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 and 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 (World Health Organization, 2011). As epidemiological studies show, disability following stroke appears, albeit not only, but most evidently, in the form of neurological dysfunctions and reduced ability to actively engage in activities of daily living, justifying the need for intervention (Geyh et al., 2004).

Economic related data reveals that in several countries 5% of the healthcare budget is allocated to stroke related costs, concerning not only the acute phase but also the subsequent, often very prolonged rehabilitation period (Quinn et al., 2009). Despite its relevant costs, agreement exists in the importance to continue to address the management of the *sequelae* of stroke. In fact, during the past decades, dramatic improvements have been made in this area and convincing scientific evidence now exists that stroke rehabilitation programs are effective at restoring functional abilities and reducing external dependency (Ottenbacher, 2005). The main obstacle encountered by therapists in clinical practice is establishing an effective bridge between the results obtained during the studies and its efficient applicability at clinical environments (Graven et al., 2011).

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 and Levin, 2007; Geyh et al., 2004).

The predominantly affected arm, contra-lateral to the committed hemisphere, 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, Ptito, 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).

A common example of the before mentioned compensations are the excessive trunk and shoulder girdle displacement seen in stroke survivors when attempting arm transport during reaching, and for hand orientation during grasping, either within and beyond arm's length, being this strategy thought to occur due to poor control of motor functions such as elbow extension and shoulder-elbow interjoint coordination (Levin et al., 2004). 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 sensoriomotor behaviour, highlighting thus the importance of the cortical reorganization through selective afferent input to optimize internal representation and influence movement control (Nudo, 2007; Raine, 2009).

Although some controversy remains regarding functional benefits of compensatory movement as it may allow the accomplishment of a given task; even in the presence of a motor deficit; studies of post-stroke motor recovery suggest that these maladaptive strategies may limit plasticity of the nervous system to enhance neuromotor recovery, thus interfering with skill reacquisition and full potential for daily living participation, even well beyond the acute phase, as research demonstrates that although arm motor improvement occurs most rapidly within the first months post stroke, meaningful gains can occur even in chronic stroke if the system is appropriately challenged (Michaelsen et al., 2006; Page, Gater, Bach-Y-Rita, 2004; Cirstea et al., 2006). 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).

A growing concern in rehabilitation is the objective monitoring and assessment of measurements associated to neuromotor recovery. Functional assessment measurement associated with post-stroke can be categorized in four general purposes:

- Discrimination of motor performance of stroke victims versus healthy individuals.
- Quantification of motor deficit.
- Establishment of potential rate for motor recovery
- Objective monitoring performance changes over the time (Nowac, 2008).

For post-stroke rehabilitation, there a few standardized clinical measures that assess upper-extremity deficits, either at the impairment level, activity limitation and participation restriction level (Lang, Edwards, Birkenmeier, Dromerick, 2008). Rivermead Motor Assessment (RMA), Fugl-Meyer Motor Assessment (FMA), Motor Assessment Scale (MAS) and Reach Performance Scale (RPS) are examples of measurement strategies that include upper-limb sections. The main disadvantage of these standardized clinical assessments is the dependence on physiotherapists' observational skills, which although valuable, remains insufficient for reliable measurement of certain quantitative features (e.g., intersegment coordination, quality of movement and smoothness) (Knorr et al., 2005). Moreover, observation-based assessment is subject to observer induced error, resulting from poor training (thus mostly confined to more experienced professionals), personal bias, limited capacity of human visual perception, just to mention some.

Referring to assessment instruments in laboratory environment, relevant to the field, one can refer to electromyography (EMG), force platforms and complex image/video analysis systems, which introduce a degree of objectivity in the interpretation of events, augmenting the therapist/physician perspectives in what refers to functional and motor characterization. However, such resources accessibility in clinical environment is scarce or null, not to mention time consuming and requiring a high-learning curve or specialized training, thus restricting their routinely usage from clinical rehabilitation practices.

Physiotherapists' clinical practice reality concerning data gathering and recording is far from being effective, despite general guidelines concerning this matter. In fact this important step of the overall rehabilitation process is often absent or, when present, tends to be mainly subjective and qualitative, based on the therapist opinions and patient's provided information, regarding movement restoration and overall progress. Such recordkeeping varies from institution to institution, from therapist to therapist, and are not necessarily updated at each session; therefore a progressive evaluation based on such records remains subjective to the experience and interpretation of the reader, which clearly contributes to a chain-cycle of deteriorating results, both in progress and outcomes. Quantitative data records provide a means for efficient and expedient analysis of the effectiveness of a therapy on a patient's progress, safeguarding from negative activities that can go unnoticed and unrecorded. Such approach strengthens and streamlines internal technological platforms, expanding their coverage and added-value; promoting the formulation of standards and protocols for patient progress monitoring, thus compensating current guidelines.

Recent advances in microelectromechanical systems (MEMS), miniaturization, wireless communication, etc., 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 that estimate 3D arm movement, based on 3 joint and three degrees of freedom rigid body quantitative models are common (Pérez et al., 2010; Zhou, Hu, Tao, 2006). Others exist which aim to detect significant movement variation, as in fall detectors, based on accelerometry analysis and angle variation (Kung et al., 2010). 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, members of a larger subject group, part of an umbrella research project. They were informed of the experimental procedures and provided written consent, in accordance with policies of the institution's ethics committee. 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 mini-mental state examination (MMSE).
4. Active range of motion in the compromised arm of at least 15º in the shoulder and elbow (Zachowski et al., 2004).

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). The FMA evaluates 33 items related to movements of the proximal and distal parts of the arm and the total score range from 0 to 66. The maximum FMA score for shoulder, elbow and coordination is 42/66 and for wrist and hand is 24/66. A maximum score of 66 corresponds to normal motor function and clinical subdivision; while cases that score between 50 – 63 correspond to mild-to-moderate motor impairment; between 46-50 to a moderate (gross and some fine movement) to severe (gross motor function only) motor impairment.

The RPS focuses on visual assessment of compensatory movements used during the transport phase of reaching, defined as the beginning of the movement until the object is grasped (Levin et al. 2004). Although this scale intends to identify and quantify the degree of motor compensations used by patients when reaching to grasp an object placed within the reach of the arm (close target) and beyond the reach of the arm (far target), it was chosen to evaluate for this purpose only the close target task. Six components were assessed: trunk displacement, movement smoothness, shoulder movements, elbow movements, quality of prehension and global score. Each component was scored between 0 and 3, where 0 refers to maximum compensation and 3 to complete absence of compensation. The scores of the trunk displacement, movement smoothness, shoulder movements, elbow movements and quality of prehension components allow for the identification of deficiencies in aspects specific to movement and these scores in conjunction with a global score can be added for a total score that can vary from 0 to 18, for each of the subcategories: close target and far 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 Middle Cerebral Artery
RMCA – Right Middle Cerebral Artery
RPS – Reach Performance Scale
FMA – Fugl-Meyer Assessment of Motor Recovery after Stroke

2.1 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). This approach on the rehabilitation of adults with central nervous system pathology is based partly upon present-day knowledge of motor control, motor learning, neural and muscle plasticity, and biomechanics (Sackett, Straus, Richardson, 2000). 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 100º of flexion, forearm in pronation with the palm of the hand resting on thigh (Wagner, Lang, Sahrmann, Edwards, Dromerick, 2007; Michaelsen, Luta, Roby-Brami, Levin, 2001). Performance was video recorded for posterior cross-reference.

2.1 System Description and Setup

A simple wearable monitoring device, named W2M2 (Wireless Wearable Modular Monitoring), was design 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 system seen on Figure 1 is based on a modular approach and almost out-of-box ready-to-use. The module's main component, the Arduino FIO, is accessible at low cost and can be used with a reduced learning curve; additionally, the ADXL345 3-axis accelerometer break-out board was used combined with a XBEE based wireless interface, transforming the module in a portable, wireless adaptable resource.

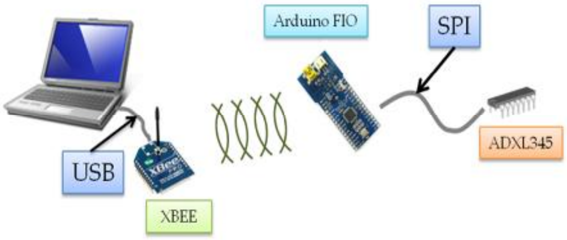

Figure 1: Component view of first W2M2 prototype.

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 (see Figure 2):

- 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 it use in numerous other locations

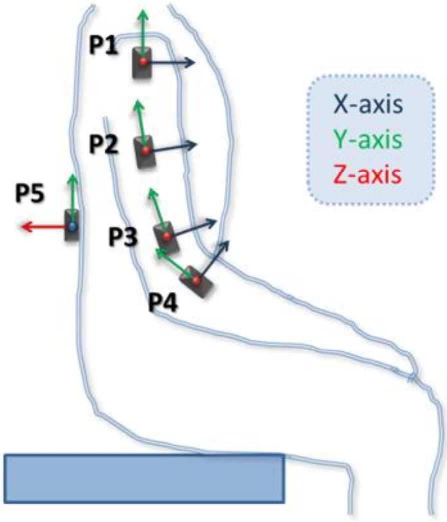

Figure 2: Sensor locations.

3 RESULTS

The accelerometers data is captured at a frequency of approximately 100 Hz, which is then buffered and transmitted wirelessly. Error correcting communication protocols can introduce data package repetition and malformation, thus the digitalized data format and sequencing needs to be verified, removing/repairing ill-formatted data packages and re-sequencing data based on timestamp if necessary. The data is resample through interpolation in order to compensate for variation in sampling due to the inherit nature of digital systems and data removed by the previously mentioned process. A smoothing procedure follows applying a simple moving average smoothing strategy, based convolution with a square pulse, in order to reduce the influence of noise and oscillations. For improved processing and limitation of "qualitative" marking of movement stages, a window differentiation function, seen in Equation 1, was applied; producing a shifted differentiation of the signal, used for automatic movement start and end determination. Experimentation determined that a window span of 300 points (milliseconds) and a 30% variation on the resulting differentiation offered reliable results. Additional plus/minus pseudo-envelope functions were generated through a moving window standard deviation approach, according to Equation 2, in order to provide visual indicators of signal stability.

$$S_{smooth} = \frac{S_{raw}\left(t+\frac{t_w}{2}\right) - S_{raw}\left(t+\frac{t_w}{2}\right)}{w} \quad (1)$$

where:

S_{smooth} = smooth signal;
S_{raw} = raw signal;
t = time;
t_w = width compensation.

$$S_{envelope}(t) = S_{smooth}(t) \pm f_{WSD}\left[\, S_{raw} \Big|_{t-\frac{t_w}{2}}^{t+\frac{t_w}{2}} \right] \quad (2)$$

where:

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

A complete reach-press and return accelerometry data is displayed in Figure 3, illustrating some of the previously mentioned obtained signals. The blue solid line, referred to by S_{smooth}, represents the processed signal, the red and green solid lines represent the plus/minus $S_{envelope}$ signals; while the red and blue dotted lines represent the inner and outer start and finish lines determined by the procedure mentioned beforehand, and its adjustment by the shift that occurs in the differentiation function.

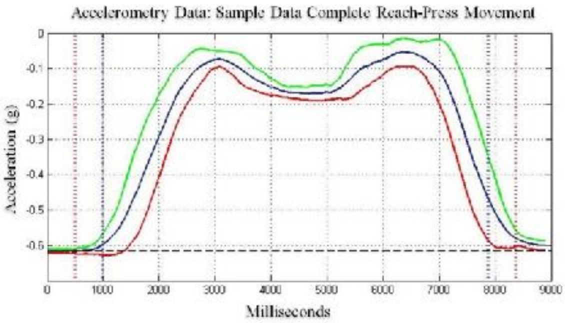

Figure 3: Sample Accelerometry data

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 4, 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 4 on two columns of graphs showing accelerometry data measured at all five sensor locations (referred to as P1, P2, P3, P4 and P5) for subjects A and B. Each position has its corresponding acceleration graphs (measured in g's) representing information in all three axes (x, y, z). 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 hemi-trunk at the transport phase. Video analysis confirms that the subject does not fully complete the functional task in that the hand does not press the target.

As for subject B, video analysis allows verification that in terms of movement components, and comparatively to subject A, presents increased selectivity in the movement, observed by the

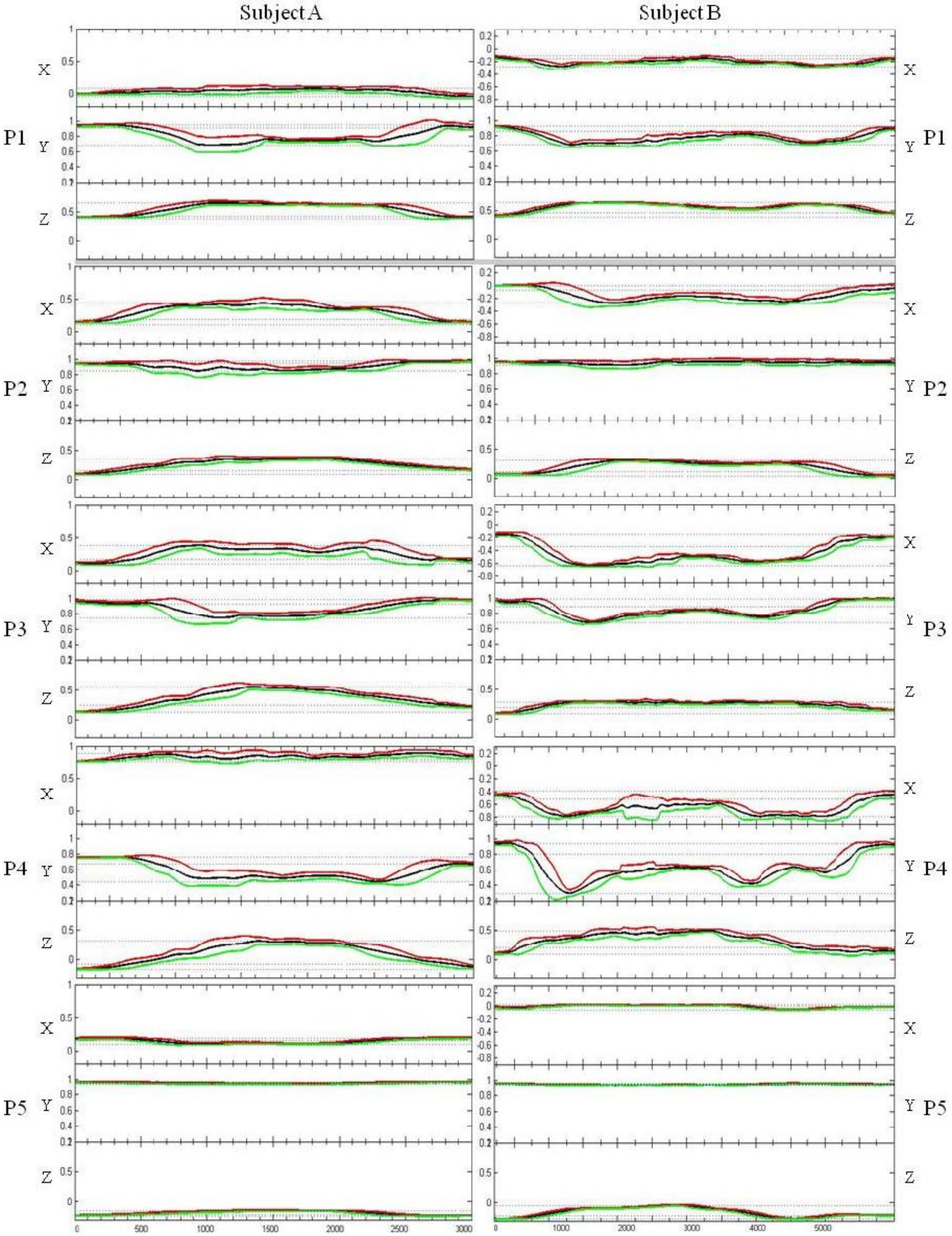

Figure 4: Accelerometry data for Subject A and B for locations P1, P2, P3, P4 and P5.

shoulder-elbow interjoint coordination, and reflected in a reduced compensatory mechanism through shoulder abduction. The subject does present 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 reach the target.

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 incapacity of reaching the target Both patients present on the collected data, elevation and abduction of the shoulder, at the initial phase of the movement, as a compensatory motor strategy, corroborating the visual analysis proportionate by the video. It should be mentioned that subject B, capable of fully completing the functional task requested, 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, the graphs of Figure 4 brings into evidence that, for both subject, there exists an increased displacements in the anterior direction (X-axis) when compared with sensor position P1; however there is a lack of marked differences observed on the global pattern of the movement. Such could suggest that sensor position P2 offers more sensitivity for the detection of such movements when compared to sensor position P1. In reference to the Y-axis, the opposite seems to occur, that is, even though visual confirmation of shoulder elevation occurs at the initial phase of the movement, this sensor position presents reduced sensibility for such detection when compared with sensor position P1, for both subject A and B. For Z-axis, also for both individuals, there seems not to exist marked differences in the gathered information from sensor positions P1 and P2.

Sensor position P3 evidences some variability among the patients, in what the detection of movements is referred. In fact, the movement in the anterior direction (X-axis) performed by subject A is more pronounced in this position, when compared with position P1; in turn, for subject B this movement is better detected when compared to both sensor position P1 and P2. A similar situation occurs in the remaining movements, i.e. superior direction (Y-axis) and lateral direction (Z-axis). It should be noted that subject B presents no pronounced differences among the sensor position P1, P2 and P3 for the lateral direction. This could be explained by such individual not recruiting so evidently this movement component 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. Referring to subject A, does not present a significant elevation component (X-axis), which could be related with the deficit in the capacity to enlist selective flexion of the elbow. On the other hand, 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.

Some evidences exist thus, 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. It should be mentioned that subject B present 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 with the fact that in contrast with the first one, this subject completed the requested task, demanding an increased movement excursion, which reflects in the emergence of the compensatory pattern at the trunk level.

Arm motor impairment was evaluated prior to measurements, with the arm subsection of FMA and the RPS (close target). Data analysis seems to suggest that the P1 position is advantageous for compensatory movement detection at the shoulder level, being however necessary to compliment with information provided by sensor location 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

Nowadays, post-stroke rehabilitation therapy is dictated by qualitative analysis based mainly on the therapist personal experience and patients' needs, leading to a subjective and sometimes inaccurate perception of patient actual condition. During the rehabilitation process the therapist must analyze patient's movements, its motor learning and evaluate motor control neurophysiology. The therapist judgment is made through visual observation and personal handling capabilities which can introduce misunderstandings and interfering with the patients' potential for recovering. 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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