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Towards a movement quantification system capable of automatic evaluation of upper limb motor function after neurological injury.

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Abstract — **The paper proposes an integrated system to automatically assess motor function after neurological injury. A portable motion capture system was developed in order to obtain all the relevant three dimensional kinematics of the upper limb movement. These kinematics were analyzed by means of a decision tree classifier which features where inferred from the Functional Ability Score (FAS) of the Wolf Motor Function Test (WMFT). In addition, the system is able to correctly quantify the performance time of each selected task of the WMFT. In terms of the FAS the system and the clinician show coherent results for 3 out of 5 patients in the first task tested and 4 out of 5 for the second task tested. Regarding performance time, the mean error between the system and the clinician was of 0.216 s for the 25 trials performed (5 patients, 5 tasks each). These results represent an important proof of concept towards a system capable of precisely evaluate upper limb motor function after neurological injury.**

I. Introduction

WHEN clinicians attempt to measure motor improvement during the early post-stroke phase, reliable and valid tools are needed. In addition, the scarcity of specialized human resources in a clinical environment limits the number of possible motor tests performed by a patient, restricting a correct assessment of performance during recovery. Furthermore, continuous monitoring of motor status would be a good help for the management of future rehabilitation plans.

In this context, the development of a system capable of an automatic assessment of motor function is of increased importance since it could allow clinicians to continuously document motor recovery and dynamically adjust the rehabilitation schedule. Another important aspect is the higher accuracy that a motion capture system, in theory, could offer by removing the subjectivity of the human analysis and allowing the quantification of specific movement performed in all three dimensions.

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Although being a rather new area of research, some distinct approaches have been proposed. Patel et al. [1] proposed the use of accelerometers in combination with a Random Forest classifier. From the accelerometer data, several parameters could be extracted, such as the mean value of the accelerometer time series. However, this approach demands that each subject performs between 5 and 20 repetitions of each task. Other studies [2] propose a video tracking system to acquire the movement performed at each task. This type of solution, based on the use of a set of video cameras, is efficient in terms of motion capture. As a downside, this technology incorporates high costs of production. Furthermore the system is easily affected by occlusions being best suited for a clean environment without movements on the background.

In order to validate our approach, we used the Wolf Motor Function Test (WMFT) as the starting point for the development of a new tool aimed at automatic upper limb function assessment. The WMFT is a valuable tool in this respect being composed by a set of tasks arranged in order of complexity, from proximal to distal joint assessment, and end with global upper limb movement evaluation [3, 4]. Additionally, is available [5] a substantial amount of data regarding minimal detectable change and clinically important difference in stroke patients.

When compared with other motor assessment scales such as the Fugl-Meyer Motor Assessment (FMA) test, the WMFT is less time consuming, easier to use and provides information that can orient contemporary functional rehabilitation strategies. Besides, when we consider evaluation of stroke patients, or other unilateral brain injury models, WMFT scores are able to depict changes on the most affected side as well as on the less affected limb. This point is crucial if we intend to evaluate the impact of cognitive training strategies on motor rehabilitation after stroke.

The aim of this study is the development and preliminary validation of a system capable of automatically evaluate the motor function of a patient in a precise and rapid form, suitable for easy implementation in an ordinary clinical environment with all the inherent constraints that are usually present.

II. Methods

The proposed system (Fig. 1) incorporates three different but clearly interconnected blocks. The sensor fusion algorithm gives an error free rotation of each quantification module in space. The Human kinematics model incorporates the rotation in each module with the biomechanical and anthropometric information of the patient. The Upper Limb Motor Function Evaluation block parameterizes the movement in several features in order to achieve a correct classification.

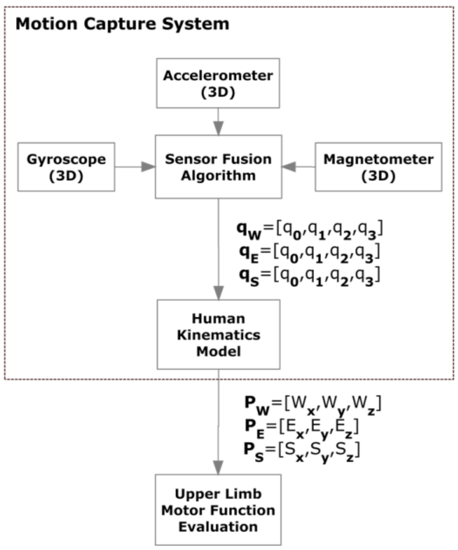

Fig. 1. Global view of the motor quantification system proposed.

A. Motion Capture System

It was clear, right from the start of this project, that the core of a system capable of correctly evaluate motor function is its underlying motion capture method. We chose to develop a novel movement quantification system based only on MARG (Magnetic, Angular Rate and Gravity) sensors. This way, since it is a portable system, it could be easily integrated in a wearable device capable of continuously monitoring motor function in ambulatory mode.

In order to obtain an error-free orientation of each module, we implemented a sensor fusion algorithm capable of correcting the error present in the three-axis rate gyroscope measurements with two other error independent sources of information, a three-axis accelerometer and a three-axis magnetometer. Details on the implementation of the sensor fusion algorithm are out of the scope of this presentation and consequently will be neglected.

The system (Fig. 1) was projected to correctly evaluate Upper Limb motor function and therefore is composed of three wireless modules (Q1, Q2, Q3) respectively placed on the wrist, arm and shoulder of the affected side of the patient (ipsilesional) and one extra module (Q4) placed on the wrist of the contralesional side of the patient. Each module has a sample sampling frequency of 50Hz and sends its data through Bluetooth to a host PC

In terms of kinematics, each limb segment is represented by the respective translational vector. For example, the right arm is represented in the avatar (Fig. 2) by the three dimensional vector RArm. The rotation of each vector in space is accomplished with the dot product between the initial vector ($\boldsymbol{R}Shoulder_{Init}, \boldsymbol{R}Arm_{Init}$ or $\boldsymbol{R}Forearm_{Init}$) and the quaternion representing the actual orientation of the limb (q_S, q_E or q_W).

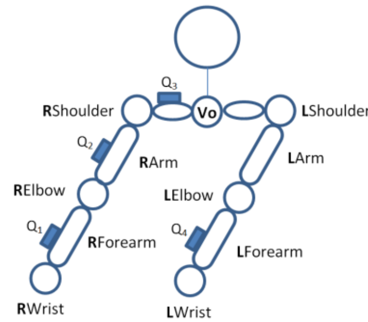

Fig. 2. Representation of the Human Kinematics Model

$$\mathbf{R}Shoulder_{\boldsymbol{Update}} = q_S \cdot \boldsymbol{R}Shoulder_{Init} \cdot q_S{}^* \tag{1}$$
$$\mathbf{R}Arm_{\boldsymbol{Update}} = q_E \cdot \boldsymbol{R}Arm_{Init} \cdot q_E{}^* \tag{2}$$
$$\mathbf{R}Forearm_{\boldsymbol{Update}} = q_W \cdot \boldsymbol{R}Forearm_{Init} \cdot q_w{}^* \tag{3}$$

The current position of the shoulder (P_S), elbow (P_E) and wrist (P_W) is obtained adding the above translational vectors with the respective starting point of the segment. The point V_0 is the model origin and therefore static.

$$P_S = V_0 + \mathbf{R}Shoulder_{\boldsymbol{Update}} \tag{4}$$
$$P_E = P_S + \mathbf{R}Arm_{\boldsymbol{Update}} \tag{5}$$
$$P_W = P_E + \mathbf{R}Forearm_{\boldsymbol{Update}} \tag{6}$$

With these three points the human kinematics model is able to reproduce any movement executed by the patient's upper limb in all three dimensions.

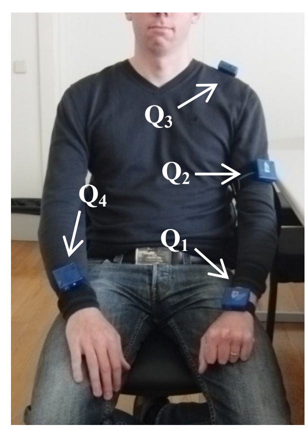

Fig. 3. Stroke Patient using the motion capture system

B. Upper Limb Motor Function Evaluation

After the development and extensive testing of the motion capture system in a laboratory environment, the first approach to motor function assessment was implemented in a subset of the 15 motor tasks of the WMFT [6]. Each task of the WMFT is evaluated according to performance time (measured in seconds) and functional ability score (on a scale of 0-5). The 5 unilateral motors tasks to be evaluated in terms of performance time are the follow:

TABLE I
MOTOR TASKS TO BE EVALUATED

Task Number	Description
1	Forearm to Table (side)
2	Forearm to Box (side)
3	Extend Elbow (side)
4	Hand to Table (Front)
5	Hand to Box (Front)

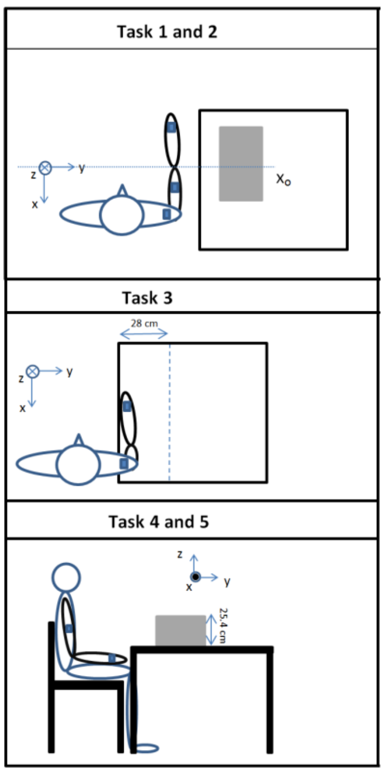

Fig. 4. Task description in terms of the human kinematics model and the frame of reference (common to all the tasks).

The system detects the start and end of the movement by using a set of adaptive thresholds applied to the movement in each axis. From these two markers it determines the performance time for each task.

Regarding the functional ability score (FAS) [6], we choose tasks 1 and 2 from TABLE I to test the proficiency of the system in the automatic assessment of the motor deficit of the patient, accordingly to the WMFT criteria. The WMFT has a specific guideline to score the motor deficit (Table II).

TABLE II
FUNCTIONAL ABILITY SCALE [6]

Score [0-5]	Description
0	Does not attempt with involved arm.
1	Involved arm does not participate functionally; however, an attempt is made to use the arm. In unilateral tasks the uninvolved extreme may be used to move the involved extremity.
2	Arm does participate, but requires assistance of uninvolved extremity for minor readjustments or change of position, or requires more than 2 attempts to complete, or accomplishes very slowly. In bilateral tasks the involved extremity may serve only as a helper or stabilizer.
3	Arm does participate, but movement is influenced to some degree by synergy or is performed slowly and/or with effort.
4	Arm does participate; movement is close to normal, but slightly slower; may lack precision, fine coordination or fluidity.
5	Arm does participate; movement appears to be normal.

In association with our clinical partners, this guideline was streamlined into the following decision tree (Fig. 5) in order to be incorporated in an automatic system.

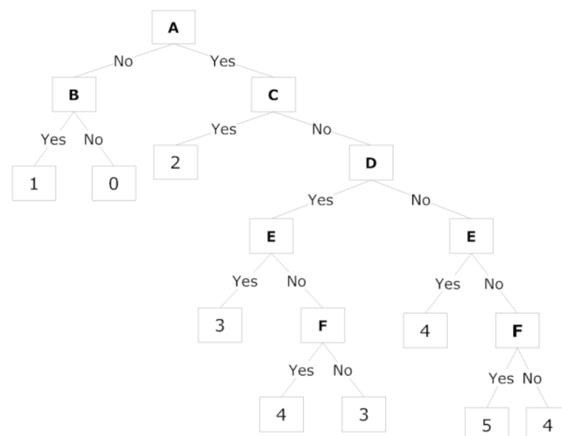

Fig.5. Decision Tree, concerning Task 1 and 2 of the WMFT, designed to classify the movement performed in a scale of 0-5.

TABLE III
DECISION TREE FEATURES

Feature	Description
A	Task Completed
B	Detected movement in involved arm
C	Detected movement in uninvolved extremity
D	Movement synergy with the shoulder joint
E	Detected movement out of the plane of action
F	Is the movement smooth

Each motor task is evaluated according to five features. The WMFT guideline determines that a task is completed if it was correctly executed in less than 120 seconds. The module placed on the wrist of the contralesional side indicates if there was movement in the uninvolved extremity.

Concerning the functional scale proposed in the WMFT the synergy with the ipsilesional shoulder is, by itself, caused by a movement performed slowly and with effort. To account for movements close to normal we found that, for Task 1 and 2, there was a displacement in relation to the predefined axis of motion. Each of these two motor tasks is predefined to be executed in the yz-plane of motion (Fig. 4). This way, in order to achieve a normal motor performance, the displacement verified in the x-axis should be minimal. These features are specific for these two tasks and not meant to be applicable to all the 15 tasks of the WMFT.

1) *Decision Tree Features*

To determine if there was a synergy with the shoulder joint (feature D from TABLE III), the distance S_S, describing the length of the path of the shoulder joint from its initial to the final position, was determined. We considered the three-dimensional path, since the synergy could occur in any dimension of the movement.

$$s_S = \int_{t_0}^{T} \sqrt{\left(\frac{dP_{Sx}}{dt}\right)^2 + \left(\frac{dP_{Sy}}{dt}\right)^2 + \left(\frac{dP_{Sz}}{dt}\right)^2}\, dt \qquad (7)$$

Regarding the movement out of the plane of action (feature E from TABLE III), and considering that the tasks 1 and 2 are performed in the yz-plane, we calculated the length of the path of the elbow joint out of the x-axis origin. The system analyses the motion quantified in the module Q2 as the origin of the frame of reference. This way, if the movement was correctly performed $P_{Ex}(n) \approx P_{Ex}(0), \forall\, n \in N$ and $s_{Ex} \approx 0$

$$s_{Ex} = \int_{t_0}^{T} \frac{dP_{Ex}}{dt}\, dt \qquad (8)$$

These two scalar metrics, S_S and S_{Ex}, are compared to the baseline obtained from the movement performed in the contralesional side. In order to quantify the smoothness of the movement (feature F from TABLE III), we used the jerk metric since it was demonstrated that it shows a higher correlation between the change in smoothness and changes in the Fugl-Meyer Score [7]. The jerk metric, as introduced by Flash and Hogan [8] is defined as:

$$jerk = \frac{1}{T}\int_{t_0}^{T} \sqrt{\left(\frac{d^3P_{Wx}}{dt^3}\right)^2 + \left(\frac{d^3P_{Wy}}{dt^3}\right)^2 + \left(\frac{d^3P_{Wz}}{dt^3}\right)^2}\, dt \qquad (9)$$

C. *Subjects*

The system was tested in five male patients aged between 35 and 73 years old. They were all right handed and were selected from the outpatient stroke clinic after signing informed consent. All patients had upper limb motor impairment (three on the right side), but not hemiplegia, after a medial cerebral artery stroke. Their performance ranged from near normal (patients 1 and 2) to moderate (patients 3 to 5) motor deficit of the affected limb. Cognitive performance was normal according to mini mental state examination.

III. RESULTS

Data regarding the evaluation of the five different features has been intentionally limited to that which was directly relevant to the specific topic of this presentation. A more detailed review on all data will be presented and discussed in future work.

The performance time error distribution between the measures by the clinician and the system has a mean of μ=0.216 s and a standard deviation of σ=0.16. Fig. 6 shows representative results from one subject.

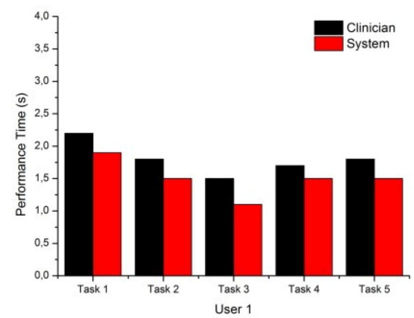

Fig.6. Performance time measured automatically by the system against the performance time measured manually by the clinician for all 5 tasks in one of the patients.

In what concerns the automatic assessment of the FAS, Fig. 7 and Fig. 8 shows a comparison of the scores estimated by the system and the scores estimated by the clinician.

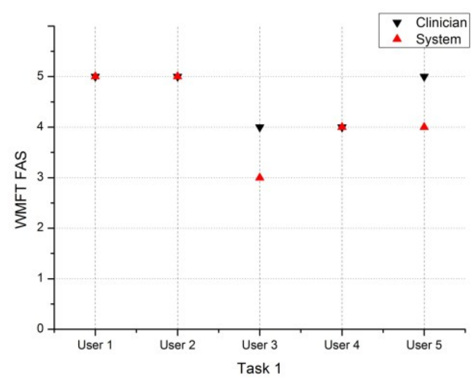

Fig.7. Functional ability scores for the 5 patients in Task 1 (forearm to table)

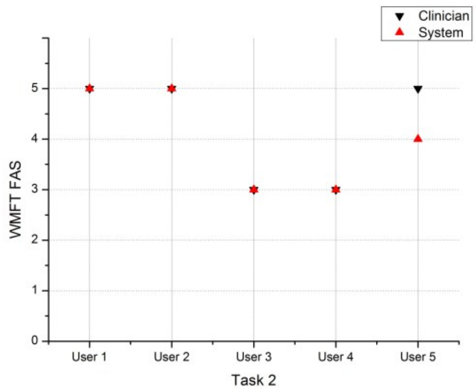

Fig.8. Functional ability scores for the 5 patients in task 2 (forearm to box)

IV. DISCUSSION

In this study we have shown the proficiency of a portable motion capture system to estimate the result of a clinical score test and performance time in a rapid and precise form. To our knowledge, this was achieved for the first time.

In relation to performance time, the mean error was of 0.216 s for the 25 trials performed (5 patients, 5 tasks each). We found that this error is due to an inherent delay by the clinician in the determination of the conclusion of the task, thus resulting on a systematic overtime (Fig. 6).

Parnandi et al. [9] proposed a portable system based on the accelerometer data gathered during performance of a set of motor tasks. In terms of performance time their study showed a mean error between the clinician and the automatic system time measures of 0.94 s. A direct analysis between error results cannot be performed due to the fact that the basis of comparison is given by different examiners with different reaction times and experience.

Regarding the FAS, in Task 1 the system and the clinician show coherent results for 3 out of 5 participants. For Task 2 the system and the clinician show the same results for 4 out of 5 participants. It was expected that the system could detect aspects of motor performance not suitable to be perceived by the clinician when analyzing the video. Indeed that occurs for patient 3 and 5 in task 1 and patient 5 for task 2. These were the individuals that presented a major deficit.

As previously denoted, the features depicted in TABLE III are specific for tasks 1 and 2 and not meant to be valid for all the 15 tasks of the WMFT. In order to evaluate the other three motor tasks (tasks 3, 4 and 5 from TABLE I) and thus expand the system, new metrics that show higher discrimination thresholds for each specific task must be introduced. As an example, a specific new metric for the motor execution denoted as elbow extension (task 3 from TABLE I) should be the movement out of the plane of action. Since this movement is predefined to be executed in the xy-plane of motion (Fig. 4), a specific feature would be determined from the length of the path of the wrist joint out of the z-axis origin.

In terms of future work, it would be important to compare the timing and FAS of the system against a global assessment performed by a board of clinicians presenting different experiences (measured in number of years of clinical practice). This way, a clear comparison and possible correlation between the experience of each clinician, subsequent scoring and the system results could be achieved, providing a more detailed insight regarding the accuracy of the system.

V. CONCLUSION

The automatic assessment of motor function based on the use of movement quality kinematic variables has been demonstrated to be of valid use in regular clinical practice by Subramanian et al [2]. The proposed system could save time being suited to be applied in a rapid form providing a higher accuracy due to the analysis of the movement in all its' three dimensional projections.

However important the proof of concept demonstrated in this study, one should keep in mind that all clinical procedures developed to date were specifically suited to be performed by a clinician and therefore doesn't take part of the full potential of a 3D motion capture system. Several important features like the acceleration on the start and end of the movement should be included. This way, it is our opinion that the development of a system capable of automatic assessment of motor function after neurologic injury should be based on the combination of clinical knowledge provided by traditional examination tests with the more refined capabilities of 3D motion capture systems.

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