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Prediction bands and intervals for the scapulo-humeral coordination based on the Bootstrap and two Gaussian methods

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ABSTRACT

Quantitative motion analysis protocols have been developed to assess the coordination between scapula and humerus. However, the application of these protocols to test whether a subject's scapula resting position or pattern of coordination is "normal", is precluded by the unavailability of reference prediction intervals and bands, respectively. The aim of this study was to present such references for the "ISEO" protocol, by using the non-parametric Bootstrap approach and two parametric Gaussian methods (based on Student's T and Normal distributions).

One hundred and eleven asymptomatic subjects were divided into three groups based on their age (18–30, 31–50, and 51–70). For each group, "monolateral" prediction bands and intervals were computed for the scapulo-humeral patterns and the scapula resting orientation, respectively. A fourth group included the 36 subjects (42 ± 13 year-old) for whom the scapulo-humeral coordination was measured bilaterally, and "differential" prediction bands and intervals were computed, which describe right-to-left side differences.

Bootstrap and Gaussian methods were compared using cross-validation analyses, by evaluating the coverage probability in comparison to a 90% target. Results showed a mean coverage for Bootstrap from 86% to 90%, compared to 67–70% for parametric bands and 87–88% for parametric intervals. Bootstrap prediction bands showed a distinctive change in amplitude and mean pattern related to age, with an increase toward scapula retraction, lateral rotation and posterior tilt.

In conclusion, Bootstrap ensures an optimal coverage and should be preferred over parametric methods. Moreover, the stratification of "monolateral" prediction bands and intervals by age appears relevant for the correct classification of patients.

1. Introduction

The assessment of scapulo-thoracic resting position and motion in relation to humerus elevation, i.e. the "scapulo-humeral coordination", plays a central role in the clinical management of patients with shoulder disorders (Ludewig and Reynolds, 2009; De Baets et al., 2012; Morais and Pascoal, 2012; Kibler et al., 2012). The alteration of scapulo-humeral coordination, also known as scapula dyskinesis, has been described in association with various shoulder pathologies, including rotator-cuff tear, adhesive capsulitis and in post-stroke patients (Ludewig and Reynolds, 2009; De Baets et al., 2012). Despite debate on its possible causative or compensatory nature (De Baets et al., 2012), consensus exists on the importance of addressing dyskinesis for a more effective treatment of shoulder injury (Kibler et al., 2013; Cools et al., 2013).

In order to overcome the limitations of observational assessments (Ludewig and Reynolds, 2009; Hickey et al., 2007), quantitative motion analysis protocols have been developed to examine the multi-planar scapulo-humeral coordination, based on a variety of measurement systems, e.g. electromagnetic, optoelectronic, inertial sensors (De Baets et al., 2012; Kontaxis et al., 2009; Struyf et al., 2011; Garofalo et al., 2009; Cutti et al., 2008). Prediction intervals (PIs) and bands (PBs) must be available for these protocols to test if the scapula resting position and motion of a subject is within the physiological range of a control group (Lenhoff et al., 1999; Duhamel et al., 2004).

For numerical data, a PI is an interval around a mean value that contains, with a predefined probability, a new observation from the same population from which a training sample is drawn

Abbreviations: PBIs, Prediction Bands and Intervals; PB, Prediction Band; PI, Prediction Interval; MP, Monolateral Pattern; MO, Monolateral Offset; DP, Differential Pattern; DO, Differential Offset

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(Lenhoff et al., 1999). PBs are similar to PIs but do apply to continuous data, such as movement patterns (curves). PIs and PBs can then be used to test if a new subject is statistically different than the population from which the PIs and PBs were computed, e.g. to understand if a patient is recovering a "normal" scapulo-humeral coordination during the course of a rehabilitation programme.

Prediction bands and intervals (PBIs) can be classified as "monolateral" or "differential" (Delval et al., 2008). Given a sample of asymptomatic control subjects, monolateral PBIs are obtained by assessing a single side of each control subject and are used to test the normality of one side of a new subject. On the contrary, differential PBIs are obtained from assessing the *difference* in scapulo-humeral coordination of the right and left side of control subjects and are used to test if the difference between the sides of a new subjects is within normality. Differential PBIs can thus support in the clinical examinations where sides are compared, as commonly done in practice (Morais and Pascoal, 2012; Fialka et al., 2005). Moreover, differential PBIs can be useful in defining and assessing rehabilitation targets, since the kinematics of the controlateral side of a subject can be a more realistic goal than the pattern from a general population. Indeed, both sides of a subject share the subject's biological and personal history to a considerable extent (Lin et al., 2005; Downie and Miller, 2012; Bodin et al., 2012).

Unfortunately, neither "monolateral" nor "differential" PBIs are available for the scapulo-humeral coordination. Considering monolateral assessments, most of the literature focused on confidence intervals for the mean pattern of scapula rotations (Borstad and Ludewig, 2005; Crosbie et al., 2008; Ludewig et al., 2009; McClure et al., 2001; Fayad et al., 2006) or reported the mean patterns ± 1 standard deviation, typically for selected humerus elevation angles (Morais and Pascoal, 2012; van Andel et al., 2009; Yano et al., 2010; Pascoal et al., 2000). The calculation of PBIs from the available results suffers from three main limitations. Firstly, a limited number of subjects was typically involved in the studies, ranging from 10 to 20 (De Baets et al., 2012), lowering the confidence in the estimations and weakening the conclusions. Secondly, subjects were usually young adults (35 year-old average – De Baets et al., 2012) or spanned a wide age-range (Crosbie et al., 2008; Endo et al., 2004), which questions the applicability of PBIs computed from the available results for the classification of older patients (Endo et al., 2004; Tempelhof et al., 1999; Lin et al., 2005; Downie and Miller, 2012). Thirdly, current mean patterns and related uncertainty intervals were established using a point-by-point method based on the Gaussian theory. Such theory assumes a normal distribution of subjects' data and ignores the correlation between the points of the curve. In gait analysis, these assumptions led to narrow prediction bands with a reduced "coverage probability", i.e. including fewer curves than expected of known asymptomatic subjects. For instance, Lenhoff and co-workers reported an actual coverage probability of 54% instead of 90% for the knee flexion–extension (Lenhoff et al., 1999).

Considering "differential" assessments, no information is available despite the relevance of side-to-side comparisons (Morais and Pascoal, 2012; Hickey et al., 2007). This lack of knowledge limits the possibility of within-patient evaluations, since a "normal variability range" is missing when assessing the difference between a patient's own sound and affected side.

The aim of this study was to overcome the state-of-the-art, by generating age-stratified "monolateral" PBIs as well as "differential" PBIs for the scapulo-humeral coordination, based on the non-parametric Bootstrap technique (Efron and Tibshirani, 1993; Olshen et al., 1989). To the authors' knowledge, this methodology has never been applied to upper limb kinematics. To verify if the Bootstrap method is a superior tool for the calculation of PBIs in shoulder motion analysis, as in gait analysis (Lenhoff et al., 1999; Duhamel et al., 2004), a further aim of this study was to calculate PBIs based on the Gaussian theory and to compare the coverage probability of the methods. An example of clinical application of the PBIs is provided in Supporting information.

2. Methods

2.1. Subjects

Asymptomatic subjects ($N=111$; mean age $\pm$ SD: 38 ± 14) were recruited for this study after giving their informed consent. Subjects were split in three age-groups:

- group 1 (G1): from 18 to 30 year-old (mean 24), including 46 subjects (35 male);
- group 2 (G2): from 31 to 50 year-old (mean 40), including 35 subjects (22 male);
- group 3 (G3): from 51 to 70 year-old (mean 60), including 30 subjects (13 male).

A fourth group (GD) included all subjects for whom the scapulo-humeral coordination of both sides was measured ($N=36$; mean age $\pm$ SD: 42 ± 13): 10 subjects from G1 (6 male), 13 from G2 (9 male), and 13 from G3 (6 male).

2.2. Motion analysis protocol

To measure the scapulo-humeral coordination, the ISEO protocol was used (Cutti et al., 2008; Parel et al., 2012), with 3 MTx sensors (Xsens Technologies, NL). Each MTx is a small ($38 \times 53 \times 21$ mm) and lightweight (30 g) inertial and magnetic measurement unit, which provides the orientation of its embedded technical coordinate system relative to a global, earth-based coordinate system (Xsens Technical Manual).

For the application of ISEO on a subject, the following steps must be followed (Cutti et al., 2008; Parel et al., 2012):

- sensor placement on thorax, scapula and humerus (Fig. 1);
- anatomical coordinate systems calculation. A static measure is performed with the subject standing in a pre-defined posture: upright position, elbow flexed at 90°, neutral forearm rotation, humerus perpendicular to the ground and in

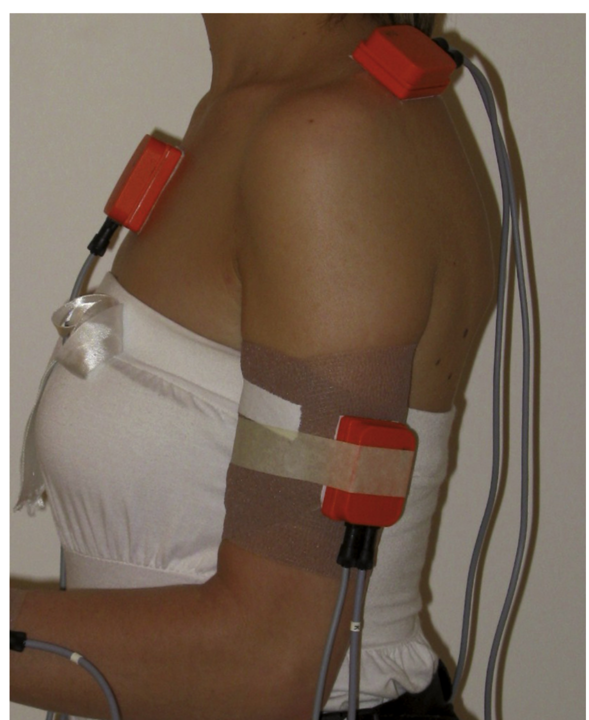

Fig. 1. Example of sensor placement for the ISEO protocol. For measuring the scapulo-humeral coordination, 3 sensors are required, positioned over thorax, scapula and humerus.