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Glenohumeral joint kinematics measured by intracortical pins, reflective markers, and computed tomography: A novel technique to assess acromiohumeral distance

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ABSTRACT

Combination of biplane fluoroscopy and CT-scan provides accurate 3D measurement of the acromiohumeral distance (AHD) during dynamic tasks. However, participants performed only two and six trials in previous experiments to respect the recommended radiation exposure per year. Our objective was to propose a technique to assess the AHD in 3D during dynamic tasks without this limitation. The AHD was computed from glenohumeral kinematics obtained using markers fitted to pins drilled into the scapula and the humerus combined with 3D bone geometry obtained using CT-scan. Four participants performed range-of-motion, daily-living, and sports activities. Sixty-six out of 158 trials performed by each participant were analyzed. Two participants were not considered due to experimental issues. AHD decreased with arm elevation. Overall, the smallest AHD occurred in abduction (1.1 mm (P1) and 1.2 mm (P2)). The smallest AHD were 2.4 mm (P1) and 3.1 mm (P2) during ADL. It was 2.8 mm (P1) and 1.1 mm (P2) during sports activities. The humeral head greater and lesser tuberosities came the nearest to the acromion. The proposed technique increases the number of trials acquired during one experiment compared to previous. The identification of movements maximizing AHD is possible, which may provide benefits for shoulder rehabilitation.

1. Introduction

The space between the humeral head and the acromion, termed as the acromiohumeral distance, is reduced during arm elevation (Bey et al., 2007; Giphart et al., 2012). This reduction may result in unsafe contact between the rotator cuff tendons and the acromion and contribute to the etiology of rotator cuff disease (Ludewig and Braman, 2011; Michener et al., 2003; Seitz et al., 2011). The development of technique for measuring the acromiohumeral distance is essential since the prevalence of rotator cuff tear exceeds 50% by the age of 60 years (Milgrom et al., 1995; Sher et al., 1995).

The acromiohumeral distance is usually measured using imaging techniques that include magnetic resonance imaging (Saupe et al., 2006), ultrasonography (Azzoni and Cabitza, 2004), and radiography (Nove-Josserand et al., 2005). These techniques are either 2D or have a low sampling rate or accuracy. Consequently, the assessment of the acromiohumeral distance has mainly been limited to series of static poses, whereas the majority of shoulder rehabilitation exercises, activities of daily living, and sports activities are dynamic. Since extrapolation of the acromiohumeral distance from static to dynamic condition remains uncertain (Thompson et al., 2011) as muscle contractions affect joint kinematics including especially glenohumeral translations (Bey et al., 2006; Carey et al., 2000), more investigations of the shoulder girdle arthrokinematics are needed under dynamic conditions (Massimini et al., 2012). To the best of our knowledge, only the studies of Bey et al. (2007) and Giphart et al. (2012) have measured the acromiohumeral distance in 3D under dynamic conditions with high accuracy. Indeed, they combined the glenohumeral kinematics obtained from biplane fluoroscopy, which provides an accuracy between 0.2 mm and 0.3 mm and between 0.1° and 1.7° for translation and rotation respectively (Giphart et al., 2012), with the scapular and the humeral geometry obtained from computed tomography scanner (CT-scan). High speed fluoroscopes permitted to capture movements at 30 Hz (Giphart et al., 2012) and 60 Hz

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(Bey et al., 2006), which is adequate for activities of daily living but remains insufficient for sports activities. Though biplane fluoroscopy has been the most suitable tool to assess the acromiohumeral distance, only two trials (Giphart et al., 2012) and six trials (Bey et al., 2007) were acquired for each participant to respect the maximum recommended dosage of radiation per year. Since the arm can elevate in planes of elevation from −150° to +150° with different axial rotations at almost any arm poses (Haering et al., 2014), only a small fraction of the shoulder range of motion can be assessed using biplane fluoroscopy. Consequently, an alternative technique to measure the acromiohumeral distance in 3D during dynamic arm elevations in several planes of elevation and axial rotations, as well as during activities of daily living and sports activities may provide great benefits in shoulder rehabilitation. Indeed, identification of arm movements that maximize the acromiohumeral distance may help to better direct treatment and guide patients' activities to hasten rehabilitation and/or reduce impingement.

As the smallest acromiohumeral distance obtained by Bey et al. (2007) and Giphart et al. (2012) was 1.2 mm and 1.8 mm respectively, 3D traditional non-invasive kinematics technique based on skin marker trajectories is an unsuitable measurement method. Indeed, the displacement of markers positioned on the arm ranged on average between 3.9 mm and 25.6 mm due to movements of soft tissues between the markers and the underlying bone (Blache et al., submitted for publication). The insertion of pins into the bones is an alternative technique to overcome soft tissues artefacts (Braman et al., 2010; Dal Maso et al., 2014). The two hours of local anesthesia (Arndt et al., 2004) are suitable to collect a much greater number of trials for each participant than biplane fluoroscopy-based technique. By securing electromagnetic sensors to pins, the glenohumeral accuracy in translation and rotation was less than 1.8 mm and 0.5° respectively (Braman et al., 2010), which is in the range of the smallest measured acromiohumeral distance (Bey et al., 2007; Giphart et al., 2012). By securing reflective markers to pins and using optoelectronic cameras to record their positions, a recent study obtained an accuracy better than 0.15 mm and 0.2° for glenohumeral translation and rotation respectively (Dal Maso et al., 2014). Combined with the CT-scan images of the bones fitted with their pins and markers, this technique may provide the kinematics of each bony part, and make possible the measure of the acromiohumeral distance with high accuracy.

The objective of this study was to evaluate a technique for measuring the acromiohumeral distance in 3D and the distances between all bony parts of the humeral head and the acromion during dynamic tasks in the entire shoulder range of motion, activities of daily living, and sports activities. Using the proposed technique, it was hypothesized that during arm abduction and flexion, the acromiohumeral distance and the nearest bony parts would be similar to previous results obtained from biplane fluoroscopy (Bey et al., 2007; Giphart et al., 2012). These results may serve as proof of concept that glenohumeral kinematics obtained from intracortical pins combined with CT-scan recordings are suitable to measure acromiohumeral distance in 3D under dynamic conditions during a greater number of trials than previous techniques. The proposed technique may therefore be used to identify movements maximizing the acromiohumeral distance and thus provide great benefit in shoulder rehabilitation.

2. Methods

2.1. Participants

The present study was approved by the local ethics committees of the Karolinska Institute (Sweden) and University of Montreal (Canada). Four male participants, age: 27, 44, 32, and 41 years; height: 1.65, 1.77, 1.72, 1.82 m, and mass: 57, 82, 80, 115 kg (P1, P2, P3, and P4 respectively), volunteered after signing an informed consent form. Their disabilities of the arm, shoulder and hand scores (Hudak et al., 1996) were less than 10.5 with no specific pain, injury, or dysfunction at the shoulder at the time of the experiment. None of the participants reported previous surgical history.

2.2. Instrumentation

Intracortical pins were inserted into the first third of the scapular spine and on the lateral aspect of the humerus just below the attachment of the middle deltoid of the participants' left side (see Dal Maso et al. (2014) for details). Before pin insertion, participants were administered local anesthesia that lasted two hours. The first hour was required to insert pins and acquire CT-scan images. The second hour was dedicated to movement acquisition and then pin removal. Supports fitted with four and five reflective markers were secured to the scapular and humeral pins respectively (supplementary material Fig. S1A). Nine and seven additional markers were placed on the skin of the scapula and humerus respectively. This included markers put on bony landmark to define segment axes (Wu et al., 2005), and technical markers located on specific areas to minimize soft tissues artefacts (Cappozzo et al., 2005). Technical markers were used to compare the orientation of the pin- and skin-based local coordinate systems at the beginning of each trial such that any rotation of the markers support on the pin or pin loosening would be identifiable. Finally, six skin markers were also placed on the thorax to calculate thoracohumeral kinematics. In line with previous studies about sports activities (Fleisig et al., 2003), marker trajectories were collected at 300 Hz using an 18-camera motion analysis system (Oxford Metrics Ltd., Oxford, UK).

The bone and marker geometry was acquired in axial mode using a CT-scan (General Electric Medical System, Milwaukee, USA). The thickness of each slice (512 × 512 pixel matrix) was 0.31 mm. The field of view ranged from 24.98 to 31.89 cm to account for the participant's size. Finally the voxel size ranged from 0.49 × 0.49 × 0.31 mm to 0.62 × 0.62 × 0.31 mm.

2.3. Experimental procedures

A series of arm flexions, abductions, rotations, and circumductions were firstly recorded to locate the optimal location of the glenohumeral joint center (Begon et al., 2007; Jackson et al., 2012). Then, 158 trials were collected for each participant. Only a subset of 66 trials was analyzed in this study. All trials started with the arm relaxed at the side. Participants were instructed to return at rest position whenever they felt discomfort during movement execution. They performed a series of arm elevations at their maximum range of motion in four planes of elevation. These elevations corresponded to adduction (*i.e.* elevation with the arm close to the chest in the direction of the opposite shoulder), flexion, abduction, and extension. Three elevations were performed in each plane of elevation with the arm successively held in maximum internal, neutral, and maximum external axial rotation (see supplementary material Fig. S2 for movement illustrations). In neutral axial rotation trials, participants were asked to elevate their arm without changing its axial rotation from the relaxed position. The elbow was kept extended throughout the elevations. Participants were instructed to perform the elevations at their own pace. A total of 12 elevations were performed, one trial in each task (4 planes of elevation × 3 axial rotations).

Then, participants were asked to perform a series of five daily living activities, namely, mimicking eating and hair combing,