

COMPENSATORY MOVEMENT DETECTION THROUGH INERTIAL SENSOR POSITIONING FOR POST-STROKE REHABILITATION

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Abstract: An increasing ageing society and consequently rising number of post-stroke related neurological dysfunction patients are forcing the rehabilitation field to adapt to ever-growing demands. In parallel, an unprecedented number of research efforts and technological solutions meant for human monitoring are continuously influencing traditional methodologies, causing paradigm shifts; extending the therapist patient dynamics. Compensatory movements can be observed in post-stroke patient when performing functional tasks. Although some controversy remains regarding the functional benefits of compensatory movement as a way of accomplish a given task, even in the presence of a motor deficit; studies suggest that such maladaptive strategies may limit the plasticity of the nervous system to enhance neuro-motor recovery. This preliminary study intends to aid in the development of a system for compensatory movement detection in stroke patients through the use of accelerometry data. A post-stroke patients group is presented and discussed, instructed to perform reach and press movements while sensors were positioned at different location on the arm, forearm and trunk, in order to assess sensor positioning influence. Results suggest that P1 is advantageous for compensatory elevation movement detection at the shoulder; P4 seems the most appropriate for detecting the abduction; and P5 presents a reasonable sensitivity for detection of anteriorization and rotation of the trunk.

1 INTRODUCTION

According to the World Health Organization (WHO), 15 million people worldwide suffer a stroke each year, being the leading cause of disability in adult population (Thrane, Emaus, Askim, Anke, 2011). Stroke is defined as an acute neurological dysfunction of vascular origin with rapid onset of signs and symptoms according to the committed areas of the brain (WHO, 2011). As epidemiological studies show, disability following stroke can evidence in the form of neurological dysfunctions and reduced ability to actively engage in daily activities, justifying the need for intervention (Geyh et al., 2004).

Impairment of upper limb function is one of the most common deficit following stroke, specifically

at the middle cerebral artery (MCA) territory, and to date, specific rehabilitation remains challenging to a significant extent, with little agreement on the procedures to be followed, despite ongoing published guidelines containing recommendations on interventions and assessment strategies targeted towards the diverse areas of post-stroke disability (Lucca, 2009; Cirstea, Levin, 2007; Geyh et al., 2004).

The predominantly affected arm may present muscular weakness; abnormal muscle tone, postural adjustments, and movement synergies; biomechanical impairments at joints and/or soft tissues level; incorrect timing of components within a movement pattern and loss of interjoint coordination (Cirstea, Ptiro, Levin, 2006). In face of the before mentioned, it is often identified in post-stroke patients when attempting to move, as in for reaching an object, the emergence of compensations

related to the available motor strategies and expressed in form of a pathological synergy (Michaelsen, Dannenbaum, Levin, 2006).

The neurophysiologic explanation highlights the post-trauma nervous system's ability to exploit the motor system's redundancy by replacing lost motor patterns elements with new ones to achieve the desired task (*ib.*). In fact, it is well known that after a lesion, the nervous system can be reorganized producing an adaptive or maladaptive sensorimotor behaviour, highlighting thus the importance of the reorganization through selective afferent input to optimize internal representation and influence movement control (Nudo, 2007; Raine, 2009). In spite of the mentioned, the use of compensations can also result in secondary complications such as muscle weakness or contractures due to joint misalignment and a lack of recovery of isolated joint movements, as elbow extension, reinforcing the idea of the maladaptive nature of such novel movement patterns post injury (Cirstea and Levin, 2007; Cirstea, et al., 2006).

Recent advances have promoted the development of wearable/portable solutions for a number of human monitoring scenarios. In parallel with such technological advances, new quantified based human movement models are commencing to emerge, applicable to neuromotor assessment. Kinematic models, based on accelerometry and angle variation, can estimate 3D arm movement and events such as falls; however, image based analysis models seem to dominate, influencing methodologies and protocols to parallel conventional medical and rehabilitation observational assessment.

2 METHODOLOGY

2.1 Subjects

The sample was composed by two post-stroke patients receiving physiotherapy care at a rehabilitation center, part of an umbrella research project. Participants had to meet the following inclusion criteria:

1. Confirmatory neuroimaging results of a single, unilateral stroke in the MCA territory, sustained at least 3 months prior.
2. Absence of hemispatial neglect.
3. Absence of major visual, perceptual or cognitive deficits, confirmed by the minimal state examination (MMSE).
4. Active range of motion in the compromised arm of at least 15° in the shoulder and elbow.

Explicit exclusion criteria included cerebellar or brain stem lesions; and pain/sub-luxation in the upper-limb.

Arm motor impairment was evaluated prior to measurements, as seen on Table 1, with the arm subsection of the Fugl-Meyer scale - FMA (Fugl-Meyer et al., 1975) and the Reach Performance Scale - RPS (close target). This clinical evaluation was performed by a team of three experienced physiotherapists with more than 10 years of clinical practice in neurological field.

Table 1: Demographic data and clinical scores of stroke patients.

	Subjects	
	Patient A	Patient B
Age/Gender	49/Male	47/Female
Location of lesion	LMCA	RMCA
Months post-stroke	66	20
RPS Score (close target)	5/18	12/18
FMA (shoulder, elbow, forearm)	4/36	20/36
FMA (wrist)	0/10	2/10
FMA (hand)	2/14	12/14
FMA (coordination)	0/6	3/6

LMCA – Left MCA; RMCA – Right MCA

2.2 Experiment Protocol

The subjects were following, at the time, conventional rehabilitation procedures associated with their condition, based on the Bobath Concept principles. This is a problem-solving approach to the assessment and treatment of individuals with disturbances of function, movement and postural control due to a lesion of the central nervous system (Raine, 2009). Although sitting balance was not measured directly, all subjects were ambulatory without aids and had no difficulty in maintaining a stable sitting posture during data collection.

As reaching is the most common upper-limb human gesture, one can understand the great amount of interest devoted to its analysis, having some studies reported the expected components of movement, when target is placed in middle line and in healthy population: elbow flexion at the beginning of sequence, followed by combined shoulder flexion, shoulder horizontal adduction and elbow extension during the middle and later phases of the reach (Levin et al., 2004).

Each subject was assessed in sitting position, with a table placed in front of them, at a height corresponding to the alignment of the iliac crests. The table limit was coincident with the distal border

of the subject's thigh, so as not to interfere with the arm trajectory. The subjects were instructed to reach and press a target placed ipsilaterally to the upper limb in study, in groups of three repetitions (as to avoid variations due to fatigue) separated by one minute rest period.

The target's placement reference was the anatomical reaching distance of the hand, using the measured distance from the acromion to the metacarpophalangeal joint of the thumb (Reisman and Scholz, 2006; Vandenberghe, Levin, De Schutter, Swinnen, Jonkers, 2010). The individual was instructed, after verbal command, to perform the functional task. The starting position for the movement followed: shoulder approximately 0° of flexion / extension and 0° of internal rotation, elbow at approximately 100° of flexion, forearm in pronation with the palm of the hand resting on thigh (Wagner, Lang, Sahrman, Edwards, Dromerick, 2007; Michaelsen, Luta, Roby-Brami, Levin, 2001). Performance was video recorded for posterior cross-reference.

2.3 System Description and Setup

A simple wearable monitoring device, named W2M2 (Wireless Wearable Modular Monitoring), was designed and implement for inertial data capturing. The device was based on commercially available components that could be assembled in a fast manner, without extensive knowledge of electronics; seeking to reduce overdependence on collaborating engineers. The resulting sensor modules had dimensions of 5.5 x 3 x 2.5 centimeters

The main rehabilitation objectives were focused on the patient's affected upper limb. In order to insure sensor placement repeatability, precise bone landmarks were required. After a physiological study of the target area and experimental trial of sensor positioning for assured subject upper limb mobility and comfort, the following positions were considered:

- P1, placed under the acromion, following the line that connects the lateral epicondyle and the acromion;
- P2, placed on the middle point between lateral epicondyle and the acromion;
- P3, immediately above lateral epicondyle, in alignment with acromion;
- P4, immediately below the lateral epicondyle, after elbow articulation;
- P5 is in the trunk on the T12.

It should be mentioned that although only these positions were considered for the present study the ease with which the patients adapted to the presence of the sensor permits to imply its use in numerous other locations.

3 RESULTS

The accelerometers data is captured at a frequency of approximately 100 Hz, which is then transmitted wirelessly. A smoothing procedure follows applying a simple moving average smoothing strategy in order to reduce the influence of noise and oscillations. Additional plus/minus pseudo-envelope functions were generated through a moving window standard deviation approach, according to Equation 1, in order to provide visual indicators of signal stability.

$$S_{\text{envelope}}(t) = S_{\text{smooth}}(t) \pm f_{WSD} \left(S_{\text{raw}} \left|_{t-\frac{t_w}{2}}^{t+\frac{t_w}{2}} \right. \right) \quad (1)$$

where:

S_{envelope} = envelope function;
 f_{WSD} = window mean standard deviation function.

Data was collected from the two target subjects, using the W2M2 device, at the established points, for the reach-press and return functional task. A set of resulting signals are presented on Figure 1, accompanied by measurements such as maximum, minimums, segment amplitude variation and base calibration references, and corresponding video for posterior cross-reference. Table 2 shows a comparative description of movement components, antero-posterior (A-P), superior-inferior (S-I) and medial-lateral (M-L), for all sensor locations analysed. A growing sensitivity scale ranging from 1 to 3 was used for the characterization by a team of physiotherapists.

Table 2: Sensitivity descriptive analysis of movement components for sensor locations.

	Subject A			Subject B		
	A-P	S-I	M-L	A-P	S-I	M-L
P1	1	3	1	1	3	2
P2	2	1	1	2	2	2
P3	2	2	2	2	2	2
P4	2	2	3	2	2	3
P5	3	3	3	3	3	3

A-P – Anterior-Posterior; S-I – Superior-Inferior;

M-L – Medial-Lateral

4 DISCUSSION

The sample data is presented in Figure 1 showing accelerometry data measured at all five sensor locations (referred to as P1, P2, P3, P4 and P5) for subjects A and B. The inherent difference in acceleration amplitudes shown especially in X-axis between subjects is related to the fact they present opposite compromise limbs (LMCA vs. RMCA). The discussion that follows is based on the multiple data collected from both subjects and their correspondent video records.

From visual analysis, subject A shows evidence of reduced segmental selectivity and poor shoulder-elbow interjoint coordination. Limited motor control of the upper limb (stability/mobility relation) causes exaggerated oscillation during movement, which propagates throughout the body. Compensations on the movement pattern were visually detected, in particular excessive elevation and abduction of the shoulder at the beginning of the movement, as well as anteriorization and rotation of the right hemitrunk at the transport phase. Video analysis confirmed that the subject did not fully complete the functional task, i.e., the hand approached but did not press the target.

Subject B presents increased selectivity in the movement, observed by the shoulder-elbow interjoint coordination, and reflected in a reduced compensatory mechanism through shoulder abduction. The subject presented a degree of tremor at the distal segments of the upper limb, evident at the final phase of the movement, which can be explained by deficit in the stability/mobility relation. One also verifies some compensation at the trunk level, in particular with the anteriorization component. This individual, comparatively with subject A, presented increased execution times, being however important to relate that in contrast with subject A, has the capacity to fully complete the task.

In relation with sensor position P1, subject A presents an average movement in the anterior direction, i.e. anterior-posterior (X-axis), with reduced pronunciation (short trajectory), which can be explained by the incapability of fully reaching the target. Both patients present on the collected data, elevation and abduction of the shoulder, at the initial phase of the movement, corroborating the visual analysis. Subject B shows that the elevation and abduction resource is also a strategy used on the return phase of the movement.

In relation with sensor position P2, there exists an increased displacement in the anterior direction

(X-axis) when compared with P1; however there is a lack of marked differences observed on the global pattern of the movement. Such could suggest that P2 offers more movement detection sensitivity when compared to P1. In reference to the Y-axis, the opposite seems to occur, i.e., presents reduced sensibility for such detection when compared with P1, for both cases. For Z-axis both individuals do not present marked differences in the gathered information from P1 and P2.

Sensor position P3 shows some variability among the patients. The movement in the anterior direction (X-axis), performed by subject A is more pronounced when compared with P1; in turn, for subject B this movement is better detected when compared to both P1 and P2. A similar situation occurs in the remaining movements, i.e. superior direction (Y-axis) and lateral direction (Z-axis). Subject B presents no pronounced differences among the sensor position P1, P2 and P3 for the lateral direction. This could be explained by lack of evident movement component recruitment as compensation during the functional task.

Given the localization of position P4, there exists a need for redefining the detected movement components by each of the axis. Thus, the movement in the antero-posterior direction is now captured by the Y-axis, and the superior-inferior direction by the X-axis, remaining the Z-axis capturing the lateral movements. Subject A, did not present a significant elevation component (X-axis), which could be related with the deficit to enlist selective flexion of the elbow. Subject B presents an increase elevation component, resulting from an improved shoulder-elbow interjoint coordination, being able to perform selective flexion of the elbow as an integrating part of the movement pattern.

The collected data suggests that sensor position P1 presents increased commitment between movement detection in the superior direction (identification of shoulder elevation as compensation) and an inter-patient variability; however a larger number of measurements and varied sample size is required for such validation.

Finally, as for sensor position P5, one verifies that such position offers increased reproducibility among trials, while presenting reduced acceleration variations (less than 0.1 g in most cases), translating into a reduced movement of the trunk, especially in the superior-inferior direction (Y-axis). Some anteriorization (Z-axis) and rotation (X-axis) is present, which behave has compensations, given the reduced capacity of enlisting shoulder flexion with elbow extension (extensor synergy); implying a

displacement of the trunk as attempting to reach the target. Subject B presents increased anteriorization of the trunk when compared to subject A. The presence of a larger compensation at this level, in a clinically less affected individual, could be related to the difference in functional task completion.

Data analysis seems to suggest that the P1 position is advantageous for compensatory movement detection at the shoulder level, being however necessary to complement with information provided by P5, in order to discriminate between shoulder or trunk elevation. The information provided by sensor locations P2 and P3 do not seem to add relevant knowledge to that provided by sensor position P1. The P4 position seems the most appropriate for detecting the abduction component of the limb; however, in relation with the superior-inferior movement, this particular sensor position is insufficient for determination of the corporal segment where the elevation occurs (shoulder/elbow/trunk), limiting its reliability for compensatory movement identification in this direction. Finally, sensor position P5 presents a good sensitivity for anteriorization and rotation detection, though lack of additional comparative data with other locations at the trunk level.

5 CONCLUSIONS

Methods based on quantitative models can help therapists and patients to effectively improve the recovery process, by providing objective assessment and monitoring, contributing to protocol validation and information sharing. This preliminary study focused on the determination of upper limb associated compensatory movement through accelerometry data and the influence of sensor positioning.

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APPENDIX

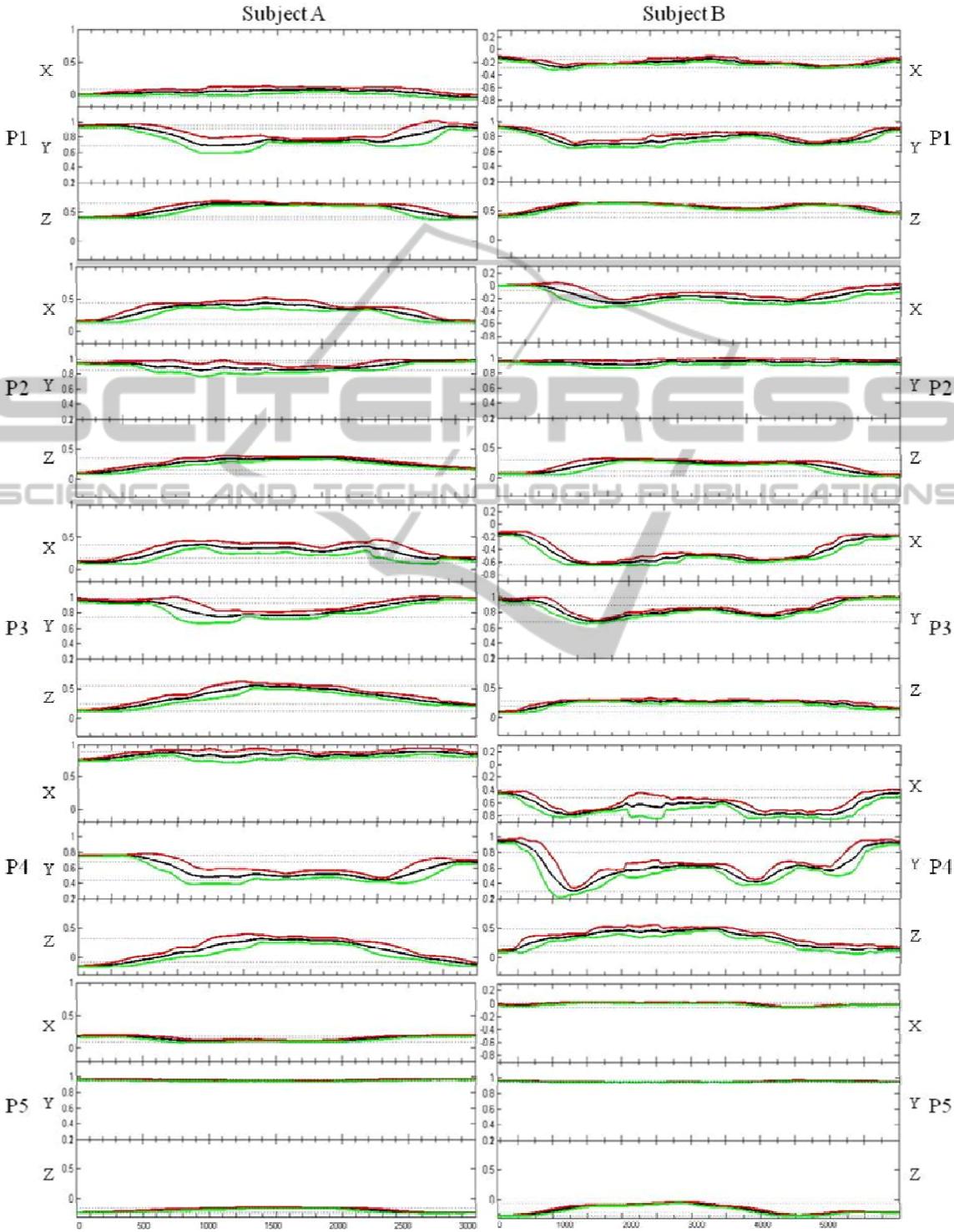


Figure 1: Accelerometry data for Subject A and B for locations P1, P2, P3, P4 and P5.