

Towards the digitalization of upper limbs rehabilitation: integration of a functional calibration procedure and usability study.

Camilla Larini, Silvia Sciamanna, Gabriele Ceruti, Giuseppe Recchia
DigitalRehab srl, Milano
 larini@digitalrehab.eu,
 sciamanna@digitalrehab.eu,
 ceruti@digitalrehab.eu,
 giuseppe.recchia@davidigitalmedicine.com

Francesca Salaorni, Marialuisa Gandolfi, Michele Tinazzi, Federico Schena
Department of Neuroscience, Biomedicine and Movement Sciences, University of Verona
 francesca.salaorni_02@univr.it,
 marialuisa.gandolfi@univr.it, michele.tinazzi@univr.it,
 federico.schena@univr.it

Alice Ravizza
 USE-ME-D, Torino
 alice.ravizza@use-me-d.com

Pietro Garofalo, Michele Raggi
 Tutorialsense Eu Lab, Forlì
 michele.raggi@tutorialsense.com,
 pietro.garofalo@tutorialsense.com

Abstract — Since neuro-motor rehabilitation has a primary relevance among healthcare services, rehabilitative therapies supported by medical devices are needed. The combination of serious games and IMUs is promising: this work focuses on a digital rehabilitation device which allows patients to perform rehabilitative sessions for upper limbs at home. The aims of this work were the integration of a functional calibration procedure, the validation study, and the usability study: results will be used for the development of a new digital rehabilitation system. The application of the calibration procedure has compensated the STS misalignment, however the comparison between calibrated data with respect to optoelectronic system outcomes has shown significant correlations along the principal axis of movement, while differences in measurements have occurred in the other axis. Usability tests results have revealed a general willingness to use NiuRion which has proven to be an easy to use and engaging tool for rehabilitation therapies.

Keywords — *Digital Rehabilitation, IMU, Serious Games, Usability, Neuro-motor Disorders, Functional Calibration.*

I. INTRODUCTION

Functional capabilities of individuals play a major role in the achievement of an optimal quality of life, since an adequate range of motion (ROM) of upper limbs is required to perform daily life activities. Digital rehabilitation devices which combine serious games and inertial measurement units (IMUs) represent promising tools: serious games merge engagement and rehabilitation purposes providing task-oriented activities in contextualized scenarios [1]. IMUs are widely used in medical devices, since they are portable, affordable, and easy to use. Data gathering is essential for the therapists to monitor the progression of the rehabilitative pathway, thus there is the need of accurate calibration procedures to reduce sources of errors, which depend on the measurement system itself and on misalignments of sensors readings with respect to underlying body segments. These latter are managed by Sensor-to-Segment (STS) calibration procedures, which estimate anatomical segment orientations. The validity and accuracy of the IMU-based system must be assessed through the comparison with the optoelectronic system (gold standard for motion analysis). This work focuses on *NiuRion*, a digital rehabilitation device which enables patients affected by neuromotor disorders or musculoskeletal conditions to perform rehabilitative sessions at home, by means of a sensorized shirt which interacts with a software of serious games. Since accuracy of the measurement system must be combined with high levels of usability, two main purposes have been identified: the integration of a functional STS calibration procedure to deal

with the misalignment between sensors and body segments, and the design of a usability study to assess the intuitiveness of the device and the adequateness of the user interface.

II. METHODS

NiuRion's hardware is composed by a shirt with five pockets in which IMUs must be inserted: two on upper arms, two on lower arms and one on the sternum. The connection of sensors to the software allows the patient to control an avatar and perform target-oriented rehabilitative exercises (Fig 1).



Fig. 1. Example of a rehabilitative exercise.

The software part consists in two user interfaces: the first allows therapists to asynchronously evaluate the progress of the therapy by assessing the scores of sessions. Kinematics parameters are used real-time to adapt the session to patient's capabilities through a feedforward artificial intelligence algorithm. The second one is the player interface: before starting the rehabilitative exercises, a calibration procedure must be performed. *NiuRion*'s software estimates joint angles measuring them as the sensors' orientations in the 3D space with respect to the N-pose. Thus, the orientation of the body segments the sensors are attached to (anatomical joint angles) is not available. Therefore, it is necessary to deal with the misalignment between sensors and anatomical segments, and to compensate it with the aim of estimating anatomical joints' kinematics.

A. Integration of a model-based functional calibration procedure

An upper limb mechanical multibody model has been designed to implement and test the STS method proposed in [3], exploiting simulated data computed through such model. The first step has concerned the definition of the sensor, anatomical and global reference frames ($\{s\}$, $\{a\}$, $\{g\}$). Then, the attribute matrix A_{STS} has been computed by means of *TRIAD* algorithm to account for the misalignment between $\{a\}$ and $\{s\}$: the longitudinal and medio-lateral anatomical directions have been assumed as the reference unit vectors, while the same directions observed in the sensor reference frame have been estimated. The application of the orientation quaternion derived from A_{STS} has allowed to calibrate raw

data from sensors according to the anatomical reference frame. Since $\{g\}$ depends on the orientation of IMUs when sensor fusion algorithm is initialized, the global reference frame related to the sensor on the chest has been taken as a reference for the alignment of the others. At the end the joint angles between two body segments have been estimated and transformed to Euler angles by means of 'XZY' convention, representing flexion-extension, abduction-adduction, internal-external rotation for shoulder joints, and flexion-extension, carrying angle and internal-external rotation for the elbow joints.

B. Validation study protocol

The validation protocol has been designed to provide the assessment of *NiuRion* as an effective measurement device after the application of the STS calibration procedure. Thus, sensors data gathered from *NiuRion* during humeral flexion and elbow flexion have been compared to the measurements simultaneously acquired by Vicon Nexus for 20 healthy subjects (within subject cross-sectional design). After the acquisition, orientation quaternions from sensors have been initialized to define the zero position for the whole test, with respect to which *NiuRion* joint angles have been calculated (they did not correspond to anatomical joint angles yet).

C. Usability study protocol

A usability tests protocol has been designed according to [4] to examine the use scenario and identify use errors. Considering that *NiuRion* is equipped with two executable interfaces, usability tests have been structured in two separated phases for 15 medical professionals and 15 patients: in both cases a task analysis procedure has been applied. The evidence from usability tests has been collected in terms of observational data and subjective data (questionnaires and received comments).

III. RESULTS

A. Validation protocol results

Concerning the movements performed, the application of the STS calibration procedure has resulted in coherent outcomes for orientation and ROM values along the principal axis of movement (X-axis). Concerning the comparison between calibrated data with respect to Vicon, measures have been compared by means of Pearson's correlation coefficients on each axis: for all the movements significant correlations have been identified only along the principal axis of movement, while no significant correlation has occurred for Y-axis and Z-axis, revealing possible differences in measurements between systems. Thus, RMSE along the three axes have been calculated to assess discrepancies between measurements: relevant errors have occurred for Y-axis and Z-axis. Humeral flexion has determined the highest divergence for rotations with RMSEY=18.7° for LS and RMSEY=15.6° for RS, while elbow flexion has shown RMSEY=15.3° for LE and RMSEY=14.3° for RE.

B. Usability protocol results

87% of the therapists have stated that clinical data are not sufficient, and they have encountered difficulties in the interpretation of some graphical results. 20% of the patients have faced major usability problems in wearing the shirt and 67% of them have not been able to

autonomously insert the sensors in the pockets due to their physical impairments. No difficulties have been encountered regarding the comfortability and fitting of the shirt as well as regarding the calibration procedure. Moreover, 60% of the patients have found the functional movement simple to perform in terms of physical effort, while other patients have encountered minor difficulties, without preventing the calibration procedure to continue. As concerns the game session, the scores related suggested a positive attitude of patients towards the use *NiuRion*.

IV. DISCUSSION

Results have suggested that the STS calibration is an essential procedure for the estimation of anatomical joint angles. The differences between the two measurement systems could be explained by the fact that the calibration protocol applied on sensors data is different from the one exploited by Vicon to compute joint angles. Nonetheless, the tendency of RMSEs between the three axis of rotation is coherent with the results of [5]: the errors referred to rotations are significantly higher than the errors of flexion and abduction/adduction. However, errors in Z-axis and Y-axis which occur in the comparison of *NiuRion* with Vicon cannot be considered negligible. Moreover, significant components in the non-preferential axes of movements have occurred despite the STS procedure, probably caused by insufficient accuracy of the initialization procedure.

Regarding the usability test outcomes, therapists have expressed their willingness to use *NiuRion* for its opportunities to increase the continuity of care having quantitative data remotely. Improvements of the clinical classification information could help the identification of the rehabilitation therapy targets.

The level of patients' confidence with the technology has not affected the possibility to carry out the calibration procedure, while the integration of sensors in the shirt tissue could overcome other usability problems.

V. CONCLUSIONS

Pursuing the purposes of assessing *NiuRion* from both a technical and a usability perspective, results have suggested it to be a promising digital rehabilitation device. The integration of the STS calibration procedure has been essential to estimate anatomical joint angles, which would be more useful for a reliable assessment of ROMs during rehabilitation sessions. From both the perspective of patients and therapists, *NiuRion* has proven to be easy to use and an engaging tool. Moreover, an adequate classification of patients could be beneficial in long-term to support the definition of standard therapeutic pathways and regulatory policies. Hence, results will lead to the development of *AuReha*, a new digital rehabilitation device that once integrated in standard clinical pathways could contribute to the digital transformation already in place.

REFERENCES

- [1] E. e. a. Koutsiana, *JMIR Serious Game*, vol. 8, n. 4, 2020.
- [2] B. Bouvier e D. S. a. al, *Sensors*, vol. 15, n. 8, pp. 18813-18833, 2015.
- [3] G. Ligorio, E. Bergamini, et. al. *IEEE Sensors Journal*, vol. 15, 2020.
- [4] British Standards Institution, «PD IEC/TR 62366-2:2016. *BSI Standards Publication*, 20