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Technical note

A novel system for automatic classification of upper limb motor function after stroke: An exploratory study

Vítor Tedim Cruz [a,b], Virgílio Ferro Bento [c,d,*], David Dieteren Ribeiro [c], Isabel Araújo [a], Catarina Aguiar Branco [e], Paula Coutinho [f]

[a] Neurology Department, Hospital São Sebastião, CHEDV, Santa Maria da Feira, Portugal
[b] Clinical Research Office, Health Sciences Department (SACS), University of Aveiro, Portugal
[c] Institute of Electronics and Telematics Engineering of Aveiro (IEETA), University of Aveiro, Portugal
[d] University Institute of Maia – ISMAI, Maia, Portugal
[e] Rehabilitation Medicine Department, Hospital São Sebastião, CHEDV, Santa Maria da Feira, Portugal
[f] UnIGENe, Instituto de Biologia Molecular e Celular, University of Porto, Portugal

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ABSTRACT

In the early post-stroke phase, when clinicians attempt to evaluate interventions and accurately measure motor performance, reliable tools are needed. Therefore, the development of a system capable of independent, repeated and automatic assessment of motor function is of increased importance.

This manuscript explores the potential of a newly designed device for automatic assessment of motor impairment after stroke.

A portable motion capture system was developed to acquire three-dimensional kinematics data of upper limb movements. These were then computed through an automatic decision tree classifier, with features inferred from the Functional Ability Score (FAS) of the Wolf Motor Function Test (WMFT). Five stroke patients were tested on both sides across five selected tasks. The system was compared against a trained clinician, operating simultaneously and blinded.

Regarding performance time, the mean difference (system vs clinician) was 0.17 s (sd = 0.14 s). For FAS evaluation, there was agreement in 4 out of 5 patients in the two tasks evaluated.

The prototype tested was able to automatically classify upper limb movement, according to a widely used functional motor scale (WMFT) in a relevant clinical setting. These results represent an important step towards a system capable of precise and independent motor evaluation after stroke. The portability and low-cost design will contribute for its usability in ambulatory clinical settings and research trials.

1. Introduction

Proper assessment of motor performance is of major importance for correct decision-making in neurorehabilitation, especially early after stroke [1,2]. This need is shared both by clinical and research settings [1], where competition for specialized human resources limits time dedicated to motor assessment. Moreover, when consecutive evaluations are needed, reproducibility and operator-dependency become important issues [1].

To improve current standards, the development and validation of a wearable system, proficient for automatic assessment of motor function in busy clinical settings is decisive [3]. It could simplify motor assessment and upgrade the management of future rehabilitation plans and clinical trials [4,5].

The research field of wearable quantification tools is currently building momentum, with distinct approaches being proposed [6,7]. One suggestion was the combination of accelerometers with a random Forest classifier, performing multiple repetitions to gather information about within subject variability [8]. Others proposed the use of video tracking systems to acquire kinematics during each task [9,10]. Although feasible, these solutions were expensive and easily affected by visual field occlusions, requiring controlled settings, without background movements. These conditions are difficult to achieve in ordinary busy clinical sceneries.

Abbreviations: FAS, Functional Ability Score; MARG, magnetic angular rate and gravity; MDC, minimal detectable change; WMFT, Wolf Motor Function Test.

* Corresponding author at: Maia Institute of Higher Education, Maia, Portugal. Tel.: +351 969529315.
E-mail address: virbento@gmail.com (V.F. Bento).

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To further study our approach, we selected the Wolf Motor Function Test (WMFT), a widely used scale. It is composed of several tasks organized in growing complexity, from proximal to distal joint assessment, ending with a global upper limb movement evaluation [11,12]. Furthermore, it is easy to use, provides information that can orient contemporary functional rehabilitation strategies and has been extensively studied in stroke patients [13,14].

The aim of this study was to develop and evaluate a portable system, designed to provide independent, real-time, automatic classification of upper limb function, according to selected items of the WMFT. The relevant environment chosen was an outpatient stroke clinic.

2. Methods

2.1. Motion capture system

The core element is a movement quantification system that allows for a continuous analysis regarding a user's kinematic data (Fig. 1). The design of the underlying motion capture method was based only on magnetic, angular rate and gravity (MARG) sensors [3]. Data were stored on an SD card, communication handled by a Bluetooth module and power supplied by a 3.7 V lithium battery charged using a USB connection [3]. These set of options increased the portability of the system (Fig. 1) that could be integrated in a low-cost wearable device capable of continuously monitoring motor function in ambulatory mode and was already tested in clinical experiments [15,16].

The system was structured according to three main blocks [3,16]:

(1) A sensor fusion algorithm in each one of the four quantification modules (Q1–4, Fig. 1), developed to estimate the kinematics of rotation of the body-frame in relation to the earth-frame, combining independent measures from three-axis gyroscope, accelerometer and magnetometer (angular velocity, linear acceleration and magnetic alignment). This minimized errors on the orientation of each module within our human kinematics model [3].

(2) The human kinematics model that incorporated the rotation perceived in each module with a biomechanical model configuration for the human upper limb (Fig. 1c), focused on the estimation of the three-dimensional orientation and position of two body segments (arm and forearm vectors) and three major joints (shoulder, elbow and wrist) [16].

(3) An upper limb motor function evaluation block (Figs. 1b and 2) that parameterized features of movement (e.g., acceleration, velocity, amplitude, execution paths, smoothness) to achieve a correct clinical classification (e.g., irregularities of tonus, rhythm or velocity, spatial deviations, synergies, fatigue) [3,15]. It compared motion dynamics of a specified task with the quality metrics of reference previously set by: clinical prescription, execution parameters from the normal side of the body, or data from a population of reference [15,16].

The wearable system was designed to evaluate upper limb motor function on both sides of the body (Fig. 1c). As an example, for the evaluation of the affected side, three wireless modules (Q1–3) were placed at the wrist, arm and shoulder (exactly over the acromio-clavicular joint) of the impaired side of the patient (ipsilesional) and an extra module (Q4) was located at the wrist of the contralesional side. The reverse setting was used to collect data from the normal side of the patient. Data from each module was acquired at a 50 Hz rate and sent wirelessly to a laptop computer.

Each limb segment corresponded to a translational 3D vector in a kinematic model, e.g., the left arm was represented by the vector ***LArm***, the left forearm by ***LForearm***, and the shoulder segment by ***LShoulder***. The length of each segment was specified according to normalized dimensions (arm length was 1, shoulder and forearm were ratios). To calculate these parameters, anthropometric dimensional data of a 40-year-old American male (95th percentile) were followed [17].

The rotation of each vector in space was accomplished with the dot product between the initial vector ($\boldsymbol{L}Shoulder_{Init}$, $\boldsymbol{L}Arm_{Init}$ or $\boldsymbol{L}Forearm_{Init}$), the quaternion representing the actual orientation of the limb (q_s, q_E or q_{Wi}) and its conjugate (q_s^*, q_E^* or q_{Wi}^*).

$$\boldsymbol{L}Shoulder_{\boldsymbol{Update}} = q_s \cdot \boldsymbol{L}Shoulder_{Init} \cdot q_s^* \tag{1}$$

$$\boldsymbol{L}Arm_{\boldsymbol{Update}} = q_E \cdot \boldsymbol{L}Arm_{Init} \cdot q_E^* \tag{2}$$

$$\boldsymbol{L}Forearm_{\boldsymbol{Update}} = q_{Wi} \cdot \boldsymbol{L}Forearm_{Init} \cdot q_{Wi}^* \tag{3}$$

The current 3D positions of the shoulder (P_S), elbow (P_E) and ipsilesional wrist (P_{Wi}) were calculated by adding the above translational vectors with the respective starting point of each segment. The point V_0 was the model origin and therefore static.

$$P_S = V_0 + \boldsymbol{L}Shoulder_{\boldsymbol{Update}} \tag{4}$$

$$P_E = P_S + \boldsymbol{L}Arm_{\boldsymbol{Update}} \tag{5}$$

$$P_{Wi} = P_E + \boldsymbol{L}Forearm_{\boldsymbol{Update}} \tag{6}$$

Knowing these three points, the kinematics model could replicate any tri-dimensional movement performed by the patient's ipsilesional upper limb. The position of the contralesional wrist (P_{Wc}) was used to evaluate whether the uninvolved extremity participated in the motor task, and was calculated applying the dot product between the static vector $\boldsymbol{R}Forearm_{Init}$ and the respective quaternion (q_{Wc}).

$$P_{Wc} = q_{Wc} \cdot \boldsymbol{R}Forearm_{Init} \cdot q_{Wc}^* \tag{7}$$

This solution optimized the clinical procedure, reducing the operative complexity and time to collect data. Furthermore, it provides the backbone for a motion normative database, since all kinematics produced by different users are suitable for a direct comparison.

2.2. Upper limb motor function evaluation

The first approach to motor function assessment was implemented over a subset of the 15 motor tasks of the WMFT [18,19]: forearm-to-table (task 1), forearm-to-box (task 2), extend-elbow (task 3), hand-to-table (task 4) and hand-to-box (task 5). Each task was evaluated according to performance time (seconds) and Functional Ability Score (FAS) [19].

To measure performance time, the system determined two markers for each task. Onset of movement was identified when the absolute velocity of one of the quantification modules exceeded 2% of peak velocity, after being below this threshold for at least 1 s [3,15,16]. End of movement was then determined as the moment when velocity resumed to zero for at least 1 s. The time window of movement analysis was set to 1 s because lower values could lead, in case of a non-smooth movement, to prematurely determine its end [3,15,16].

For FAS analysis, tasks 1 and 2 were chosen to test the proficiency of the system in the automatic assessment of the motor deficit. This was done according to the WMFT criteria and specific guidelines provided for scoring functional ability of movement [19]. For example, an FAS of 3 is achieved if in the unilateral motor task the "*Arm does participate, but movement is influenced to some degree*