ergonomic and clinical problems are related to arm tasks which are often constrained, the equations were also applied on a new set of data describing a non-constrained arm abduction from about 15° to a maximal elevation of about 175° (which exceeds the 150° elevation in the estimation group 1) in the scapular plane. In this data set of n=5 subjects one subject was identified as an outlier. Excluding this subject from the validation resulted in a RMSE in the same order of magnitude of group 2.

DISCUSSION

The regression equations were based on the observations of 5 subjects. The results were validated for 10 subjects of which one was identified as outlier. For a multi-degree of freedom system as the shoulder mechanism is, it is surprising that a model, based on five subjects represents the shoulder movements of 14 subjects. For all angles about 60% of the residual error is less than 5°, about 85% of the residual error is less than 10° and only some recordings exceed the 15°.
The residual variability is low with respect to the inter-individual variance of about 10°-12°measured by Groot (1997[a]). This is explained by the fact that the individual variables like the orientation of the clavicle and the rest positions S_y0 and S_x0 are predictive for the position of the scapula.

The individual characteristics are not completely described by the regression equations. This was expressed by the fact that the individual average residual errors did not average to 0. In fact morphological characteristics (except body length) did not significantly appear in the regression equations. The inter-individual differences might be due to other morphological parameters (e.g. orientation and size of the glenoid surface) or different neuromuscular control patterns. These parameters are difficult to be determined while the presented equations did result in a representative estimate of the 'average' $SH_{3\text{-}D}$ pattern.
The regression model defined the $SH_{3\text{-}D}$ for a large range of humeral postures with different load di-

rections but the model is not complete. The axial rotation about the local y-axis of the humerus was constant while the loads on the arm are only about the local x-axis of the humerus. Differences in posture and load cases imply an extrapolation of the regression model. However, the force balance around the different joints in the shoulder mechanism is a complex and interactive task. Muscles that have positive moment arms about the axes of the external forces, create 'secondary' moments around other axes. Though the external load seemed to excite a limited set of joint torques, internal interactions increased the variability of joint torques. The effect of extrapolation due to different load cases was not expected to be of influence on the SH_{3-D} regression model.

The model can be of great use in biomechanics and ergonomics. The measurement of the scapular position remains difficult in the study of dynamic tasks (e.g. wheelchair propulsion (Veeger, 1992). The parameters necessary for applying the equation can be measured by means of video or cinematographic systems recording skin-fixed markers. As it was shown that dynamics negligibly influenced the position of the scapula (Groot, 1997[c]) it is now possible to predict a global/average scapular position from thoracic and humeral recordings.

CONCLUSIONS

It was shown that a regression model based on humerus orientation and clavicle orientation with respect to the thorax can predict the global position of the scapula within reasonable limits.

It is now possible to determine the orientation of the scapula by measuring the landmarks of the thorax, the clavicle and the humerus in the actual movement, together with the orientation in a standardized 'resting-position'.

This facilitates the recordings of the movements of the upper extremities for biomechanical and ergonomic studies on groups of subjects. However, for individual predictions or clinical studies it is hazardous to apply the model as it is not possible to identify outliers from the normal rhythm. In these cases the scapulo-humeral rhythm is to be recorded by means of the previously mentioned methods.

REFERENCES

Bagg SD, Forrest WJ (1988). A biomechanical analysis of scapular rotation during arm abduction in the scapular plane. *Am. J of Phys Med. & Rehab.* 67:238-245.

Doody SG, Freedman L, Waterland JC (1970). Shoulder movement durin abduction in the scapular plane. *Arch. Phys. Med. Rehab.* 51: 595-604.

Freedman L, Munro RR (1966). Abduction of the arm in the scapular Plane: Scapular and glenohumeral movements. *J. of Bone and Joint Surg.* 48.A no.8:1503-1510.

Groot J.H. de (1996). Variation in the scapulo-humeral rhythm due to projection effects. Proceedings of the Netherlands Orthopaedic Society 1995. *Acta Orthop. Scand. (Suppl 267)* 67:9.

Groot J.H. de (1997[a]). The reproducibility of the shoulder kinematics measured by means of the palpation method. *J. Clin. Biomech.* (submitted).

Groot J.H. de (1997[b]). The scapulo-humeral rhythm: Effects of 2-D roentgen projection. *J. Clin. Biomech.* (accepted).

Groot J.H. de, Valstar E.R., Arwert H.J. (1997[c]). Velocity effects on the scapulo-humeral rhythm. *J. Clin. Biomech.* (accepted).

Högfors C., Peterson B., Sigholm G, Herberts P. (1991). Biomechanical model of the human shoulder joint-II. The shoulder rhythm. *J. of Biomech.* 24.8 : 699-709.

Inman VT, Saunders JB, Abbott LC (1944). Observations on the function of the shoulder joint. *J. of Bone and Joint Surg.* 26A:1-30.

Johnson GR, Stuart PR, Mitchell S. (1993). A method for the measurement of three-dimensional scapular movement. *Clin. Biomech.* 8:269-273.

Poppen NK, Walker PS (1976). Normal and abnormal motion of the shoulder. *J. of Bone and Joint Surg.* 58A:195-200.

Pronk GM, Van der Helm FCT, (1991). The palpator, an instrument for measuring the positions of bones in three dimensions. *J. Med. Eng. Techn.* 15:15-20.

Pronk GM (1988). Three-dimensional determination of the position of the shoulder girdle during humerus elevation. *Biomechanics XI-B*, eds.:Groot G de, Hollander AP, Huijing PA, Ingen Schenau GI van, pp.1070-1076, 11th ISB-Congress, Amsterdam.

Pronk GM (1991). The shoulder girdle. *Doctoral thesis*, chapter 7, Delft University of Technology, Faculty of mechanical Engineering and Marine Technology, Delft, The Netherlands. ISBN 90-370-0053-3.

Saha AK (1961). Theory of the shoulder mechanism: descriptive and applied. Charles C. Thomas, Springfield.

Van der Helm FCT(1994). Analysis of the kinematic and dynamic behavior of the shoulder mechanism. *J. Biomech.* 27.5 : 527-550.

Van der Helm FCT, Pronk GM (1995). Three dimensional recording and descriptionof the shoulder mechanism. *J. Biomech. Engineering* 117 : 27-40.

Veeger H.E.J. (1992). Biomechanical aspects of the manual wheelchair propulsion. *Doctoral thesis.* Faculty of movement Sciences. Free University of Amsterdam. The Netherlands. ISBN 90-5389-016-5.