INTRODUCTION
The lateral (LE) and medial epicondyles (ME) and the gleno-humeral joint rotation centre (GHRC) are recommended by the International Society of Biomechanics to define the local coordinate system of the humerus [1]. Contrary to LE and ME which can be palpated and consequently adapted to each subject, GHRC is usually estimated with predictive or functional methods. The predictive methods calculate the centre of rotation (CoR) from empirical relations between specific anatomical landmarks [2]. The functional methods compute the CoR from the relative motion of adjacent body segments and are reported as accurate [3-5].

Contrary to GHRC, the hip joint centre (HJC) has been largely studied to compare the predictive and functional methods. The validation of the most widely used methods for estimating the position of the CoR were based in fact on simplified mechanical models that may functionally mimic this specific joint [5,6] or on computer based simulation [7]. The underlying mathematical approaches can be divided into two categories [3]. The first includes variants of "sphere fitting methods", where the centre and the radii of spheres are optimised to fit the trajectories of marker positions. The second type of approach considers the distance between markers on each joint segment fixed to enable the definition of a local coordinate system. Appropriate transformation of these local systems for all time frames into a common reference system enables approximation of the joint centre at a fixed position. These techniques are considered as "coordinate transformation methods".

These studies have been more focused on the accuracy of the different algorithms taking into consideration the nature of movement (range of motion and velocity), the type of movement (flexion-extension, abduction-adduction and circumduction). To our knowledge, none studies have assessed the coincidence of the estimation of GHRC with the gleno-humeral anatomical rotation centre (GHAC) considering several range of motion during the functional movements. The aim of this study is to investigate the accuracy of five functional methods and to estimate the most suitable amplitude of functional movements applied to the estimation of GHRC with respect to accuracy.

METHOD
Seven subjects (25.8±3.26 years, 1.77±0.09m and 68.3±8.03 kg) without upper extremity disorders took part in the experiments.

The motion analysis system Vicon (Vicon, Oxford Metrics Ltd, Oxford, UK) was used to track the kinematical data with nine infrared cameras (120 Hz).

Subjects were instructed to perform upper arm movements continuously: three flexions/extensions, three abductions/adductions and three circumductions. The movements were repeated three times with three different ranges of motion (small, medium and high). The small range of motion did not exceed 30° of arm elevation. The arm elevation was between 0° and 60° for the medium range of motion. The high elevation was limited to 90°. The limits were shown by the experimenter.

Four markers were fixed on the upper arm as far as possible from the deltoid in order to reduce the errors caused by skin movement artifacts. A rigid cluster of three markers was fixed to the flat part of the acromion. Three specific landmarks of the scapula (Angulus Acromialis, Trigonum Spinae and Angulus Inferior) were defined with respect to the acromion coordinate system during a calibration phase using a scapular locator. Then, they were reconstructed during the movement trials based on the position and orientation of the cluster.

The estimation of GHRC was computed from the 3D trajectories of the 4 technical markers of upper arm with respect to the scapula coordinate system. The functional methods to estimate GHRC were the algorithm of Gamage and Lasenby [4] (Gamage), the bias compensated method of Halvorsen [8] (Hal), the SCoRE method [3] (SCoRE), the Normalization Method [9] (NM) and the Helical Axis [10] (HA).

Immediately after the motion capture, an imaging of their scapula and arm were performed using a low-dose stereoradiographic imaging (EOS) (EOS imaging, France). This technique produces simultaneously a frontal and lateral X-ray of the whole body in a standing position with a very low exposure to radiations [11] (up to ten times less irradiating than conventional radiography).

The 3D position of the GHAC and the anatomical markers on scapula were determined from the 2 planar images using circle fitting to approximate the humeral head (Figure 1). GHAC was then defined with respect to the coordinate system of the scapula.

The Euclidian distance between GHRC and GHAC was computed for each subject, functional method and range of motion. A two way-analysis of variance (ANOVA) on error accuracy was performed to establish differences between functional methods and range of motion. Independent...
variables were functional methods and range of motion.

Figure 1: Radiography of the scapula and upper arm with the EOS system.

RESULTS AND DISCUSSION

The method to solve the estimation of GHRC and the range of motion influence the accuracy (p = 0.02 for the functional methods and p = 0.006 for the range of motion). There is also a significant difference for the interaction functional methods x range of motion (p = 0.000).

The table 1 presents the mean and standard deviation of the Euclidian distances according the functional methods and ranges of motion.

The more the subjects perform high range of motion during the functional methods the more the Euclidian distance increases for Gamage, NM and Hal (sphere fit methods) contrary to SCoRE and HA (transformation approaches). For these 2 methods, the errors are smallest when the range of motion is high. Ehrig et al. [4] stated that the error played a large role in the accuracy of each approach, particularly for the sphere fit methods, which performed well when one segment was held stationary, but became relatively less accurate when movement and noise were applied to both segments, case of the scapula and humerus during functional movements. The SCoRE and other transformation-based approaches, however, fared relatively better with the additional movement of the second segment, producing the most accurate estimations of the CoR.

The smallest distance (9.01±4.79 mm) was obtained with Gamage with a small range of motion for the group of sphere fit methods whereas for the transformation methods, HA give the smallest error (11.89±3.06 mm) with high range of motion. The error accuracy depends also on the reproductibility to find the humeral head in the two radiographs. Indeed, Ohl et al. [12] showed that the location reproducibility of shoulder bony landmarks using the EOS low-dose stereoradiography system was 1.09 mm with 95% confidence interval for the humeral head.

CONCLUSIONS

The accuracy of functional methods was studied in-vivo in comparison with medical imaging obtained by the new imaging system EOS. We observed that the functional methods seem sensitive to the range of motion of the upper limb movement performed during the procedure. Future works should confirm these results with a greater sample of subjects.

REFERENCES


Table 1: Mean (mm) and standard deviation of the distance between GHRC and GHAC.

<table>
<thead>
<tr>
<th>Range of motion</th>
<th>Gamage</th>
<th>NM</th>
<th>Hal</th>
<th>SCoRE</th>
<th>HA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>9.01 (4.79)</td>
<td>10.91 (3.17)</td>
<td>12.05 (3.76)</td>
<td>14.05 (5.81)</td>
<td>14.32 (5.31)</td>
</tr>
<tr>
<td>Medium</td>
<td>11.30 (2.02)</td>
<td>16.83 (8.39)</td>
<td>17.34 (8.46)</td>
<td>12.62 (4.71)</td>
<td>12.54 (3.99)</td>
</tr>
<tr>
<td>High</td>
<td>18.17 (6.26)</td>
<td>23.78 (8.71)</td>
<td>23.92 (8.75)</td>
<td>12.46 (2.79)</td>
<td>11.89 (3.06)</td>
</tr>
</tbody>
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