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EXECUTIVE SUMMARY OF THE THESIS

VALIDATION OF AN INERTIAL SYSTEM FOR HOME REHABILITATION BY COMPARATIVE MEASUREMENTS WITH THE OPTOELECTRONIC SYSTEM

TESI MAGISTRALE IN BIOMEDICAL ENGINEERING – INGEGNERIA BIOMEDICA

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1. Introduction

Rehabilitation through exercise is considered an essential tool in the treatment of musculoskeletal disorders.

In recent times, there has been a transition towards telerehabilitation, which is defined as a means of delivering distance-based services and interventions, aimed at enabling, restoring, improving, or maintaining the psycho-physical functioning of individuals.

In this context, it is crucial to monitor the quality and the compliance of physical exercises carried out in a non-clinical environment, to ensure the effectiveness of a rehabilitation program [1].

Biomechanical biofeedback systems providing real-time information to users based on inertial measurement units (IMUs) have proven to be useful tools for movement evaluation [2].

When combined with exergames (i.e., videogames that also serve as physical exercise) and suitable user interfaces, such systems have enabled the development of innovative solutions for real-time monitoring of home-based rehabilitation therapies and remote supervision by clinicians [3].

However, to ensure the correct adoption of these new technologies in rehabilitation, it is necessary to evaluate their accuracy, reliability, and precision [4].

In particular, the performance of inertial sensors must be compared to that of optoelectronic systems, considered the gold standard for motion analysis [5].

Furthermore, since the incorrect placement of IMUs on body segments, during unsupervised use, can compromise system performance, the sensitivity of the sensor output to sensor misplacement must be evaluated [6].

The present study assessed the accuracy of a motor rehabilitation device based on a single inertial unit (Kari, Euleria Health, Rovereto, Italy) in measuring joint angles across a set of motor task for trunk and lower limbs by comparison with the optoelectronic system. Additionally, the sensitivity of the sensor output to sensor mispositioning was explored.

2. Material and methods

2.1 Participants

The present study was conducted at the "Luigi Divieti" Posture and Movement Analysis Laboratory, Department of Electronics, Information and Bioengineering (Politecnico di Milano), on twenty-one healthy individuals (M:12/F:9; age: 23.5±1.3 years; height 175.3±8.7cm; weight 68.5±11.6kg; BMI 22.1±2.1kg/m^2) recruited on a voluntary basis.

2.2 Instrumentation

During the laboratory acquisitions, each volunteer was equipped with both the IMU and passive markers, applied on specific anatomical locations of the body using elastic bands or double-sided tape respectively. In order to compare the outputs of the two systems, participants' movements were recorded simultaneously by the two systems.

2.2.1 Laboratory setup

The optoelectronic system used for optical data collection (BTS Bioengineering SPA, Milan, Italy) is equipped with eight cameras and detects the spatial position of passive markers at a sampling rate of 100 Hz.

2.2.2 Commercial rehabilitation device based on a single inertial measurement unit

Kari is a medical device designed for rehabilitation and training, consisting of a single IMU connected via Bluetooth to a tablet on which the mobile application is installed.

The mobile app guides the patient during the execution of the exercises assigned by the practitioner, through audio and video feedback. The IMU integrates three triaxial sensors (i.e., accelerometer, gyroscope, and magnetometer) and uses a sampling rate of 30 Hz. Depending on the motor task performed, the sensor is placed with an elastic band on the body segment of interest and records in real time the value of the segment angle with respect to its own reference system.

2.3 Study design

For the evaluation of the accuracy of the sensor measurements, participants performed the following motor tasks:

- Right/left knee extension from a sitting position.
- Semi-squat.
- Anterior trunk flexion.
- Right/left lateral trunk flexion.
- Right/left hip abduction.
- Right/left hip flexion.
- Right/left hip extension.

In the hip, trunk and knee exercises, the sensor was placed on the thigh, chest, and shank, respectively.

For the assessment of the sensitivity of the sensor output to its misplacement, the following exercises were performed with the sensor displaced medially and laterally from the correct position by the 10% of the participant's thigh circumference:

- Right/left hip flexion.
- Right/left hip extension.

During the execution of each motor task, an artifact was introduced to be used as a trigger for the synchronization of the signals obtained from the two systems. Each participant performed two repetitions of the exercise, followed by three rapid movements that produced a series of spikes visible from the recordings of both systems.

2.3.1 Subject preparation and marker set

In accordance with the Davis protocol [7], anthropometric measurements were taken for each volunteer and 22 markers were placed on participants’ bodies at specific anatomical landmarks. An additional marker (i.e., “Kari”) was placed on the sensor in order to use its signal as reference for synchronization.

2.4 Data analysis

For each exercise and for each participant, the raw data collected by the optoelectronic system were processed to calculate the kinematic parameters under investigation, i.e., anterior and lateral trunk flexion angles, hip abduction, flexion and extension angles, and knee extension angle.

In general, the trunk and pelvis angles are absolute angles, (i.e., referred to the laboratory coordinate system), while the hip, knee and ankle angles are relative ones.

In the present study, the thigh angle was also computed as an absolute angle.

The angles measured by the sensor were compared with the angles retrieved from the optoelectronic system, in terms of both relative and absolute ones.

To evaluate the sensitivity of sensor output to sensor misplacement, the angles measured by the correctly positioned IMU were compared with those measured by the misplaced IMU.

2.4.1 Data analysis: evaluation of sensor measurement accuracy

The data recorded by the IMU and those obtained by the optoelectronic system were time-synchronized. The acceleration signal along the vertical axis of the sensor reference system (i.e., x-axis) detected by the accelerometer was compared to the position signal of the "Kari" marker along the vertical axis of the laboratory coordinate system (i.e., y-axis) obtained by the optoelectronic system and resampled at 30 Hz, in which vertical peaks (i.e., the synchronization trigger) were clearly visible.

The reference signals were manually cut to isolate a window containing the spikes and cross-correlation analysis was performed to calculate the delay between the two signals.

The angular signals recorded by the optoelectronic system were resampled at 30 Hz, low-pass filtered and temporally aligned with the angles recorded by the IMU, using the previously calculated delay. The amplitude offset between the two angle signals was then removed.

Each repetition of the exercise was identified, isolated from the two signals, and then normalized with respect to the duration of the motor task and to its maximum amplitude value.

The working phase of each repetition was isolated by selecting angle values greater than the 90% of the maximum amplitude value.

For each repetition, the range of movement (ROM) was obtained as the difference between the average angle value in the working phase and the angle value in the resting phase.

The average ROM value of the total repetitions was calculated to obtain the ROM value of the motor task.

2.4.2 Data analysis: evaluation of sensor sensitivity to incorrect positioning

For each exercise performed with the misplaced sensor, the procedure described in the previous section was performed to calculate the ROM of each repetition. The ROM value of each exercise performed with the misplaced sensor was calculated as the average of the ROM values of the total number of repetitions.

2.5 Statistical analysis

The Anderson-Darling test was carried out to assess the normality of ROM values.

For the exercises performed bilaterally, the ROM values of the exercise performed on the right side and those of the exercise performed on the left side were combined, since the result of the preliminary t-test showed no statistically significant differences between them.

To compare the angular outputs of the sensor with those of the optoelectronic system, Pearson's correlation coefficient, p-value, Lin's concordance correlation coefficient (CCC), percent accuracy, and Root Mean Square Error (RMSE) were calculated and Bland-Altman plots were plotted, for each motor task.

To assess the sensitivity of device output to device mispositioning, the RMSE between the ROM values obtained from the measurements of the correctly positioned sensor and those obtained from the measurements of the mispositioned sensor was calculated.

3. Results

3.1 Comparison of the outputs of the two systems

For a qualitative analysis, the trend of the angle measured by the IMU was plot together with that obtained from the optoelectronic system, for each motor gesture. The overall trend in the angle traces recorded by the sensor was consistent with that obtained by the optoelectronic system for each motor task, with differences of varying magnitude in the amplitude reached by the two signals.

Figure 1 shows an example of the angle trend estimated by the IMU compared with that obtained by the optoelectronic system, in the hip abduction exercise.

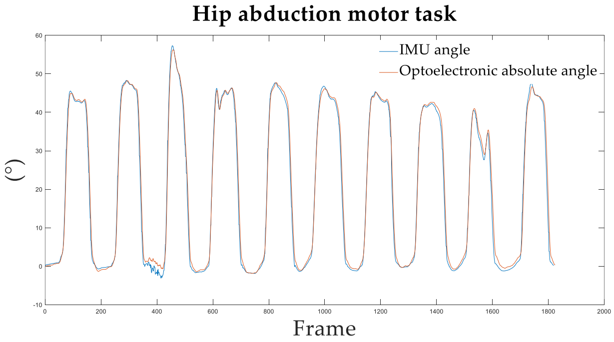

Figure 1. IMU angle (blue line) vs optoelectronic absolute angle (orange line) in the hip abduction motor task.

For every participant, the ROMs of each motor task were calculated from the angular measurements obtained by the sensor and by the optoelectronic system. Regarding the exercises performed bilaterally, the preliminary t-test did not show a statistically significant difference between the ROM values of the exercises performed on the right side and those of the exercises performed on the left side. Therefore, these values were combined, and the total number of repetitions was considered for further analysis.

The Anderson-Darling test showed that the ROM values of the motor tasks followed a normal probability distribution.

The mean ROM of each motor task was thus calculated as the average of the participants' ROM values as reported in Table 1, together with the respective standard deviation.

The average difference between the ROMs obtained from the IMU measurements and those obtained from the absolute angles acquired by the optoelectronic system was 4.3°± 3.4°, while the average difference between the ROMs calculated from the sensor measurements and those calculated from the relative angles obtained by the optoelectronic system was 7.2°± 5.3°.

	ROM (°)		
	IMU	**Optoelectronic (relative)**	**Optoelectronic (absolute**
Hip flexion	30.28 (5.24)	27.48 (5.10)	31.32 (5.17)
Hip extension	17.08 (3.75)	13.87 (3.76)	23.40 (4.26)
Hip abduction	30.93 (6.09)	21.27 (3.81)	35.12 (5.90)
Hip flexion (semi-squat)	33.92 (7.34)	49.19 (15.82)	34.80 (9.33)
Anterior trunk flexion	40.15 (8.36)		30.15 (5.50)
Trunk bending	26.53 (5.33)		30.10 (6.06)
Knee extension	71.05 (10.28)	66.15 (9.95)	

Table 1. Mean ROM values for each motor task, together with their standard deviations.

In the comparison between the angles estimated by the IMU and the relative angles obtained by the optoelectronic system, the average percentage accuracy was 11.03%, while in the comparison with the absolute angles acquired by the optoelectronic system, the average percentage accuracy was -3.91%.

With the exception of the hip extension and hip abduction motor tasks (when comparing the angles detected by the IMU with the relative angles obtained by the optoelectronic system) and the anterior trunk flexion exercise (when comparing the angle detected by the IMU and the absolute angle obtained by the optoelectronic system), there was a strongly positive correlation between the ROM values obtained from the IMU measurements and those obtained from the optoelectronic system measurements, as highlighted by the values of Pearson correlation coefficient greater than 0.7. The results of Pearson's correlation analysis are in line with those of the CCC.

When comparing the IMU angle measurements with the absolute angles obtained from the optoelectronic system, the CCC was greater than 0.7 in the hip flexion, hip abduction, semi-squat, and lateral trunk flexion motor tasks, indicating agreement between the two measurement techniques, while when comparing the IMU measurements with the relative angles obtained from the optoelectronic system, this value was greater than 0.7 in the hip flexion and knee extension exercises.

Bland-Altman plots compared the ROM values obtained from the IMU measurements with the ROM values obtained from the absolute and relative angles estimated by the optoelectronic system. The analysis of these diagrams confirmed the agreement between the two measurement techniques.

In the comparison between the angles estimated by the IMU and the relative angles obtained by the optoelectronic system, the mean RMSE was 9.1°± 5.7°, with the minimum value (4.5°) in the hip flexion exercise and the maximum value (17.95°) in the semi-squat exercise.

When comparing the angles recorded by the IMU with the absolute angles obtained by the optoelectronic system, the average RMSE was 6.9°± 4.2°, with the minimum RMSE value (3.68°) in the hip flexion exercise and the maximum value (14.55°) in the anterior trunk flexion exercise.

3.2 Sensitivity of sensor measurement to sensor misplacement

The average difference between the ROMs obtained from the measurements of the correctly positioned IMU and those obtained from the measurements of the mispositioned IMU was 3.0°±1.6°.

In particular, the laterally and medially misplaced sensor overestimated the hip flexion angle by 2.58° and 1.38°, respectively.

In the hip extension motor task, the movement angle was underestimated by 5.18° in the lateral mispositioning configuration and overestimated by 2.9° in the medial mispositioning configuration.

In the hip flexion and hip extension motor tasks, the RMSE between the ROM values obtained with the correctly positioned sensor and those obtained with the laterally and medially displaced sensor ranged from 4.86° to 7.09°, with an average value of 5.55°± 1.03°.

4. Discussion, conclusions and future perspectives

The main purpose of the present study was to evaluate the accuracy of the angular measurements of a commercial IMU-based device for motor rehabilitation by comparing them with those obtained by the optoelectronic system, considered the gold standard for motion analysis.

From an initial qualitative analysis, the overall trends of the graphs of the angles recorded by the sensor resulted consistent with that obtained from the optoelectronic system for each of the exercises considered, with differences in the peak values.

For the motor tasks involving the hip, the graphs showed a discrepancy between the peak values of the angles recorded by the IMU and the angles defined as relative (i.e. describing the orientation of the thigh segment with respect to the pelvis) obtained by the optoelectronic system, but a more concordant trend between the angles recorded by the IMU and the angles defined as absolute (i.e. describing the angle of the thigh segment with respect to the laboratory coordinate system) obtained by the optoelectronic system, as the sensor measures angles as absolute with respect to its own coordinate system.

The quantitative evaluation of ROM values confirmed what had already been observed qualitatively. In fact, for the motor tasks involving the hip, the angles recorded by the IMU were compared with the absolute angles obtained by the optoelectronic system.

In the hip abduction, extension, and flexion motor tasks, the sensor underestimated the range of motion, with an RMSE of 6.4°, 8.5°, and 3.7°, respectively.

In the hip abduction and hip flexion tasks, the RMSE values were consistent with those obtained in a recent study [8].

In the semi-squat exercise, the right hip flexion angle detected by the IMU was 2.5% lower than the angle obtained by the optoelectronic system, with an RMSE of 3.7°.

The hip extension angle measured by the sensor was discordant with the angle obtained by the optoelectronic system. This difference could be due to sensor placement, movement pattern, or joint mobility of the participant.

The IMU overestimated the knee extension angle by 4.9° on average, with an RMSE of 5.9°, results consistent with those obtained in two previous studies [6] [8].

The sensor underestimated the lateral trunk flexion angle, with an RMSE of 4.5°, value in agreement with that obtained in a previous study [9].

In the hip flexion, hip abduction, semi-squat, knee extension and lateral trunk flexion motor tasks, the results obtained by the IMU and by the optoelectronic system showed a strongly positive correlation, as evidenced by the values of Pearson correlation coefficient greater than 0.7. The graphical analysis of the Bland-Altman plots and the values of Lin concordance coefficient exceeding 0.7 indicated a concordance between the two measurement techniques.

The sensor overestimated the anterior trunk flexion angle by 33.2%, with an average difference of 10° and an RMSE of 14.6°, results in contrast with those obtained in previous studies [6][9]. The angular values obtained in the present study in the anterior trunk flexion motor task could be due to either the placement of the sensor on the chest, the use of a single IMU for movement angle estimation, or the implementation of the Davis protocol. The use of a different biomechanical protocol, dividing the trunk into different regions, such as the one developed in a previous study [10], could lead to different results.

Another purpose of the present study was to evaluate the sensitivity of sensor measurement to sensor mispositioning.

The obtained results are consistent with those reported in a previous study [6].

A reduction in the angle recorded by the mispositioned IMU was observed in the hip flexion exercise, compared with the angle obtained by the correctly positioned sensor, with an RMSE of 5.1°. In the hip extension exercise, the laterally misplaced sensor recorded a lower movement angle, with an RMSE of 7.1°, while the medially misplaced sensor recorded a higher angle, with an RMSE of 4.9°.

As hypothesized, the misplacement of the sensor resulted in decreased accuracy of angle measurements.

The discrepancy between the angles measured by the correctly positioned IMU and by the mispositioned IMU was greater in the case of lateral displacement. However, the RMSE values are limited to just a few degrees.

In addition, medial or lateral displacement greater than that examined in this study, results in the failure of the sensor calibration phase and in the displaying of a warning message to the user. Therefore, the improper placement of the sensor during unsupervised use in home rehabilitation programs does not seem to compromise the overall performance of the device.

In conclusion, the results obtained in the present study showed that the IMU-based rehabilitation device enables reliable motion measurements, consistent with those obtained in previous studies using more complex systems. In particular, the device was found to be accurate enough to be used in lower limb and trunk home rehabilitation programs. In fact, the device seems to be able to provide a reliable esteem of the angular motion that allow the professional to remotely monitor the progress of the rehabilitation pathway and change in patient’s motor function.

Further future research could focus on the evaluation of the measurement accuracy in upper limb motor tasks and in the implementation of alternative biomechanical protocols. In addition, because the present work involved only healthy subjects, future studies could evaluate the measurement accuracy in the case of individuals with functional limitations.

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