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# Multibody kinematic optimization with marker projection improves the accuracy of the humerus rotational kinematics

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## Original Article

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## 1 **Abstract**

2 Markers put on the arm undergo large soft tissue artefact (STA). Using markers on the  
3 forearm, multibody kinematic optimisation (MKO) helps improve the accuracy of the arm  
4 kinematics especially its longitudinal rotation. However deleterious effect of STA may persist  
5 and affect other segment estimate. The objective was to present an innovative multibody  
6 kinematic optimization algorithm with projection of markers onto a requested axis of the local  
7 system of coordinates, to cancel their deleterious effect on this degree-of-freedom. Four subjects  
8 equipped with markers put on intracortical pins inserted into the humerus, on skin (scapula, arm  
9 and forearm) and subsequently on rigid cuffs (arm and forearm) performed analytic, daily-living,  
10 sports and range-of-motion tasks. Scapulohumeral kinematics was estimated using 1) pin markers  
11 (reference), 2) single-body optimisation, 3) MKO, 4) MKO with projection of all arm markers  
12 and 5) MKO with projection of a selection of arm markers. Approaches 2-4 were applied to  
13 markers put on the skin and the cuff. The main findings were that multibody kinematic  
14 optimization improved the accuracy of 40 to 50% and the projection algorithm added an extra  
15 20% when applied to cuff markers or a selection of skin markers (all but the medial epicondyle).  
16 Therefore, the projection algorithm performed better than multibody and single-body  
17 optimizations, especially when using markers put on a cuff. Error of humerus orientation was  
18 reduced by half to finally be less than  $5^\circ$ . In conclusion, this innovative algorithm is a promising  
19 approach for estimating accurate upper-limb kinematics.

20

## 21 **Keywords**

22 Upper-limb; Multibody kinematic optimization; Marker projection algorithm.

## 23 **1. Introduction**

24 An accurate estimate of the three-dimensional scapulohumeral joint kinematics – especially  
25 axial rotation and elevation – can be clinically relevant to assess the rotator cuff muscles  
26 disorders (Anglin and Wyss, 2000; Lawrence et al., 2014). Unfortunately, sensors or markers put  
27 on the arm undergo soft tissue artefact (STA) (Blache et al., 2016; Hamming et al., 2012) that  
28 compromises the accuracy. In particular, the axial rotation tends to be underestimated (Cutti et  
29 al., 2005a; Ludewig et al., 2002; Schmidt et al., 1999) and errors up to 30° on the arm axial  
30 rotation were found due to STA, when using an electromagnetic sensor attached to the lateral  
31 aspect of the arm (Hamming et al., 2012). Using seven skin markers spread over the arm, this  
32 error can be reduced by about 10° (Begon et al., 2015). However, this last study has shown that  
33 single-body optimization with marker weightings fails to improve the arm kinematics, since  
34 optimal weightings are subject- and task-specific (Begon et al., 2015). According to the marker-  
35 cluster geometrical transformations proposed by Dumas et al. (2014) to describe STA, the  
36 movement of a cluster of markers put on the arm with respect to the bone corresponds mainly to a  
37 rigid transformation (*i.e.* translation and rotation) (Blache et al., 2016). Consequently, algorithms  
38 using additional markers/sensors on the forearm have been the most promising avenue to  
39 accurately estimate the scapulohumeral joint kinematics (Cutti et al., 2005b; Lin and Karduna,  
40 2013; Roux et al., 2002; Schmidt et al., 1999). In fact, there is less soft tissue around the forearm  
41 and the humeroulnar joint can be modelled as one degree-of-freedom (DoF) in flexion, which  
42 decreases the complexity of the multibody system. However, these models have not been  
43 validated using the true humeral bone kinematics for a large variety of movements yet, and some  
44 algorithms fail when the elbow is fully extended.

45 In multibody kinematic optimization, markers put on the forearm may correct the arm axial  
46 rotation (Roux et al., 2002). Markers put on the olecranon and proximally on the dorsal border of  
47 the ulna also may improve the estimation of the arm axial rotation because of the small soft tissue  
48 thickness and, above all, because some markers are distant from the arm longitudinal axis when  
49 the elbow is bent. The drawback of multibody least-squares minimization is that markers with  
50 large STA may negatively affect the kinematics of adjacent segments. For example, some  
51 markers on the arm may affect the forearm pro-supination estimation. To the best of our  
52 knowledge, no algorithm has been proposed to cancel this deleterious effect. To address this  
53 shortcoming, said STA-affected markers could be projected onto an axis of the local frame to  
54 ensure that they do not participate to the estimation of the rotation along this axis.

55 The performance of multibody kinematic optimization algorithms depends on the joint  
56 constraints (Duprey et al., 2010), model parameters (e.g. segment length (El Habachi et al.,  
57 2013)) and the markers/sensors involved (Begon et al., 2008). Unfortunately, no optimal marker  
58 set or sensor placement exist yet (Anglin and Wyss, 2000). Electromagnetic sensors and cuffs  
59 with reflective markers remain the standard in upper-limb biomechanics (Anglin and Wyss,  
60 2000). Also, it has been recommended to not attach markers/sensors on anatomical landmarks  
61 (Kontaxis et al., 2009). However, recent studies have highlighted that the medial epicondyle  
62 presented small STA (Blache et al., 2016) and skin markers performed well (Begon et al., 2015),  
63 by comparison with a single electromagnetic sensor (Hamming et al., 2012). Our hypothesis was  
64 that skin markers undergo different STA that compensate each other, but this was not confirmed.  
65 Since seven markers were put on the arm, it was expected that, in line with simulation-based  
66 studies (Challis, 1995; Monnet et al., 2010), the accuracy achieved from them outperformed that

67 from a single 6-DoF sensor. New multibody kinematic optimization algorithms should then be  
68 assessed using different marker sets.

69 The objective of this study was to present an innovative multibody kinematic optimization  
70 algorithm, based on the projection of all or selected markers, onto a requested axis of the local  
71 system of coordinates (SoC), to cancel their deleterious effect on this DoF. Its benefit was  
72 assessed on the upper-limb against true bone kinematics, by comparison to single-body and  
73 standard multibody optimizations.

74 **2. Methods**

75 *2.1. Experiment*

76 The experimental protocol with pin insertion and skin markers is described in Dal Maso et al.  
77 (2015) and Begon et al. (2015). It was approved by the local ethic committees of the Université  
78 de Montréal and Karolinska Institutet. Four asymptomatic males (ages: 41, 32, 44 and 27 years,  
79 heights: 1.82, 1.72, 1.77 and 1.65 m, masses: 80, 82, 115 and 57 kg) volunteered in this study.  
80 Markers were placed on a pin screwed into their humerus and on skin. Subsequently, markers  
81 placed on thermoformed cuffs attached to the arm and forearm replaced the skin markers. Marker  
82 trajectories were acquired at 300 Hz using an 18-camera motion analysis system (Oxford Metrics  
83 Ltd., Oxford, UK). **Fig. 1** illustrates the markers needed for this secondary use of data.  
84 Participants performed 18 movements allocated in four categories (**Tab. 1**): 1) analytic  
85 movements similar to Hamming et al. (2012); 2) mimics of activities of daily living (ADL) (van  
86 Andel et al., 2008); 3) mimics of sports activities and 4) movements with maximal range of  
87 motion (Haering et al., 2014). In the condition with cuffs, only analytic movements and ADL  
88 were performed due to the anesthetic duration.

*Please insert Fig. 1 here*

*Please insert Fig. 2 here*

*Please insert Tab. 1 here*

89 *2.2. Models and kinematic reconstruction*

90 For each participant, five multibody kinematic models were developed according to the  
91 framework of Kontaxis et al. (2009) and the ISG recommendations (Wu et al., 2005) about  
92 anatomical frames definition. They mainly differed in joint and motor constraints. Partially  
93 described in Jackson et al. (2012), the models were composed of a common root: thorax

94 (6 DoFs), clavicle (2 DoFs), scapula (3 DoFs) (**Fig. 1**). Skin markers were used for these three  
95 body segments as proposed by Jackson et al. (2012), including three markers put on the  
96 acromion. The joint between the pelvis and thorax was functionally located (Ehrig et al., 2006),  
97 while sternoclavicular and acromioclavicular joint locations were defined using markers placed  
98 on the most ventral point on the sternoclavicular joint and the most dorsal point on the  
99 acromioclavicular joint (Michaud et al., 2016). The generalized coordinates ( $\mathbf{q}$ ) of this common  
100 root were first obtained by solving a non-linear least-squares problem as described by  
101 Laitenberger et al. (2015).

102 In the 1<sup>st</sup> and 2<sup>nd</sup> models (termed as *Humerus* and *Arm* models, respectively), the arm had 6  
103 DoFs with respect to the scapula; the two models differed in the markers used in the inverse  
104 kinematics algorithm: pin markers vs. skin/cuff markers, respectively. The *Humerus* model  
105 corresponded to the reference bone kinematics. The *Arm* model was about making a single-body  
106 optimization. The 3<sup>rd</sup> to 5<sup>th</sup> models (*UpLimb*, *UpLimbP* and *UpLimbS*) included the arm (3 DoFs)  
107 and forearm (1 DoF) with skin markers. *UpLimb* model corresponded a standard multibody  
108 kinematic optimisation. In the *UpLimbP* model, all the skin markers of the arm were projected  
109 onto its longitudinal axis ( $y$ ). In the *UpLimbS* model, selected skin markers (all of the arm but the  
110 medial epicondyle) were projected onto its longitudinal axis. The coordinate systems of the  
111 segments and joints were in accordance with the ISG recommendations, based on the same  
112 anatomical landmarks for all the models. As suggested by Michaud et al. (2016), the  
113 scapulohumeral joint center was determined using the predictive method of Rab et al. (2002). The  
114 humeroulnar joint was functionally located (O'Brien et al., 1999).



115 In all the models, the generalized coordinates ( $\mathbf{q}$ ) of the upper-limb were obtained by solving a  
 116 non-linear least-squares problem and adapted to include a projection function of observed marker  
 117 global coordinates  $\mathbf{M}_{obs}^G$  onto desired axes,  $\mathbf{P}_{obs}^G = p(\mathbf{M}_{obs}^G, \mathbf{q})$ :

$$\min_{\mathbf{q}} \frac{1}{2} \|p(\mathbf{M}_{obs}^G, \mathbf{q}) - f(\mathbf{q})\|^2, \quad (1)$$

118 where  $f(\mathbf{q})$  is the forward kinematic function generated using RBDL (Felis, 2011). In models with  
 119 projection, the markers local coordinates, but that along the longitudinal axis of the arm, were set  
 120 at 0. At each iteration of the nonlinear optimization, observed markers were projected onto the  
 121 arm longitudinal axis:

$$\mathbf{M}_{obs}^L = \mathbf{T}_G^L(\mathbf{q}) \mathbf{M}_{obs}^G \quad (2a)$$

$$\mathbf{P}_{obs}^L = [0 \ \mathbf{M}_{obs(y)}^L \ 0 \ 1]^T \quad (2b)$$

$$\mathbf{P}_{obs}^G = \mathbf{T}_L^G(\mathbf{q}) \mathbf{P}_{obs}^L. \quad (2c)$$

122 where  $\mathbf{T}_G^L$  are 4x4 homogenous transformation matrices from the Global (G) to the Local (L)  
 123 frames. For each frame, Eq. [1] was solved using a Levenberg-Marquardt algorithm. The initial  
 124 guess was the generalized coordinates vector found in the previous frame ( $\mathbf{q}=\mathbf{0}$  in the first frame).  
 125 At each iteration, the Jacobian matrix of the projection was analytically calculated. The *Arm*,  
 126 *UpLimb* and *UpLimbP* models were reconstructed using two different marker sets, namely: four  
 127 markers on each cuff, four skin markers on the arm and forearm, as shown in **Fig. 2**. The  
 128 *UpLimbS* model was reconstructed with skin markers only.

### 129 2.3. Data processing

130 The variety of movements did not allow to have an angle sequence without passing through  
 131 gimbal lock positions which makes difficult to reliably maintain continuity in angle time histories  
 132 (Cutti et al., 2008; Phadke et al., 2011; Senk and Chèze, 2006). To avoid such numerical issues,

133 the data were post-processed and analyzed as follow. For each model, the scapulohumeral  
 134 matrices of rotation were calculated using the generalized coordinates. Since high frequency  
 135 noise may come from multibody kinematic optimization (Fohanno et al., 2014), a zero-lag 2<sup>nd</sup>  
 136 order Butterworth filter (cuff-off 5 Hz) was applied to the time histories of each matrix  
 137 component, which are continuous. Then, in each frame, the nearest orthonormal matrix ( $\mathbf{R}$ ) was  
 138 obtained using Horn's algorithm (Horn et al., 1988):

$$\mathbf{R} = \mathbf{Q}(\mathbf{Q}^T\mathbf{Q})^{-1/2}, \quad (3a)$$

with

$$(\mathbf{Q}^T\mathbf{Q})^{-1/2} = \sum_{i=1}^3 \frac{1}{\sqrt{\lambda_i}} e_i e_i^T, \quad (3b)$$

139 where  $\mathbf{Q}$  is the non-orthonormal matrix after signal processing,  $\lambda_i$  the eigen values and  $e_i$  the  
 140 eigen vectors of  $\mathbf{Q}^T\mathbf{Q}$ .

141 The scapulohumeral matrix of the *Arm*, *UpLimb* and *UpLimbP* models were compared to that  
 142 of the *Humerus* model. The misorientation was characterized by four angular deviations, namely:  
 143 the total deviation value (Eq. [4a],  $\Delta_{tot}$ ) (Begon et al., 2015; de Vries et al., 2010) and the three  
 144 axial deviations (Eq. [4b-d]), *i.e.* the smallest angles between the vectors  $x$ ,  $y$  and  $z$  (de Vries et  
 145 al., 2010) of the *Arm*, *UpLimb*, *UpLimbP* or *UpLimbS* local frame relative to the local axes of the  
 146 *Humerus* model:

$$\Delta_{tot}^m = \cos^{-1} \left( \frac{\text{trace}(\mathbf{R}_1^T \mathbf{R}_m) - 1}{2} \right) \quad (4a)$$

$$\Delta_{ant}^m = \cos^{-1}(x_1 \cdot x_m) \quad (4b)$$

$$\Delta_{long}^m = \cos^{-1}(y_1 \cdot y_m) \quad (4c)$$

$$\Delta_{lat}^m = \cos^{-1}(z_1 \cdot z_m) \quad (4d)$$

147 where the 1-index is relative to the *Humerus* model and *m*-index is relative to the *Arm*, *UpLimb*,  
148 *UpLimbP* or *UpLimbS* model. These four angles vary between 0 and 180° and are continuous  
149 throughout any movement (*i.e.* without  $\pm 2\pi$  jumps) by contrast to Euler/Cardan angles.

150 To not artificially underestimate the average misorientation, the static phases at the beginning  
151 and end of each movement were removed. Since the number of repetitions was different between  
152 subjects – due to discomfort or reduced anesthetic time –, trials of similar movements were  
153 concatenated before statistical analysis (**Tab. 1**). Then, data were reduced to both average and  
154 peak values (noted  $\bar{\Delta}$  and  $\hat{\Delta}$ , respectively) of the total and the axial deviations for each movement  
155 and each subject. Results were reported as mean  $\pm$  standard deviation. Since all the models have a  
156 common root, these deviations corresponded to the humeral misorientation. To test the effect of  
157 the model, mean and peak deviations were analyzed using separated repeated measures ANOVAs  
158 with Bonferroni-corrected contrasts ( $\alpha=0.05$ ). Based on our hypotheses, the post-hoc tests were  
159 limited to *Arm* vs. *UpLimb*, *UpLimb* vs. *UpLimbP* and *UpLimb* vs. *UpLimbS* ( $\alpha=0.05/3$ ). The  
160 gain in accuracy when using a multibody kinematic model and then marker projection was  
161 calculated. Finally, 2D correlation coefficients were calculated for time histories of the  
162 scapulohumeral unit vectors (lateral, anterior and longitudinal vectors, *i.e.* the columns of the  
163 scapulohumeral rotation matrix) between *Arm*, *UpLimb*, *UpLimbP* or *UpLimbS* models and the  
164 *Humerus* model to assess their shape agreement.

### 165 3. Results

166 The last columns of **Tab. 1** summarize the number of frames available in each movement (*i.e.*  
167 a series of trials) for calculating average and peak values of humeral deviations. The movements  
168 had between  $2103 \pm 810$  and  $11269 \pm 7325$  frames, *i.e.* they last up to 38 seconds. The deviation  
169 values that characterized the misorientation in humeral kinematics with respect to the true bone  
170 kinematics are summarized in **Tab. 2** and illustrated in **Fig. S1-S4**. When using the *Arm* model  
171 (*i.e.* single-body optimization), the average total deviation  $\bar{\Delta}_{tot}$  exceeded  $10^\circ$  with peaks up to  
172  $21.1^\circ$ . When using cuff markers, the deviation of the longitudinal axis ( $\Delta_{long}$ ) showed lower  
173 values than anterior and lateral deviations. With skin markers, the three axes deviations gave  
174 similar values.

175 All the ANOVAs with the models as independent variables were significant (all  $p < 10^{-4}$ ). Post-  
176 hoc tests revealed that there was a systematic gain in accuracy (all  $p < 10^{-4}$ ) from *Arm* to *UpLimb*  
177 models, with both cuff and skin markers. The gain ranged between 37% ( $\bar{\Delta}_{lat}$  with skin markers)  
178 and 63% ( $\hat{\Delta}_{long}$  with skin markers). Using a multibody model, the total deviation dropped on  
179 average to  $6.1 \pm 3.2^\circ$  and  $5.3 \pm 1.9^\circ$  for the cuff and skin markers, respectively, with peaks up to  
180  $11.1 \pm 4.8^\circ$  for cuff markers but  $\leq 10^\circ$  when using skin markers.

181 With marker projection on the longitudinal arm axis, the gain relative to a standard multibody  
182 kinematic optimization (*UpLimb*) was different depending on the set of markers (skin vs. cuff)  
183 and the model (*UpLimbP* vs. *UpLimbS*). When markers were stuck on cuffs, average deviations  
184 were significantly reduced ( $0.0011 < p < 0.0023$ ) except for  $\hat{\Delta}_{long}$  ( $p = 0.3219$ ). The gain on the total  
185 deviation was 18%. However, the peak values were not significantly different between *UpLimbP*  
186 and *UpLimb* models (all  $p > 0.6590$ ). Similar results were found when three skin markers of the  
187 arm (all but the medial epicondyle) were projected (*UpLimbS*): average misorientations were

188 improved up to 20% and the peak values were not improved. Using this innovative projection  
189 algorithm (*UpLimbP* with cuff markers and *UpLimbS*), the average error in humeral orientation  
190 remained below 5°.

191 When all the skin markers of the arm were projected (*UpLimbP*) onto its longitudinal axis,  
192 results were opposite. The average misorientation was not significantly improved (all  $p>0.4843$ )  
193 and all misorientation peak values were significantly increased (all  $p<0.0005$ ), of about 30%, *i.e.*  
194 3°.

195 All 2D-correlation coefficients (Table 3) were excellent ( $r>0.96$ ). They corroborated the  
196 results of the ANOVAs since their value increased when using standard multibody kinematic  
197 optimization (*UpLimb* vs *Arm*) and even more with projection of cuff markers (*UpLimbP*) and  
198 selection of skin markers (*UpLimbS*).

*Please insert Tab. 2 here*

*Please insert Tab. 3 here*

## 199 4. Discussion

200 An innovative multibody kinematic optimization algorithm with marker projection was  
201 developed, validated against true bone kinematics and compared to single-body and multibody  
202 optimizations. Its originality relies on the projection of markers onto a chosen anatomical axis to  
203 cancel their deleterious effect on the associated rotation due to large STA. Said algorithm was  
204 applied to the upper-limb with projection of the arm markers onto the longitudinal axis. The main  
205 findings were that multibody optimization improved the accuracy of 40 to 50% and the projection  
206 added an extra 20% when applied to cuff markers or a selection of skin markers. While only four  
207 subjects were involved, the findings relied on 4 categories of movements (analytic, ADL, sports  
208 activities and range of motion) including 18 movements from 5 to 36 seconds composed of up to  
209 10 trials.

### 210 4.1. Accurate humeral kinematics due to multibody optimization

211 Without multibody optimization, the maximal total deviation exceeded 20° with larger  
212 deviation for axial rotation than flexion and abduction (**Fig. S2**). These results agree with study of  
213 Hamming et al. (2012), also based on pin data. Large deviations were also found in ADL, sports  
214 activities, and range of motion, which reinforces the need of improved models for any kind of  
215 motion analysis.

216 When forearm markers were involved in the multibody system optimization, the deviation  
217 dropped to a few degrees with improved 2D correlation coefficients. This confirms the advantage  
218 of multibody over single-body optimization on the upper-limb, mainly highlighted using  
219 simulation (Roux et al., 2002). The values of the axis deviations ( $\Delta_{lat}$ ,  $\Delta_{ant}$ ,  $\Delta_{long}$ ) being similar,  
220 the remaining deviation was not associated anymore to the axial rotation. Similar results were  
221 found in Lin and Karduna (2013) for three movements exciting one DoF at a time. The present

222 study generalises the fact that reconstructions including markers on the forearm are efficient to  
223 estimate humeral kinematics, based on true bone kinematics and a large variety of movements.

224 The projection of markers onto a desired axis related to a degree-of-freedom is the most  
225 innovative feature in this study. In some conditions, it contributed to improve the accuracy to  $5^\circ$ .  
226 The remaining deviation may be associated to the estimation of both the elbow flexion axis and  
227 the shoulder joint center locations. Similarly to Lin and Karduna (2013), a functional elbow axis  
228 was preferred to the midpoint between the medial and lateral epicondyles. The axis obtained from  
229 skin/cuff markers did, however, not coincide with the axis given by the pin markers. Also, the  
230 scapulohumeral joint location was not chosen as a gold standard position, often unknown in  
231 clinical evaluation. An error of about 5 mm in the scapulohumeral joint location (Michaud et al.,  
232 2016) may result in about  $5^\circ$  as shown for the lower-limb (Stagni et al., 2000). As a perspective,  
233 the sensitivity of the method to anatomical axis estimation should be tested. By respecting all the  
234 recommendations to accurately define a multibody kinematic model and reconstruct the shoulder  
235 kinematics,  $5^\circ$  may be the floor value when using non-invasive approaches based on  
236 optoelectronic systems.

#### 237 *4.2. Algorithm advantages and limitations*

238 The multibody optimization with selected marker projection improved the joint kinematics for  
239 a broad range of movements, for four subjects with different anthropometry (IMC from 21 to  
240  $35 \text{ kg/m}^2$ ). The main advantage of the method is to not have subject- or movement-specific  
241 correction, contrary to weighted single-body optimization (Begon et al., 2015) to compensate for  
242 the STA of each marker (Blache et al., 2016). However, the selection of markers to be projected  
243 remains.

244 ADL are generally performed with some elbow flexion (Buckley et al., 1996) but most of the  
245 biomechanical evaluation in clinics are composed of arm elevation with extended elbow (Robert-  
246 Lachaine et al., 2015). Previous algorithms have to be adjusted when the elbow is extended (Cutti  
247 et al., 2006; Schmidt et al., 1999). On the other hand, multibody optimization with or without  
248 marker projection is robust to movements where the elbow is extended, such as abduction,  
249 flexion (ADL category) and arm elevation with neutral or maximal internal/external arm rotation  
250 (RoM category).

251 The effect of marker projection was favorable when using cuff markers or with a selection of  
252 skin markers. Indeed, the forearm skin markers were put close to the ulna to minimize the effect  
253 of the pro-supination which was not included in the model. However, markers put on the cuff  
254 may undergo pro-supination. Similarly to the arm markers, these markers may be projected onto  
255 the pro-supination axis of the forearm which should be functionally estimated, as previously  
256 suggested by Cutti et al. (2006), since it is not orthonormal to the elbow flexion axis. Further  
257 studies are required to assess the algorithm combined with an upper-limb model including pro-  
258 supination and hand which may interfere with other DoFs.

259 This algorithm with marker projection may be applied to other segments, especially the thigh  
260 and the scapula to offset the deleterious effect of markers with respect to selected DoFs. Since the  
261 thigh has a larger diameter and knee flexion varies between 0 and 20° during the stance phase  
262 (Cheze, 2000; Reinschmidt et al., 1997), the projection of the thigh markers onto its longitudinal  
263 axis may result in some correction of the thigh rotation. The main limitation would be the  
264 estimation of the knee model, which is key in the lower-limb kinematics estimation (Duprey et  
265 al., 2010). Regarding the scapula, markers are subject to large STA, except for the acromion and  
266 lateral part of the scapula spine (Blache et al., 2016; Matsui et al., 2006). The projection of the



267 former markers may improve the estimation of the tilt and upward rotation without compromising  
268 that of the external rotation. While this algorithm is specific to optoelectronic systems, it could be  
269 adapted to electromagnetic/inertial sensors. In fact, the angle associated to the arm rotation  
270 should not be introduced into the fusion algorithm (*e.g.* extended Kalman filter) of the upper-limb  
271 multibody system.

272 As in the study of Hamming et al. (2012), the scapulohumeral joint kinematics for all the  
273 models was obtained using a common root segment. The error was consequently relative to the  
274 humerus only; additional misorientation may come from the scapula. Also, the scapulohumeral  
275 joint was modelled as a ball-and-socket joint, while this joint is subject to translations up to  
276 12.4 mm (Dal Maso et al., 2015; Dal Maso et al., 2014). Another drawback of our method was to  
277 *a priori* select four skin markers from the seven available in the experiment. This choice was  
278 motivated by three reasons. First, the four markers were selected for comparison to the cuff  
279 markers (n=4) and, more broadly, to conditions in clinics. Second, the marker put under the  
280 deltoid insertion was close to the pin. This marker has shown small STA (Blache et al., 2016)  
281 which may be underestimated due to the closeness of the pin. Unlike recommendations of  
282 Kontaxis et al. (2009), lateral and medial epicondyles were used because several clinical studies  
283 (Anglin and Wyss, 2000) include these markers and our recent study showed a small deformation  
284 energy associated to the medial epicondyle (Blache et al., 2016). Finally, the study emphasis was  
285 on the multibody kinematic optimisation; further studies should focus on optimal marker sets.

## 286 **5. Conclusion**

287 To cancel the deleterious effect of some markers on a selected-DoF kinematic reconstruction,  
288 an innovative multibody kinematic optimization algorithm with marker projection was presented,  
289 where some markers were projected onto the axis associated to the desired DoFs. This innovative

290 projection algorithm performed better than multibody and single-body optimizations, especially  
291 when using markers put on a cuff. Error of humeral orientation was reduced by half to finally be  
292 less than 5°.

293 **Conflict of interest statement**

294 Authors declare no conflict of interest.

295 **Acknowledgments**

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299 **References**

300 Anglin, C., Wyss, U.P., 2000. Review of arm motion analyses. Proceedings of the Institution  
301 of Mechanical Engineers, Part H: Journal of Engineering in Medicine 214, 541-555.

302 Begon, M., Dal Maso, F., Arndt, A., Monnet, T., 2015. Can optimal marker weightings  
303 improve thoracohumeral kinematics accuracy? Journal of Biomechanics, In Press, Corrected  
304 Proof

305 Begon, M., Wieber, P.B., Yeadon, M.R., 2008. Kinematics estimation of straddled movements  
306 on high bar from a limited number of skin markers using a chain model. Journal of Biomechanics  
307 41, 581-586.

308 Blache, Y., Dumas, R., Lundberg, A., Begon, M., 2016. Main component of soft tissue artefact  
309 of the upper-limbs with respect to different arm movements. Journal of Biomechanics (in  
310 revision).

311 Buckley, M.A., Yardley, A., Johnson, G.R., Cams, D.A., 1996. Dynamics of the Upper Limb  
312 during Performance of the Tasks of Everyday Living - A Review of the Current Knowledge  
313 Base. Journal of Engineering in Medicine 210, 241-247.

314 Challis, J.H., 1995. A procedure for determining rigid body transformation parameters. Journal  
315 of Biomechanics 28, 733-736.

316 Cheze, L., 2000. Comparison of different calculations of three-dimensional joint kinematics  
317 from video-based system data. Journal of Biomechanics 33, 1695-1699.

318 Cutti, A.G., Cappello, A., Davalli, A., 2005a. A new technique for compensating the soft tissue  
319 artefact at the upper-arm: in vitro validation. Journal of Mechanics in Medicine and Biology 5, 1-  
320 15.

321 Cutti, A.G., Cappello, A., Davalli, A., 2006. In vivo validation of a new technique that  
322 compensates for soft tissue artefact in the upper-arm: Preliminary results. *Clinical Biomechanics*  
323 21, S13–S19.

324 Cutti, A.G., Giovanardi, A., Rocchi, L., Davalli, A., Sacchetti, R., 2008. Ambulatory  
325 measurement of shoulder and elbow kinematics through inertial and magnetic sensors. *Medical &*  
326 *Biological Engineering & Computing* 46, 169-178.

327 Cutti, A.G., Paolini, G., Troncossi, M., Cappello, A., Davalli, A., 2005b. Soft tissue artefact  
328 assessment in humeral axial rotation. *Gait & Posture* 21, 341-349.

329 Dal Maso, F., Raison, M., Lundberg, A., Arndt, A., Allard, P., Begon, M., 2015.  
330 Glenohumeral translations during range-of-motion movements, activities of daily living, and  
331 sports activities in healthy participants. *Clinical Biomechanics* 30, 1002-1007.

332 Dal Maso, F., Raison, M., Lundberg, A., Arndt, A., Begon, M., 2014. Coupling between 3D  
333 displacements and rotations at the glenohumeral joint during dynamic tasks in healthy  
334 participants. *Clinical Biomechanics* 29, 1048-1055.

335 de Vries, W.H.K., Veeger, H.E.J., Cutti, A.G., Baten, C., van der Helm, F.C.T., 2010.  
336 Functionally interpretable local coordinate systems for the upper extremity using inertial &  
337 magnetic measurement systems. *Journal of Biomechanics* 43, 1983-1988.

338 Dumas, R., Camomilla, V., Bonci, T., Cheze, L., Cappozzo, A., 2014. Generalized  
339 mathematical representation of the soft tissue artefact. *J Biomech* 47, 476-481.

340 Duprey, S., Cheze, L., Dumas, R., 2010. Influence of joint constraints on lower limb  
341 kinematics estimation from skin markers using global optimization. *Journal of Biomechanics* 43,  
342 2858-2862.

343 Ehrig, R.M., Taylor, W.R., Duda, G.N., Heller, M.O., 2006. A survey of formal methods for  
344 determining the centre of rotation of ball joints. *Journal of Biomechanics* 39, 2798–2809.

345 El Habachi, A., Duprey, S., Cheze, L., Dumas, R., 2013. Global sensitivity analysis of the  
346 kinematics obtained with a multi-body optimisation using a parallel mechanism of the shoulder.  
347 *Comput Method Biomec* 16, 61-62.

348 Felis, M.L., 2011. RBDL – Rigid Body Dynamics Library : <http://rbd.bitbucket.org/>.

349 Fohanno, V., Begon, M., Lacouture, P., Colloud, F., 2014. Estimating joint kinematics of a  
350 whole body chain model with closed-loop constraints. *Multibody System Dynamics* 31, 433-449.

351 Haering, D., Raison, M., Begon, M., 2014. Measurement and description of three-dimensional  
352 shoulder range of motion with degrees of freedom interactions. *Journal of biomechanical*  
353 *engineering* 136, 084502.

354 Hamming, D., Braman, J.P., Phadke, V., LaPrade, R.F., Ludewig, P.M., 2012. The accuracy of  
355 measuring glenohumeral motion with a surface humeral cuff. *Journal of Biomechanics* 45, 1161-  
356 1168.

357 Horn, B.K.P., Hilden, H.M., Negahdaripour, S., 1988. Closed-form solution of absolute  
358 orientation using orthonormal matrices. *Journal of the Optical Society of America A* 5, 1127-  
359 1135.

360 Jackson, M., Benkhemis, I., Begon, M., Sardain, P., Vallée, C., Lacouture, P., 2012.  
361 Identifying the criterion spontaneously minimized during the take-off phase of a sub-maximal  
362 long jump through optimal synthesis. *Multibody System Dynamics* 28, 225-237.

363 Kontaxis, A., Cutti, A.G., Johnson, G.R., Veeger, H.E.J., 2009. A framework for the definition  
364 of standardized protocols for measuring upper-extremity kinematics. *Clinical Biomechanics* 24,  
365 246-253.

366 Laitenberger, M., Raison, M., Perie, D., Begon, M., 2015. Refinement of the upper limb joint  
367 kinematics and dynamics using a subject-specific closed-loop forearm model. *Multibody System*  
368 *Dynamics* 33, 413-438.

369 Lawrence, R.L., Braman, J.P., Staker, J.L., LaPrade, R.F., Ludewig, P.M., 2014. Comparison  
370 of 3-dimensional shoulder complex kinematics in individuals with and without shoulder pain,  
371 part 2: glenohumeral joint. *Journal of orthopaedic & sports physical therapy* 44, 646-643.

372 Lin, Y.-L., Karduna, A.R., 2013. Sensors on the Humerus Are Not Necessary for an Accurate  
373 Assessment of Humeral Kinematics in Constrained Movements. *Journal of Applied*  
374 *Biomechanics* 29, 496-500.

375 Ludewig, P.A., Cook, T.M., Shields, R.K., 2002. Comparison of surface sensor and bone-fixed  
376 measurement of humeral motion. *Journal of Applied Biomechanics* 18, 163-170.

377 Lundberg, A., Aguilera, A., Cappozzo, A., Arndt, A., Begon, M., 2014. Entropy in the List of  
378 Authors of Scientific Papers. *Annals of improbable research* 20, 15-17.

379 Matsui, K., Shimada, K., Andrew, P.D., 2006. Deviation of skin marker from bone target  
380 during movement of the scapula. *Journal of Orthopaedic Science* 11, 180-184.

381 Michaud, B., Jackson, M., Arndt, A., Lundberg, A., Begon, M., 2016. Determining in vivo  
382 sternoclavicular, acromioclavicular and glenohumeral joint centre locations from skin markers,  
383 CT-scans and intracortical pins: A comparison study. *Medical engineering & physics* 38, 290-  
384 296.

385 Monnet, T., Begon, M., Vallée, C., Lacouture, P., 2010. Improvement of the input data in  
386 biomechanics: kinematic and body segment inertial parameters, in: Jerrod H. Levy (Ed.),  
387 *Biomechanics: Principles, Trends and Applications*. Nova Science Publishers, Inc., pp. 353-385.

388 O'Brien, J.F., Bodenheimer Jr, R.E., Brostow, G.J., Hodgins, J.K., 1999. Automatic joint  
389 parameter estimation from magnetic motion capture data. Georgia Institute of Technology.

390 Phadke, V., Braman, J.P., LaPrade, R.F., Ludewig, P.M., 2011. Comparison of glenohumeral  
391 motion using different rotation sequences. *Journal of Biomechanics* 44, 700-705.

392 Rab, G., Petuskey, K., Bagley, A., 2002. A method for determination of upper extremity  
393 kinematics. *Gait & Posture* 15, 113-119.

394 Reinschmidt, C., van den Bogert, A.J., Lundberg, A., Nigg, B.M., Murphy, N., Stacoff, A.,  
395 Stano, A., 1997. Tibiofemoral and tibiocalcaneal motion during walking: external vs. skeletal  
396 markers. *Gait & Posture* 6, 98-109.

397 Robert-Lachaine, X., Allard, P., Gobout, V., Begon, M., 2015. Shoulder Coordination During  
398 Full-Can and Empty-Can Rehabilitation Exercises. *Journal of Athletic Training* 50, 1117-1125.

399 Roux, E., Bouilland, S., Godillon-Maquinghen, A.P., Bouttens, D., 2002. Evaluation of the  
400 global optimisation method within the upper limb kinematics analysis. *Journal of Biomechanics*  
401 35, 1279-1283.

402 Schmidt, R., Disselhorst-Klug, C., Silny, J., Rau, G., 1999. A marker-based measurement  
403 procedure for unconstrained wrist and elbow motions. *Journal of Biomechanics* 32, 615-621.

404 Senk, M., Chèze, L., 2006. Rotation sequence as an important factor in shoulder kinematics.  
405 *Clinical Biomechanics* 21, S3-S8.

406 Stagni, R., Leardini, A., Cappozzo, A., Grazia Benedetti, M., Cappello, A., 2000. Effects of  
407 hip joint centre mislocation on gait analysis results. *Journal of Biomechanics* 33, 1479-1487.

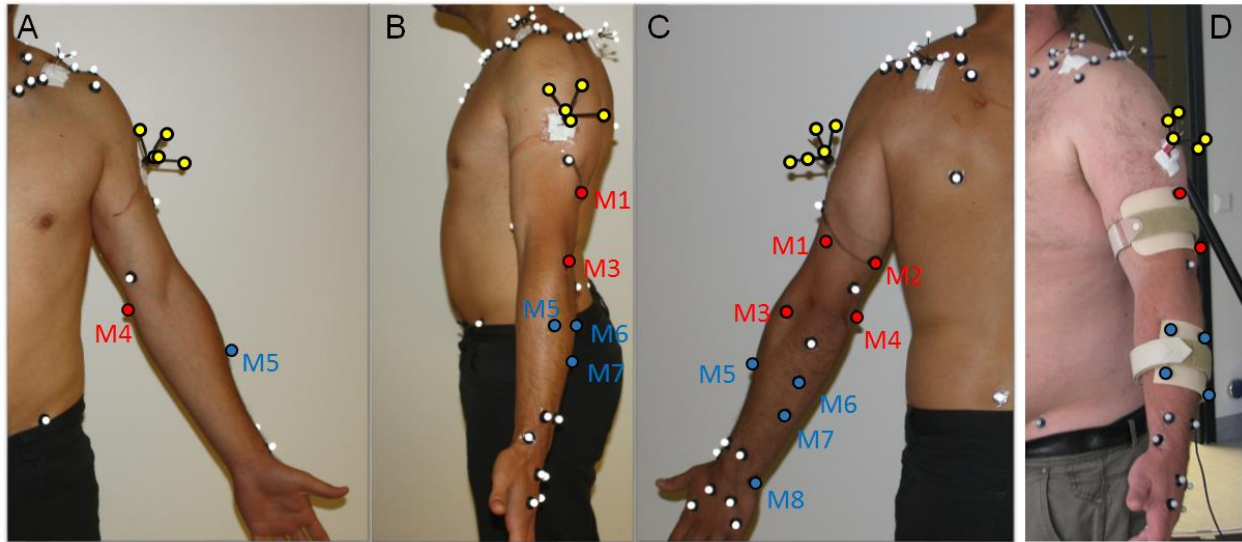
408 van Andel, C.J., Wolterbeek, N., Doorenbosch, C.A., Veeger, D.H., Harlaar, J., 2008.  
409 Complete 3D kinematics of upper extremity functional tasks. *Gait & Posture* 27, 120-127.

410 Wu, G., van der Helm, F.C.T., Veeger, H.E.J., Makhsous, M., Van Roy, P., Anglin, C.,  
411 Nagels, J., Karduna, A.R., McQuade, K., Wang, X.G., Werner, F.W., Buchholz, B., 2005. ISB  
412 recommendation on definitions of joint coordinate systems of various joints for the reporting of  
413 human joint motion - Part II: shoulder, elbow, wrist and hand. *Journal of Biomechanics* 38, 981-  
414 992.

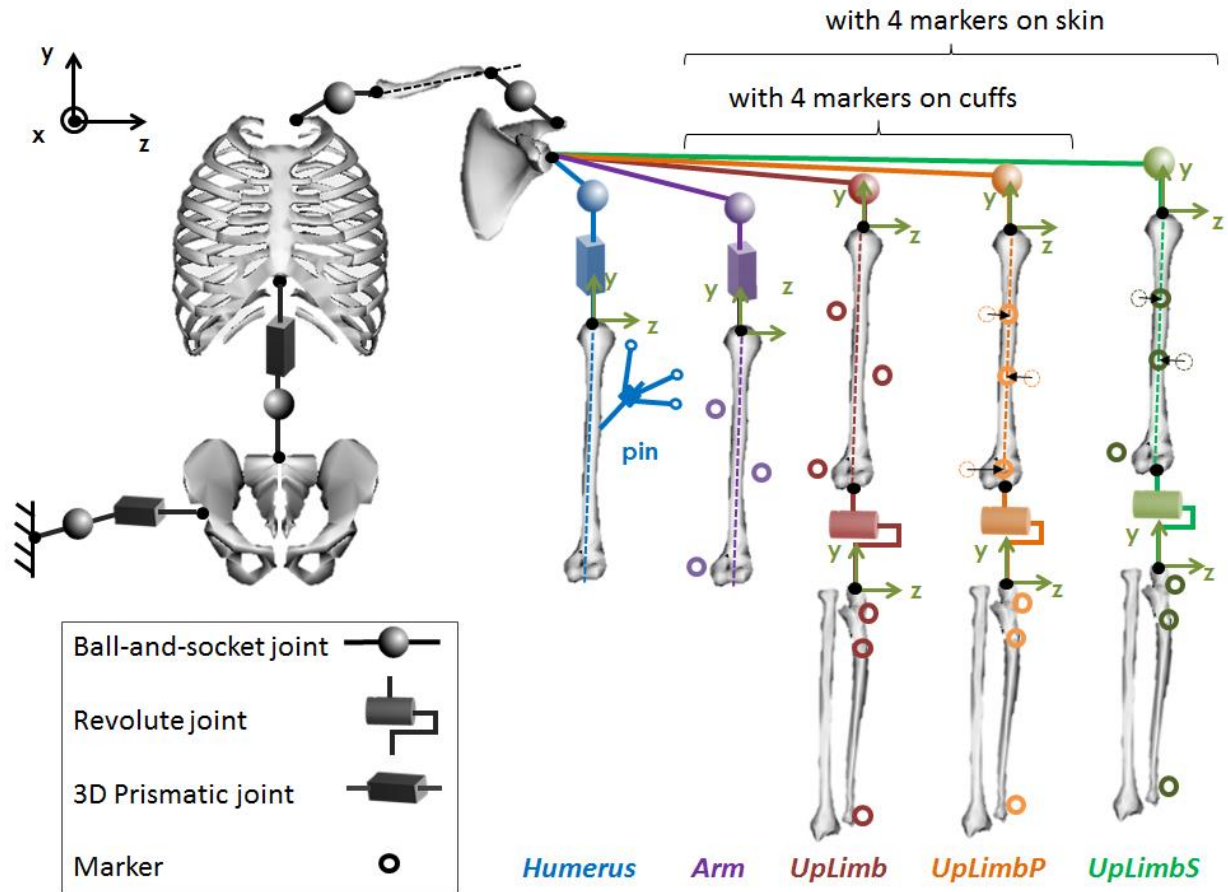
415



## Figures and Tables



**Fig. 1:** (A-C) Markers were put on an intracortical pin (in yellow), on the skin of the arm (red) and forearm (blue) and (D) on the cuffs. Specifically, the skin markers were placed as follow: laterally (M1) and medially (M2) to the belly of the triceps, lateral epicondyle (M3), medial epicondyle (M4), medial (M5) and lateral (M6) aspects of the brachioradialis, at the end of the triangle formed by the brachioradialis (M7) and on the ulnar styloid (M8).



**Fig. 2:** Five models with the common root (pelvis-thorax-clavicle-scapula) and their degrees-of-freedom, from left to right: *Humerus* with 6 DoFs and based on the markers attached to the intracortical pin screw in the humerus; *Arm* with 6 DoFs and based on the skin or cuff markers; *UpLimb* with 3 DoFs at the scapulohumeral joint and 1 DoF at the elbow based on skin and cuff markers; *UpLimbP* similar to *UpLimb* but all markers on the arm (skin or cuff) are projected onto the longitudinal axis; *UpLimbs* similar to *UpLimb* but three markers on the arm (M1-3, not M4) are projected onto the longitudinal axis.

**Tab. 1:** Description of the four categories of movements. The last two columns indicate the number of frames retained (mean±SD) for the analysis using trials with markers put on the skin or fixed on the cuffs (sampling rate: 300 Hz).

Categories	Movements	Comments	Number of Frames	
			Skin	Cuff
Analytic movements	1. Abduction	up to 10 repetitions	11188±6548	9067±6158
	2. Flexion	up to 10 repetitions	11269±7325	9550±6240
	3. Internal-External rotations with adducted arm		3806±1750	4042±1165
	4. Internal-External rotations with 90° of arm elevation in the scapular plan		2782±1572	3464±582
Activities of daily living (mimics of)	5. Eat**	with a spoon but no food	2988±866	2449±603
	6. Comb	with a comb	4607±1437	3851±1251
	7. Attach a bra in the back**	reach back	3394±989	3089±1321
	8. Wash armpit***	reach opposite armpit	1987±870	2103±810
	9. Reach front and back pockets	ipsolateral pocket	5979±3358	4899±2782
Sports activities (mimics of)	10. Tennis forehands and backhands	with a racket but no ball	4355±1042	N/A
	11. Throw a ball	without ball	3243±1139	N/A
	12. Clap		1547±520	N/A
	13. Punch*	in a piece of foam* with a stick but no puck	3088±988 3962±130	N/A N/A
	14. Hockey shoot			
Movements with maximal range of motion	15. Maximal arm elevation with the arm maximally internally rotated	in adduction, flexion, abduction and extension	4823±1757	N/A
	16. Maximal arm elevation with the arm maximally externally rotated	in adduction, flexion, abduction and extension	5511±1058	N/A
	17. Maximal arm elevation with the arm in neutral rotation	in adduction, flexion, abduction and extension	4110±1516	N/A
	18. Maximal internal-external rotation	for each combination of adduction, flexion, abduction and extension at 0°, 45°, 90°, 135° and 180°	9833±3827	N/A

\* This movement was not performed by subject 1 with skin markers.

\*\* This movement was not performed by subject 3 with cuffs.

N/A not applicable: this movement was not performed with cuff.

**Tab. 2:** Mean and standard deviation (SD) in degrees (°) of the four deviations (average  $\bar{\Delta}$  and peak  $\hat{\Delta}$  values) for models *Arm*, *UpLimb*, *UpLimbP* and *UpLimbS* relative to Humerus. P-values of the ANOVA and post-hoc tests are in bold when significant and the gain in accuracy (*UpLimb* vs *Arm*, *UpLimbP* vs *UpLimb* and *UpLimbS* vs *UpLimb*) is provided. Values are summarized for two marker sets, namely A) four cuff markers, B) four skin markers on the arm and forearm.

**A) Cuff markers** (n=35, 9 movements x 4 participants, except for subject 3 who performed 8 movements)

	<i>Arm</i>		<i>UpLimb</i>			<i>UpLimbP</i>			<i>p-values</i>		
	Mean	(SD)	Mean	(SD)	Gain	Mean	(SD)	Gain	ANOVA	<i>UpLimb</i> vs <i>Arm</i>	<i>UpLimb</i> vs <i>UpLimbP</i>
$\bar{\Delta}_{tot}$	10.5	(5.4)	6.1	(3.2)	<b>42%</b>	5.0	(2.3)	<b>18%</b>	<b>0.0000</b>	<b>0.0000</b>	<b>0.0023</b>
$\bar{\Delta}_{lat}$	9.4	(5.4)	5.4	(3.2)	<b>42%</b>	4.2	(2.1)	<b>22%</b>	<b>0.0000</b>	<b>0.0000</b>	<b>0.0017</b>
$\bar{\Delta}_{ant}$	9.4	(5.0)	5.3	(2.7)	<b>43%</b>	4.1	(2.0)	<b>22%</b>	<b>0.0000</b>	<b>0.0000</b>	<b>0.0011</b>
$\bar{\Delta}_{long}$	5.5	(3.3)	3.5	(2.4)	<b>36%</b>	3.3	(2.0)	5%	<b>0.0000</b>	<b>0.0000</b>	0.3219
$\hat{\Delta}_{tot}$	19.1	(8.7)	11.1	(4.8)	<b>42%</b>	10.9	(5.2)	2%	<b>0.0000</b>	<b>0.0000</b>	0.8067
$\hat{\Delta}_{lat}$	17.8	(8.2)	9.9	(4.6)	<b>44%</b>	9.7	(4.6)	3%	<b>0.0000</b>	<b>0.0000</b>	0.7112
$\hat{\Delta}_{ant}$	17.2	(7.8)	10.2	(4.6)	<b>41%</b>	9.9	(5.1)	3%	<b>0.0000</b>	<b>0.0000</b>	0.6590
$\hat{\Delta}_{long}$	12.1	(6.0)	7.4	(4.3)	<b>39%</b>	7.5	(4.2)	-2%	<b>0.0000</b>	<b>0.0000</b>	0.6970

**B) Skin markers** (n=70, 18 movements x 4 participants, except for subject 1 who performed 16 movements)

	<i>Arm</i>		<i>UpLimb</i>			<i>UpLimbP</i>			<i>UpLimbS</i>			<i>p-values</i>			
	Mean	(SD)	Mean	(SD)	Gain	Mean	(SD)	Gain	Mean	(SD)	Gain	ANOVA	<i>UpLimb</i> vs <i>Arm</i>	<i>UpLimbP</i> vs <i>UpLimb</i>	<i>UpLimbS</i> vs <i>UpLimb</i>
$\bar{\Delta}_{tot}$	10.2	(5.3)	5.3	(1.9)	<b>48%</b>	5.3	(1.8)	0%	4.4	(1.5)	<b>16%</b>	<b>0.0000</b>	<b>0.0000</b>	0.9835	<b>0.0020</b>
$\bar{\Delta}_{lat}$	6.8	(4.0)	4.3	(1.7)	<b>37%</b>	4.1	(1.7)	4%	3.4	(1.4)	<b>20%</b>	<b>0.0000</b>	<b>0.0000</b>	0.4843	<b>0.0010</b>
$\bar{\Delta}_{ant}$	8.4	(4.5)	4.7	(1.8)	<b>44%</b>	4.7	(1.7)	-1%	3.9	(1.4)	<b>17%</b>	<b>0.0000</b>	<b>0.0000</b>	0.9144	<b>0.0023</b>
$\bar{\Delta}_{long}$	8.7	(4.8)	3.6	(1.5)	<b>59%</b>	3.6	(1.3)	-1%	3.0	(1.1)	<b>14%</b>	<b>0.0000</b>	<b>0.0000</b>	0.8370	<b>0.0017</b>
$\hat{\Delta}_{tot}$	21.1	(12.2)	9.6	(3.9)	<b>54%</b>	12.4	(4.9)	<b>-29%</b>	9.3	(3.7)	4%	<b>0.0000</b>	<b>0.0000</b>	<b>0.0000</b>	0.5362
$\hat{\Delta}_{lat}$	17.0	(10.5)	8.5	(3.2)	<b>50%</b>	11.2	(4.7)	<b>-32%</b>	8.2	(3.6)	3%	<b>0.0000</b>	<b>0.0000</b>	<b>0.0000</b>	0.6368
$\hat{\Delta}_{ant}$	17.9	(9.7)	8.9	(3.7)	<b>50%</b>	11.6	(4.7)	<b>-30%</b>	8.5	(3.4)	5%	<b>0.0000</b>	<b>0.0000</b>	<b>0.0001</b>	0.4757
$\hat{\Delta}_{long}$	18.7	(11.7)	6.8	(3.2)	<b>63%</b>	8.5	(3.9)	<b>-25%</b>	6.8	(3.0)	1%	<b>0.0000</b>	<b>0.0000</b>	<b>0.0005</b>	0.9295

**Tab. 3:** Mean and standard deviation (SD) of the 2D correlation coefficients of lateral ( $r_{lat}$ ), anterior ( $r_{ant}$ ) and longitudinal ( $r_{long}$ ) axes of the *Arm*, *UpLimb*, *UpLimbP* and *UpLimbS* models and the *Humerus* model. Values are summarized for two marker sets, namely A) four cuff markers, B) four skin markers on the arm and forearm.

**A) Cuff markers** (n=35, 9 movements x 4 participants, except for subject 3 who performed 8 movements)

	<i>Arm</i>		<i>UpLimb</i>		<i>UpLimbP</i>	
	Mean	(SD)	Mean	(SD)	Mean	(SD)
$r_{lat}$	0.985	(0.016)	0.996	(0.004)	0.997	(0.003)
$r_{ant}$	0.965	(0.036)	0.988	(0.015)	0.992	(0.014)
$r_{long}$	0.998	(0.003)	0.999	(0.002)	0.999	(0.002)

**B) Skin markers** (n=70, 18 movements x 4 participants, except for subject 1 who performed 16 movements)

	<i>Arm</i>		<i>UpLimb</i>		<i>UpLimbP</i>		<i>UpLimbS</i>	
	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	(SD)
$r_{lat}$	0.978	(0.115)	0.998	(0.002)	0.998	(0.002)	0.998	(0.002)
$r_{ant}$	0.975	(0.074)	0.994	(0.005)	0.994	(0.005)	0.996	(0.005)
$r_{long}$	0.981	(0.023)	0.998	(0.002)	0.998	(0.002)	0.998	(0.002)