



Closed-loop multibody kinematic optimization coupled with double calibration improves scapular kinematic estimates in asymptomatic population

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ARTICLE INFO

Keywords:

Scapula
Scapulo-thoracic
Shoulder
Scapula locator

ABSTRACT

Non-invasive methods still need to better estimate scapular kinematics because of soft tissue artifact issue. This study aimed to develop and assess new procedures to estimate scapular kinematics by combining closed kinematic chain optimization and double calibration. Sixteen healthy volunteers performed static postures mimicking analytical and daily living movements. Scapulo-thoracic angles were computed either with a scapula locator (*Ref*), or with a closed-loop multibody kinematic optimization (*Ell*) or with double calibration involving linear (*DClin*), exponential (*DCexp*) or logarithmic (*DClog*) correction. Double calibration corrections enforced scapulo-thoracic angles to be the same than those measured with *Ref* at the end of the movement performed. *DClin* and *DClog* significantly ($p < 0.01$) reduced scapulo-thoracic misorientation for at least the second third of the movement with averaged improvement ranging from 9° to 32°. Moreover, for arm elevation in the sagittal plane, internal rotations and mimicking hair combing, the beneficial effect of *DClin* and *DClog* propagates up to half of the movement. To conclude, when a kinematic chain is required, coupling double calibration (using either linear or logarithmic correction), to a closed-loop multibody kinematic optimization is an efficient and fast method in regard with improvement in scapular kinematic estimates in healthy population.

1. Introduction

Scapular kinematic assessment is of great interest for populations performing overhead sports (Rogowski et al., 2015), manual handling task (Goubault et al., 2020) or for patients suffering from shoulder disorders (Fu et al., 2019). Nevertheless, non-invasive assessment of scapular kinematics through skin-marker based methods is subject to soft tissue artifact leading to inaccurate evaluation of scapular movements (Blache et al., 2017). Consequently, non-invasive methods still need to better estimate scapular kinematics in either healthy or symptomatic individuals.

Several procedures have been suggested to improve scapular kinematic estimates by reducing deleterious effects of soft tissue artifact (Lempereur et al., 2014). Acromion marker cluster method is usually proposed (Lempereur et al., 2012; Shaheen et al., 2011a; Van Andel et al., 2009) to assess scapular kinematics and was improved with double (Brochard et al., 2011) or multiple calibrations (Prinold et al.,

2011). More recently, linear (Nicholson et al., 2017; Rapp et al., 2017; Richardson, 2021) or non-linear regressions (Matsumura et al., 2019) based on an acromion marker cluster and multiple calibrations have also been developed to improve scapular kinematics. Although all these procedures enable accurate estimation of scapular kinematics, they are not appropriate when a multibody kinematic chain is needed for musculoskeletal modeling purpose. Most of musculoskeletal models (Quental et al., 2016; Sarshari et al., 2021; Seth et al., 2016) require a constant clavicle length to avoid abnormal joint dislocation, which is not considered for acromion cluster marker methods.

Multibody kinematic optimization, which consists of optimizing joint angles by minimizing the distance between the position of experimental markers and the position of the virtual markers of the kinematic chain model, is also commonly used to assess scapular kinematic (Duprey et al., 2017). Such algorithms have been improved with a closed-loop ensuring the scapula to slide along an ellipsoid representing the sliding plane between the thorax and the scapula (El Habachi et al.,

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2015; Michaud et al., 2017; Prinold and Bull, 2014; Seth et al., 2016). Although closed-loop kinematic chain, implemented with a single calibration, avoids abnormal joint dislocation and improves scapular kinematic estimates, Michaud et al. (2017) still observed non negligible scapular misorientation. High scapular misorientation, especially above 90° of humerothoracic elevation, might be reduced based on a second calibration performed at the end of the movement. In addition, current double calibration methods relies on linear correction (Brochard et al., 2011; Zhang, 2002), which might be inappropriate whether scapular misorientation increases non-linearly through the movement. It may be assumed that coupling closed-loop kinematic chain to double calibration with linear or non-linear correction can be a promising approach to improve scapular kinematic estimates when a kinematic chain is required.

This study aimed, therefore, to develop and assess new procedures to estimate scapular kinematics when combining closed-loop kinematic chain optimization and double calibration.

2. Methods

2.1. Participants

Sixteen healthy volunteers (12 males and 4 females, age: 27.6 ± 4.3 years; height: 173.2 ± 8.5 cm; mass: 69.7 ± 10.6 kg) took part in this study. They declared no history of shoulder injury during the year prior to the experimentation. The local ethical committee of the University approved the study, and all participants signed an informed consent form.

2.2. Data collection and procedure

While standing upright the participants were equipped with 10 reflective markers (Fig. 1). Then a scapula locator was calibrated to each participant's scapula by palpating the posterior part of the acromion angle, the trigonum spinae and the inferior angle (Fig. 1). The intra-rater reliability of the scapula locator calibration was defined by intraclass

coefficient of correlation (ICC) ranging from 0.73 to 0.94 and relative standard error of measurement (SEM) from 2.8% to 5.3% (see supp-1 file for more details). Marker trajectories were recorded using a 10-camera optoelectronic system (Qualysis, Sweden).

The participants randomly mimicked five analytical and two daily-living movements: arm elevations in the sagittal, scapular and frontal planes, humerothoracic internal rotation either with the arm along the trunk or abducted at 90° in the frontal plane, hair combing and lifting a 2-kg-box. As static measurements were required to assess scapula orientation with the scapula locator, each movement was broken down into five static poses (P1 to P5). For arm elevations and internal rotations, a guide was used to ensure poses at about 0% (0° - resting pose), 25% (about 40°), 50% (about 80°), 75% (about 110°) and 100% (about 135°) of maximal humerothoracic elevation or rotation. For the two daily living movements the five poses split the movements equally from its start to its end (see supp-2 file for more details). At each pose the scapula locator was placed after palpation on the three bony landmarks of the scapula (Shaheen et al., 2011b). The intra-rater reliability of the scapula locator measurements was defined by ICC ranging from 0.72 to 0.99 and SEM from 1.56° to 4.71° (see supp-3 file for more details).

2.3. Kinematics

Subject-specific kinematic models were calibrated regarding the recommendations of the International Society of Biomechanics (Wu et al., 2005) with joint centers of rotation and segment lengths computed while the participant stood upright in an anatomical pose (Michaud et al., 2016). All models were composed of three segments (thorax, clavicle and scapula) and six degrees of freedom (DoF) between the ground and the thorax. Then, five multibody kinematic optimizations were developed to estimate scapulo-thoracic angles. The reference method (*Ref*) allowed for six DoF between the scapula and the thorax, while the scapula-locator marker-coordinates were used for kinematic reconstruction. The second method (*Ell*) allowed for five DoF between the scapula and the thorax, namely, two DoF for the translation of the scapula center along an ellipsoid representing the thorax (Michaud

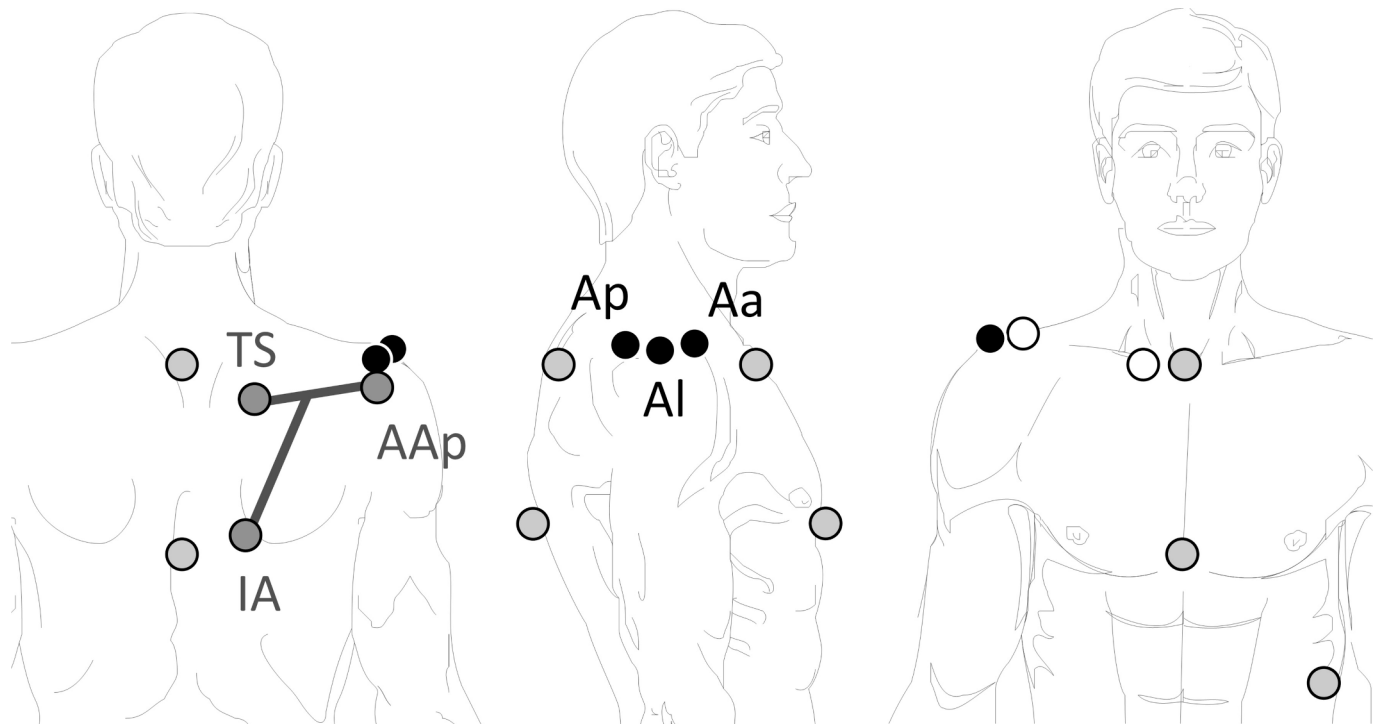


Fig. 1. Marker set up. Five markers on the thorax, two markers on the clavicle, three markers on the acromion process (Aa, Al, Ap) and the scapula locator defined by AAp, TS and IA.

et al., 2017) and three DoF for rotations following the sequence upward/downward rotation, internal/external rotation and anterior/posterior tilt. An equality constraint was implemented to ensure a constant clavicle length. For this procedure three skin markers located on the acromion were used for scapular reconstruction. The three other methods consisted of performing a double calibration using the initial and final poses obtained with *Ref*. Linear (*DClin*) [Eq.1] (Zhang, 2002), exponential (*DCexp*) [Eq.2] and logarithmic (*DClog*) [Eq.3] corrections were applied to scapulo-thoracic angles estimated with *Ell* such that a progressive correction nullifies joint angle difference between *DClin*/*DCexp*/*DClog* and *Ref* at the final pose of the movement.

$$\theta_{Clin}^j(t) = \theta_{Ell}^j(t) + X_{Clin} \cdot (\theta_{Ref}^j(T) - \theta_{Ell}^j(T)), \quad (1)$$

$$\theta_{Cexp}^j(t) = \theta_{Ell}^j(t) + e^{(X_{Cexp})} \cdot (\theta_{Ref}^j(T) - \theta_{Ell}^j(T)), \quad (2)$$

$$\theta_{Clog}^j(t) = \theta_{Ell}^j(t) + \ln(X_{Clog}) \cdot (\theta_{Ref}^j(T) - \theta_{Ell}^j(T)), \quad (3)$$

with θ^j : the humerothoracic angles for the j^{th} DoF computed with *Ref* or *Ell* models; either for *Lin*, *Exp* or *Log* corrections, $X_C = X_{min} + (t-1) \cdot [(X_{max} - X_{min}) / (T-1)]$, with t the frames from 1 to T (with T , the final sample frame of the simulated movement); minimal and maximal values of X_{Clin} , X_{Cexp} and X_{Clog} verifying $X_{Clin,min} = e^{(X_{Cexp,min})} = \ln(X_{Clog,min}) = 0$ and $X_{Clin,max} = e^{(X_{Cexp,max})} = \ln(X_{Clog,max}) = 1$. As exponential function presents a horizontal asymptote, $X_{Cexp,min}$ was set at -7 to approximate $e^{(X_{Cexp,min})} = 0$.

In order to compare scapular kinematics estimated with *Ell*, *DClin*, *DCexp* and *DClog* to those computed with *Ref*, scapular misorientation was computed through the helical axis angle (γ) [Eq.4] (De Vries et al., 2010).

$$\gamma^i = \arccos \left(\frac{\text{trace}(R_{Ref}^T \cdot R_i) - 1}{2} \right), \quad (4)$$

with R the scapulo-thoracic rotation matrix of *Ref* and i the four other methods

2.4. Statistics

Linear mixed models were used to assess the interaction effect of the kinematic method (*Ell*, *DClin*, *DCexp*, *DClog*) and the pose of the movement (from P1 to P4) on scapular misorientation relative to *Ref* method. The participants were entered as the random intercept. The level of significance was set at $p < 0.05$. The linearity, homoscedasticity and normality of the residuals were graphically controlled. Finally, when an interaction effect was revealed by the linear mixed model, each pose was independently analyzed, and the effect of the kinematic method was tested using Tukey post-hoc tests. Cohen's d was used for effect sizes. All analyses were executed using lme4 package of R 3.2 (R Foundation for Statistical Computing, Vienna, Austria.).

3. Results

The mean interindividual variability in humerothoracic elevation and rotation angles measured for analytical poses was $7.8^\circ \pm 4.4^\circ$. Regardless of the movement and DoF, scapulo-thoracic angles varied among kinematic methods (Fig. 2 and Supp-4 file). Scapular misorientation ranged from 6.7° to 33.5° , 0° to 27.9° , 0° to 28.7° , 0° to 28° for *Ell*, *DClin*, *DCexp* and *DClog* respectively (See Supp-5 file for more details).

For the last pose (P5) and when no correction was applied with *Ell*, mean scapular misorientation ranged between 8.0° and 15.7° while no scapular misorientation was observed with *DClin*, *DCexp* and *DClog*. For all movements, linear mixed models revealed an interaction effect

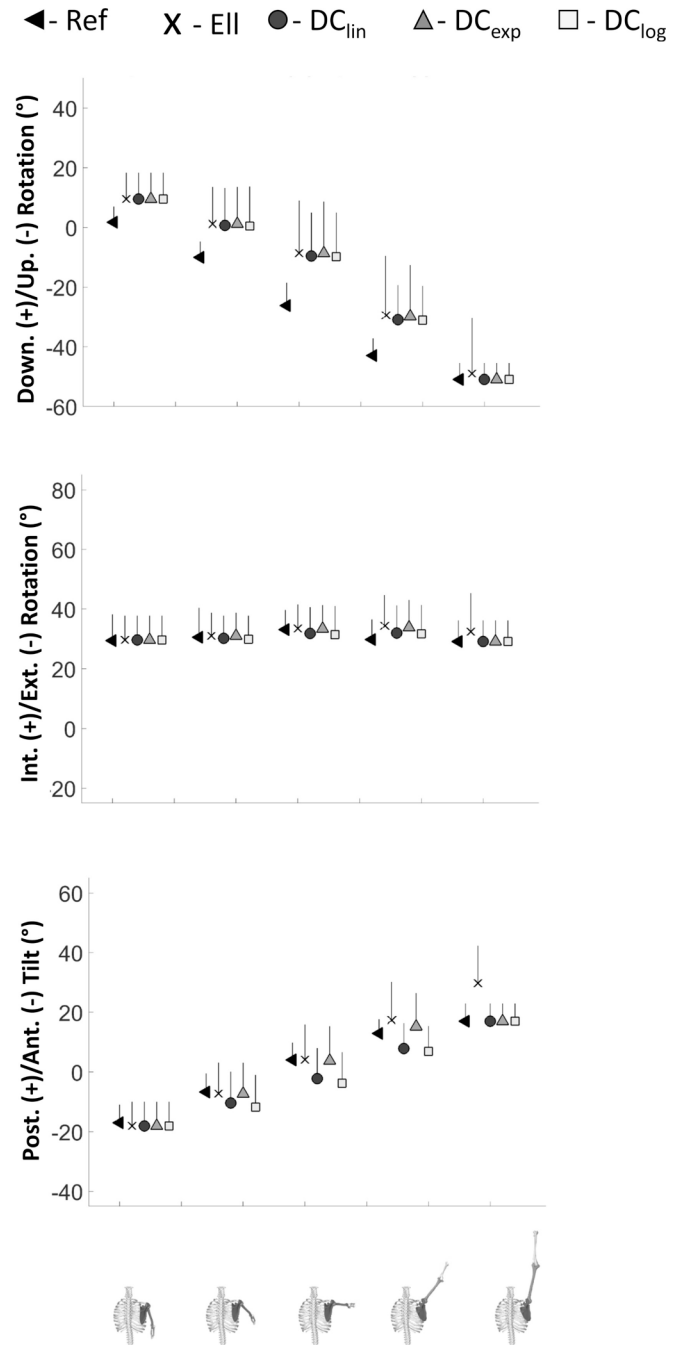


Fig. 2. Scapulo-thoracic angles at the five poses when mimicking arm elevation in the scapular plane computed with the reference (*Ref*), ellipsoid (*Ell*) models, linear (*DClin*), exponential (*DCexp*) and logarithmic (*DClog*) double calibrations.

between the kinematic method and the pose on scapular misorientation ($F[2.2-4.4]$, $p < 0.01$). When comparing kinematic methods for the fourth pose (P4) of each movement, both *DClin* and *DClog* methods presented significant lower scapular misorientation than *Ell* (Cohen's d : $[0.52-1.48]$, $p < 0.001$) for at least 88% of the participants, and represented an averaged improvement ranging from 9° to 32° (Figs. 3–5). For internal rotation with the arm along the thorax and hair combing, both *DClin* and *DClog* also improved scapular kinematic estimates at the third pose (P3) in comparison to *Ell* (Cohen's d : $[0.34-0.88]$, $p < 0.001$) for at least 75% of the participants (Figs. 4 and 5). Concerning arm elevation in the sagittal plane and internal rotation with the arm abduction at 90° , scapular kinematic estimates were also improved with

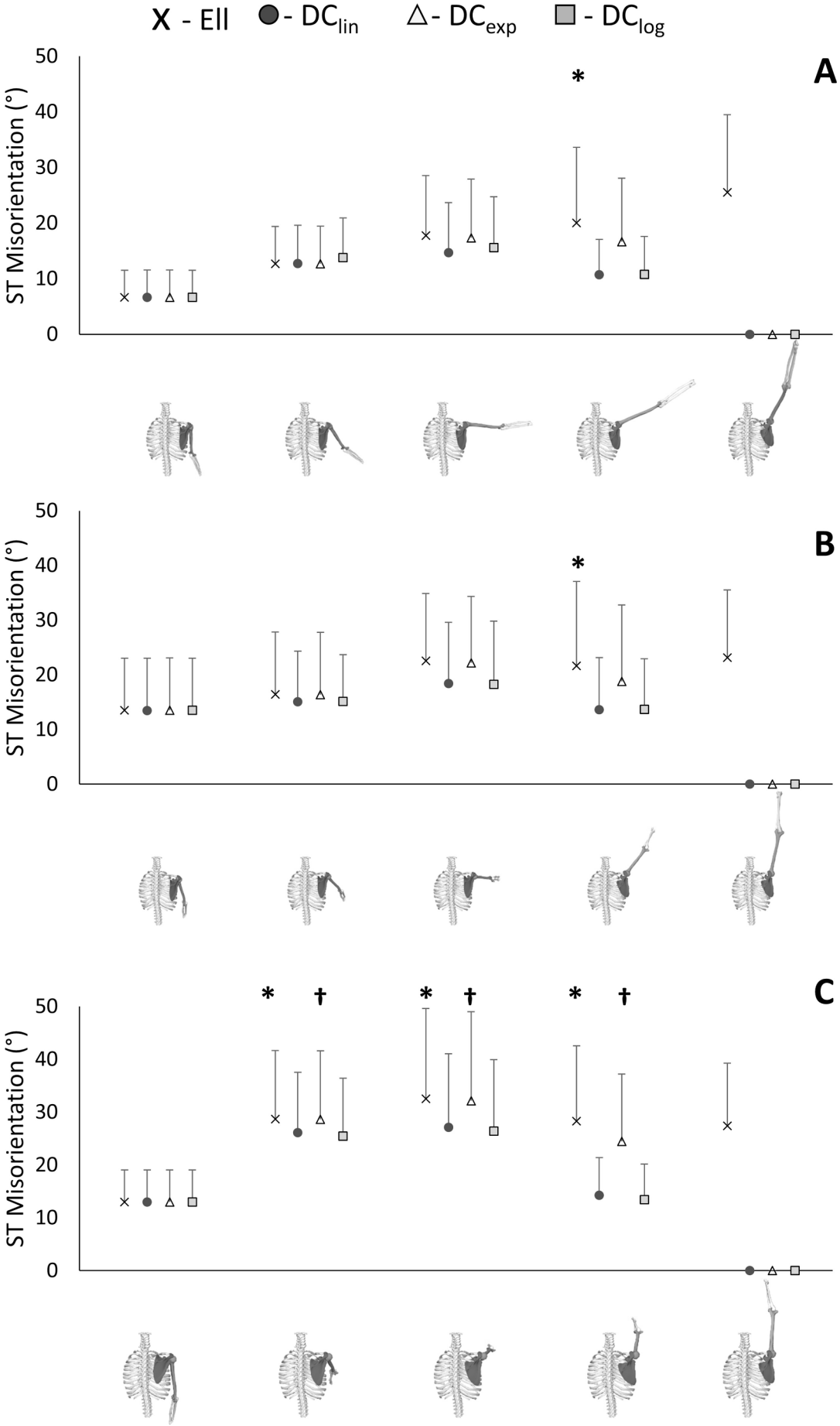


Fig. 3. Scapula misorientation for Ellipsoid model (Ell), linear (DClin), exponential (DCexp) and logarithmic (DClog) double calibrations relative to the reference model for the five poses (from P1 to P5) of **arm elevation in the frontal (A), scapular (B) and sagittal (C) plane**. * denotes Ell significantly ($p < 0.05$) different from DClin and DClog; † denotes DCexp significantly ($p < 0.05$) different from DClin and DClog.

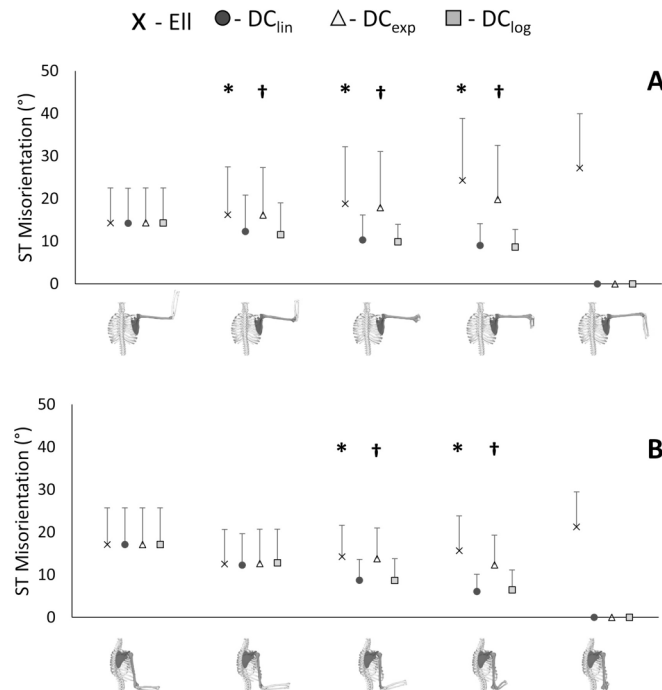


Fig. 4. Scapula misorientation for Ellipsoid model (Ell), linear (DClin), exponential (DCexp) and logarithmic (DClog) double calibrations relative to the reference model for the five poses (from P1 to P5) of **arm internal rotation at 90° (A) and 0° (B) of humerothoracic elevation**. * denotes Ell significantly ($p < 0.05$) different from DClin and DClog; † denotes DCexp significantly ($p < 0.05$) different from DClin and DClog.

both *DClin* and *DClog* in at least 73% and 80% of the participants for the second (P2) and third (P3) poses, respectively (Figs. 3 and 4). By contrast, regardless of the movement, *DCexp* did not significantly improve scapular kinematics estimates in comparison with *Ell*.

4. Discussion

The main findings of this study were that double calibration improves scapular kinematics for the last 25% to 50% of the movement with either linear or logarithmic correction.

Despite using a closed-loop kinematic chain improves scapular kinematics estimates, scapula misorientation up to 21° were still depicted for arm elevations (Michaud et al., 2017). Although similar scapular kinematic misorientation were observed without correction, we confirmed that adding a double calibration is more accurate for the second third of the movement during arm elevations (Brochard et al., 2011), with similar gains for internal rotations and daily living movements. More interestingly, for arm elevation in the sagittal plane, internal rotations and mimicking hair combing, the beneficial effect of the double calibration propagates up to half of the movement. Our results also suggest that scapular misorientation did not increase exponentially but rather linearly or logarithmically during the movement in healthy individuals. Nevertheless, the calibration of non-linear correction is made difficult with two calibration poses only. Besides, a large variability among DoF or participants was observed, confirming that soft tissue artifact are movement- and subject-specific (Blache et al., 2017). Implementing linear or logarithmic double calibration coupled with a closed-loop multibody kinematic optimization would be therefore

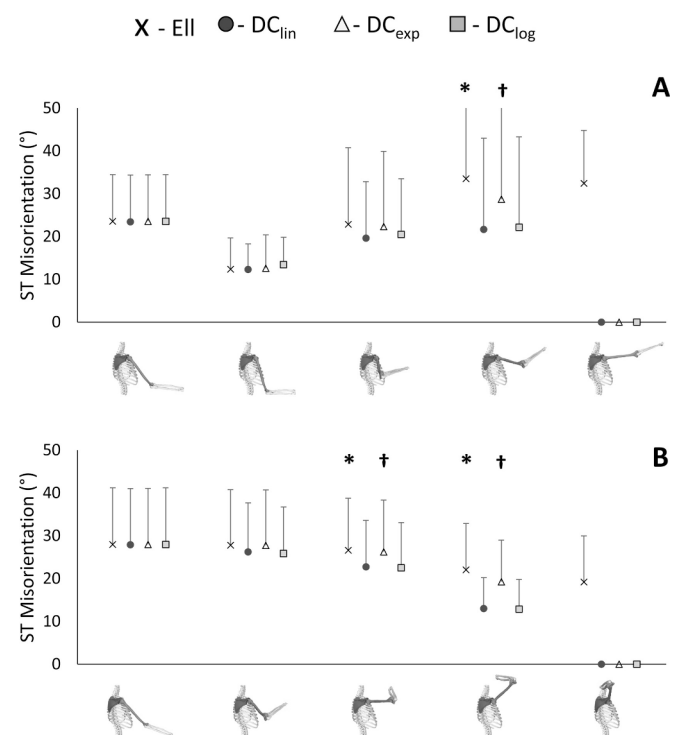


Fig. 5. Scapula misorientation for Ellipsoid model (Ell), linear (DClin), exponential (DCexp) and logarithmic (DClog) double calibrations relative to the reference model for the five poses (from P1 to P5) of **mimicking a box lifting (A) and hair combing (B)**. * denotes Ell significantly ($p < 0.05$) different from DClin and DClog; † denotes DCexp significantly ($p < 0.05$) different from DClin and DClog.

efficient to decrease deleterious effects of soft tissue artifact.

Multiple calibrations procedures have also proven their accuracy to estimate scapular kinematics (Prinold et al., 2011). Such methods could also be integrated to multibody kinematic optimization and are probably necessary to decrease scapular misorientation which is still not negligible after double calibration for flexion or daily living movements for instance. Nevertheless, from an experimental point of view, multiple calibrations are far more time consuming than double calibration and are subject to uncertainty: participants could not adopt the same scapular kinematics during the movement as during the static poses performed to calibrate the model.

This study presents some limitations. First, the scapula locator is only a “silver standard method” and is subject to palpation accuracy. Scapular angles measured using the scapular locator nevertheless showed good to excellent reliability and were similar to those obtained using intra-cortical pins (Ludewig et al., 2009). Second, double calibration methods were validated for static poses, while scapular positioning might be different during dynamic movements. Further studies combining bi-planar fluoroscopy or intra-cortical pins and skin markers need to address this issue. Third, interdependency in joint angles was not taken into consideration when corrections were performed, since the double calibration process occurs after the multibody kinematic optimization. Further studies need to perform sensitivity analysis to assess in what extend independent improvement of the three scapular rotations led to a better final orientation of the scapula.

To conclude, when a kinematic chain is required coupling double calibration, using either linear or logarithmic correction, with a closed-

loop multibody kinematic optimization is a fast and efficient method which improves scapular kinematic estimates in healthy individuals.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This study was carried out within the framework of the Associated International Laboratory EVASYM.

Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jbiomech.2021.110653>.

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