SCAPULO-THORACIC INTERACTION USING NATURAL COORDINATES FOR SHOULDER GIRDLE BIOMECHANICAL MODEL

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Abstract: This work aims to compare two algorithms to perform a kinematic consistency for modeling the scapulo-thoracic interaction (ST) using natural coordinates. The rib cage is usually represented by a fixed ellipsoid on the thorax reference system, while the scapula movement remains limited by a holonomic constraint modeled by two fixed points to the scapula reference system that belong to the ellipsoid surface. A movement acquisition, using a motion analysis system that captured the anatomical landmarks tracking of the thorax and shoulder girdle, was performed. The natural coordinates were calculated through the anatomical landmarks coordinates and used to perform an optimization to make the movement kinematically consistent. The calculus of the ellipsoid constraint is trivial, unlike the Jacobian matrix. It is proposed a way for calculate the Jacobian of the constraint that model ST. The optimization for kinematic consistency was performed through the MatLab Optimization Toolbox and through the Augmented Lagrangian approach. Both approaches were able to make the constraint violation remainbelow the tolerance. The first one needed more iterations (11.26±11.91 – mean±SD) leading to a higher CPU-time (0.18±0.17) when compared with the second one (0.03±0.01) which, in turn, needed less iterations (7.81±0.38). The inverse kinematics was performed to compare each approach and they were similar when compared with the tolerance. Despite the fact the first approach is more robust, as usually motion analysis acquisition provides a good first approximation for the solution, the use of the Augmented Lagrangian approach seems to be more convenient due to its efficiency.

Keywords:biomechanical model, kinematic consistency, shoulder girdle, natural coordinates, upper limb.

Introduction

The shoulder girdle is composed by a joint complex that builds up a closed kinematic chain that includes, among others, the sterno-clavicular and the acromio-clavicular joints. Human body has no direct interaction between rib cage and scapula due to muscle and tendon between them. However, it is common to model such an interaction to make the scapula movement more stable [1].

Garner and Pandy provided a large database of geometric parameters for the upper part of the human body derived from medical images of the Visible Human Project [2]. An ellipsoid was fitted on the right side of the rib cage. Its center and attitude were assumed to be stationary relatively to the thorax reference system. Two fixed points of the medial border of the scapula were selected and its movement was restricted by three interaction points: the sliding of these two first over the ellipsoid surface and a third point shared with the lateral end of the clavicle, which was modeled as a spherical joint.

To model a mechanism, the use of dependent coordinates has increased due to its robustness and easy implementation. Among them, there is the so-called natural coordinates. They are coordinates made of Cartesian points, also called basic points, and unit vectors that change its attitude with the element they belong to. They were firstly introduced in the 80’s for planar cases [3,4] as well as for spatial cases [5,6].Its application has been used in several areas and recently it has been used on biomechanics [7].Some of the main advantages of this approach are the possibility to generate a constant mass matrix for dynamic analysis and the fact that the constraint equations that come up from them are linear or quadratic, which makes their Jacobian matrix be constant or linear. Both of these reasons result to a high efficiency on data processing which makes the natural coordinates be widely used in real-time applications [8].

The constraint equation to simulate the scapulo-toracic interaction (ST) can be easily derived, which is not the case of its Jacobian. Here, we use the natural coordinates to propose a way to calculate the Jacobian as well as compare efficiency and robustness of two ways to perform the optimization for kinematic consistency to the ST, which plays an important role in the kinematic and dynamic analysis of the upper limb modeling.

Materials and methods

A motion analysis BTS Smart-D Motion Capture System (BTS Bioengineering, Italy) [9] was used to record the coordinates of each reflexive marker, 200 Hz of sample frequency [10]. The coordinates were low-pass filtered (7 Hz) with an off-line Butterworth filter. The marker-set chosen and the guide-lines to calculate the local coordinate system of each body segment (i.e. thorax, clavicles and scapulas) follwed the recomendation given by the International Society of Biomechanics [11].

The natural coordinates were calculated from the Cartesian coordinates of the anatomical landmarks. However, errors from the motion analysis system and from the skin movement relatively to the bone turns the coordinates kinematicaly inconsistent [12]. There was performed the following optimization to solve this problem:

$$\min f(\mathbf{q}) = \frac{1}{2}(\mathbf{q}-\mathbf{q}^*)^{\mathrm{T}}\mathbf{W}(\mathbf{q}-\mathbf{q}^*)$$

$$\text{subject to}\,\boldsymbol{\phi}(\mathbf{q}) = 0 \qquad (1)$$

where $\mathbf{q}$ is the set of kinematically consistent natural coordinates[n by 1], while $\mathbf{q^*}$ is the set that comes from the acquisition; $\mathbf{W}$is the diagonal weighting matrix [n by n], whose each nonzero element is the rate between the standard deviation and the mean of the respective coordinate; and $\boldsymbol{\phi}(\mathbf{q})$ is the vector of the constraint equations [m by 1].

This optimization was performed through the MatLab Optimization Toolbox (mathworks, version 2010)for a constrained nonlinear multivariable function, which was called method 1; and through the augmented Lagrangian minimization process [13], what was called method 2:

$$\left(\mathbf{W}+\boldsymbol{\phi}_{\mathrm{q}}^{\mathrm{T}}\alpha\boldsymbol{\phi}_{\mathrm{q}}\right)\Delta\mathbf{q}_{\mathrm{i+1}} = -\mathbf{W}(\mathbf{q}_{\mathrm{i}}-\mathbf{q}^*) - \boldsymbol{\phi}_{\mathrm{q}}^{\mathrm{T}}(\boldsymbol{\alpha\phi}+\boldsymbol{\lambda}_{\mathrm{i}})$$

$$\boldsymbol{\lambda}_{\mathrm{i+1}} = \boldsymbol{\lambda}_{\mathrm{i}} + \alpha\boldsymbol{\phi} \qquad (2)$$

, where $\Delta\mathbf{q}_{i+1} = \mathbf{q}_{i+1}\text{-}\mathbf{q}_i$; $\boldsymbol{\phi}_{\mathbf{q}}$ is the Jacobian matrix of the vector of constraint equations [m by n]; $\boldsymbol{\lambda}$ is the vector of Lagrange multipliers [m by 1]; and α is the penalty factor (scalar ~10^7).

The ST simulates a constraint generated by an ellipsoid surface, thus, it must have theform:

$$\boldsymbol{\phi} = \frac{(\mathrm{x}-\mathrm{x}_0)^2}{\mathrm{r_x}^2} + \frac{(\mathrm{y}-\mathrm{y}_0)^2}{\mathrm{r_y}^2} + \frac{(\mathrm{z}-\mathrm{z}_0)^2}{\mathrm{r_z}^2} - 1 = 0 \quad (3)$$

where (x_0,y_0,z_0) are the coordinates of the ellipsoid center and (r_x,r_y,r_z) are itssemiaxes. These parameters were taken from the literature [2]. (x,y,z) are thecoordinates of the point on the ellipsoid surface which, in the constraint, represents one of the points that belongto the scapula. Using natural coordinates and taking into account the attitude of the ellipsoid relative to the GlobalCoordinate System (GCS), the constraint introduced by equation (3) becomes, inmatrix form:

$$\boldsymbol{\phi} = \mathbf{q}^{\mathbf{T}}\mathbf{C}^{\mathbf{T}}\mathbf{R_V}\mathbf{R_C}^{\mathbf{T}}\,\mathbf{D}\,\mathbf{R_C}\mathbf{R_V}^{\mathbf{T}}\mathbf{Cq} - 1 = 0 \quad (4)$$

where $\mathbf{C}$ is the mapping matrix [3 by n] that turns the natural coordinates into the trio of coordinates of the point in the ellipsoid surface relatively to its center;$\mathbf{D}$ is a digonal matrix [3 by 3] in which each nonzero element is the inverse of the square of the corresponding ellipsoid semi-axes; $\mathbf{R_C}$ is a constant rotation matrix representing the rib cage attitude relative to the thorax; and $\mathbf{R_V}$is a variable rotation matrix representing the thorax attitude relative to the GCS.The former matrix variates with $\mathbf{q}$, as shown in equation (5).

$$\mathbf{R_V} = \langle \mathbf{C_1q}\,|\mathbf{C_2q}\,|\mathbf{C_3q}\,\rangle \qquad (5)$$

where $\mathbf{C}_i$ (i = 1,2,3) are the mapping matrices that turns thenatural coordinates into the respective base vectors of the thorax coordinate system.

Differentiating equation (4) with respect to vector $\mathbf{q}$, and assuming $\mathbf{K}=\mathbf{R_C}^{\mathbf{T}}\mathbf{D}\mathbf{R_C}$, the correnspondingJacobian can be calculated, in the reduced form,through equation (6).

$$\boldsymbol{\phi}_{\mathbf{q}} = 2\mathbf{q}^{\mathbf{T}}\mathbf{C}^{\mathbf{T}}\mathbf{R_V}\mathbf{K}\left(\mathbf{R_V^T}\mathbf{C} + \mathbf{R_{V_q}^T}\mathbf{Cq}\right) \qquad (6)$$

where $\mathbf{R_{V_q}^T}$ represents the transpose of the partial derivative of matrix $\mathbf{R_V}$ relative to $\mathbf{q}$. Observing equation (6),it can be noticed that the term $\mathbf{P} = \mathbf{R_{V_q}^T}\mathbf{Cq}$should lead to matrix [3 by n]. The product $\mathbf{P}$was calculated as shown in equation (7):

$$\mathbf{P} = \begin{bmatrix} \mathbf{q^TC^TC_1} \\ \mathbf{q^TC^TC_2} \\ \mathbf{q^TC^TC_3} \end{bmatrix} \qquad (7)$$

The robustness of each approach was tested by adding a white noise as shown in equation (8):

$$\mathbf{q_n^*} = \mathbf{q}^* + \mathrm{s}\cdot\mathbf{n} \qquad (8)$$

, where $\mathbf{n}$ is a white noise vector [n by 1] whose mean is zero and standard deviation is one ands is a scalar.The tolerance to reach the kinematic consistency was 10^{-8} m and the inverse kinematics, through Grood and Suntay proposal [14], was performed to compare the results obtained from each method. The Bland-Altman test was performed to evaluate the concordance between both result [15].

Results

Both approaches were able to reach the kinematic consistency keeping the constraint violation below the tolerance (Figure 1a).The number of iterations required for each method to achieve such a convergence was different (Figure 1b) which led to a different CPU-time (Figure 1c). To achieve convergence, method 1 needed 11.26±11.91 iterations (mean±SD) and it took 0.18±0.17 units of CPU-time, while method 2 needed 7.81±0.38 iterations spending 0.03±0.01 units of CPU-time.

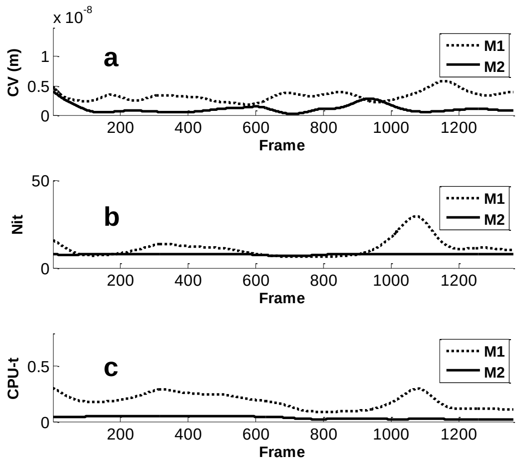

Figure 1: (a) Constraint violation (m); (b) number of iterations required to achieve convergence; and (c) UCP-time.

The angles taken from the scapula relative to the thorax (Figure 2) had a high concordance according to the Bland-Altman test. The summary of the results are described in the Table 1.

Table 1: Results from the Bland-Altman test.

Angle	conc	md	r_{ang}	r_{md}
Protraction	99.93	0.14±4.00	0.999	0.051
Abduction	99.93	0.10±6.00	0.999	0.007
Tilt	99.89	0.29±11.00	0.998	0.010

Conc is the percenctual of concordance (%); md is the mean of the difference between both methods ($\cdot 10^{-4}$m); r_{ang} is the Pearson correlation between angles and r_{md} is the Pearson correlation between the mean and the difference of the angles.

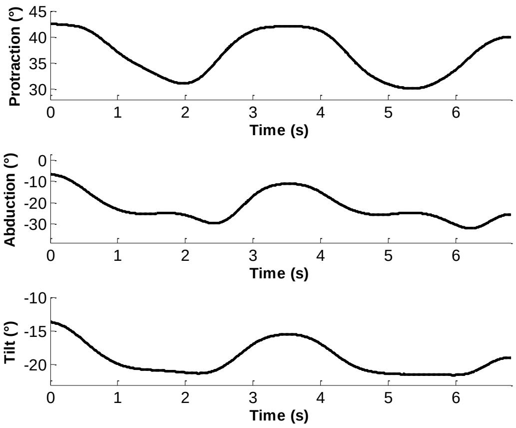

Figure 2: Scapula angles relative to the thorax for both methods in the right side. They are "visually" coincident.

Table 2 shows the results for the test of robustness. It was made keeping the same condition for maximum number of iterations, minimum increment to the variable and the tolerance for constraint violation. When s (equation 8) had a value of 0.1, only the method 1 showed a constraint violation in the same magnitude order of the tolerance for kinematic consistency. From this value on, none of the approaches converged.

Table2: Robustness test.

s		10^{-2}	10^{-1}	10^{-0}
$\lvert\phi\rvert$	M1	0.4	3.4	~
$\lvert\phi\rvert$	M2	0.1	~	~

The values for $\lvert\phi\rvert$ is multiplied by 10^{-8} m.

Discussion and Conclusion

This work provided a way to calculate the Jacobian of the constraint equation that model ST. The approaches reached the kinematic consistency with 10^{-8}m tolerance, although the number of iterations was different between method1 and 2. As a consequence, the CPU-time was distinct as well, and taking into account only this, method 2 was more efficient.

The kinematic data taken from both solutions do not show any difference that could be noticed visually (Figure 2). The Bland-Altman test showed a concordance above 99% for all the three scapula angles relative to the thorax. As it is supposed to be for variables with high agreement between each other, the Pearson correlation between the angle was high, while between the mean and the difference was low (Table 1). These results support that there is not a significant difference between the solutions found by both methods.

Furthermore, the method 1 seems to be more robust

(Table 2). Although, when the white noise (equation 8) is not added and the error comes from only the typical sources [12], the method 2 converges to a consistent solution for all the frames.

Regarding that is not a significant difference between solutions from both methods, the augmented Lagrangian minimization process(method 2) seemsto be better choice due to its efficiency. Moreover, it work well taking into account the range of error that come up in the kinematic signal taken from the motion analysis system.

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References

[1]Van Der Helm FCT, Veeger HEJ, Pronk GM, Van Der Woude LHV, Rozendal RH.Geometry parameters for musculoskeletal modelling of the shoulder system. Journal of Biomechanics – 1992; 25(2): 129-144.

[2] Garner BA, Pandy MG. A kinematic model of the upper limb based on the visible human project (VHP) image dataset.Computer Methods in Biomechanics and Biomedical Engineering – 1999; 2: 107-124.

[3] García de Jalon J, Serna MA, Avilés R.A computer method for kinematic analysis of lower pair mechanisms. Part I: Velocities and accelerations and Part II: Position problems.Mechanism and Machine Theory – 1981; 16: 543-566.

[4] Serna MA, Avilés R, García de Jalón J. Dynamic analysis of plane mechanisms with lower-pairs in basic coordinates. Mechanism and Machine Theory – 1982; 17: 397-403.

[5] García de Jalon J, Unda J, Avello A. Natural coordinates for the computer analysis of multibody systems. Computer Methods in Applied Mechanics and Engineering – 1986; 56: 309-327.

[6] García de Jalon J, Unda J, Avello A, Jiménez JM. Dynamic analysis of three-dimensional mechanisms in natural coordinates. ASME J. of Mechanisms, Transmissions and Automation in Design – 1987; 109: 460-465.

[7] Lugrís U, Cartín J, Luaces A, Cuadrado J. Gait analysis system for spinal cord-injured subjects assisted by active orthoses and crutches. Proc of the Institution of Mechanical engineers, Part K: Journal of Multi-Body Dynamics – 2013; 227(4): 363-374.

[8] García de Jalon J, Bayo E. Kinematic and Dynamic Simulation of MultibodySystems: The Real-Time Challenge. Berlin: Spring-Verlag; 1994.

[9] BTS Smart-D: High Frequency Digital System for Biomechanical Motion Analysis, BTS Bioengineering

[10] Nunes MO, Menegaldo LL, Soares GLOL, Pino AV, Souza MN. Inverse kinematics of push-up exercise using joint coordinate system. Journal of Medical Imaging and Health Informatics – 2013; 4(1): 83-91.

[11] Ge Wu, et al. 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. Journal of Biomechanics – 2005; 38: 981-992.

[12] Leardini A, Chiari L, Croce UD, Cappozzo A. Human movement analysis using stereophotogrammetry – Part 3: Soft tissue artefact assessment and compensation.Gait and Posture – 2005; 21: 212-225.

[13] Alonso FJ, Cuadrado J, Lugrís U, Pintado P. A compact smoothing-differentiation and projection approach for the kinematic data consistency of biomechanical systems. Multibody System Dynamics – 2010; 24: 67-80.

[14] Grood ES and Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: Application to the knee. Journal of Biomechanical Enginnering – 1983; 105: 136-144.

[15] Bland JM and Altman DG. Measuring agreement in method comparison studies. Statistical Methods in Medical Research – 1999; 8: 135-160.