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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

Validation of IMU-based simulation for water exercises kinematics

Laurea Magistrale in Biomedical Engineering - Ingegneria Biomedica

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1. Introduction

MOtion CAPture (MOCAP) is the most accurate and widely used method for clinical movement analysis. The MOCAP procedure consists of placing infrared cameras around the subject while they are wearing retro-reflective surface markers in precise anatomical points. The acquisition of the motor gesture is realised by tracing the trajectory of these markers. However, due to the cumbersome equipment, MOCAP remains limited for use outside of controlled environments. Conversely, Inertial Measurement Unit (IMU) based systems can provide a viable alternative for motion analysis in real-life contexts outside of controlled environments, especially in the sports field [5]. IMUs consist of accelerometers, gyroscopes, and magnetometers allowing the measurement of kinematic motion parameters such as joint angles, velocity, and acceleration during exercises, which can be used to assess the effectiveness of the rehabilitation program. IMUs are ideal for measuring motion outdoors or underwater, once the waterproofing is ensured because they can record for a longer period of time. Although IMU-based motion capture is minimally invasive, faster, cheaper and more versatile than MOCAP, straightforward and immediate visualisation of the data recorded via customised IMUs remains challenging. In particular, the data fusion algorithms needed to combine the three sensing components, the time-consuming processing and interpretation of the data and results obtained, often requires highly-technical operators, limiting the use of these devices in the research field. OpenSim is an easy-to-use, open-source software created by Stanford University in the early 2000s to simulate the cause-effect relationships of neuromusculoskeletal diseases. The software can analyze the kinematics of the subject, including joint angles and also measure muscle fibre length and enables simulations. OpenSim generally uses the data from a MOCAP system with retroreflexive markers, while the novel toolkit uses as input data IMU measurement providing all the features of the original software. To overcome these limitations placed on IMU-based systems for motion analysis, OpenSim has developed a toolkit that allows for the creation of a digital twin from wearable sensor data, called OpenSense [1, 2]. So far, OpenSense's workflow has only been used with commercial sensors from APDM or Xsens (Movella Inc.) and has not yet been tested on custom IMU-based devices. Furthermore, there is a lack of software tools which allow for the integration of custom IMU-based systems. The first contribution of this MSc Thesis (Phase 1) is the development of an algorithm for rapid and precise analysis of body kinematics, using OpenSense software with IMUs prototypes, called *TinyTag*. They are built by Tallinn University of Technology (TalTech) in Estonia and have the fundamental feature of being water-resistant. Phase 1 of this work aims to validate the use of these customized TinyTag (TT) IMUs with the OpenSense toolkit for human motion analysis. Such validation is conducted by comparing the kinematic estimates obtained from OpenSense driven by TT with established reference tools to verify their accuracy: the MOCAP system and OpenSense driven by commercial Xsens IMUs (X). The second main contribution of the Thesis (Phase 2) is the application of the developed algorithm in a water environment exploiting the main feature of the sensors. Phase 2 investigated the physiological Range Of Motion (ROM) for lower limb joints during basic exercises in aquatic settings exploiting TT and OpenSense's validated method developed in Phase 1. Joint angles of healthy young participants are assessed to define the physiological range of motion for a distinct population performing four simple exercises commonly used in aquatic physical therapy. This study assumes that there are benefits of physical activity in an aquatic setting, including buoyancy, hydrostatic pressure, and temperature. These properties reduce joint stress, improve training intensity and proprioception, and provide a relaxing and safe environment. The use of water is applied in sports and clinical fields for recovery from fatigue and treatment of chronic conditions. However, the quantitative assessment of underwater motion is limited due to the inadequacy of traditional techniques. Several studies have already been conducted on the use of IMUs in aquatic environments, with promising results.[3, 4] However, there are still some limitations to using IMUs in aquatic environments. One issue is the difficult waterproofing of commercial IMUs, which can affect the accuracy of the measurements and can lead to measurement errors or damage to the equipment. Overall, the use of customised IMUs in aquatic environments shows great promise for evaluating underwater motion, but further research is needed to overcome the limitations of processing and visualization and fully exploit the potential of this technology.

2. Materials and methods

2.1. Phase 1

In this phase, three systems for biomechanical assessment of motion were compared: the *gold standard* BTS optoelectronic SmartDX 400 system, MTw Awinda IMUs by Xsens and the waterproof TinyTag. All three measurement systems chosen have the sampling frequency of the data set at 100 Hz, no resampling process was required. Two types of TinyTag sensors were used in this study, they differ just in the external dimension and in the life battery but the IMU is the same. The TinyTag is composed, further to the Inertial Measurement Unit, also of a pressure and temperature detector, additionally the data can be read by a USB port and has an internal memory capable of saving the sensor orientation acquired from the moment the sensor is switched on to the switched off one both done by using a magnet. The positioning of the markers for the optoelectronic system followed the *Davis protocol*, instead, for both the IMUs systems, one sensor is placed on the back of the pelvis area, and three for each leg are placed on every segment of the limb, following Outwalk protocol.

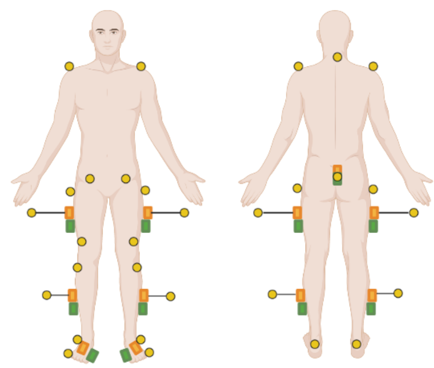

Figure 1: Placement of IMU sensors (orange boxes Xsens and green TinyTag) and retro-reflective markers (yellow dots) on the subject (in frontal view and posterior view).

The raw data acquired by the MOCAP system are processed with BTS-licensed software suited by an ad-hoc designed protocol to measure the joint angles. The acquired recording is saved in *.trc* files and then imported into the SMART Tracker (Version: 1.10.469.0) software, where a

label is associated with each marker to ensure correct movement recognition. This step is time-consuming but crucial for accurate data analysis. After this, the SMART Analyzer software is used for inverse kinematics, involving filtering and interpolating the marker traces and identifying the internal centre of instantaneous rotation for each joint. Joint angles are then estimated and reported as graphs. The recording of Xsens data sensors is obtained using its licensed software. The loggers are synchronized and calibrated using the MVN software through a specific procedure, which involves standing still and walking for a few seconds. Although the Xsense software consents to estimate joint angles and kinematic parameters, the focus of this study is the use of OpenSense for inverse kinematics analysis. Hence, the quaternion orientation data from Xsens are saved and made compatible with the OpenSim format using MATLAB 2022a code provided by OpenSense.
Lastly focusing on TinyTag sensors, to synchronize them, prior to being attached to the investigated subject through Velcro straps, they are placed inside a metallic coil and supplied with an electrical impulse to generate a signal recorded by magnetometer data allowing via an ad-hoc MATLAB code a post-processing synchronization. The raw sensor data are then calibrated for gyroscope, accelerometer, and magnetometer readings and turned into a format readable from OpenSense. Specifically, a Savitzky-Golay polynomial filter is applied to make the data smoother and less affected by noise and a Madgwick filter sensor fusion algorithm is used to obtain quaternions orientations. While the IMUs recorded multiple exercises, the original data is split into individual exercises and repetitions to reduce gyroscope low-frequency bias and drift prior to the filtering and processing. The data from the two IMU systems are imported into OpenSim (Version 4.3, USA). A calibration process is performed to register the IMUs to the corresponding body segments. The biomechanical model `3DGaitModel2392.osim` (23 DOF, 76 muscles) is chosen. The IMU Inverse Kinematic Tool in OpenSim is then used to calculate joint angles and produce a *.mot* file containing motor information. This workflow allows the study of inverse kinematics and the prediction of movements using IMUs data. Four simple exercises often exploited in water rehabilitation protocols were selected: Squat (S), Frontal Leg Swing (FLS), Knee To Chest (KTC) and Heel To Hamstring (HTH). The experimental protocol of Phase 1 takes place in the "Luigi Divieti" Posture and Movement Analysis Laboratory of Politecnico di Milano (Italy). Each of them starts from a standing position and finishes as shown in Figure 2, where it is also highlighted the joint angle considered for the analysis.

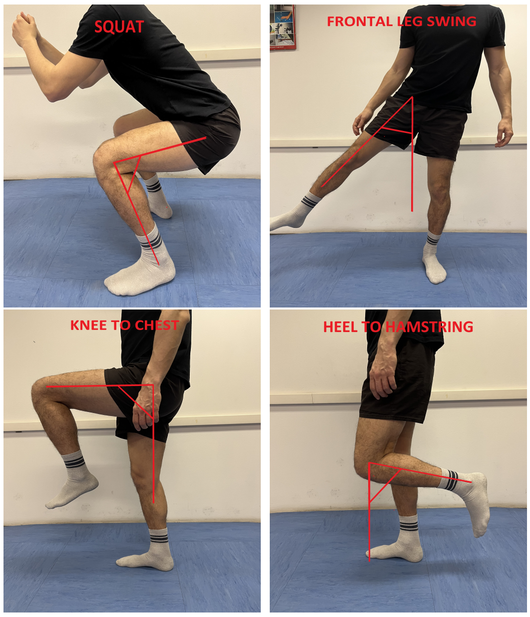

Figure 2: Visualization of the four exercises with respective joint angles considered. Knee flexion/extension angle, Hip abduction/adduction angle, Hip flexion/extension angle, Knee flexion/extension angle.

To assess the validity of the OpenSense estimates with inertial sensors, especially the TT, a comparison of the joint angles measured by the optoelectronic system and Opensense is made. Two healthy subjects (Age: 24 (±0) years; Height: 176 (±4) cm; Weight: 72.5 (±7)Kg) are acquired while performing the four exercises with five repetitions each. Every session described is repeated twelve times for each subject for a total of twenty-four sessions. The statistical indexes evaluated were:

- Root Mean Squared Error (RMSE): measures the distance between two graphs point by point and is a commonly used evaluation parameter in motion studies. A smaller RMSE value indicates a better fit between the predicted and observed values.

- Spearman's correlation coefficient: measures the monotonic relationships between two variables, when the distribution of the data isn't normal. In order to use this type of parameter, a check of the distribution was made using the Kolmogorov-Smirnov statistical test, which showed the results of non-normal distribution ($p < 0.05$). A perfect Spearman non-parametric coefficient of +1 or -1 occurs when each of the variables is a perfect monotone function of the other.
- Intraclass Correlation Coefficient (ICC): measures the reliability of ratings among raters and ranges from 0 to 1, with 0 indicating no reliability and 1 perfect reliability. The Two-way mixed effects model with the absolute agreement and single rater was used.
- Bland-Altman plot: a visualization tool used to compare measurements of the same phenomena done with two instruments or techniques by displaying the average measurement and difference in measurements between the two instruments. It also shows the bias (average of the differences) and 95% confidence interval for the average difference.

2.2. Phase 2

It is foreseen the creation of a benchmark physiological ROM for the four exercises and joint angles previously described, on land and in water. In order to do that, TT IMUs and the analysis through the workflow OpenSense developed in Phase 1 is used. Twenty-five healthy young adults (Age: 22.4 ±1.7 years; Height: 176 ±7.8 cm; Weight: 70.16 ±10.4 Kg) are recruited, following the directive of the Estonian ethical committee, and the same four exercises with five repetitions for the squats and five for each leg of the other motions are performed. The experimental protocol included two sessions, one underwater and one on land, both done within a week and took place in the Õismäe Leisure Centre, Tallinn municipal swimming pool. During each protocol, seven TinyTags are firmly placed on the subjects as previously described and the estimation of joint kinematics followed the same workflow applied in Phase 1. From the data of the resulting joint angles, a comparison between the ROM expressed on land and underwater is performed to investigate possible differences.

3. Results

3.1. Phase 1

For brevity, only the main results of the comparison between TT and MOCAP are hereafter reported and discussed. The comparisons between Xsens and MOCAP and TT and Xsens are described in detail in the full manuscript. The validation indexes of RMSE, Spearman coefficient and ICC of the comparison between TT and MOCAP are summarized in Table 1, while the values of the BlandAltman plot's bias are displayed in Figure 3, divided by exercise.
For problems of incorrect acquisitions, only nineteen sessions were used in the statistical analysis.

Exercise	RMSE [°]	Spearman	ICC
S	2.52(±1)	0.98(±0.1)	0.99(±0.0)
FLS	10.40(±5)	0.71(±0.2)	0.58(±0.2)
KTC	5.03(±2)	0.85(±0.1)	0.93(±0.1)
HTH	8.20(±3)	0.75(±0.1)	0.88(±0.1)

Table 1: Validation indexes for the comparison between MOCAP and T expressed in mean (±standard deviation) for each exercise.

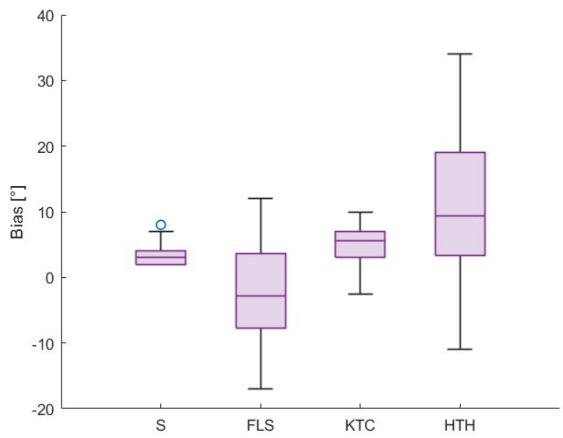

Figure 3: Boxplot of the Bland-Altman's bias between MOCAP and OpenSense driven by TT for all the subjects in the four different exercises.

The RMSE shows a value of less than 5° angle concerning the S and KTC exercises in which also a strong correlation is shown by the Spearman and ICC coefficients. Lower values are reached by the hip adduction/abduction angle and the knee flexion/extension angle respectively of the FLS and HTH exercises which however present the higher standard deviation, meaning the presence of some data perfectly correlated.

3.2. Phase 2

Of the 25 subjects acquired, only 15 (7 females and 8 males) are used in the statistical analysis due to defects in the data, caused by misplacement or corruption in one of the two sessions (underwater or on land). ROM results are analysed in three ways: averaging the excursion measured in each repetition (Table 2) and comparing the two environments through boxplots (Figure 4), exploring the differences between single repetitions with violin plots and creating graphs that show the physiological ROM of each exercise. Results of the squat exercise are represented: the violin plot for the five repetitions of squat on land and underwater is appreciable in Figure 5 while Figure 6 shows the ROM pattern normalized over the five repetitions (mean and standard deviation).
A further study was done on excursion differences between participants of opposite genders, the results of which did not report relevant statistical significance.

Exercise	WATER	LAND	DIFF
S	83.03(±12)	81.80(±12)	1.5%
FLS	48.91(±11)	44.30(±14)	10.1%
KTC	94.57(±15)	84.69(±10)	11.1%
HTH	110.49(±9)	98.29(±9)	11.8%

Table 2: Mean (± standard deviation) values and differences of ROM excursions in the exercises for the environments.

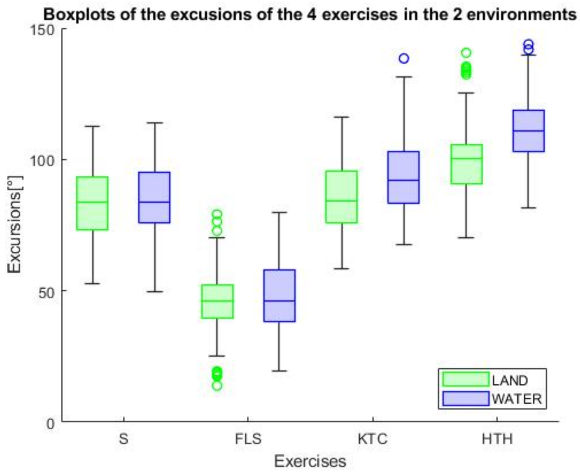

Figure 4: Boxplot comparison between underwater (blue) and on land (green) sessions of the ROM for the subjects in the four exercises.

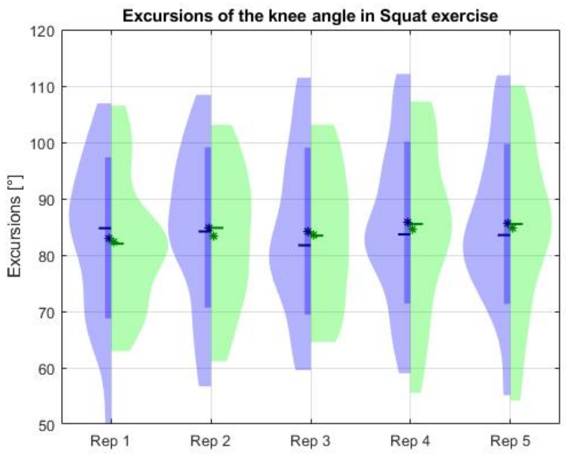

Figure 5: Examples of obtained graphs for violin plot in the 5 repetitions of squat underwater (blue) and on land (green).

4. Discussion and conclusion

The **Phase 1**, whose main objective is to validate the calculation of motor kinematic variables by OpenSense driven by TinyTag sensors demonstrate a perfect concordance in the S exercise. The FLS exercise is not accurately acquired by OpenSense due to limitations in the software, which has severe difficulties to follow a motion that takes place on the frontal plane.

In fact, OpenSense, even with the data from the validated Xsens IMUs, is not able to follow the motion. The KTC exercise is still acceptable, with slight differences between the two systems. Finally, the HTH exercise is found to have an error caused by the drift effect, which is due to multiple reasons. These causes include the electromagnetic field sources in the laboratory, the dynamics of the exercise and the duration of the acquisition. Since the error of the drift is a summation over time, it has the biggest impact on this exercise because it is performed as last. To be sure that this is the cause, another acquisition is done with as the first exercise the HTH, and the results show less drift error.

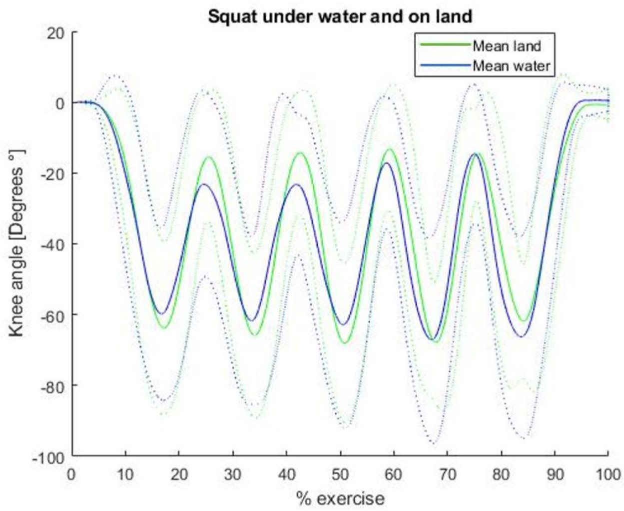

Figure 6: Examples of physiological ROM obtained for squat underwater (blue) and on land (green).

Future studies could be focused on creating more effective ways to reduce the drifting impact and find a way to study successfully frontal motions with OpenSense software.
However, it can be said that for controlled exercises that take place mainly on the sagittal plane, the method based on TinyTag sensors can be used without losing any important information. It works very well, especially in environments where the optoelectronic system is not available and if the acquisition duration is kept low.
In **Phase 2**, the validated method developed in Phase 1 by TinyTag and OpenSense is utilized to investigate the physiological Range of Motion for lower limb joints during basic exercises in aquatic settings. The obtained results highlighted the fact that for the exercises where the balance is granted by only one foot, the excursion of the motion is higher when it's performed underwater (Table 2). This is because the medium itself helps with maintaining balance, allowing the subject to focus only on the movement of the other leg. This aspect, together with the benefits of water in unloading the joints and stimulating the muscles, gives major importance to the described exercises and to the value of underwater physical activities.
The only exercise where no angle difference is noticed is the S, but this is due to the depth of the pool, which forced most of the participants to put their heads underwater to fully perform the motion. Therefore some of them decided to limit the ROM keeping their head out of the water. A future study could use a pool with adjustable depth to address this limitation and investigate the correct knee angle difference in the Squat movement underwater and on land.
This study, despite the low number of analysed subjects, is able to give very interesting, but more important, quantitative information about underwater motion. In this way, it would be possible to provide clinicians with a simple assessment tool that will later allow a direct comparison between normal and pathological motion, or predict the effectiveness of different rehabilitation processes.

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