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Distribution of arm velocity and frequency of arm usage during daily activity: Objective outcome evaluation after shoulder surgery

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ABSTRACT

In clinical settings, functional evaluation of shoulder movement is primarily based on what the patient thinks he/she is able to do rather than what he/she is actually performing. We proposed a new approach for shoulder assessment based on inertial sensors to monitor arm movement in the daily routine. The detection of movement of the humerus relative to the trunk was first validated in a laboratory setting (sensitivity > 95%, specificity > 97%). Then, 41 control subjects and 21 patients suffering from a rotator cuff tear were evaluated (before and after surgery) using clinical questionnaires and a one-day measurement of arm movement. The quantity of movement was estimated with the movement frequency and its symmetry index (SI_{Fr}). The quality of movement was assessed using the Kolmogorov–Smirnov distance (*KS*) between the cumulative distribution of the arm velocity for controls and the same distribution for each patient. SI_{Fr} presented differences between patients and controls at 3 month follow-up ($p < 0.05$) while *KS* showed differences also after 6 months ($p < 0.01$). SI_{Fr} illustrated a change in dominance due to the disorder whereas *KS*, which appeared independent of the dominance and occupation, showed a change in movement velocity. Both parameters were correlated to clinical scores (R^2 reaching 0.5). This approach provides clinicians with new objective parameters for evaluating the functional ability of the shoulder in daily conditions, which could be useful for outcome assessment after surgery.

1. Introduction

In clinical settings, shoulder function is primarily evaluated by subjective tools which are based on what the patient is, or thinks he/she is, able to do rather than what he/she is actually performing [1]. Shoulder disorders such as rotator cuff tears result in pain and weakness [2], which may affect arm mobility during everyday life [3]. Assessment of actual arm movement during daily life conditions is thus essential for the objective evaluation of upper limb function and treatment outcome [4,5]. Indeed the clinical follow-up after surgery is important in controlling the treatment quality, detecting any complication and improving rehabilitation. Although numerous different instruments are available to evaluate shoulder function [6,7], a gold standard for objective assessment is still lacking.

Nowadays wearable measurement systems enable long-term recordings of kinematic data in daily conditions [8,9]. Nevertheless, only certain studies analyse the actual upper limb movement performed during a single day [1,5,10,11]. These studies mainly focus on the movement of the forearm or wrist and there is a clear need to study the movement of the humerus relative to the trunk to gain further insights in shoulder disorders. Gyroscopes attached to the humerus have been used to report the frequency of movement per direction [12]. However, simultaneous trunk movements which can falsely be detected as arm movements were not considered. Moreover, arm usage is not only characterised by the number of arm movements, but also by the quality of movement, e.g. amplitude or velocity. Previous studies showed that velocity is relevant in evaluating the effect of disorder and pain on shoulder mobility [13,14].

The aims of this study were, first to validate a method based on body-worn inertial sensors to detect movement of the humerus relative to the trunk, and second to provide outcome parameters

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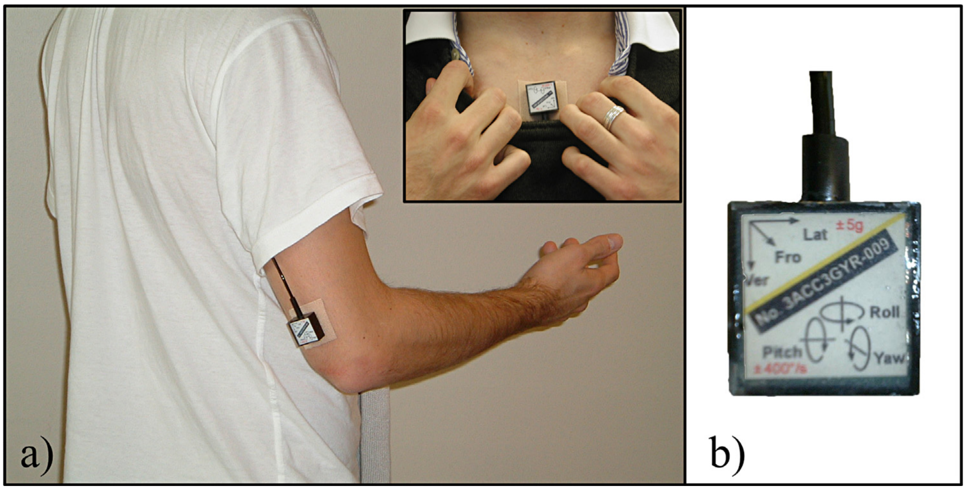

Fig. 1. Measurement system: (a) the inertial modules attached to the dorsal side of the humerus and to the sternum; the sensors were attached using dermatological adhesive patches. (b) Detail of an inertial module consisting of a tri-axial gyroscope and a tri-axial accelerometer.

reflecting both quantity and quality aspects of arm movement during long-term measurement of daily activity. Such outcome parameters could add new features to the routine clinical tests and provide objective evaluation during rehabilitation.

2. Methods

2.1. Subjects and materials

The measurement system included three inertial sensors each consisting of a miniature three-dimensional gyroscope and accelerometer [12]. Inertial sensors were fixed by a trained evaluator on each humerus and on the sternum using patches (Fig. 1): the vertical and lateral axes of each sensor were aligned to the longitudinal and mediolateral axis of each segment respectively [12]. The sensors were linked to an embedded datalogger (Physilog®, BioAGM, CH) worn at the waist and data were recorded at 200 Hz. Ethical approval was given by the Institutional Ethics Board committee and all participants gave informed and signed consent prior to the measurements.

Laboratory setting: Six control subjects (28 ± 2.8 years old) without any history of shoulder disorder and five patients (53 ± 5.3 years old) diagnosed with a rotator cuff tear were enrolled.

Subjects were asked to displace bottles of 1.5l and pens while standing, with the trunk free to move. Every object was displaced up and down a shelf and left-right on the table. Controls performed six displacements for every direction and object, patients were asked to perform three displacements to avoid pain and fatigue. Participants were free to use their preferred arm and an observer reported which arm was used for each task: if the subject chose to displace the object with the right arm, the left arm was considered as at rest.

Daily routine monitoring: 41 control subjects (34 ± 9 year old) and 21 patients (53 ± 9 years old) with unilateral rotator cuff disease (transmural supraspinatus tendon rupture) were enrolled. Ten patients were affected on the non-dominant side (PND group) and 11 on the dominant side (PDo group). Patients were assessed before the rotator cuff repair (baseline) and at 3, 6 and 12 month follow-up. Participants completed three clinical scores: (1) the Constant score [15] (containing subjective items and measurement of range of motion and strength); (2) the Disabilities of the Arm, Shoulder and Head questionnaire (DASH) [16]; and (3) the Simple Shoulder Test (SST) [17]. The latter two are self-reported questionnaires. Participants were then monitored for seven continuous hours during a weekday where a trained evaluator attached the measurement system in the morning and instructed the subject to perform his/her usual activities without restriction.

2.2. Arm movement detection

Arm movements were detected using the angular velocity of the humerus and trunk. First each period where the angular velocity norm of the humerus was larger than a threshold specific to each patient (defined similarly as proposed by Coley et al. [12]) were identified. If the angular velocity norm of the humerus was larger than the one of the trunk, the period was detected as an arm movement. Otherwise, the period was classified as a motion induced by the trunk and no movement was assigned to the arm. To validate the algorithm, the results were compared to the observer report in the laboratory setting.

2.3. Arm usage analysis

In daily routine monitoring, body postures including sitting and standing were identified separately using the trunk sensor [18]. As the tendencies were similar for both postures, the parameters were reported together. Walking periods were not considered as these involve mainly cyclic arm movements that are inherent to walking, rather than voluntary movements. Periods of arm movement were estimated by applying the arm movement detection algorithm. The quantity of arm usage was characterised by the movement frequency (Fr) computed as the number of detected arm movements divided by the number of hours of sitting and standing postures. In addition, the symmetry index [19] of Fr in dominant and non-dominant arms (SI_{Fr}) was considered:

$$SI_{Fr} = 100 \cdot \frac{Fr_{dominant} - Fr_{non-dominant}}{Fr_{dominant}} [\%] \quad (1)$$

The quality of arm usage was assessed by comparing the arm velocity distribution of the individual patient to that of the control group. For each period T of detected movement, the mean arm velocity v was estimated according to the angular velocity norms of arm $\|\vec{\omega_a}\|$ and trunk $\|\vec{\omega_t}\|$ ($\|\vec{\omega_a}\| < \|\vec{\omega_t}\|$ for movement period): $\|\vec{\omega_a}\| > \|\vec{\omega_t}\|$

$$v = \text{mean}_T\left(\|\vec{\omega_a}\| - \|\vec{\omega_t}\|\right) \quad (2)$$