BIOMECHANICAL MODEL FOR UPPER LIMBS MOVEMENT ANALYSIS: APPLICATION ON NORMAL SUBJECTS

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Abstract
Traditionally, movement analysis has been focused on lower limbs movements. However, a quantitative biomechanical analysis of upper limbs movements is fundamental especially for people affected by upper extremities pathologies. We developed a biomechanical model and an experimental protocol for three-dimensional analysis of upper limbs movements. We validated the model and applied it to a population of normal subjects using an optoelectronic system acquiring reflective passive markers. The subjects performed three basic movements, that allowed us to evaluate affordability, repeatability and precision of the model. Moreover normality bands for the selected movements were built from the performed experimental acquisitions.

Key Words
Biomechanics, movement analysis, modelling, rehabilitation engineering, upper extremities

Introduction
In medical and scientific literature, movement analysis has been principally focused on lower limbs movements and particularly on gait analysis. However, many pathological subjects are not able to walk, thus, to have a quantitative measure of these patients’ mobility, it results of fundamental interest to perform an affordable and reliable analysis of upper limbs movements. The basic idea of a complete biomechanical model for the analysis of upper limbs movements comes therefore from the clinical aim to have a practical tool for the evaluation of treatment effectiveness in non-walking patients. Besides, upper limbs movements result very interesting, since they are more variable and complicated than lower limbs ones. Some investigations ([1], [2], [3], for example) have been done on upper limbs kinematics, but none achieved a complete 3D description of upper limbs movements.

The main goal of this project is to develop an adequate experimental protocol and a biomechanical model for upper limbs movement analysis to be used in a three-dimensional environment without any constraints. This new protocol will be suitable also as integration to the already existing gait analysis protocols.

In this paper we focus our attention on three simple movements (described in the next section), that were selected to evaluate repeatability, affordability and precision of the biomechanical model.

Material and Methods
Experimental protocol:
The experimental protocol is based on the positioning of 13 reflective passive markers on specific bony landmarks (C7, Left acromion, Right acromion, Left humeral wand, Right humeral wand, Left humeral epicondyle, Right humeral epicondyle, Left ulnae styloid, Right ulnae styloid, Left radium epiphysis, Right radium epiphysis, Left third metacarpal head, Right third metacarpal head) of the analysed subject (see Fig. 1).

Fig. 1: experimental protocol: marker positioning

We focused our attention on 7 segments that can be identified using 3 markers each: trunk, left and right upper arm, left and right forearm, left and right hand. Each segment is treated as a rigid body as far as movement is concerned. The proposed marker positioning consists of three non-collinear markers for each segment; therefore it allows the definition of an orthogonal right-hand system of axes embedded in each segment.

26 normal subjects (age 24.4±2.7, no musculoskeletal problems referred) were analysed with the new protocol.
using a 6 TVC optoelectronic system (Elite, BTS, Milan, IT). Each subject signed an informed consent after precise explanation of the experimental trials. The optoelectronic system gave as output the 3D coordinates of each marker. Each subject was asked to perform flexion of the straight arm from anatomical position to 90° and back (elevation in the sagittal plane), abduction of the straight arm from anatomical position to 90° and back (elevation in the frontal plane) and flexion of the elbow from anatomical position to 90° and back. The subject was instructed to perform each movement as precisely as possible at preferred speed. Each movement was performed three times for each arm to control repeatability within each trial session. These movements were chosen to evaluate the precision of the model in the identification of angles when angles and movements are almost known “a priori”. In fact, every movement is expected to be performed in a single plane of the subject (the first and third in the sagittal plane and the second in the frontal plane), thus we expect to see a “major” angular variation in that plane for the segment performing the movement, and almost no variations in the other two planes.

Biomechanical model: from the 3D coordinates of three non-collinear markers an embedded right-hand coordinate system is determined for each of the 7 segments. In each coordinate system X axis is directed along the major dimension of the segment the Y axis points laterally to the left and Z axis points consequently downwards (example of the right-hand coordinate system for the trunk segment is in Fig. 2).

![Fig. 2: right-hand coordinate system visualization for the trunk segment](image)

These local systems allow us to calculate relative motion between the analysed segments using position matrices [4], which contain the director cosines of the orthogonal axes and the 3D coordinates of their origin. The relative positions and the motion are then expressed using Cardan angles. The calculation sequence for Cardan angles is such that YXZ sequence corresponds to flexion-extension, abduction-adduction and internal-external rotation. We used this sequence as default one, although the calculation algorithm allows the operators to change the Cardan sequence as they like.

All joints are modelled as ball-and-socket joints, because we didn’t want to have constraints “a priori” in the model. Joint centres are not fixed, since they are not calculated anatomically but as those points with minimum 3D movement during the whole trial (i.e. the points, whose 3D Eulerian distance from their starting position is the lowest). We decided not to calculate joint centres anatomically, because there is lack of precise information in literature about how to locate shoulder joint centre and we wanted to avoid other sources of potential error.

Biomechanical model validation: comparing angular values obtained from three successive acquisitions, that were made without changing the experimental set up, we found a tolerance value corresponding to “acquisition noise”. This tolerance has a maximum value of 0.5° and it has to be taken into consideration when evaluating the results of experimental trials on subjects.

Sensitivity to marker positioning was evaluated by repeating static acquisitions after perturbing the position of three markers by 1 cm along two different axes and then recalculating the relative angles between the segment, containing the perturbed marker and the most proximal one. Marker replacement was done “in succession”, without going back to the first, basic configuration. Thus, replacement error propagates from one acquisition to the next and two different comparisons can be done: the first involves the differences between each configuration and the first (or “basic” configuration), the second involves the differences between each configuration and the previous (taking into account only the last replacement). Since it is the most common case, we present results only relative to the second comparison. It was found that wrist markers (ulnae styloid in our case) are the most sensitive to marker repositioning: in particular, the biggest “error” was 3.81° (standard deviation 0.242°) in forearm internal-external rotation for a 1 cm displacement in Z direction.

The validation procedure of the biomechanical model in dynamic conditions was divided into two parts: the first was conducted using a simple mechanical model of the arm consisting in a unique planar joint and thus performing “pure” movements. This procedure allowed us to verify algorithm accuracy and system stability during planar movements. Two different kind of movements were tested: flexion-extension and abduction-adduction both from 0° to 90° and back, ten trials were performed for each movement.

Marker placement is slightly different in relation to the movement to be tested. In fact, flexion-extension movement is performed simulating the relative movement of the arm and the forearm, while abduction-adduction movement is performed simulating the relative movement of the trunk and the arm. Therefore, in the first case 6 markers are needed (referring to a right arm: right acromion, right wand, right humeral epicondyle, right ulnae styloid, right radium epiphysis, right third metacarpal head, see Fig. 3), while in the second case only 5 markers are to be used (C7, right and left acromion, right or left wand and right or left humeral epicondyle).

Results for flexion – extension movement are provided in Table 1 by giving mean range values and standard deviation values for the three Cardan angles in the ten performed trials.
Fig. 3: right arm marker positioning for flexion-extension movements

<table>
<thead>
<tr>
<th>Flexion – Extension movement</th>
<th>Flex-ext(°)</th>
<th>Abd-add(°)</th>
<th>Int-ext rot(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>91.87456</td>
<td>2.856652</td>
<td>10.56321</td>
</tr>
<tr>
<td>Std. Dev</td>
<td>2.654715</td>
<td>0.421755</td>
<td>3.214588</td>
</tr>
</tbody>
</table>

Table 1: dynamic test: flexion-extension (0°-90°) movement

Abduction – adduction movement gave comparable results. (For a more complete description of the validation see [5]). The second part of the validation procedure was performed using a Cardan joint performing three-dimensional movements, whose trajectory can be precisely monitored since the angular values are known at the end points of the joint movement. At the end, repeatability tests were performed. The calculation procedure gave high repeatability in all tested conditions and the system was proved to be stable even in “critical” positions (near 90° adduction for example).

Results

The main results on the precision of the model in the identification of the Cardan angles are provided using graphical examples, that show for each movement the “normality” bands, obtained from the trials of our 26 subjects, for all three Cardan angles. Numerical results are also summarized in the following tables for the three considered movements.

1) Arm flexion-extension movement (to 90° and back) (Fig.4, Table 2).

<table>
<thead>
<tr>
<th>Flex/Ext</th>
<th>Abd/Add</th>
<th>Int/Ext rot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean value</td>
<td>5.9842°</td>
<td>5.7290°</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>15.15°</td>
<td>7.57°</td>
</tr>
</tbody>
</table>

Table 2: mean value and bandwidth of Cardan angles for the first selected movement

The bandwidth is within 16° (mean s.d.: 15.15°) for the required movement (arm flexion extension). In the same movement, for abduction-adduction angle the mean value is 5.9842°, mean s.d. 7.5698°, while for internal-external rotation angle the mean value is 5.7290° with mean s.d. of 18.0973°.

The same calculations were made for the other two movements: arm abduction-adduction to 90° and back (Fig.5, Table 3) and flexion-extension of the forearm to 90° and back (Fig.6, Table 4) obtaining similar results.

2) Arm abduction – adduction (to 90° and back)

<table>
<thead>
<tr>
<th>Flex/Ext</th>
<th>Abd/Add</th>
<th>Int/Ext rot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean value</td>
<td>-23.41°</td>
<td>-18.89°</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>20.32°</td>
<td>14.29°</td>
</tr>
</tbody>
</table>

Table 3: mean value and bandwidth of Cardan angles for the second selected movement

3) Flexion of the forearm relative to the upper arm (to 90° and back)
Fig. 6: Normality bands for flexion of the forearm relative to the upper arm (to 90° and back): flexion-extension, abduction-adduction, internal-external rotation angle

<table>
<thead>
<tr>
<th>Mean value</th>
<th>Flex/Ext</th>
<th>Abd/Add</th>
<th>Int/Ext rot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-4.5907°</td>
<td>-24.6723°</td>
<td>15.2431°</td>
</tr>
</tbody>
</table>

Table 4: mean value and bandwidth of Cardan angles for the third selected movement

Discussion

We developed a new biomechanical model and experimental protocol for upper limbs movement analysis. The model is based on the collection of 3D coordinates of 13 reflective surface markers. The biomechanical model was validated through specific tests on mechanical models of the upper extremity. Three simple movements were then tested on a population of healthy subjects. Since all tested movements are basically planar movements we were interested in the bandwidth of the major angle and in both the mean value and the bandwidth for the other two angles. For instance, if the required movement is arm flexion – extension to 90° and back, the major angle is flexion – extension angle of the upper arm relative to the trunk. The measure of the bandwidth gives the amplitude of the normality band, which is the range covered by healthy subjects. The result is important for future comparison with pathological subjects. As for the other two angles (which are in this case abduction – adduction and internal – external rotation), we are interested both on their mean value and on their bandwidth. Their mean value should be as close to zero as possible, because the requested movement involves in theory only one plane. The results show that this hypothesis is completely verified for the subjects involved in our experimental trials. This demonstrates on one hand that our subjects could perform the requested movements almost perfectly on a single plane (and this was also expected since they are normal subjects) and on the other hand that the biomechanical model can correctly calculate the angles along all three directions. The bandwidth also should be as little as possible, since it evidences the deviation from the mean value. The result could also be very interesting for the comparison with a pathological population, because, if using a different motion strategy due to physical limitation, pathological subjects are expected to deviate from zero values in these two angles.

All tested movements resulted appropriate for the evaluation of precision, affordability and repeatability of the measures. The precision in the calculation of Cardan angles depends, as usual, on the chosen calculation order: as for our initial decision, the most precise angle is the flexion-extension angle, followed by abduction-adduction and internal-external rotation. The construction of normality bands could be very helpful for future comparison with pathological populations.

Conclusions

From our results we can conclude that, the proposed model is suitable for upper limbs movement analysis. Its application on a population of normal healthy subjects confirmed some logical hypothesis on the strategy adopted by normal people for the required movements. The experimental protocol is quick and very easy to modify, therefore it could be easily applied to pathological subjects. We tested only three simple and almost planar movements, we think that for the analysis of pathological subjects some more “clinical oriented” movements are expected to be chosen.

In conclusion, we feel that upper limbs movement analysis is very complex and it seems far to be completely comprised, but it is our hope that this work will help in understanding and learning more about upper extremity kinematics.

References