Joint angles tracking for rehabilitation at home using inertial sensors: a feasibility study

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ABSTRACT

Joint angles are commonly measured in physical rehabilitation to evaluate joint function. Evidences showed that wearable inertial sensors can accurately quantify human motion information, however, the most advanced and accurate methodologies require the execution of complex calibration movements which are unsuitable to inexpert users and inadequate for a home context. This way, four different joint angles estimation methods requiring no calibration movement were developed in order to track the main human body joint angles in real time. IMUs mounted in bracelets were used to restrict sensor positioning on the limbs. For six different exercises, the estimated absolute and relative joint angles were evaluated against the marker-based video tracking software Kinovea ground-truth. Correlation analysis between estimated and ground-truth joint angles indicated a very strong and statistically significant correlation. The average error in estimated joint angles is below 5 degrees for all four methods employed, which may be an acceptable result for the rehabilitation at home scenario.

Author Keywords

Rehabilitation; Physical Therapy; Angular kinematics; Range of Motion; Joint movements; Inertial Sensors; Sensor Fusion.

ACM Classification Keywords

C.3 [Computer Systems Organization] Special-purpose and application-based systems: Signal processing systems; J.3 [Computer Applications] Life and medication sciences: Health.

INTRODUCTION

Physical therapy is a broad field addressing the recovery and treatment of physical impairments, injuries, disabilities and diseases related to motor and balance dysfunctions that affect many daily life activities. A rehabilitation process is usually necessary for patients after a specific type of injury involving physical (impingement, surgery, arthritis, etc.) or neurological (strokes, neuropathies, etc.) impairments [1].

Rehabilitation is traditionally delivered in a hospital or clinical environment [2], requiring a cyclic process of physical examination and assessment, treatment planning or modification and intervention [1]. The rehabilitation process is usually intensive, repetitive and time consuming, leading to non-engaging experiences, which ultimately challenges patients' involvement and adherence [1].

Recent years have therefore witnessed an increasing demand for more efficient health care delivery [2]. Home-based rehabilitation emerged in this context as a complementary solution to improve treatment efficacy and instrumentation to accurately monitor movement in real-time was rapidly recognized as a useful tool to provide coaching and feedback on exercise execution and give the patient a clear perception of improvement [1].

Low-cost, nonintrusive, wearable inertial sensors have been extensively applied to the physical therapy context and evidences showed that they are capable of providing accurately quantified human motion information [3]. However, the inherent complexity of human movement and human body surfaces, aligned with sensor limitations and unpractical calibration procedures makes the objective and quantitative assessment of movement a non-trivial problem to which many different solutions have been proposed in the literature [4].

A common approach to detect and evaluate physical therapy exercises using inertial measurement units (IMUs) is the application of template matching and pattern recognition algorithms. Algorithms, such as dynamic time warping (DTW), are applied to evaluate the performance of an exercise relative to its template, which is previously recorded at the clinic under the supervision of the physiotherapist [7-8]. This kind of approaches assumes a consistent sensor configuration and enables the exercise to be classified as having been correctly or incorrectly executed. More complex approaches for rehabilitation tracking are based on joint angles tracking, which require the neighboring body links to be monitored for changes in orientation. Naturally, the number of IMUs required increases with the complexity and granularity of the movement to be tracked [7]. Most of the methodologies require that the local coordinate system of the sensor is perfectly aligned with the joint axes, however, due

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to the non-planar surface of the body structures, a perfect alignment can hardly be achieved, which can be an issue when considering a home-based rehabilitation scenario [4]. Calibration procedures based on calibration movements or postures and complex mathematical models have been proposed to correct sensor misalignment [8-9], however, the most advanced and accurate methodologies require the execution of complex movements which are unsuitable to inexpert users and increase user burden, making them unsuitable to interactive applications [4].

In fact, the use of interactive game-based contexts is one of the most interesting applications where sensing is put in favor of users, having the potential to enhance the engagement and motivation needed to drive the rehabilitation process [10]. However, for a practical use of the system at home noncomplex setups and requirements are needed, while sufficient tracking accuracy is necessary to effectively guide users and follow their evolution over time. The same is true in the context of group-based interventions, in which multiple users may play together while being evaluated and the need of complex setups or calibration procedures is not realistic.

In this study, several approaches to track human body joint angles in real time were developed relying on data acquired from one or two IMUs mounted in bracelets. Algorithms were applied to the main joints of the human body, i.e. shoulder, elbow, hip and knee, so that bracelets could be conveniently wore in the adjacent segments, i.e. arm, forearm (wrist), thigh and lower leg (ankle). While some approaches required the users to perform a calibration posture before starting the movements, others required only the correct colocation (i.e. with the expected orientation) of the sensors on the body segment.

The objectives of the paper were threefold: 1) Investigate the reliability of different approaches to dynamically measure joint angles; 2) Identify the set of requirements and restrictions needed to maintain the levels of accuracy reported; 3) Evaluate the impact of the encountered inaccuracies against setup and execution complexity, considering the application of the system in a real usage scenario at home or in a group context.

MOVEMENT CHARACTERIZATION

Inertial sensors, also known as IMUs include triads of three-axial accelerometers, gyroscopes and magnetometers, which are capable of measuring acceleration, angular velocity and magnetic field vectors, respectively. They can be used to estimate the 3D orientation or attitude of the device relative to a fixed earth frame and, when attached to a body segment, they can be used to track angular and linear movements of the segment. Sensor data can then be used to characterize movements in real time.

Sensor fusion

Due to their ability to sense environmental properties, including gravity and magnetic fields, inertial sensors can be used to estimate 3D orientation or attitude relative to the earth frame (defined by vertical-north-east directions). However, measurements from each individual sensor in an IMU are characterized by several uncertainties which compromise the reliability of the orientation estimates. Inertial sensor fusion is therefore an important computation step for acquiring reliable 3D orientation.

Therefore, in this work, data were fused using a second order complementary filter, bringing together the relevant information of each sensor to compute the orientation of the device relative to the earth frame with increased accuracy. The orientation obtained was represented by quaternions which could easily be used to convert data to the earth frame. The developed sensor fusion algorithm takes into account the long-term reference to the gravity direction (provided by the accelerometer), together with the short-term accuracy of the gyroscope in measuring the angular rotation of the device. As the magnetometer information was not considered (i.e., no reference to the North was available) the earth frame consisted of a vertical axis and two arbitrary perpendicular horizontal axis that would not necessarily point to the North and East directions. In practice, though, the knowledge of the orientation of the sensor relative to the North is not required, as it is not relevant to each horizontal direction the user is facing at; in fact, only relative changes in orientation need to be considered. When two sensors are used, one need to take into account that they will not share the same earth coordinate frame for reference, therefore, careful analysis and interpretation of sensor data is required.

Angular kinematics

Human body movement is generated as a consequence of the contraction and relaxation of muscles that are attached to the bones. Movement is allowed due to the presence of joints, or articulations, in which adjacent bones come together and are allowed to move smoothly against each other. The movement of a body segment is due to the rotation of its preceding joint. Complex human body movements are generated as a combination of movements of multiple joints, which take place in the cardinal planes and around the cardinal axes of movement [11].

The human body joints can have different structures, allowing different degrees of freedom (DOF) and types of movements. Each DOF of each joint has its range of motion (ROM) which corresponds to the amount of rotation (an angle) achieved during a certain time interval. ROM is commonly used to assess the joints function of patients during physical rehabilitation [11].

Joint angles can be described in two different ways: an absolute angle represents the angular orientation of a single body segment with respect to a fixed line of reference (e.g. vertical), and a relative angle is the angle formed between the longitudinal axes of two adjacent body segments linked by a joint. The absolute angles are useful for posture evaluation (i.e. of the trunk) when only one segment is moving. The relative angles are more suitable for evaluating the angles during exercises (i.e. in which the two segments are moving).

Therefore, the process of tracking a single joint angle can be simplified by tracking the movement of its adjacent body segments. For body segment tracking, it is usually enough to define a vector that is aligned with the long axis of the body segment, and whose orientation will be changing relative to another body vector.

Coordinate frames and models

Considering that inertial sensors sense environmental properties of the earth, two coordinate systems will naturally be involved in the process: the sensor/device frame and the earth frame. To track the movement of a body segment, a sensor is placed on the segment in a certain position (which is assumed to be known), so the body frame can also be involved. Additionally, a fourth coordinate system will be considered: the pivot frame, which corresponds to the sensor frame during a calibration phase; this process enables a system to define a common frame relative to which information can be represented.

To facilitate movement parameterization and description a vector which aligns with the segment is defined. During the movement its orientation will change relative to the earth and the global body frame. Typically, the human body is modeled as a system of rigid segments (links) connected by joints (nodes). Each segment can only rotate about its preceding joint, and the number of axes which a given segment can rotate about will define the DOF of its preceding joint.

Taking into account the main joints of the human body and their movements, two planes of movement were considered: the sagittal and the frontal plane. An illustration of an absolute angle θ_{abs} is depicted in Figure 1, which represents the hip abduction/adduction movement in the frontal plane.

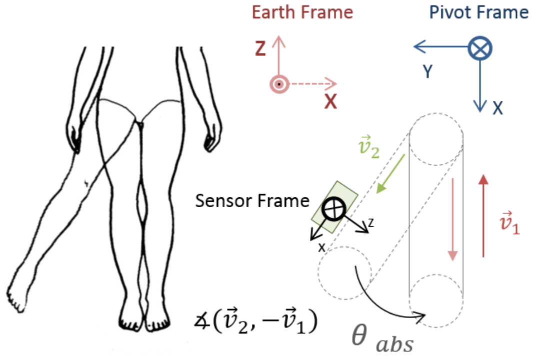

Figure 1. Hip abduction/adduction and coordinate frames: Earth, sensor and pivot frame are illustrated. $\overrightarrow{v_1}$ represents a vertical line and $\overrightarrow{v_2}$ the thigh segment.

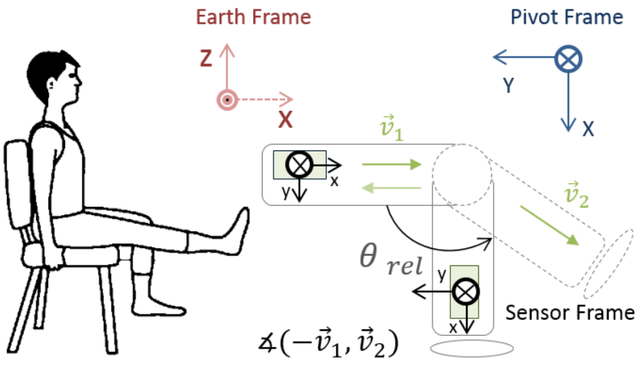

Figure 2. Knee extension/flexion and coordinate frames: Earth, sensor and pivot frame are illustrated. $\overrightarrow{v_1}$ represents the thigh and $\overrightarrow{v_2}$ the lower leg segment.

An illustration of a relative angle θ_{rel} is depicted in Figure 2, which represents the knee flexion/extension movement in the sagittal plane.

Considering the coordinate frames mentioned above and segments defined by vectors it was possible to track the relative and absolute joint angles by employing four different methods.

JOINT ANGLES ESTIMATION

One or two bracelets were placed on the body depending on the exercise to be executed. The use of the bracelets enabled the orientation of the sensors relative to the body to be already restricted to some extent, but instructions were given to participants in order to properly position them on the limbs. Four methodologies were developed for this study and employed to track the joint angles in real time. These four approaches do not rely on any calibration movement, being in principle suitable for application in unsupervised environments, like home. However, these four approaches differ on the setup's requirements and restrictions needed to accurately measure joint angles as well as on the type and amount of information that can be extracted from the movements. The description of the four methods is presented below, exploring each method's advantages and limitations.

Method 1 – Angle between two 3D vectors

The most practical approach to be employed would just require bracelets to be correctly placed on the body, so that a limb vector could be directly estimated. As the bracelet was restricting (at least to some extent) the orientation of the limb axis relative to the sensor, this assumption was considered as reasonable, so the limb vector was considered to be known. Limb vectors were expressed in earth coordinates and their orientation in the horizontal plane was eliminated, so that only changes relative to the vertical component would be considered (i.e., vectors were expressed as $\left[\sqrt{x^2+y^2}, z, 0\right]$). The angle between two 3D vectors was calculated as:

$$\theta = acos\left(\frac{\overrightarrow{v_1}.\overrightarrow{v_2}}{|\overrightarrow{v_1}||\overrightarrow{v_2}|}\right) \tag{1}$$

where $\overrightarrow{v_1}$ and $\overrightarrow{v_2}$ represent two limb vectors in earth coordinates (i.e. for relative angles) or a limb vector and the gravity vector (i.e. for absolute angles).

This approach has the practical advantage of not requiring any specific calibration procedure, however, unsigned angles are determined at the end, not allowing movement to be fully characterized, i.e. cannot distinguish e.g. shoulder extension from flexion and cannot differentiate planes of movement. The behavior of this method may in principle approximate the behavior of a traditional inclinometer used at clinics.

Method 2 – Signed angles with vertical

The ability to estimate signed angles requires the knowledge of an axis that is normal to the plane of movement. As a proof-of-concept, this axis was assumed to be known for each exercise considered, assuming that the sensor was correctly aligned with the limb. This normal vector, $\overrightarrow{v_n}$, was expressed in earth coordinates using the output quaternion of each sensor. A signed angle was determined between the limb vector and the gravity vector; knee and elbow angles were indirectly determined from each individual angle with vertical, using basic trigonometric relationships. Signed angles were determined using equation (2):

$$\theta = atan2\left((\overrightarrow{v_1} \otimes \overrightarrow{v_2}).\overrightarrow{v_n}, \overrightarrow{v_1}.\overrightarrow{v_2}\right) \qquad (2)$$

in which $\overrightarrow{v_1}$ and $\overrightarrow{v_2}$ may be inverted vectors and cross product between vectors may change its order depending on the adopted convention for the sign of the angle to be calculated.

The major source of errors may come from the imperfect alignment of the sensors with the body frame. Also, inaccuracies in the estimation of $\overrightarrow{v_n}$ may cause the sign of the angles to be wrongly determined.

Method 3 – Angles between plane-projected vectors

To report signed joint angles solely on the desired plane of movement, an alternative approach was employed. In this case, limb vectors were first projected onto the desired plane of movement, i.e. sagittal or frontal plane, depending on the exercise, and then expressed in 2D for angle estimation. The sagittal plane was considered to be the body's YZ-plane, whereas the frontal plane was considered to be the XZ-plane. So, basically, the limb vector was expressed as a combination of two projections: a projection onto the axis of movement (i.e. the cross product between the vertical and a normal to the plane, $\overrightarrow{v_n}$) and a projection onto the gravity vector. After projecting vectors onto the plane of movement, a signed angle between vectors could be calculated, using again equation (2).

This method, like the previous one, requires the knowledge of an axis normal to the plane of movement, i.e. a rotation axis. Despite being now assumed to be known a priori for each exercise, it could also be automatically estimated from the exercise itself, through the estimation of the main axis of rotation while doing the exercise (like in [9]), that may not necessarily match a cardinal axis of movement. However, the major interest would be in characterizing the movement using the cardinal planes of movement, therefore a vector normal to each body plane needs to be used. The ability to project vectors onto different planes of movement enables it to be fully characterized, for example, to understand if a person is doing the movement only on the desired plane or not.

In this case, the major source of errors may come from the imperfect alignment of the sensors with the body frame. But also the determination of $\overrightarrow{v_n}$ is critical, since an improper projection of vectors on plane may occur as a consequence of an inaccurate normal vector.

Method 4 – 3D orientation tracking

The last method employed requires the user to execute a calibration posture, in which the neutral upstanding position is maintained for a small amount of time before starting to do the exercise. During this time, orientation of the sensors relative to the earth is measured and averaged, providing a third reference frame, coincident with the sensors orientation at the beginning, the pivot frame. The limb vector, expressed in earth coordinates can then be expressed in pivot coordinates, using the inverted averaged pivot quaternion, i.e. all vectors will share the same coordinate system, which is aligned with the neutral position. This means that limb vectors can now be expressed using body coordinates, which enables the movements to be fully characterized in 3D, without a previous knowledge of the movement to be executed.

The major source of errors may come from the imperfect alignment of the sensors with the body frame and the imperfect alignment of the two sensors relative to each other. Moreover, quaternion drift may over time lead to inaccuracies in conversions between coordinate frames, which may periodically require a recalibration of the system.

VALIDATION

Subjects

Five healthy people, average age 27 ± 1 years old, 2 men, 3 women participated in the study. Subjects requiring physical rehabilitation were not included in this first stage of the study, since only the feasibility of different methods was explored at this stage.

Instruments

One or two wearable sensors were used to monitor movements. Sensors communicated wirelessly with a laptop via Bluetooth Low Energy, and data from each individual sensor (i.e. gyroscope and accelerometer) were collected at 50Hz (Figure 3).

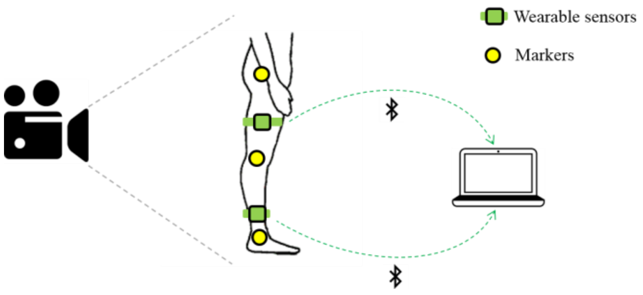

Figure 3. Hardware setup.

Yellow markers were placed on key anatomical positions and video recordings of people executing the movements were collected (Figure 3). A camera (2.07 megapixels, 1920x1080) with a frame rate of 25 frames per second was used. Video recordings were analyzed with the video analysis software Kinovea v0.8.25 [12].

Protocol

Before starting data acquisition, the camera was manually aligned with the acquisition scenario, so that it could properly capture all the movements in the desired plane. With the help of a physiotherapist, some basic exercises were defined. These exercises were based on simple rotation movements around each joint's DOFs where it was useful to measure the joint angles. The following movements were executed:

- Shoulder Flexion and Extension
- Shoulder Adduction and Abduction
- Hip Flexion and Extension
- Hip Adduction and Abduction
- Knee Flexion and Extension
- Elbow Flexion and Extension

The participants placed the sensors by themselves on the required places according to the exercise. Shoulder joint movements were tracked using one sensor placed on the lateral midsection of the upper arm, with the x-axis pointing to the hand. The hip joint was also tracked using one sensor, which was placed on the lateral midsection of the thigh, using the same convention. Elbow and knee joint angles required the use of two sensors simultaneously: one on the already defined positions and the other on the lateral midsection of the forearm (in the case of the elbow joint) or in the lateral midsection of the thigh (in the case of the knee joint).

Yellow markers were placed on the subject, following the standard convention used in goniometry [13-14]. Markers were placed on the arm – acromion process (center of humeral head), lateral epicondyle, radial styloid and midline of humerus – and leg – greater trochanter, lateral epicondyle, lateral malleolus, anterior superior iliac spine and center of patella. For each exercise, verbal instructions were given to the participants. The exercises were executed slowly to ensure that each movement was performed in the right plane according to the physiotherapy principles. Participants were requested to do three repetitions of each exercise, achieving the maximum amplitude of movement and backing to the starting position also three times. Before starting an exercise, subjects were requested to maintain a neutral position for a count of 5 seconds. Subjects positioned themselves so that the plane of movement in each exercise would be perpendicular to the camera line of sight. The experiment took place in a room with sufficient light and space for the exercises to be performed and recorded. In order to stand out the markers the participants were asked to wear dark and tightly fitted clothes.

Data Analysis

Video recordings were analyzed using Kinovea software. Yellow markers were manually annotated and automatically tracked using the object tracking functionality. When required, object point location was manually adjusted. Markers locations in the video timeframes of interest were exported to csv (with a rate of ~19Hz) and afterwards analyzed using Python 2.7.11. Considering that all exercises were executed very slowly (approximately 5s per repetition) and, in order to eliminate some rapid oscillations in tracked markers locations, a low pass filter (forward-backward Butterworth filter, with a cutoff of 2Hz) was applied to smooth signals. Afterwards, joint angles were calculated from the markers locations to be used as a ground-truth (example in Figure 4).

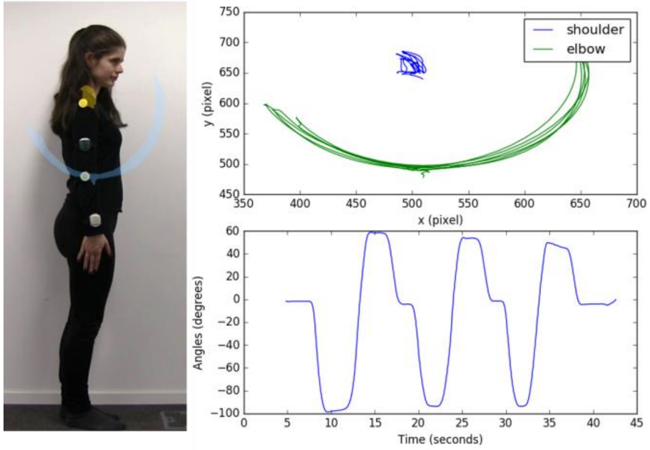

Figure 4. Tracking of shoulder and elbow markers using Kinovea. *Left and Right-up:* visual representation of trajectories; *Right-down*: the angle of the upper arm relative to the vertical.

Joint angles were also calculated from the inertial sensors data, using the four methods described previously. Calculated angles were compared with the ground-truth after a temporal alignment of the two signals (synchronization), which tested all possible alignments and decided for the lowest distance between signals, i.e. the best alignment. Data were resampled for a common sampling frequency of 25Hz.

All methods, except method 1 (angle between two 3D vectors), were able to provide signed angles; therefore, the absolute value of ground-truth angles was calculated for a fair comparison with method 1 results. As for the other methods, ground-truth data were kept unaltered.

Median, percentiles, maximum and minimum absolute errors were calculated for each exercise and method employed. Moreover, Pearson correlation coefficients were calculated together with the corresponding p-values to assess whether the correlation was statistically significant or not.

RESULTS

A total of 30 samples containing 3 repetitions of each exercise were collected from the five subjects in the study. Joint angles were extracted for each exercise by employing each of the four methods described previously and ground-truth angles were extracted from the video recordings. Signals were synchronized after the application of a signal alignment mechanism. An example of the joint angles measured on the shoulder flexion/extension exercise is presented in Figure 5.

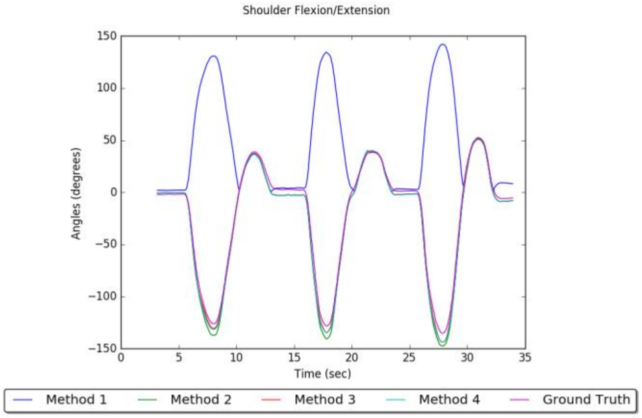

Figure 5. An example of the joint angles tracking for the shoulder flexion/extension exercise.

As can be observed in the example (Figure 5), all methods employed reveal a signal pattern that is very close to the signal extracted from the video (the ground-truth). However, as expected, the angles calculated using method 1 are always positive, as the method is not able to distinguish the direction of the movement. For a fair comparison with the ground-truth, the angles extracted from the video were made positive before calculating the errors associated to method 1.

The absolute difference between joint angles obtained from video analysis and angles obtained using inertial sensors was calculated for each of the four methods employed. Box and Whisker charts were created in order to compare the distribution of errors associated to each method (Figure 6). Before extracting all relevant measures, outliers[1] were removed.

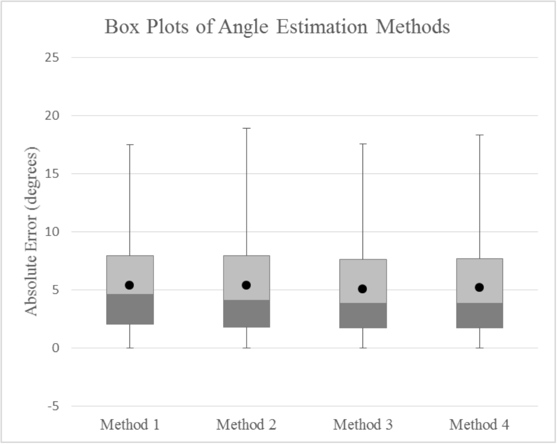

Figure 6. Absolute errors of joint angles tracking for each method employed (● marks – average values).

According to Figure 6, errors in estimate joint angles are generally low, with median values below 5 degrees and IQR interval around 6 degrees for all methods employed.

No clear differences between the four methods used can be observed in Figure 6, which means that all methods could be interchangeably applied without major impact in the accuracy of joint angles estimation.

The following table (Table 1) presents the results achieved with each method for each exercise performed.

Exercise	M	Median	IQR	r_P	p-value
Shoulder flexion and extension	1	4,57	3,63	0,99	<0.01
	2	4,93	3,73	0,99	<0.01
	3	3,75	3,29	1,00	<0.01
	4	3,74	2,87	1,00	<0.01
Shoulder abduction and adduction	1	6,23	4,90	0,99	<0.01
	2	4,98	3,95	0,99	<0.01
	3	5,19	4,01	0,99	<0.01
	4	3,05	2,67	1,00	<0.01
Hip flexion and extension	1	4,30	3,63	0,99	<0.01
	2	3,16	2,22	0,99	<0.01
	3	3,16	2,38	0,99	<0.01
	4	3,09	2,06	1,00	<0.01
Hip adduction and abduction	1	5,36	5,90	0,95	<0.01
	2	5,73	4,04	0,98	<0.01
	3	6,01	4,31	0,98	<0.01
	4	5,46	4,12	0,98	<0.01

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[1] All values outside the interval [Q1-1.5*IQR: Q3+1.5*IQR] were considered to be outliers (IQR – Interquartile Range).

Knee flexion and extension	1	9,02	6,15	0,96	<0.01
	2	6,85	5,33	0,97	<0.01
	3	7,06	5,54	0,98	<0.01
	4	4,79	7,41	0,98	<0.01
Elbow flexion and extension	1	6,92	5,59	0,99	<0.01
	2	11,32	12,82	0,99	<0.01
	3	12,18	9,61	0,99	<0.01
	4	11,68	13,64	0,99	<0.01

Table 1. Absolute errors (in degrees) of joint angles tracking for each exercise and method employed and respective correlations with angles extracted from video recordings; M – Method, IQR – Interquartile range, r_P- Pearson correlation coefficient; when p<0.05 the correlation is considered to be statistically significant.

A very strong correlation[2] exists between angles extracted using each method and angles extracted from the video recordings (r_P > 0.90, p<0.01). Correlations are positive, which means that signals from sensors and video evolve in the same direction (after making video angles positive for the comparison with angles calculated using method 1). Moreover, as observed in Table 1, 75% of the evaluated cases have a median absolute difference below 7 degrees.

Knee and elbow flexion/extension exercises reveal the highest median errors in general, with elbow flexion/extension revealing the highest errors.

DISCUSSION

All methodologies employed to measure joint angles based on inertial sensor data revealed an acceptable accuracy, with median error below 5 degrees and 75% of the evaluated cases with median absolute difference below 7 degrees. In fact, this was considered as an acceptable result, with accuracies in the same order of the goniometer measurements used traditionally at clinics (with an accuracy of 6 to 7 degrees [16]). However, one need to take into account that a small number of subjects took part in the study, which may limit the validity of the results. Moreover, tests were executed under controlled conditions, i.e. subjects were performing the movements as expected, on the required planes of movement. Not so much control was taken over the placement of inertial sensors on the body, since only verbal instructions were followed by the participants who were in charge of placing the bracelets on the limbs. This means that errors associated to the imperfect colocation of the sensors on the body are present in our results and that these errors may be normally associated to a joint angle measurement process when an inexpert user is requested to do the measurement himself.

It was observed that errors on angles measured on elbow flexion/extension exercise were higher than in the other exercises, which may be a consequence of two different factors: 1) the complex anatomy of the arm with non-planar surfaces may have had an impact on the correct alignment of the sensors; 2) arm movements have more degrees of freedom than leg movements, i.e. it is more difficult to execute and isolate the plane of movement during the exercise. In fact, the methods that were more sensitive to these two factors (i.e. methods 2-4) were more penalized in this exercise.

Joint angles requiring the use of two sensors simultaneously (i.e. knee and elbow flexion and extension) had the highest errors (Table 1), possibly due to an accumulation of errors from both sensors individually. This means that relative angles may be more prone to errors than absolute angles, which is also an expected result.

Another source of errors may come from the video recordings analysis itself. In fact, it is difficult to guarantee that the camera is perfectly perpendicular to the plane of movement. Also, the coordinates of the markers on the video may have some problems, not only due to tracking errors, but also due to the distortions that are introduced on the image while capturing the video. However, the reliability of Kinovea in measuring joint angles had been previously demonstrated [17], therefore, it was considered an as acceptable source of information that could be used as reference in the evaluation of the results.

Despite all methods employed had revealed low errors in comparison with video, method 1 is the least sensitive to sensor misalignments and to the imprecise estimation of the plane of movement. However, it is not able to differentiate neither planes nor directions of rotation, which may limit its application when this kind of information is required. The other methods, contrarily, are sensitive to planes and directions of rotation: while methods 2-3 require an accurate estimation of an axis of rotation, which may be automatically determined based on the exercise itself, method 4 requires a perfect alignment of the sensors on the body, which may be achieved with calibration postures. The selection of the methods to employ may depend on the specificities of the target group and the requirements for the movement characterization. However, the setup proposed is not complex when compared with other methodologies requiring multiple calibration movements, as happens in [9]. Despite the complexity of this kind of approaches, [9] reports average angular differences between measured and reference systems around 6.4 degrees.

Despite the results obtained were acceptable for a study developed in a controlled environment, it is possible to implement any of the methods described in this paper in a

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[2] According to the classification proposed by Callegari-Jacques (2003) [15].

rehabilitation scenario at home or in a group context according to the specificities of the target group and the requirements for the movement characterization. By making the bracelets with the sensors with a unique configuration enables users to easily place them in a single, known, orientation, which can then be used to track body movements by employing any of the four methods described. Further evaluation of the methods may be required in real usage scenarios at home, where further challenges may be encountered which can compromise the reliability of the results..

CONCLUSION

This paper describes four different approaches to estimate absolute and relative human joint angles during physical exercises. For that purpose, data were acquired from one or two IMUs mounted in bracelets that were placed on the body depending on the exercise to be executed and instructions were given to participants in order to properly position them on the limbs. This way, the orientation of the body segment where the sensor was placed was obtained though sensor fusion. Vectors representing the body segments were defined and with their orientation relative to the earth, four different approaches were developed to estimate absolute and relative angles.

Measured angles were evaluated against the marker-based video tracking software Kinovea. Correlation analysis of the estimated and ground-truth angles indicated a statistically significant and very strong correlation. Moreover, the median errors were below 5 degrees and 75% of the evaluated cases had a median absolute difference below 7 degrees for all four methods employing inertial data. These differences are mainly due to the human body anatomy which make it difficult to place the bracelets on the body on the expected position.

Despite these errors, all methods showed reliable results taking into account their respective requirements and restrictions, which are not very high in comparison with other approaches found in the literature. Assuming that the bracelets are worn in a certain position, this approach could be useful for first stages of rehabilitation in a real usage scenario at home or for group interventions.

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