Upper Limb Robot Assisted Rehabilitation Platform Combining Virtual Reality, Posture Estimation and Kinematic Indices

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Abstract Upper limb rehabilitation is critical for patients affected by spinal cord injury (SCI). Currently, robotics and Virtual Reality (VR) have changed the way in which rehabilitation therapies are provided. However, a still unreached precondition for these systems is the precise and practical estimation of limb posture and an objective evaluation of patient's improvement. In this manuscript we present an upper limb rehabilitation platform combining VR, patient posture estimation and objective kinematic indices. This manuscript describes the software platform and criteria which integrate the modules of the system. We report preliminary results of the kinematic indices and platform usability by practitioners.

1 Introduction

The upper extremity (UE) function is affected in more than 50 % of spinal cord injuries [1]. In rehabilitation, considerable amounts of practice are required to induce neuroplastic changes and functional recovery of neurological motor deficits. In the literature, many rehabilitation platforms combine robotic devices and VR to control and quantify the intensity of practice in therapy and to objectively measure changes in movement kinematics and forces [2, 3]. However, current platforms lack of accu-

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rate methods capable to assess patient's improvement from a functional perspective. This manuscript describes the architecture of a robot assisted neurorehabilitation platform for the upper limb developed within the Hyper Project [4], which integrates VR and modules for patient posture estimation and functional patient evaluation [5]. This article also presents the preliminary validation of the patient assessment indices and the platform usability evaluation.

2 Materials and Methods

The platform is constituted by four principal components (Fig. 1): (a) the Armeo Spring exoskeleton, (b) the Software application, (c) the posture estimation module and (d) the patient evaluation module. The Armeo Spring exoskeleton is a passive robotic device produced by Hocoma AG (Volketswill, Switzerland) that helps to support the patient arm weight by using springs [4, 6]. The following sections describe the platform software architecture, the posture estimation module and the objective kinematic indices for patient improvement evaluation.

2.1 Software Architecture

The architecture is built on open source libraries, such as Qt for the Graphical User Interface (GUI), Open Scene Graph (OSG) for the VR environment and V-rep (Virtual robotic experimentation platform) for the posture estimation module. The outer-

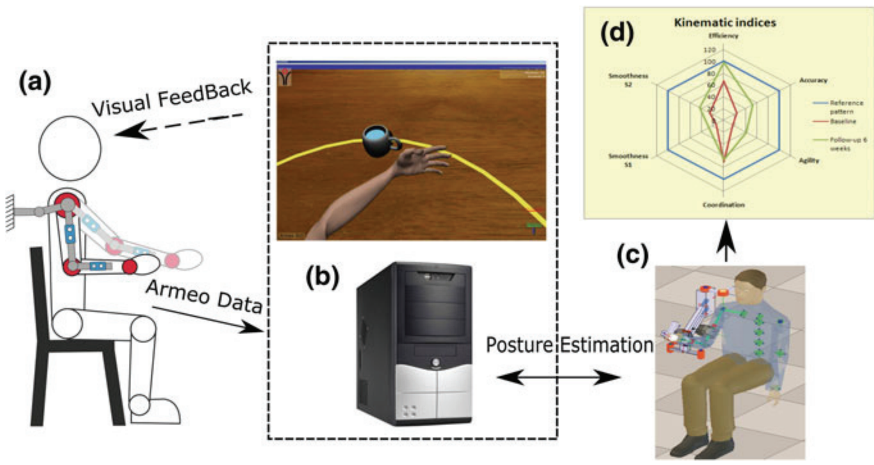

Fig. 1 Platform components and their connections

most layer has been implemented as a state machine, changing its behaviour depending on the input selected in the GUI. Specific classes separately manage the different aspects of the session: the data flow between devices and modules, game logic and data storing and exporting. Therapists can store and retrieve patient information from an internal database. Three VR serious games have been developed, allowing the patient to train simple 1-DOF or compound movements involving the whole arm (e.g. drinking, and pick and place). The game difficulty can be adjusted by the therapist, and it is possible to adapt the range of motion (RoM) according to the patient's handicap. The posture estimation module (Sect. 2.2) allows providing a more realistic representation and animation of the VR avatars.

2.2 Patient Posture Estimation

The patient posture is estimated with the computational method in [6], which considers the Limb and Exoskeleton as parallel kinematic chains related by the cuff constraints that fix them together. Then, the IK problem of the parallel chain is solved, in real time, to find the limb joint angles. The performance of the method has been assessed for simple (1-DOF) and compound movements, providing joint angle estimates with mean errors in the range of 3–5°. Estimations with this method were found to be considerably more accurate than the standard procedure -in particular for all angles of the shoulder [7]—and required no additional sensors other than the exoskeleton encoders.

2.3 Patients' Evaluation Metrics

A set of kinematic indices were proposed for quantifying UE ability and dexterity in terms of movement characteristics as accuracy, agility, efficiency, coordination and smoothness. Accuracy and efficiency are computed from the hand trajectories during the performance of the drinking task. Agility and smoothness are computed from the hand velocity profile, and coordination from the flexion-extension movement in the shoulder and elbow joints. The indices development involved the motion study of healthy and patient groups (incomplete SCI). The indices allow identifying pathological conditions, as healthy motion patterns [8] are used as the reference for the assessment. Said feature constitutes the main advantage of the implemented indices over other proposals in literature.

3 Results

This section presents the results of a clinical study on a group of patients in terms of the evaluation metrics (Sect. 2.3). Moreover, a questionnaire to evaluate the platform usability has been fulfilled by the patients involved in the study.

3.1 Clinical Study

The clinical study involved seven patients with incomplete cervical SCI, classified by the American Spinal Injury Association Scale (AIS) as C or D. Ethical approval for the clinical study has been obtained by the ethical committee and patients were selected following a defined inclusion criteria and signed the corresponding informed consent. The training was unilateral with a frequency of 3 times per week for 6 weeks. One session lasted 15 min and consisted of intense repetitive performance of 3 recordings of 10 executions of the VR drinking game. In the study, five healthy subjects were included for computing the reference kinematic indices. Subject movement was estimated using the method in Sect. 2.2 and recorded for posterior analysis. In healthy subjects, the mean movement time was 12.62 s and the hand path length was 1.96 m. ADL movement took to patients around 37.5 % more, in terms of execution time, than healthy subjects and the hand trajectory resulted around 12.2 % longer than the reference path. As a consequence, the results of accuracy, efficiency and agility indices from patients are lower than the ones of healthy subjects.

3.2 Platform Acceptability

To evaluate platform usability, we asked the users to fulfil a questionnaire of ten questions that explored their perception about the game's appeal, the physical demand, as well as their engagement and motivation playing the game. The score of questions 1–9 ranged between 1 (strongly agreed) and 5 (strongly disagree). Question 10 used the Borg scale of perceived exertion, which ranged from 6 (No exertion at all) to 20 (Maximal Exertion). Questions are presented in Table 1, as well as the

Table 1 Mean values and Standard Deviations of the questions answered by the patients—questions in bold have been found with statistical significance with p-value

Question	Mean	Dev
I would like to use these games in therapy	2.29	1.25
The game was more engaging than typical OT/PT	2.43	1.13
The game was more strenuous than typical OT/PT	**4.57**	**0.53**
I could see myself playing this game in the future	3.00	1.73
It was hard to understand game's directions	**4.86**	**0.38**
I felt frustrated while playing the game	**4.86**	**0.38**
I was motivated to keep playing the game	**1.71**	**0.76**
I found easy to understand how to use the controller	**1.14**	**0.38**
I would benefit from playing these games in therapy	2.14	1.46
Borg scale of perceived exertion	**7.86**	**2.27**

answers' mean and statistical deviations. In addition, the results of preliminary statistical tests are presented, which show significant results on 6 out of the 10 questions (high agreement between patient answers).

4 Conclusion

We present an innovative rehabilitation platform for the upper limb that combines various element to assist, engage, monitor and evaluate the patient. Results show that the platform is capable to assess patients' performance and has a high degree of usability among them. Future developments will be focused on an extended validation and improvement of the biomechanical model used in patient posture estimation.

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