An experimental characterization of human arm motion

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Abstract. In this paper an experimental characterization of human arm motion is presented by using test results with an experimental layout with wearable sensors. The problems for characterizing the human arm motion are studied to design a low-cost user-oriented experimental equipment based on IMU that can be used also outdoor in daily life. Lab results are presented both to show the feasibility of the proposed procedure and to use the experiments for a characterization of human arm motion.

Key words: Biomechanics, Experimental Mechanics, Kinematics, Upper Limb, IMU.

1 Introduction

The aim of this works is to characterize experimentally the upper limb kinematics (position and velocity measures) with a low-cost equipment that is based on inertial measurement units (IMU). Nowadays there is a lack of a standardization in the upper limb kinematic measurements [1].

A characterization of human arm motion can potentially provide meaningful information for different fields of application like ergonomics, rehabilitation, sport and other fields. Many researches have worked out upper limb kinematics using different methodologies and equipment but there are not yet standard protocols to evaluate it. Therefore, there is not yet a unified procedure for the analysis of characteristic movements of the arm during daily life activities (ADL).

A measurement of the kinematics of the upper limb using inertial measurement units (IMUs) with gyroscope and accelerometers was experienced as reported in [2]. A filter was designed that constrains the abduction in the elbow to improve the estimation of the orientation but still with errors in the measurement. In [3] an experiment is reported to obtain the kinematic parameters of the human arm using a wire tracking system. In [4] a protocol is developed to measure the kinematics of scapula, humerus and elbow by using a system with four Xsens ® inertial and magnetic measurement systems (IMMS). In [5] a methodology is proposed to establish local coordinate systems and to measure the kinematics in each body segment of the upper limb with IMMs.

This work focuses the attention in evaluating the upper limb kinematics by using a system with inertial measurement sensors (IMU). This paper is arranged in the following way: First, relevant characteristics of the upper limb are introduced. Then the system to be used is designed and the experiments as well as the experimental layout are presented. In the results section the data are analyzed to obtain the main parameters that describe upper limb kinematics during the performed tasks.

2 Human arm and attached problem

The upper limb is one of the most complex and important part of the human body due to its high dexterity. It is composed by the shoulder complex, the arm, the elbow, the forearm, the wrist and the hand, Fig 1a. Its main bones are the clavicle, scapula, humerus, radius, ulna and the bones of the hand, Fig. 1.b. They are connected by different articulations that allow a great mobility to the upper limb.

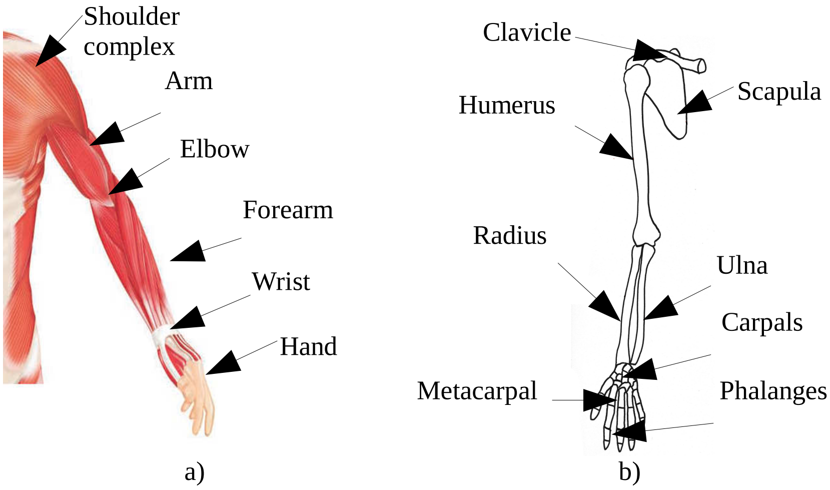


Fig. 1 Anatomy of upper limb: a) body segments with muscles; b) main bones

The shoulder is composed by the sternoclavicular joint (sternum and clavicle union), acromioclavicular joint (scapula and clavicle union), glenohumeral joint (humerus and scapula union) and the scapulotoracic joint (union of the scapula with the thorax through muscles of the back).

The shoulder is capable of combination of translation and rotation over a very wide range. The shoulder girdle can reach 180° in abduction due to the movement of the scapulothoracic and glenohumeral joint. The movements of the glenohumeral joint are the abduction-adduction of the humerus, Fig.2.a, flexion-extension, Fig.2.b, and internal-external rotation, Fig.2.c, [2].

The elbow joint is composed by two articulations and allows flexion and extension of the forearm, Fig. 2.d. These articulations act in conjunction with the joints in the forearm and make possible the pronation and supination of the hand, Fig. 2.e.

The radiocarpal joint (wrist) is a biaxial joint that is composed of the distal end of the radius and the carpal bones. The active movements of the wrist are flexion-extension, Fig. 2.f, adduction (ulnar deviation)-abduction (radial deviation), Fig. 2.g. These two movements are performed around oblique axes [6].

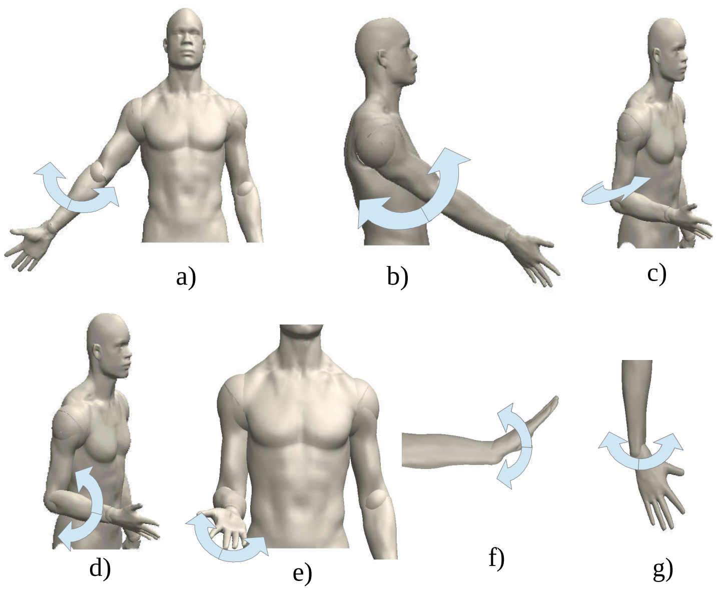


Fig. 2 Typical upper limb movements: a) Shoulder abduction-adduction; b) Shoulder flexion-extension; c) Shoulder internal-external rotation; d) Flexion-extension of the elbow; e) Pronation-supination of the forearm; f) Flexion-Extension of the wrist; b) Radial-Ulnar deviation

In order to analyze the kinematics of the upper limb, a kinematic model can be defined specifying the number of links and degrees of freedom. This model depends of which joint will be analyzed in detail.

In this work the arm, forearm and the hand are considered. Therefore, the analyzed joints are the shoulder, elbow and wrist. The shoulder joint is modelled as a socket and ball joint to represent the movements of the flexion-extension, abduction-adduction and internal-external rotation [2].The elbow is described as a cardan joint, despite in reality the flexion-extension and pronation-supination axes are not perpendicular [7]. In order to represent the two axes of movement of the wrist joint a cardan joint is again considered. Therefore, the kinematic model of human arm is an anthropomorphic 7-revolute joint serial arm.

The problems for a motion characterization of the human arm can be divided in identification of kinematic parameters of the model and motion, and in an evaluation of motion performance.

3. Experimental layout and procedure

The analysis of the upper limbs kinematics involves the measurement of the position, velocity and acceleration of the body segments. In this work the upper limb movement is considered relative to the trunk. Therefore, in a set of defined tasks, the orientation of the arm, forearm and hand were measured with respect to the trunk.

The experiments were performed following the procedure shown in the flowchart in Fig. 3. Four IMU sensing units were connected to a PC via a Wi-Fi module. Each unit is a 9 DOF module (magnetic and inertial sensors) that is connected to a microcontroller, inside a lightweight small box. The sensor module is the GY-88 which contains an accelerometer, magnetometer and gyroscope and has a price around $10 USD. The microcontroller used is a ESP8266, which is a microcontroller with Wi-Fi module and cost about $5 USD. Before the experiment, each sensor of the IMU was calibrated. The calibration of the accelerometer is applied by relating the maximum output reading of each axis of the sensor to the gravity while the IMU is in static position. The gyroscope calibration was performed by measuring the reading offset in each axis while the IMU is not moving. The magnetometers were calibrated using the method described by Hoseini et al. [8]. To ensure a better measurement, a sensor fusion was performed with a two-step Kalman filter [9]. The information provided by the IMU sensors is the orientation of a body. This orientation is measured using the vector gravity and the magnetic north as reference frame.

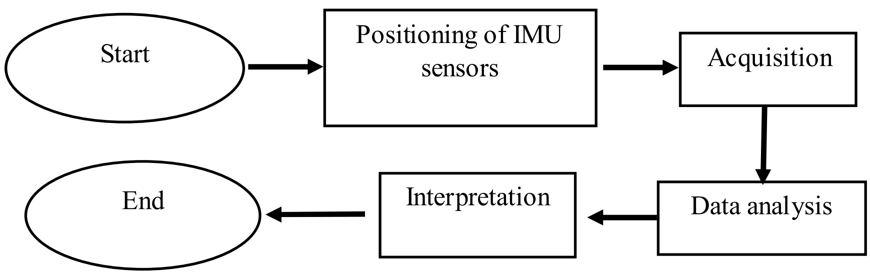
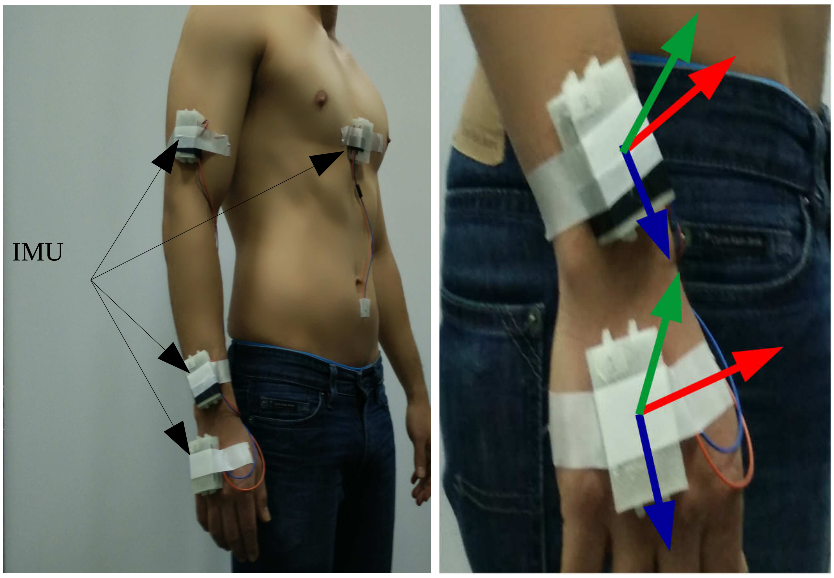


Fig 3. Flowchart of the experiment

The IMU sensors were placed using skin tape in order to ensure that the sensors recorded the movement in a suitable way and to minimize the sensor displacement with respect to the skin, Fig 4a). The IMU locations were chosen to minimize the influence of the skin and muscle movement. These locations are at the sternum, in the lateral distal humerus, in the dorso distal forearm and over the II and III metacarpals. Before the experiment, each movement was explained in detail to the test subject as part of a testing protocol.

To measure the motion kinematics using IMUs, it is necessary a calibration procedure to relate the coordinate system of the body segments to the local coordinate system of the sensors (LCS), Fig.4b. There are three options to create the LCS, namely one is the reference method where the measurements are related to anatomical axis definitions, the second is the functional method in which the local coordinate systems are defined from the functional axes of rotation of the segments and a third one uses reference and functional method as described in [10].



a) b)

Fig 4. Location of IMU sensors on a testing subject: a) IMUs on the subject body; b) local coordinate system of the IMU

In this work for calibration purposes a set of movements and gestures were used in a procedure as reported in [5]. The calibration is performed with specific poses and a sequence of two uniaxial rotations for each body segments. This allows to define a primary and a secondary axis of rotation for every joint of interest.

The determined axes are used with the aim of establishing a local coordinate system in each body segment to analyze its specific movement. Thus the procedure in [5] to define the LCS matches the convention of the ISB [11].

After the calibration, six range of motion (RoM) with different tasks were performed to characterize the motion of the joints in the upper limb according to the movements in Table 1. Five ADL tasks were performed with the right arm to characterize the movements of the upper limb. The activities were performed three times each. In this work three tasks are reported as related to:

- Wash axilla/ zip jacket (Fig 9): the start position is with the arm in the standard anatomical position (Standing position with arms alongside the body and palms facing to the front). The end point is reached when the hand touches the external region of the opposite shoulder.
- Combing hair (Fig 10): the start gesture is the anatomical position; the subject moves his hand to the forehead and continues to move the hand over head towards the neck (as combing the hair). Once the subject reaches the nape, he moves the hand back to the anatomical position.
- Hand to back pocket (perineal care): the start position is with the hand at the anatomical position and the end position is reached when the hand is placed on the left back pocket of his jeans.

4 Test results

During the calibration procedure, a series of uniaxial movements were performed to relate the orientation given by the IMU to the functional axes of rotation of the joints. Two different movements were performed for each joint. Each movement of the calibration was repeated three times to assure statistical significance. During the movements the angular velocity vectors were recorded, with results like in the example shown in Fig.5. Table 1 summarizes the values obtain with IMU measurements and the common range of motion values of the human arm joints [6]. The RoM activities were performed three times each to ensure statistical significance.

The velocity data of each experiment were analyzed by single value decomposition. The eigenvector associated to the biggest singular value of the single value decomposition gives an instant axis of rotation ($\mathbf{V_1}$ or $\mathbf{V_2}$). Between each trial of the calibration procedure, the calculated axes have presented a low dispersion. This ensures a good repeatability of the experiments. Fig. 6 shows the axes calculated for two different movements of the shoulder joint when performed three times. It can be seen that the axes that are calculated for a single movement during the different trials are close to each other. The average value of the calculated axes in the three trials was the one used to define the reference coordinate system and it is reported in Fig. 6.

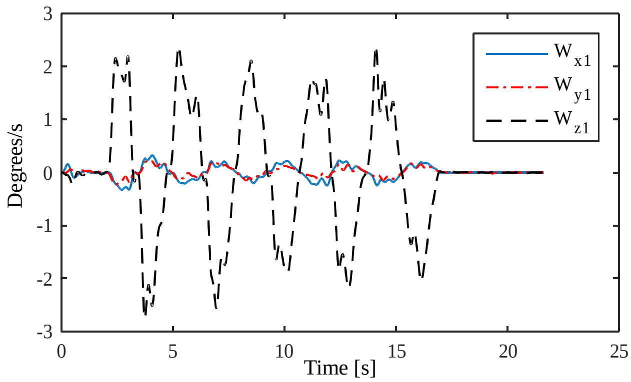


Fig.5 Acquired components of the angular velocity during forearm pronation-supination

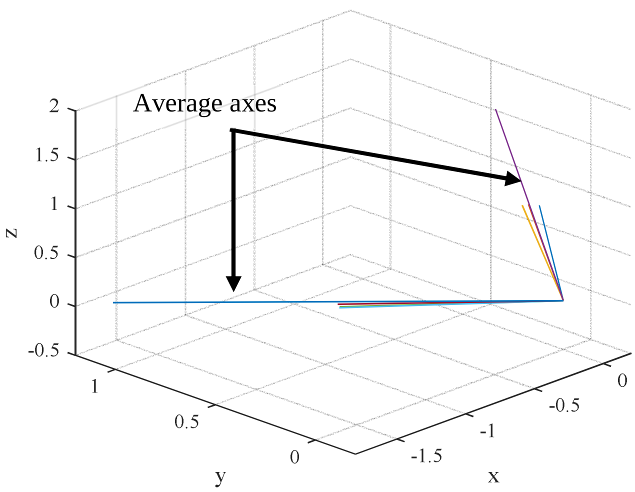


Fig. 6 An example of the identified functional axes during the calibration of the shoulder joint.

The calculated axes define a primary (**e1**) and secondary (**e2**) functional axes of rotation for each joint as referring to a local Cartesian frame of reference. With these calculated axes, an orthonormal basis that relates the IMU coordinate system to the body segment coordinate system was defined according to the expressions

$$e_1 = \frac{v_1}{\|v_1\|} \tag{1}$$

$$e_2 = \frac{v_1 \times v_2}{\|v_1 \times v_2\|} \tag{2}$$

$$e_3 = e_1 \times e_2 \tag{3}$$

Where the axes $\mathbf{e_1}$, $\mathbf{e_2}$ and $\mathbf{e_3}$ define the transformation matrix from the LCS of the sensor to the functional axes of rotation of the corresponding body limb as

$$^{LCS}R_{Functional-Axes} = [e_1 \quad e_2 \quad e_3] \tag{4}$$

From equation (5) to (7) the following matrixes represent the rotation of each body segment with respect to the global frame :

$$^{Global}R_{Thorax} = R_{IMU-Thorax} \times {}^{LCS\text{-}Thorax}R_{Functional-Axes-Thorax} \tag{5}$$

$$^{Global}R_{Humerus} = R_{IMU-Humerus} \times {}^{LCS\text{-}Humerus}R_{Functional-Axes-Humerus} \tag{6}$$

$$^{Global}R_{Forearm} = R_{IMU-Forearm} \times {}^{LCS\text{-}Forearm}R_{Functional-Forearm} \tag{7}$$

where:

R_{IMU-x} Represent the orientation matrix of the IMU sensor that is attached to the corresponding body segment.

Therefore, the orientation of the humerus with respect to the thorax is defined by

$$^{Thorax}R_{Humerus} = ({}^{Global}R_{Thorax})^T \times {}^{Global}R_{Humerus} \tag{8}$$

and the orientation of the forearm with respect to the humerus is defined by

$$^{Humerus}R_{Forearm} = ({}^{Global}R_{Humerus})^T \times {}^{Global}R_{Forearm} \tag{9}$$

Using functional axes instead of anatomical axes makes possible to overcome crosstalk in the joints measurements, by avoiding to measure rotation of one movement not corresponding to the measured axis.

The defined coordinates systems provided a mean to straightforward relate the information of the IMUs with the movement of the analyzed joints. Fig 7a shows the angles that are measured in the elbow during a flexion-extension test. Due to the misalignment between the axes of the IMU and the axes of rotation of the body segments, it can be seen that there is measured angular movement around all the axes. With the measurements expressed in the calculated coordinate system, the information is related to the axes of rotation of the joint and therefore the kinematics can be properly evaluated, as can be seen in Fig. 7b where it is shown the movement of the elbow joint during a test with the significant values for flexion extension motion.

Similar results are obtained in a test for shoulder motion that shows a smooth characterization with a range of 120° in abduction, Fig 8. The acquired data show three phases of the measured motion, namely an approaching fast movement, a stationary reach, and a returning action. The slope of the approaching and return movements look similar. These behaviors are experienced as common in single articulation movements.

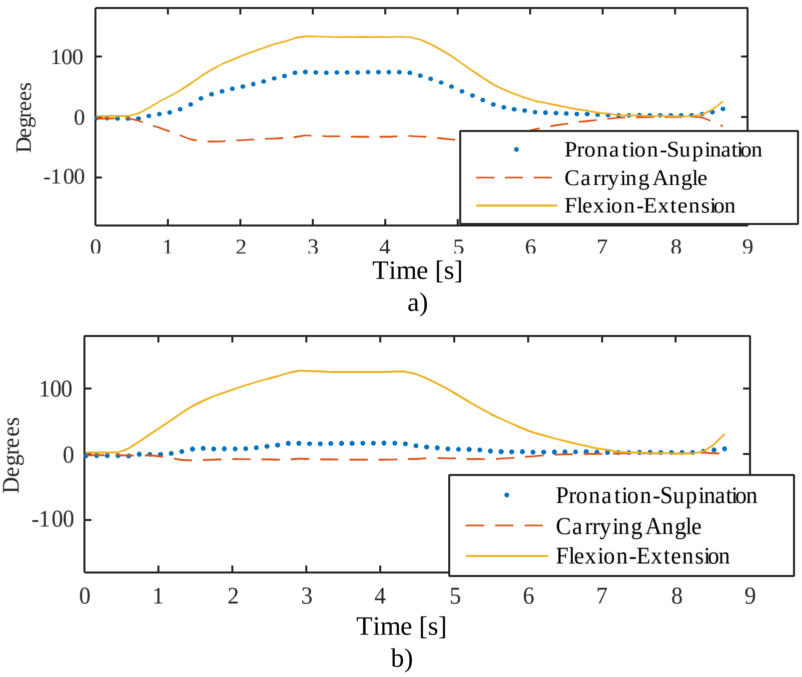


Fig 7. Measured angles of elbow joint during flexion-extension test: a) Before calibration; b) After calibration.

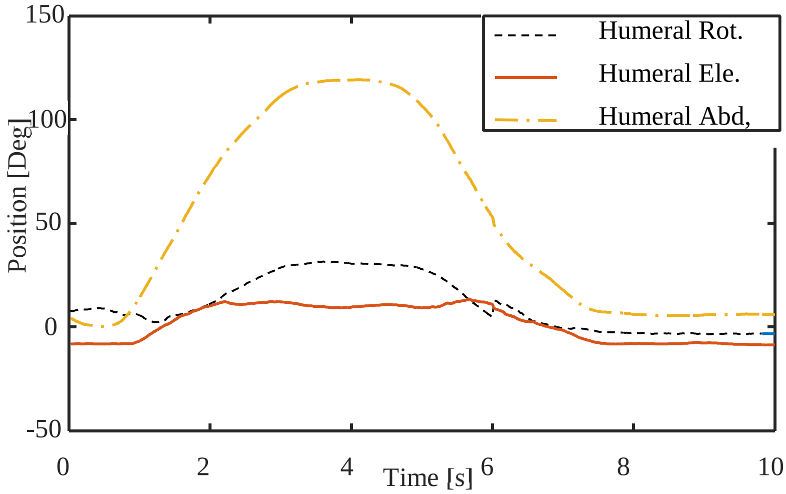


Fig.8 Measured angles of shoulder motion during a test for shoulder abduction after calibration.

In the touching opposite shoulder test the main movement is the flexion of the humerus and flexion of the elbow, Fig. 9. During the entire activity the hand remains aligned with the forearm and therefore there is not measured movement in the wrist.

It is to note that in arm motion with combined movements of the articulation, the measured joint angles show action in all different articulations with a time evolution in which the approaching and return phases are much more limited than in the core phase. The measured values with ranges of 90° for the elbow flexion and 100° for the shoulder flexion are in the RoM but well within the maximum capability.

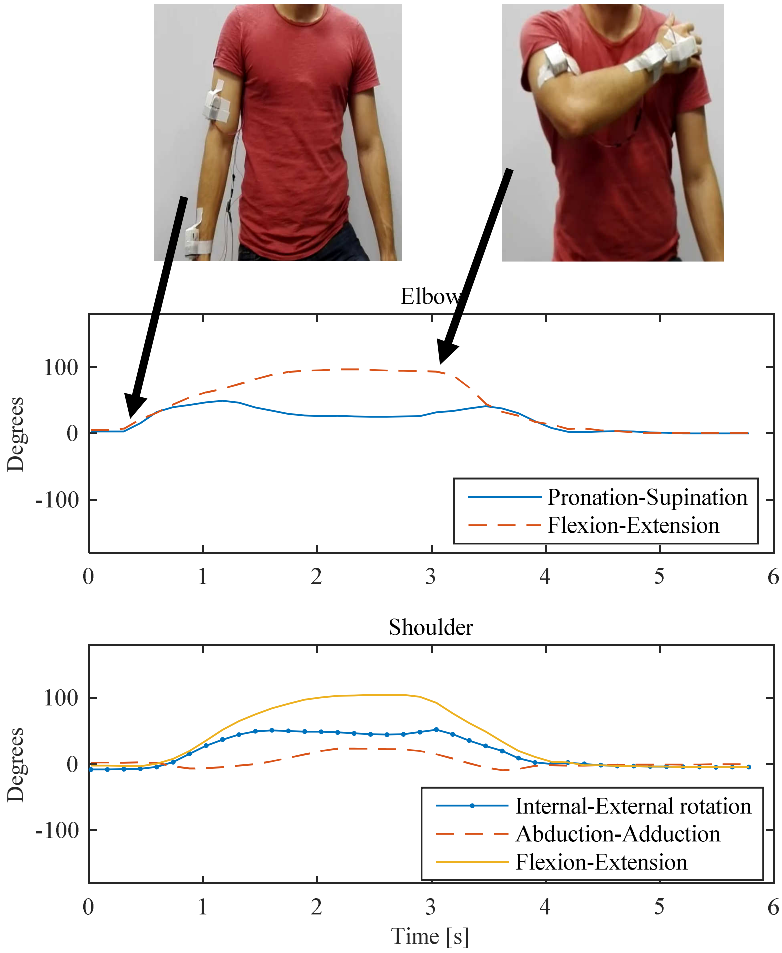


Fig.9 Measured angles of the shoulder and elbow joint during the touching shoulder test.

In the combing hair test the results show that there is simultaneous motion in the articulations, Fig. 10. The subject performed a flexion movement of the shoulder larger than in the previous test, since the target is located in a higher place. In comparison to the touching shoulder test where there is an adduction movement, in this experiment it is necessary the abduction of the shoulder. In this case movement of the wrist is also active. It can be seen that while the hand is in the top traveling along the head, the main movement is performed by the pronation and supination of the elbow joint. The approaching a return phases are shorter in duration than in the core phase. The maximum recorded values are the elbow flexion with a range of 115° and the shoulder flexion with 115°.

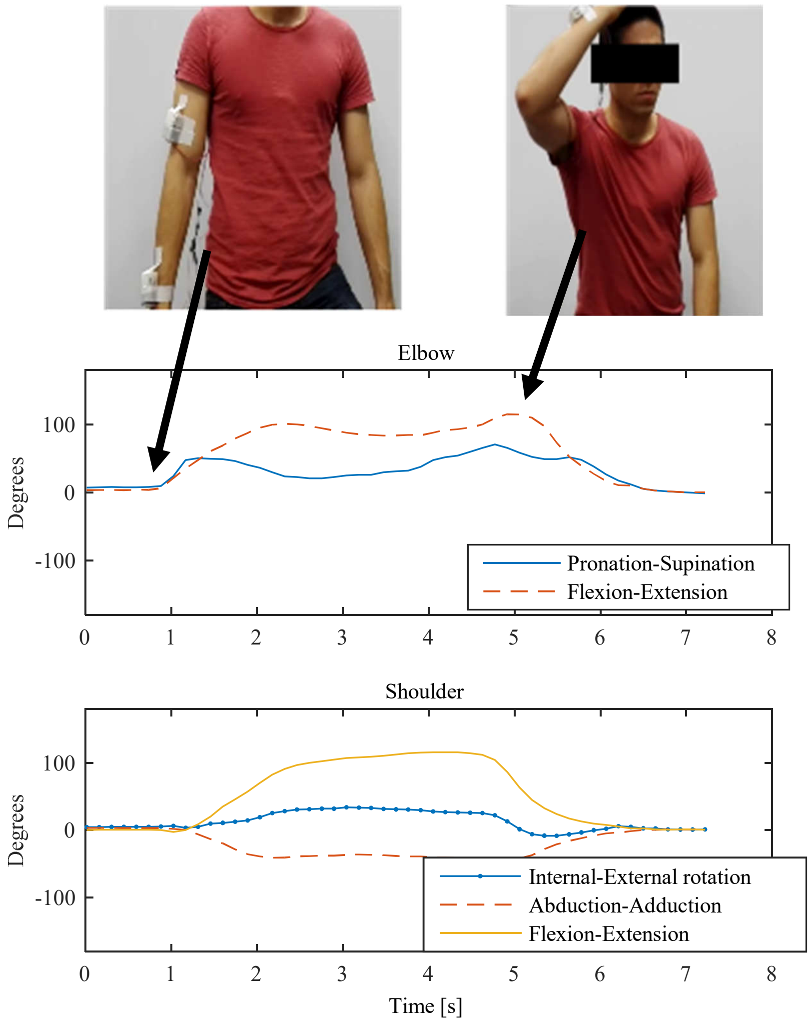


Fig.10 Measured angles of the shoulder and elbow joint during the combing hair task.

In the test with the perineal care motion, most of the movement is performed with the shoulder extension and the internal rotation, Fig. 11. The elbow movement is also engaged mainly with flexion. In this test the maximum range of motion was the flexion of the elbow with 50°. In comparison with the test of Fig. 9 and 10, this was the only activity that required shoulder extension as expected because it is the only task where the target is located behind the human frontal plane.

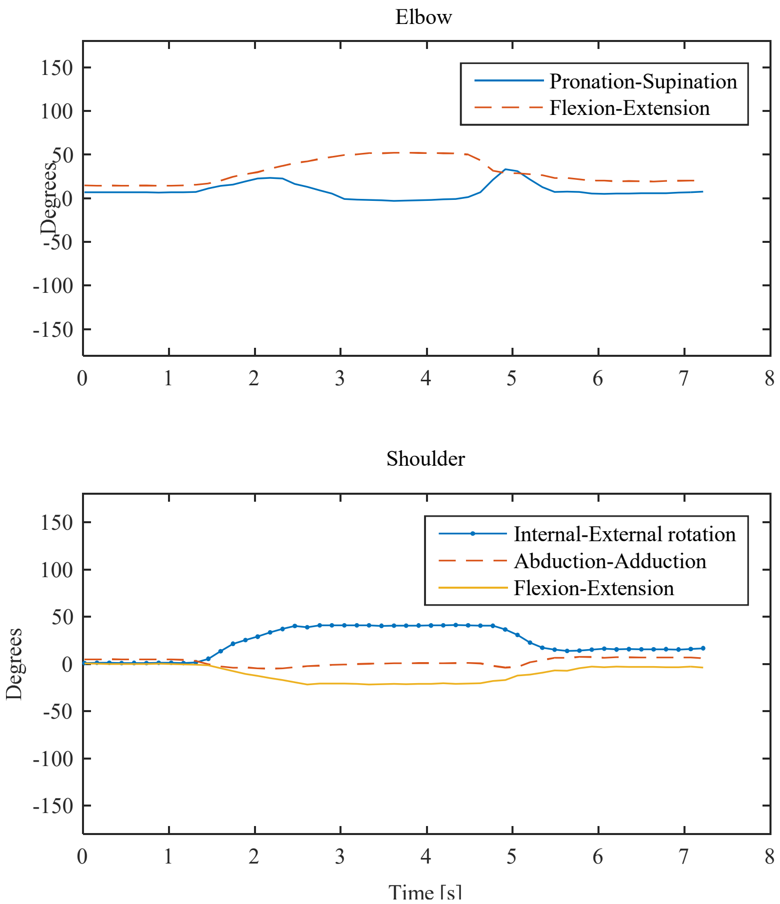


Fig.11 Measured angles of the shoulder and elbow joint during the perineal care test.

In the experienced daily live activities, the results show that the main movements for performing tasks with combined articulation movements are the humeral flexion and internal rotation, even if abduction motion can be relevant too. These three motions did not require external rotation to achieve a prescribed task. The amount of movement in the wrist is lower when compared with the other joints.

Differences in the values of Table 1 can be attributed to the fact that most of the reported values are measured with respect to anatomical references and not with respect to functional axes. In addition, the range of motion of the shoulder joint depends of the angle of internal-external rotation of the humerus also if there is movement of the scapula.

The Table 2 summarizes the maximum values of the movements during the reported tests in Figs. 9, 10 and 11.

Table 1. Comparison between the measured range of motion during tests with IMUs and the reported values in literature.

Movement	*Range [degrees] measured with IMU*		*Range [degrees] reported values in literature [6]*	
Forearm pronation/supination	Pronation 55	Supination 65	Pronation 85	Supination 90
Elbow flexion/extension	Flexion 125	Extension 0	Flexion 145	Extension 0
Internal/external rotation of humerus	Internal 30	External 25	Internal 100	External 80
Anterior flexion/extension of upper arm	Flexion 160	Extension-35	Flexion 180	Extension 50
Abduction/adduction of upper arm	Abduction 120	Adduction 0	Abduction 180	Adduction 0

Table 2. Measured values during ADL tests.

Movement	*Combing Hair (Fig. 9)*	*Touching Shoulder (Fig.10)*	*Perineal Care (Fig. 11)*
Wrist flexion(+)/extension(-)	20°	0°	15°
Wrist ulnar(+)/radial deviation(-)	10°	0°	10°
Forearm pronation(+)/supination(-)	0°	-20°	-40°
Elbow flexion/extension(-)	115°	95°	50°
Flexion(+)/extension(-) humerus	115°	105°	-20°
Abduction(+)/adduction(-) humerus	35°	-20°	0°
Internal(+)/external(-) rotation h.	30°	45°	40°

The experiences with lab tests, as those reported in the paper, show that the IMU-based system is useful with the proposed procedure to acquire and evaluate articulation movements during arm motion in terms both of numerical characteristics values and kinematic behavior.

5 Conclusions

In this work a low-cost fairly-easy IMU based instrumentation is proposed with an experimental procedure to analyze the upper limb kinematics. A proper calibration has been elaborated to permit a straightforward acquisition of the articulation movements during arm motion. The reported tests give results for a motion characterization with measured angles values for basic movements and daily actions.

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