



POSTURAL CONTROL FUNCTION ASSOCIATED WITH UPPER-LIMB PERFORMANCE IN POST-STROKE SUBJECTS

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To André, Rodrigo and Ricardo

To my Mother and Father

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TABLE OF CONTENTS

Acknowledgements.....	iii
List of Figures	ix
List of Tables	xiii
Resumo	xv
Abstract	xvii
Abbreviations and Symbols	xix
 CHAPTER 1 Introduction.....	 1
1.1. Context and Motivation.....	3
1.1.1. Movement versus Posture Organization	3
1.1.2. Upper-Limb Function	6
1.1.3. Atypical Upper-Limb Function.....	8
1.2. Thesis Objectives	11
1.3. Thesis Organization.....	12
 CHAPTER 2 Methodological Considerations	 17
2.1. Participants.....	19
2.2. Task and Related Variables	21
2.3. Biomechanical Parameters.....	24
2.4. Studies Sequence	26

CHAPTER 3	Research Studies.....	29
3.1.	Study I – Kinematic Characterization of Reaching in Post-Stroke Subjects: an analysis of ipsilesional and contralesional Limbs.....	31
	Abstract	32
3.1.1.	Introduction.....	33
3.1.2.	Methods.....	35
3.1.3.	Results	38
3.1.4.	Discussion	45
3.1.5.	Conclusion.....	48
	Acknowledgements.....	49
	References	49
3.2.	Study II – Co-Activation Study of Upper-Limb Muscles During Reaching in Post-Stroke Subjects: an Analysis of Ipsilesional and Contralesional Limbs	75
	Abstract	76
3.2.1.	Introduction.....	77
3.2.2.	Methods.....	80
3.2.3.	Results	86
3.2.4.	Discussion	89
3.2.5.	Conclusion.....	92
	Acknowledgements.....	92
	References	93
3.3.	Study III – Anticipatory Postural Adjustments of Reaching while Sitting: an Analysis of the Contralateral Body Side to Movement Execution in Post-Stroke Subjects	99
	Abstract	100
3.3.1.	Introduction.....	101

3.3.2. Methods.....	102
3.3.3. Results.....	106
3.3.4. Discussion	110
3.3.5. Conclusion	113
Acknowledgements.....	113
References.....	114
3.4. Study IV – Anticipatory Postural Adjustments of Reaching while Standing: an Analysis of the Contralateral Body Side to Movement Execution in Post-Stroke Subjects	119
Abstract.....	120
3.4.1. Introduction.....	121
3.4.2. Methods.....	122
3.4.3. Results.....	126
3.1.1. Discussion	130
References.....	132
CHAPTER 4 Discussion, Conclusion and Future Work.....	137
4.1. Global Discussion.....	139
4.2. Conclusions.....	144
4.3. Future Work.....	145
References	147

LIST OF FIGURES

- Figure 1:** Schematic representation of a proposed simplified model for the predominantly global planning of postural control during the reaching movement with both upper-limbs in healthy subjects. 8
- Figure 2:** Proposed division of the reaching movement based on postural control demands..... 22
- Figure 3:** Movement time. The duration of the movement performed in both sagittal and scapular planes are illustrated for the dominant limb of healthy subjects (DOM) vs the ipsilesional limb of post-stroke subjects (IPSI) (A), and for the non-dominant limb of healthy subjects (NDOM) vs the contralesional limb of post-stroke subjects (CONTRA) (B). Columns plot the median and 25th and 75th percentiles; whiskers reveal the min and max values obtained. * $p < 0.05$ represent significant differences between IPSI (A) / CONTRA (B) limbs vs DOM (A) / NDOM (B) limbs, considered as their respective controls. 39
- Figure 4:** Peak velocity. The peak velocity in both sagittal and scapular planes are illustrated for the dominant limb of healthy subjects (DOM) vs the ipsilesional limb of post-stroke subjects (IPSI) (A), and for the non-dominant limb of healthy subjects (NDOM) vs the contralesional limb of post-stroke subjects (CONTRA) (B). Columns plot the median and 25th and 75th percentiles; whiskers reveal the min and max values obtained. * $p < 0.05$ represent significant differences between IPSI (A) / CONTRA (B) limbs vs DOM (A) / NDOM (B) limbs, considered as their respective controls..... 40
- Figure 5:** Trunk displacement. The trunk displacement in both sagittal and scapular planes are illustrated for the dominant limb of healthy subjects (DOM) vs the ipsilesional limb of post-stroke subjects (IPSI) (A), and for the non-dominant limb of healthy subjects (NDOM) vs the contralesional limb of post-stroke subjects (CONTRA) (B). Columns plot the median and

25th and 75th percentiles; whiskers reveal the min and max values obtained. * $p < 0.05$ represent significant differences between IPSI (A) / CONTRA (B) limbs vs DOM (A) / NDOM (B) limbs, considered as their respective controls. 41

Figure 6: Elbow extension. The elbow extension in both sagittal and scapular planes are illustrated for the dominant limb of healthy subjects (DOM) vs the ipsilesional limb of post-stroke subjects (IPSI) (A), and for the non-dominant limb of healthy subjects (NDOM) vs the contralesional limb of post-stroke subjects (CONTRA) (B). Columns plot the median and 25th and 75th percentiles; whiskers reveal the min and max values obtained. * $p < 0.05$ represent significant differences between IPSI (A) / CONTRA (B) limbs vs DOM (A) / NDOM (B) limbs, considered as their respective controls. 42

Figure 7: Shoulder elevation. The shoulder elevation in both sagittal and scapular planes are illustrated for the dominant limb of healthy subjects (DOM) vs the ipsilesional limb of post-stroke subjects (IPSI) (A), and for the non-dominant limb of healthy subjects (NDOM) vs the contralesional limb of post-stroke subjects (CONTRA) (B). Columns plot the median and 25th and 75th percentiles; whiskers reveal the min and max values obtained. * $p < 0.05$ represent significant differences between IPSI (A) / CONTRA (B) limbs vs DOM (A) / NDOM (B) limbs, considered as their respective controls. 44

Figure 8: Movement units. The movement units in both sagittal and scapular planes are illustrated for the dominant limb of healthy subjects (DOM) vs the ipsilesional limb of post-stroke subjects (IPSI) (A), and for the non-dominant limb of healthy subjects (NDOM) vs the contralesional limb of post-stroke subjects (CONTRA) (B). Columns plot the median and 25th and 75th percentiles; whiskers reveal the min and max values obtained. * $p < 0.05$ represent significant differences between IPSI (A) / CONTRA (B) limbs vs DOM (A) / NDOM (B) limbs, considered as their respective controls. 45

- Figure 9:** Proposed division of the reaching movement based on postural control demands..... 79
- Figure 10:** Activation timing of contralateral scapular/upper-trunk muscles during reaching movement of the ipsilesional upper-limb of post-stroke subjects and the dominant upper-limb of healthy subjects. The activation timings are illustrated for upper trapezius (A), inferior trapezius (B) and latissimus dorsi (C) muscles. Open squares represent muscle activation timing of each post-stroke subject, whereas open circles represent muscle activation timing of healthy subjects; bold vertical lines represent the mean values of both groups. Time zero indicates movement initiation. The interval that shows APAs is marked in gray. 107
- Figure 11:** Activation timing of contralateral scapular/upper-trunk muscles during reaching movement of the contralesional upper-limb of post-stroke subjects and the non-dominant upper-limb of healthy subjects. The activation timings are illustrated for upper trapezius (A), inferior trapezius (B) and latissimus dorsi (C) muscles. Open squares represent muscle activation timing of each post-stroke subject, whereas open circles represent muscle activation timing of healthy subjects; bold vertical lines represent the mean values of both groups. Time zero indicates movement initiation. The interval that shows APAs is marked in gray.. 109
- Figure 12:** Schematic representation of a proposed simplified model for global planning of postural control during the reaching movement of upper-limbs. Panel A illustrates a schematic organization of the predominantly circuits for postural control in healthy subjects during reaching with both upper-limbs. Panels B and C represent reaching with the contralesional and the ipsilesional limbs, respectively, in post-stroke subjects in which corticoreticular projections were affected. 112
- Figure 13:** Activation timing of contralateral scapular/upper-trunk muscles during reaching movement of the ipsilesional upper-limb of post-stroke subjects and the dominant upper-limb of healthy subjects. The activation timings are illustrated for upper trapezius (A), inferior trapezius (B) and latissimus dorsi (C) muscles. Open squares represent muscle timing of

each post-stroke subject, whereas open circles represent muscle timing of healthy subjects; bold vertical lines represent the mean values of both groups. Time zero indicates movement initiation. The interval that shows APAs is marked in gray.....127

Figure 14: Activation timing of contralateral scapular/upper-trunk muscles during reaching movement of the contralesional upper-limb of post-stroke subjects and the non-dominant upper-limb of healthy subjects. The activation timings are illustrated for upper trapezius (A), inferior trapezius (B) and latissimus dorsi (C) muscles. Open squares represent muscle timing of each post-stroke subject, whereas open circles represent muscle timing of healthy subjects; bold vertical lines represent the mean values of both groups. Time zero indicates movement initiation. The interval that shows APAs is marked in gray. 129

LIST OF TABLES

Table 1: Post-stroke group characterization regarding age, gender, weight, height, time post-stroke and location of lesion.	36
Table 2: Post-stroke group characterization regarding age, weight, height, time post stroke and location of lesion.	81
Table 3: Anatomical references used to locate the electrodes. Electrode locations were confirmed by palpation of the muscular belly with the subject in the test position.	83
Table 4: Antagonist co-activation ratios in the first sub-phase of reach movement. Median values and interquartile range of the co-activation ratio in both sagittal and scapular planes are presented for the dominant limb of healthy subjects vs the ipsilesional limb of post-stroke subjects and the non-dominant limb of healthy subjects vs the contralesional limb of post-stroke subjects, for LD/PM , PD/AD, TRlat/BB and TRlat/BR muscle pairs.	87
Table 5: Antagonist co-activation ratios in the second sub-phase of reach movement. Median values and interquartile range of the co-activation ratio in both sagittal and scapular planes are presented for the dominant limb of healthy subjects vs the ipsilesional limb of post-stroke subjects and the non-dominant limb of healthy subjects vs the contralesional limb of post-stroke subjects, for LD/PM , PD/AD, TRlat/BB and TRlat/BR muscle pairs.	88
Table 6: Characterization of the post-stroke group regarding age, gender, weight, height, post-stroke time evolution and affected artery.....	103
Table 7: Characterization of the post-stroke group regarding age, gender, weight, height, post-stroke time evolution and affected artery.....	123

RESUMO

A ligação neuronal entre áreas motoras e a formação reticular (conexão corticoreticular) justifica que a capacidade para a realização do movimento regulado e dirigido do membro superior tenha por base a actividade de sistemas predominantemente orientados para a função de controlo postural. Dado que estes sistemas apresentam uma disposição predominantemente ipsilateral, existe, após a ocorrência de um acidente vascular encefálico, forte possibilidade de se verificar um comportamento atípico no âmbito do controlo postural, também no hemicorpo ipsilesional. Face a isto, foi objectivo deste trabalho investigar o comportamento motor associado à performance do gesto de alcance em ambos os membros superiores (ipsilesional e contralesional) de indivíduos com história de lesão de estruturas subcorticais intervenientes nos mecanismos de controlo postural, decorrentes de um acidente vascular encefálico. Participaram neste estudo 15 indivíduos saudáveis e 13 indivíduos que sofreram um acidente vascular encefálico. Procedeu-se à caracterização biomecânica do gesto funcional de alcance dos dois membros superiores de ambos os grupos, através da análise tridimensional e electromiográfica da tarefa. Obtiveram-se dados referentes a variáveis relacionadas com o mecanismo de controlo postural, nomeadamente: tempo de execução do movimento, velocidade máxima da mão, deslocamento do tronco, extensão do cotovelo, elevação do ombro e unidades de movimento (variáveis cinemáticas); índices de co-activação de pares musculares e tempos de activação de músculos posturais. De uma forma global, os resultados sugerem que os indivíduos com acidente vascular encefálico evidenciam alterações no âmbito do controlo postural no hemicorpo ipsilesional, justificando a necessidade de encarar estes indivíduos, quer no âmbito da intervenção, quer da investigação, numa perspectiva global.

Palavras-Chave: CONTROLO POSTURAL, ACIDENTE VASCULAR ENCEFÁLICO, HEMICORPO IPSILESIONAL, ALCANCE

ABSTRACT

The neuronal connection between motor areas and the reticular formation (corticoreticular connection) justifies that the ability to produce purposeful upper-limb movement is also dependent on the activity of neuronal systems mainly related to postural control function. Given that these systems present a predominantly ipsilateral disposal, it is highly probable to find, after a stroke, an atypical postural control behavior also in the ipsilesional body side. Therefore, the goal of this dissertation was to investigate the motor behavior associated to the performance of the reaching task with both (ipsilesional and contralesional) upper-limbs of post-stroke subjects with subcortical damage of structures related to ipsilateral postural control. Fifteen healthy and thirteen post-stroke subjects participated in this study. In each group both upper-limbs' functional task of reaching was biomechanically characterized, through tridimensional movement and EMG analysis. Data concerning postural control mechanism was collected, namely: movement time, hand peak velocity, trunk displacement, elbow extension, shoulder elevation, and movement units (kinematic variables); antagonist co-activation ratios and activation timings of postural muscles. Generally, the results suggested that post-stroke subjects presented a postural control dysfunction in the ipsilesional body side, which highlights the importance of a global perspective within these clinical cases, both during intervention and investigation scenarios.

Keywords: POSTURAL CONTROL, STROKE, IPSILESIONAL BODY SIDE, REACHING.

ABBREVIATIONS

AD	Anterior Deltoid
APAs	Anticipatory Postural Adjustments
aAPAS	Accompanying Anticipatory Postural Adjustments
BB	Biceps Brachii
BMI	Body Mass Index
BR	Brachioradialis
CNS	Central Nervous System
EMG	Electromyography
FMA	Fugl-Meyer Motor Assessment
LD	Latissimus Dorsi
LT	Lower Trapezius
MCA	Middle Cerebral Artery
pAPAs	Preparatory Anticipatory Postural Adjustments
PASS	Postural Assessment Scale for Stroke patient
PD	Posterior Deltoid
PM	Pectoralis Major
RMA	Rivermead Motor Assessment
RPS	Reach Performance Scale
SMA	Supplementary Motor Area

Abbreviations

TRlllat	Triceps Brachii Lateral Head
UT	Upper Trapezius
WHO	World Health Organization

CHAPTER 1

INTRODUCTION

1.1. CONTEXT AND MOTIVATION

1.1.1. MOVEMENT VERSUS POSTURE ORGANIZATION

Movement is crucial to human life and, although it seems a simple process, the complexity within the mechanisms that underlie motor actions have been extensively described, reflecting an intricate system, comprising several variables (Enoka, 2008; Latash, 1998). Indeed, human movement cannot be understood strictly as a motor function but, instead, as a consequence of a continuous interaction between motor, perceptual and cognitive processes (Carey et al., 2005). Thus, the study of human movement must consider the miscellaneous knowledge of different but interconnected areas such as physiology, biomechanics, neuroscience and behavioral sciences (Gjelsvik, 2007).

A coordinated action of the nervous system (both peripheral and central) with the musculoskeletal system is needed to achieve an optimal performance of a skillfully motor action (Frank et al., 1990; Ghez et al., 2000; Massion et al., 1988; Massion, 1998). This is influenced by external and internal constraints, such as gravitational and reaction forces from supporting surfaces, obstacles, the acceleration imposed by the actions (external), the geometric configuration and inertial characteristics of the body segments and the forces associated with muscle contraction (internal) (Massion, 1992). Despite the presence of the referred constraints, the healthy central nervous system (CNS) is able to manage an inherently unstable system with redundant (or abundant) degrees of freedom, through the development of flexible synergies according to actions and context specificities (Latash et al., 2006; Latash, 2012; Stuart, 2005; Winter, 1995).

Over the recent years, the scientific community has devoted an increasing interest about the comprehension of the mechanisms underlying the complexity of mobility (movement execution) against a frame of stability

(posture organization). Extensive research has been developed and two distinct possibilities about the central organization of movement *versus* posture were proposed. One considers that movement control and posture adjustment are dependent on two distinct, albeit parallel and coordinated control systems (Massion, 1992; Massion et al., 2004), while the other assumes that focal and postural commands are in the dependency of a single, common central controller (Aruin et al., 1995; Latash et al., 1995). According to the latter, the activity of postural muscles is, by itself, an inherent part of the overall control mechanisms underlying a motor action (Latash, 1998). Even though the coordination process between movement and posture is still highly controversial, it is accepted as a fact that postural control is an essential foundation for movement variability and efficiency (Massion et al., 2004; Pollock et al., 2000).

To better comprehend this issue, it becomes fundamental to understand the functional relationship of the neuronal systems involved in posture and movement organization. Neuronal pathways mainly responsible for postural control are anatomically distributed in ventral and medial regions of the spinal cord (Lawrence et al., 1968). Indeed, descending ventromedial pathways, acting on axial and proximal muscles, and comprising vestibulospinal and reticulospinal tracts, play an important role in the production, distribution and maintenance of postural tone (Lalonde et al., 2007; Matsuyama et al., 2004). Of these, the reticulospinal tract, which forms a continuous anatomical system with the corticoreticular pathway and allows the structural and functional link between the cerebral cortex and the spinal cord, has an essential contribution for postural control function (Matsuyama et al., 2004), namely through the generation of anticipatory postural adjustments (APAs). In fact, corticoreticular neurons, originating from motor area 6 (which includes premotor cortex and supplementary motor area), amongst other areas, descend through the internal capsule and terminate in the reticular formation, originating the pontine and the medullary reticulospinal pathways, which descending ipsilaterally and bilaterally, respectively, are involved in postural responses (Brodal, 1981; Matsuyama et al., 2004; Schepens et al., 2008). Such an anatomical disposal

justifies that reticulospinal neurons can produce postural widespread effects, both ipsilaterally and contralaterally to the cortical motor areas.

While the ventromedial pathways are mainly related to postural control function, movement execution is strongly dependent on the integrity of dorsolateral pathways, the most relevant one being the corticospinal tract, especially when referring to upper-limbs function (Castiello, 2005; Muir et al., 1983; Porter et al., 1993; Siegel et al., 2011). This system also includes neurons originated from motor area 6 (Brodal, 1981; Siegel et al., 2011), which constitutes an argument in favor of the interdependence between posture and movement. Another argument sustaining this interdependence relies on the concept of neuronal interconnectivity (Alstott et al., 2009). Indeed, current knowledge emphasizes that, more than a sample of systems involved in movement execution, neuroscience should explore the functional dynamics between structures *versus* systems through the comprehension of neuronal networks (Silva, 2012). Thus, it is understandable that the reference to systems involved in functional tasks should be replaced for the reference to neuronal networks, namely; in the specific case of the upper-limb function, the cortico-pontine-cerebellum-cortical network (Lalonde et al., 2007; Smith et al., 1981). In fact, in all functional tasks where the upper-limb is involved to achieve a goal, the neuronal link between the motor cortex (mostly pre-motor cortex, supplementary motor area, posterior parietal cortex and primary motor cortex) and reticular formation allows the preparation of postural adjustments to support movement performance (Ghez et al., 2000; Haines, 2002).

Therefore, and although historically a great deal of attention has been devoted to the role of corticospinal tract in the production of skillfully movement, current knowledge emphasizes that purposeful and coordinated movement is dependent on the well-orchestrated function of both the ventromedial and the dorsolateral pathways.

1.1.2. UPPER-LIMB FUNCTION

Upper-limb's function constitutes the basis of important motor skills, often performed in daily life. Indeed, this body segment have the capacity of organize itself in space, with specific goals, always related with a motor concretization, whether that is reaching or pointing for an object, grasping and manipulating tools and throwing or catching a ball (Champiom et al., 2009; Rau et al., 2000). Therefore, it is clear that upper-limb function is highly dependent of a movement decision-making process (cortical), being the sub-cortical structures activated (pontine), for postural purposes, as well as the main regulatory structure (cerebellum), after what neuronal flow returns to the cortical areas (cortical) for movement performance (output) (Brodal, 1981; Lalonde et al., 2007; Smith et al., 1981).

The relationship between postural control and movement performance, allied to the disposal of the ventromedial and dorsolateral systems, is the basis to acknowledge that each upper-limb movement is preceded (preparatory anticipatory postural adjustments – pAPAs) and accompanied (accompanying anticipatory postural adjustments – aAPAs) by anticipatory adjustments that must also occur in the contralateral side to movement execution (Matsuyama et al., 2004; Schepens et al., 2006; Schepens et al., 2004; Schepens et al., 2008). These neuronal mechanisms allow for movement versatility of the upper-limb, which is well expressed by its ability to perform several different tasks in a variety of contexts (Lum et al., 2009; Rau et al., 2000; Shumway-Cook et al., 2007a). Moreover, this inherent variability reflects the mechanical abundance of the three major joints (shoulder, elbow and wrist), which need to be intrinsically coordinated with trunk postural activity so that purposeful actions with the arm can occur (Yanga et al., 2002). In fact, upper-limb's movement efficiency is dependent on the ability to move freely one limb in relation to the other, as well as away from the trunk, which requires dynamic stability of the thoracoscapular interface on the contralateral and ipsilateral body sides, so that functional and successful movement of one or both arms can occur (Champiom et al., 2009). In other words, scapular stabilizing

muscles must be recruited prior to focal upper-limb's movement onset, so that the scapular stability can act as an anchor of movement (Mottram, 1997; Voight et al., 2000). In summary, upper-limb's performance requires a proper and dynamic relationship between stability (postural control) and mobility. In fact, movement execution, strongly related with motor cortex output relies, for stability purposes, on the neuronal link between it, and the pontomedullary reticular formation, which main goal is, as already stated, the preparation of postural adjustments, that support movement execution (Lalonde et al., 2007; Schepens et al., 2004; Schepens et al., 2008). Moreover, electrophysiological and anatomical studies have shown that neurons of the pontomedullary reticular formation, acting on axial and proximal muscles through the reticulospinal system, may influence muscle activity both ipsilaterally and contralaterally (Rothwell, 2012; Schepens et al., 2004; Schepens et al., 2008). When a voluntary task of the upper-limb is performed, like reaching an object, which is mainly related to the motor cortex output of the contralateral hemisphere, pontomedullary reticular formation influences postural adjustments that occur in both the ipsilateral and contralateral sides to movement execution, i.e., contralaterally and ipsilaterally to movement control hemisphere, respectively (see Figure 1).

1.1 Context and Motivation

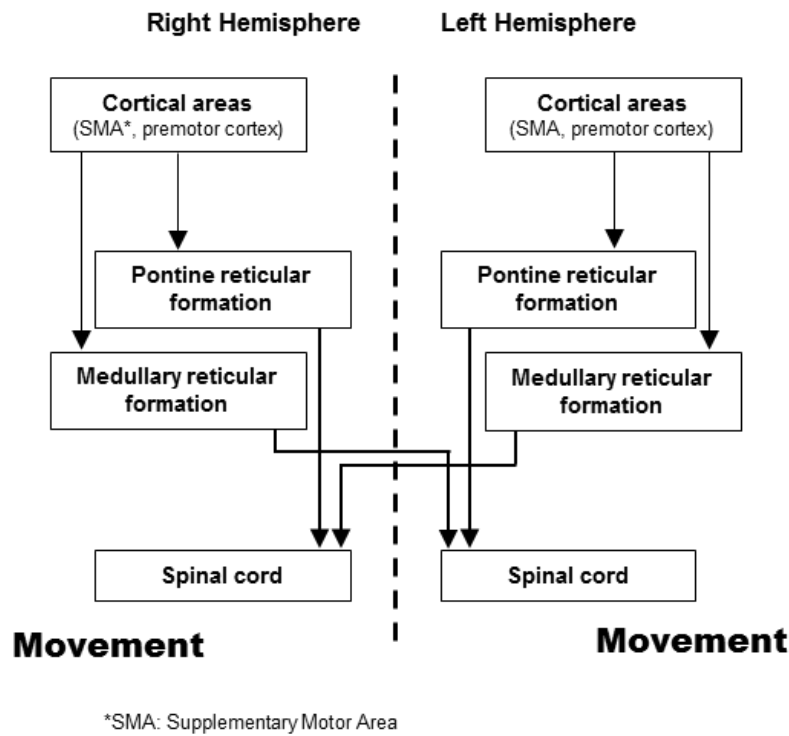


Figure 1: Schematic representation of a proposed simplified model for the predominantly global planning of postural control during the reaching movement with both upper-limbs in healthy subjects.

1.1.3. ATYPICAL UPPER-LIMB FUNCTION

Successful and efficient reaching is an essential task performed by the human arm, being strongly associated with daily independency (Lum et al., 2009; Sejnowski, 1998; Wagner, Dromerick, et al., 2007). In fact, any lesion that interferes with this functional gesture ability interferes with important independency related tasks, such as dressing, eating and personal hygiene (McCrea et al., 2005). Although there are a great number of lesions potentially affecting the upper-limb dynamics, CNS lesions are probably those that interferes the most. Indeed, disability of the upper-limb is probably the most common long-term consequence following a CNS lesion, namely stroke (Nakayama et al., 1994; Parker et al., 1986; Ryerson et al., 1997). In fact, epidemiological data show that a large percentage of stroke survivors exhibit

functional impairments of the upper extremity, which persist chronically (Faria-Fortini et al., 2011; Nakayama et al., 1994; Sveen et al., 1999).

The recommended standard World Health Organization (WHO) defines stroke as a focal (or at times global) neurological impairment of sudden onset, and lasting more than 24 hours (or leading to death), and of presumed vascular origin (WHO, 2004).

Considering the estimation of 10.3 million stroke survivors worldwide in 2005, and that this clinical condition is projected to remain a leading cause of disability-adjusted life years (DALYs) through 2030, stroke care represents a major burden on global healthcare system (Evers et al., 2004; Lopez et al., 2006; Strong et al., 2007). In Portugal, stroke is the leading cause of death, and the mortality rates are one of the highest comparing to other European countries, where stroke remains still the third cause of death (*Programa Nacional de Prevenção e Controlo das Doenças Cardiovasculares*, 2011).

Considering the global economic impact and the devastating consequences in the quality of life of the committed subjects and their relatives, it becomes increasingly important to improve rehabilitation strategies to minimize the burden of stroke. Therefore, research that might contribute to motor relearning is fundamental in order to eventually contribute to improve overall neuromotor outcomes.

Attending to the organization of the motor systems, post-stroke motor deficits seem more evident in the contralateral body side to the committed hemisphere, hereby denominated as contralesional side (Morris et al., 2012). Based on this evidence, most studies about stroke subjects focused on understanding the nature of these contralesional motor deficits (Beer et al., 1999; Beer et al., 2004; Bourbonnais et al., 1989; Busse et al., 2006; Cirstea et al., 2000, 2007; Cirstea, Mitnitski, et al., 2003; Cirstea, Ptito, et al., 2003; el-Abd et al., 1993; Fellows et al., 1994; Gowland et al., 1992; Levin, 1996a; Michaelsen et al., 2006). Following this line of research, most of the current stroke rehabilitation approaches are mainly focused on improving

contralesional upper-limb functionality (Mani et al., 2013). For example, constraint-induced movement therapy advocates repetitive and forced use of the contralesional upper-limb, further restraining the use of the ipsilesional one (Mark et al., 2004; Taub et al., 1993; Wolf et al., 2006).

Besides the contralesional deficits and its overall function, there is increasing literature about the interaction between postural control and movement performance in the ipsilateral body side to the committed hemisphere, hereby denominated as ipsilesional side (Silva, Sousa, Pinheiro, et al., 2012; Silva, Sousa, Tavares, et al., 2012; Sousa et al., 2013). These studies focused on the function of lower-limbs and, to our knowledge, no evidence exists about a similar relation in the function of the upper-limbs. However, when taking in consideration that the most frequent brain lesion territory, following stroke, is within middle cerebral artery (MCA) territory (de Niet et al., 2007; Mohr et al., 2004; Ng et al., 2007), the compromise of neuronal networks responsible for posture and movement relationship are well justified (Brodal, 1981; Rothwell, 2012; Siegel et al., 2011). Indeed, the neuronal flow from motor area 6 to the reticular formation, i.e., the corticoreticular path (responsible for APAs organization), as well as the corticospinal tract (responsible for movement execution) are within the MCA anatomical irrigation territory (Brodal, 1981; Haines, 2002; Siegel et al., 2011).

Despite this theoretical assumption, research focusing on the study of the ipsilesional upper-limb is still scarce. Moreover, most of the research concerning this issue points out that the atypical behavior observed in ipsilesional upper-limb (mostly focused in hand dexterity) is related with the ipsilateral disposal of the corticospinal system (Nowak, 2008; Yarosh et al., 2004). However, this can be questioned since there is not total agreement of the functional role of this system in adulthood (Martin, 2005). On the other hand, most of the research concerning the ipsilesional upper-limb has been focused on distal components, not taking into account the behavior of the proximal segments (Nowak et al., 2007; Quaney et al., 2005; Sunderland et al., 1999). However, it is known that proximal deficits might compromise distal

efficiency, being possible that conclusions about distal behavior may be biased by a proximal commitment (Chapiom et al., 2009).

In addition to the organization of the neural systems, there are a wide number of neurophysiological mechanisms contribute that to an adequate muscle co-activation through different levels of reciprocal innervation. Indeed, mechanisms of reciprocal inhibition assure a selective variation of muscle's activity during functional tasks. In stroke subjects, this is a mechanism that seems to be compromised very often (Busse et al., 2005; Chae et al., 2002; Hammond et al., 1988; Stoeckmann et al., 2009). Although some research has already been developed in this area, mostly studying voluntary muscle's relationship, such as biceps versus triceps (Dewald et al., 1995; Hu et al., 2007; Kamper et al., 2001; Levin et al., 2000), the agonist-antagonist relationship of postural muscles is yet to be clarified.

Summarizing, the role of the postural control contralaterally to movement execution still needs to be clarified. Therefore, research about the upper-limb's function in post-stroke subjects should also include the ipsilesional body sides, i.e, the often referred as the "non-affected side".

1.2. THESIS OBJECTIVES

The main goal of this dissertation was to allow for new insights on the relationship between postural control and movement of the upper-limb in post-stroke subjects by systematically investigating the behavior of variables related to postural control while performing a reach task with both the ipsilesional and the contralesional upper-limbs.

The specific objectives of this study were:

- To investigate the motor behavior of both the ipsilesional and contralesional upper-limb's performance, during the functional task of reaching, through the analysis of:
 - i. kinematic variables (movement time, hand peak velocity, trunk displacement, elbow extension, shoulder elevation, and movement units);
 - ii. antagonist co-activation ratios of stability related muscle pairs (Latissimus Dorsi (LD) / Pectoralis Major (PM)) and movement related muscle pairs (Posterior Deltoid (PD) / Anterior Deltoid (AD), Triceps Lateral (TRlat) / Biceps Brachii (BB); Triceps Lateral (TRlat) / Brachioradialis (BR));
 - iii. temporal parameter of APAs of contralateral scapular/upper-trunk muscles (Upper Trapezius (UT), Lower Trapezius (LT) and Latissimus Dorsi (LD)) during both sitting and standing reaching.

1.3. THESIS ORGANIZATION

The present dissertation follows the “Scandinavian model” structure, which consists of a collection of already published or submitted articles.

Therefore, this thesis initiates with a general introduction, in which the major topics of interest under the scope of the thesis' objectives and relevant state-of-the-art literature are presented. The second chapter contains the most pertinent methodological considerations that were adopted throughout the investigation, while Chapter 3 presents the scientific articles already published or submitted to relevant journals in the field, namely:

Paper 1:

Kinematic characterization of reaching in post-stroke subjects: an analysis of ipsilesional and contralesional limbs.

Paper 2:

Co-activation study of upper-limb muscles during reaching in post-stroke subjects: an analysis of ipsilesional and contralesional limbs.

Paper 3:

Anticipatory postural adjustments of reaching while sitting: an analysis of the contralateral body side to movement execution in post-stroke subjects.

Paper 4:

Anticipatory postural adjustments of reaching while standing: an analysis of the contralateral body side to movement execution in post-stroke subjects

Finally, in Chapter 4, the overall research outcomes and main conclusions are discussed and presented.

Alongside with the research here presented, other related studies were developed (co-authored):

Ferreira, S., **Silva, C.**, Carvalho, P., Silva, A., Santos, R. (2011). Anticipatory postural adjustments in post-stroke during reaching. In R. Jorge, J. Tavares, M. Pinotti & A. Slade (Eds.) Technology and Medical Sciences. January 2011

- Silva, C.**, Correia, M.V., Vilas Boas, J.P., Santos, R. (2011). “Caracterização biomecânica do gesto de alcançar em indivíduos pós AVE”. In L. Roseiro & A. Neto (Eds.), 4º Congresso Nacional de biomecânica, pp. 599-604. Coimbra, Portugal, Sociedade Portuguesa de Biomecânica.
- Ferreira, S., **Silva, C.**, Carvalho, P., Silva, A., Santos, R. (2011). “Activation timings of the scapular stabilizers in subjects with a stroke affecting the right versus left hemispheres”. Preecedings of the 16th International WCPT Congress. Amsterdam- Holland.
- Silva, C.**, Borges, C., Salazar, A., Silva, A., Correia, M.V., Santos, R., Vilas-Boas, J.P. (2011). Post-stroke patients functional task characterization through accelerometry data for rehabilitation intervention and monitoring. 17th Portuguese Conference on Pattern Recognition. October 2011. Casa da Música. Porto.
- Borges, C., **Silva, C.**, Salazar, A., Silva, A., Correia, M.V., Santos, R., Vilas-Boas, J.P. (2012). Compensatory movement detection through inertial sensor positioning for post-stroke rehabilitation. In Proceedings of the International Conference on Bio-inspired Systems and Signal Processing (BIOSIGNALS2012). Vilamoura, Portugal. pp. 297-302. DOI: 10.5220/0003798102970302
- Salazar, A., Silva, A., **Silva, C.**, Borges, C., Correia, M.V., Santos, R., Vilas-Boas, J.P. (2012). W2M2: Wireless wearable modular monitor. In Proceedings of the International Conference on Biomedical Electronics and Devices (BIODEVICES 2012). Vilamoura, Portugal. pp.213-218. DOI: 10.5220/0003785702130218
- Pereira, S., **Silva, C.C.**, Ferreira, S., Silva, C., Oliveira, N., Santos, R., Vilas-Boas, J.P., Correia, M.V. (2013). Anticipatory postural adjustments during sitting reach movement in post-stroke subjects. Journal of Electromyography and Kinesiology (in press)

- Salazar, A.J., Silva, A.S., **Silva, C.**, Borges, C.M., Correia, M.V., Santos, R.S., Vilas-Boas, J.P. (2014). Low-cost wearable data acquisition platform for stroke rehabilitation: initial studies on accelerometry data gathering for functional task assessment. Topics in Stroke Rehabilitation (in press)
- Silva, A., Sousa, A., **Silva, C.**, Calheno, T., Tavares, J., Santos, R., Sousa, F. Antagonist coactivation in stroke vs healthy subjects – Sit-to-stand and Stand-to-Sit – submitted to an International Journal
- Silva, A., Sousa, A., **Silva, C.**, Tavares, J., Santos, R., Sousa, F. Electromyographic activity variations in stroke subjects with higher H-reflex - Sit-to-stand and Stand-to-Sit – submitted to an International Journal
- Silva, A., Sousa, A., **Silva, C.**, Tavares, J., Santos, R., Sousa, F. Coactivation in double support phase of walking – stroke vs healthy subjects – submitted to an International Journal

CHAPTER 2

METHODOLOGICAL

CONSIDERATIONS

For all research studies, carefully and thoughtful decisions regarding methodological procedures were need to be taken. Since some of these options were not fully justified in the included papers, a detailed description is presented hereby.

2.1. PARTICIPANTS

Healthy participant's selection criteria considered eligible subjects with no history of musculoskeletal pathology, neck and/or upper-limb pain, given that these conditions potentially interfere with upper-limb's function (Kamper et al., 2002; Matias et al., 2006; Michaelsen et al., 2006), and with more than 45 years old, since it was important to match as much as possible the age of the subjects included in each group. Indeed, there is enough scientific evidence to support the influence of age in postural control behavior (Gill et al., 2001; Hageman et al., 1995; Huang et al., 2013; Melzer et al., 2004). Regarding the gender, although there was the same matching concern, the sample selection constraints did not allow the desirable matching, especially in the papers three and four, where five males and two females were included in the post-stroke group against three males and five females in the healthy group. Despite this, we did not consider this fact as a major problem, since there is some evidence reporting the absence of gender-related changes in postural control outcomes (Duncan et al., 1990; Hageman et al., 1995; Maki et al., 1990; Stribley et al., 1974). Besides age, anthropometric characteristics and the lifestyle adopted were assessed. About anthropometric characteristics, no differences between groups were found in the body mass index (BMI); about the lifestyle, sedentary subjects were selected, viewed in the sense of low level of physical activity (Bennett et al., 2006) since non sedentary healthy subjects have different neuromuscular characteristics that have a direct influence on the task performance (Lattier et al., 2003). Although this statement has a more

profound impact when referring to the lower-limb's function, we chose to consider it, so as to avoid that different levels of physical activity among the healthy group could interfere with the neuromuscular outcomes.

Stroke subjects were judiciously selected, concerning the lesion territory (sub-cortical Middle Cerebral Artery (MCA) territory), not only because it is the most frequently affected vascular territory (de Niet et al., 2007; Mohr et al., 2004; Ng et al., 2007), but also because this investigation intended to selectively evaluate the impact of a lesion affecting the neuronal connection between motor cortex and reticular formation, i.e. the corticoreticular pathway, which anatomical disposal is throughout the internal capsule, thus within MCA influence (Brodal, 1981; Haines, 2002; Siegel et al., 2011). Many studies do not report a carefully selection regarding lesion territory (de Niet et al., 2007; Kamper et al., 2002; Murphy et al., 2011; Sukal et al., 2007; van Vliet et al., 2007; Wagner, Lang, et al., 2007), while others, despite selecting one specific artery, for instance, the MCA, include both cortical and sub-cortical territories (Archambault et al., 1999; Cirstea, Mitnitski, et al., 2003; Cirstea, Ptito, et al., 2003). However, brain patterns of activation are different according to the lesion location (Liepert et al., 2005; Luft et al., 2004), which justifies this careful selection, also for homogeneity purposes. Furthermore, selecting only sub-cortical strokes allowed the minimization of potential interference with impaired cortical function, such as apraxia or neglect.

Moreover, the time of evolution since the stroke episode was considered, and only subjects classified as being in a chronic period of evolution (six months or more) were selected, given that they presented a stable neurological status (Suenkeler et al., 2002).

2.2. TASK AND RELATED VARIABLES

Extensive research concerning upper-limb function through biomechanical assessment have used essentially analytical movement performance (for example arm flexion or abduction) due to the greater simplicity in developing protocols for data collecting and analysis (Dickstein et al., 2004; Garland et al., 1997; Horak et al., 1984). However, the analysis of purpose-oriented movement, frequently performed in daily living, provide an in-depth insight about upper-limb's ability to organize itself in space, allowing the study of multiple variables that in fact interfere with this segment performance in real life scenarios (Murphy et al., 2006). According to this, reaching was selected as the goal-standard movement within this investigation.

The great complexity of the reaching gesture imposes some difficulties on its characterization. Comparing to the cyclical process of human walking which is clearly divided into sub-phases, reaching is not so clearly defined due to an infinite number of available options in the selection of arm trajectories to the target (Supuk et al., 2007). Commonly, reaching is divided in two components, the transport phase, which involves the translation of the hand from a starting position to the desired location; and the grasp phase, which involves hand shaping and the manipulation of the target, according to its characteristics (Jeannerod, 1984). Furthermore, typical reaching movement involves the coordination between trunk, scapula and arm, which contributes to an adequate control of the distal segments in a given context (Champion et al., 2009; Massion et al., 1988). The role of the trunk and scapula depends largely on the target's placement. When within arm's length, they act mainly as postural stabilizers, while when beyond it, need to participate in conjunction with shoulder and elbow joint for target attainment (Kaminski, 1995). Indeed, although the roles of the trunk and scapula are well established among researchers and clinicians, the postural control demands according to movement sub-phases is not yet fully explored.

Therefore, in this thesis, a division of the reaching movement was proposed based on postural control demands (Figure 2):

- a) the first sub-phase, named as the elbow flexion phase, which includes the period since movement initiation till the maximum of elbow flexion; this phase requires a highly demanding proximal postural control; and
- b) the second sub-phase, here named as the shoulder flexion phase, starts when the elbow reaches its maximum flexion and ends when the target is reached; this phase is predominantly movement demanding, especially in the shoulder joint.

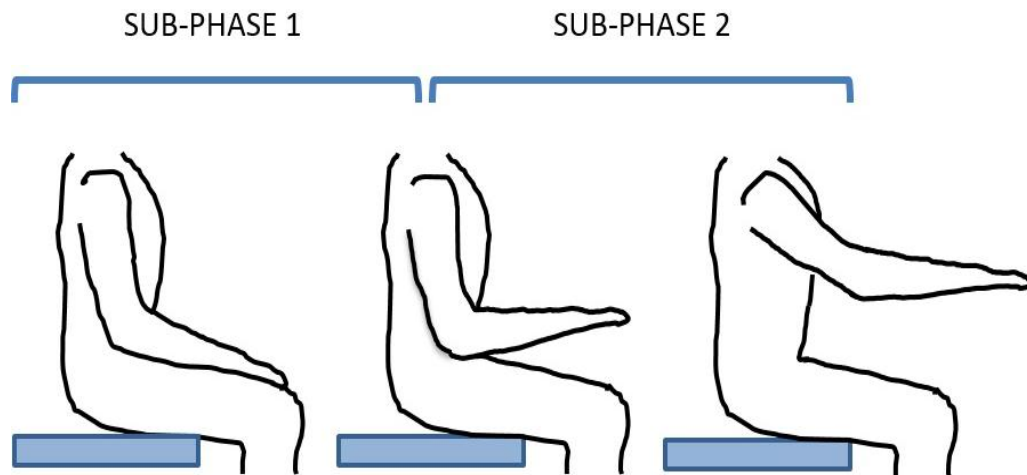


Figure 2: Proposed division of the reaching movement based on postural control demands.

Although the main point of interest was the transport phase of the gesture, the grasp component was included in the instruction in order to promote a more natural movement pattern. Moreover, it has been a concern to provide, within the experimental protocol, a functional context as close as possible to real life situations, so that the obtained data could be interpreted outside the laboratory set (Butler et al., 2010). So, a juice glass (5.5 cm of diameter) was selected as the target to be reached, with the purpose of

recreating, as much as possible, the neural circuits associated with this familiar task (Castiello, 2005; Trombly et al., 1999). However, in the third and fourth papers' experimental set up involved the use of a plastic water bottle, instead of a glass. That was due to the fact that the equipment used in these studies for kinematic data collection required the selection of a different supporting surface for the object, than the table used in papers one and two, since the table did not allowed the continuous tracking of all the reflective markers, along the entire movement. As the selected supporting surface consisted in a smaller frame, the use of a plastic object intended to create enough confidence in the subjects so they would not feel any constrain if accidentally dropped the object. Nonetheless, a plastic water bottle is still a very commonly daily living object that it is often reached. Moreover, in these studies (3 and 4), which aimed to explore APAs during reaching, the scapular plane of movement was selected, given that this position is central to most daily and occupational tasks (Faria et al., 2008). Moreover, as we intended to evaluate scapular muscles behavior, this alignment provides the best mechanical advantages for their actions (Matias et al., 2006).

No instructions were given concerning movement velocity, since we aimed to explore postural responses during routine tasks performed as naturally as possible.

As this investigation was focused on postural control function, namely the stability function associated with the trunk segment as a reference frame for the mobility of the upper-limb, target was positioned within arm's length, so that the desirable movement outcome would only need elbow and shoulder recruitment. Indeed, extensive research consistently reports that within reaching movement, the boundary for trunk recruitment lays around the distance defined by the arm's length (Kamper et al., 1999; Levin et al., 2002; Mark et al., 1997; Roby-Brami et al., 2000). Accordingly, minimal trunk displacements were expected to be observed in healthy subjects as opposed to post-stroke group, whose postural control impairment would reflect in higher

values of trunk displacement, during task performance (Cirstea et al., 2000; Michaelsen et al., 2004; Michaelsen et al., 2001).

Several studies (Levin, 1996a; Levin et al., 2002; Wagner, Lang, et al., 2007), chose the dominant limb of healthy subjects for comparison purposes with a pathological group. However, as this methodological option might have contributed to disadvantageous comparisons between groups (especially when the contralesional upper-limb of post-stroke subjects was the previous dominant limb), in an attempt to lessen this potentially disadvantage, we follow the methodology used by Dickens et al. (2004), i.e. the post-stroke contralesional limb was compared with the healthy non-dominant limb, while the ipsilesional was compared with the dominant limb (Dickstein et al., 2004).

2.3. BIOMECHANICAL PARAMETERS

For human movement analysis, whether it is referred to daily life gestures or skillful sports performance, it is fundamental to understand the interaction between the underlying neuronal and biomechanical factors. Although such understanding represents a challenge, the growing technological progress within movement analysis area has provided with new insights about motor control function, allowing and motivating continuous and further research in neurophysiological and biomechanical domains. Indeed, motion analysis is progressively becoming a commonly used tool to assess the neurophysiological and biomechanical features of human posture and movement (Bartolo et al., 2009). Unquestionable, this is a key element guiding the physiotherapist's clinical reasoning process that underlies the design of the intervention. In fact, the assessment of motor performance, which requires accurate clinical and field measurements, constitutes the basis of successfully therapeutic programs (Patel et al., 2010).

The Rivermead Motor Assessment (RMA), Fugl-Meyer Motor Assessment (FMA), Postural Assessment Scale for Stroke patient (PASS) and the Reach Performance Scale (RPS) are examples of viable and reliable

assessment tools commonly used in physiotherapy (Salazar et al., in press). These standardized clinical motor assessments rely on physiotherapists observational skills which, although valuable, remain insufficient for reliable measurement of certain quantitative features (e.g. intersegment coordination, quality and smoothness of movement). Moreover, observation-based assessments are more susceptible to observer personal bias and limited to the human visual perception sensitivity (de los Reyes-Guzman et al., 2010; Jaspers et al., 2009; Murphy et al., 2006; Salazar et al., in press). Therefore, biomechanical analysis, specifically kinematic and electromyography analysis constitute interesting tools to complement data obtained from standardized clinical scales. In fact, although biomechanical analysis of the upper-limb is still more technically challenging when compared to the lower-limb, due to the non-cyclical nature of its functional use and the greater amount of degrees of freedom to coordinate, the characterization of upper-limb's functional movement is increasing (Alt Murphy et al., 2013; Butler et al., 2010; Murgia et al., 2010; Murphy et al., 2011). Three-dimensional (3D) movement analysis, which is considered a powerful tool for quantitative assessment, constitutes an example of a more and more widespread instrument, although still limited to laboratory scenarios due to the inherent use of complex and costly equipment requiring specialized spaces and trained technicians.

Although still little explored, kinematic measures to identify and quantify postural control impairments in post-stroke subjects, when performing functional tasks with the ipsilesional upper-limb, have been used. In fact, although some research has already focused the problematic associated with deficits of the ipsilesional upper-limb deficits in post-stroke subjects (Chow et al., 2011; Kim et al., 2003; Noskin et al., 2008; Nowak et al., 2007; Sunderland et al., 1999), to our knowledge none, so far, has addressed the postural control function in the ipsilesional body side. In addition, the relationship between these deficits and ventromedial systems dysfunction has not yet been fully explored.

Lack of consensus among researchers about which kinematic variables should be preferred to assess motor performance and discriminate typical versus atypical behavior is still present (Murphy et al., 2011). However, a set of variables were proposed by Murphy et al. (2011) based on their power to discriminate healthy versus post-stroke performance, as well as different impairment levels within post-stroke subjects. These authors shown that movement time, velocity profiles, number of movement units, trunk displacement and shoulder elevation were discriminative parameters between and within groups (Alt Murphy et al., 2013; Murphy et al., 2011). Alongside with these variables, within this investigation, elbow extension was also assessed.

Surface electromyography (EMG) seems to be one of the options often considered when selecting valid and relatively easy to use tools for motor performance assessment. In fact, signals acquisition through EMG translates into a very useful information gathering method, which allows an extensive and in-depth characterization of the neuromuscular system behavior. This information, once related to movement performance, is extremely important to orientate the clinical reasoning process. During this investigation, the EMG signal was used to assess antagonist co-activation ratios of upper-limb muscles pairs (paper 2) and activation timings of scapular/upper trunk postural muscles (papers 3 and 4), so that temporal parameter of APAs could be assessed.

2.4. STUDIES SEQUENCE

Although post-stroke subjects are frequently considered as hemiplegic, i.e. with neuromotor dysfunctions in one body side, clinical observations and selective movement analysis within physiotherapy practice allowed the question if such an assumption would be correct. Instead of partial, the impairments should, perhaps, be considered as global. This hypothesis orientated the design of the experiments within this study, i.e, instead of

exclusively assessing the neuromotor behavior of the contralesional body side (most often studied among the scientific community), our aim was also to explore the ipsilesional side, reporting a global perspective. Hence, the paper 1 assessment design intended to evaluate the motor performance of the ipsilesional upper-limb, through the comparison of this limb kinematics with healthy subjects, during reaching performance. The results suggested the presence of a postural control dysfunction. After this, we raised the hypothesis that also the neuromuscular level should be dysfunctional as well. Consequently, paper 2 assessed and confirmed the deregulation of neurophysiologic mechanisms, such as the reciprocal innervation, expressed with altered co-activation levels between postural muscle pairs (antagonist co-activation ratio) associated with the ipsilesional upper-limb movement. These findings (altered movement kinematics and antagonist co-activation ratios in the ipsilesional side), although suggestive of a postural control dysfunction, needed in-depth research, specifically directed to the confirmation of this possible impairment. Moreover, the indicators of postural control dysfunction were present during the movement execution, justifying the investigation of postural control mechanisms prior to movement onset, which are a relevant feature of overall postural control system (Aruin, 2002). Therefore, the design of the paper 3, focused on the evaluation of anticipatory postural adjustments' behavior, intended to clarify this aspect. Specifically, this study goal was to explore the existence of impairments in the muscle activation timings (temporal parameter of APAs) of the scapular/upper-trunk postural muscles, of post-stroke subjects, during sitting reaching, in the contralateral side to movement execution. The results showed that APAs were dysfunctional in the ipsilesional upper-trunk, corroborating the hypothesis of a postural control dysfunction in this body side. Since postural adjustments modulation are intrinsically dependent on the postural set selected and changes in muscles response patterns according to different body configurations may occur, we intended to verify if the dysfunctional behavior found in the ipsilesional body side would still be present when the task was performed in standing. Also, we intended to assess if post-stroke subjects who exhibit, in sitting, postural adjustments

compatible with APAs in the contralesional body side, would still present them in standing position, since results about this are still highly controversial (Garland et al., 1997; Horak et al., 1984; Kusoffsky et al., 2001; Slijper et al., 2002). The results confirmed the pattern evidenced in sitting position, although no significant statistical differences were found between post-stroke and healthy subjects.

CHAPTER 3

RESEARCH STUDIES

3.1. STUDY I – KINEMATIC CHARACTERIZATION OF REACHING IN POST-STROKE SUBJECTS: AN ANALYSIS OF IPSILESIONAL AND CONTRALESIONAL LIMBS

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ABSTRACT

The goal of this study was to characterize movement kinematics in post-stroke patients, in both ipsilesional and contralesional upper-limbs, during reaching movement.

Nine healthy and nine post-stroke subjects were instructed to reach a target, placed in the sagittal and scapular planes of movement. Kinematic variables, namely movement time, hand peak velocity, trunk displacement, elbow extension, shoulder elevation, and movement units, were assessed through APAS system, for the dominant and non-dominant limbs of healthy subjects as well as for the ipsilesional and contralesional limbs of post-stroke subjects.

When compared to the dominant limb of healthy subjects, the performance of the ipsilesional limb of post-stroke subjects was associated with a significantly increased trunk displacement in the scapular plane, a longer movement time as well as more movement units in both sagittal and scapular planes. Between the contralesional limb of post-stroke subjects and the non-dominant limb of healthy subjects, statistical differences were observed in all the analyzed variables, except the shoulder elevation, in both planes of movement.

Our findings suggest that post-stroke subjects exhibit compensatory movements associated with the performance of both ipsilesional and contralesional limbs. Instead of considering this motor behavior as a result of the deficits in the contralesional side, we advance with the hypothesis that it might be mostly related to the dysfunctional ipsilaterally descending ventromedial pathways.

Keywords: stroke, reaching, kinematics, ipsilesional limb

3.1.1. INTRODUCTION

The reaching gesture constitutes the most evident example of upper-limb's ability to organize itself in space, with specific goals, always related with a motor concretization (Shumway-Cook et al., 2007a; Shumway-Cook et al., 2007b). In fact, numerous daily-living activities require the coordinated action of the upper-limb segments, in order to successfully reach the target (Bernhardt et al., 1998; de los Reyes-Guzman et al., 2010). These assumptions clearly justify the selection of this functional movement as a representative task to be studied, especially amongst post-stroke subjects. In this specific population, impaired upper-limb function is one of the most common problems found, being the recovery prognosis often poor (Langhorne et al., 2009; Shelton et al., 2001).

There is increasing evidence that the functional linkages between joints and/or muscles (synergies) involved in reaching are changed in post-stroke subjects (van Kordelaar et al., 2012). In an attempt to move, as in for reach an object, compensatory motor strategies are often observed, in a form of a pathological synergy (Michaelson et al., 2006).

Though compensatory movements might allow for the accomplishment of a given task, even in the presence of a motor deficit, some controversy remains about their functional benefits. Studies of motor recovery of post-stroke patients suggest that this maladaptive strategies may limit the plastic ability of the nervous system to enhance neuromotor recovery (Levin, 1996b; Takeuchi et al., 2012). Ultimately, skill's reacquisition and full potential for participation in daily life may be compromised (Roby-Brami et al., 2003). In addition, 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 et al., 2007; Cirstea, Ptito, et al., 2003). Some studies state that the presence of ipsilesional compensatory movement, namely at the lower-

limb, are essentially a consequence of the dysfunctional motor behavior at the contralesional side (Lamontagne et al., 2000). However, recent evidence suggests as a possible justification for the altered ipsilesional behavior, the encephalic lesion itself, due to the bilateral dysposal of the neuronal systems related to the postural control mechanism (Silva, Sousa, Pinheiro, et al., 2012; Silva, Sousa, Tavares, et al., 2012; Sousa et al., 2013). According to this, it may be hypothesized that the presence of compensatory movements associated with the ipsilesional upper-limb performance, may emerge as a consequence of postural control dysfunction. In fact, given that postural control is essentially modulated by the descending ventromedial system, which projects mostly ipsilaterally (Schepens et al., 2004; Schepens et al., 2008), a postural control dysfunction would be expressed primarily at the ipsilesional side.

While contralesional motor deficits following stroke are well documented (Bobath, 1990; Bourbonnais et al., 1989; Burke, 1988), ipsilesional deficits have been less explored among scientific community and mainly related with hand dexterity, rather than postural control (Desrosiers et al., 1996; Sunderland et al., 1999). However, considering the current neuroscientific knowledge about motor system's organization and neuronal disposal, proximal ipsilesional deficits can no longer be ignored. Nevertheless, research focusing motor behavior of ipsilesional upper-limb, concerning not only dexterity but also proximal components (i.e. trunk, shoulder and elbow) constitutes, without any doubt, a main field of study still unexplored. Biomechanics includes interesting tools for obtaining objective data in this domain (de los Reyes-Guzman et al., 2010). Therefore, the goal of this study was to characterize both ipsilesional and contralesional upper-limbs reaching movement in post-stroke patients. Our driven hypotheses was that post-stroke subjects present altered kinematic variables associated with the movement of the ipsilesional limb, besides the contralesional limb exhibiting signs of postural control deficits in both sides.

3.1.2. METHODS

Participants

Eighteen subjects, included in two distinct groups (healthy, $n=9$, mean age: 52.3 ± 4.9 , mean body mass index: 26.1 ± 1.8 ; and post-stroke, $n=9$, mean age: 55.0 ± 9.6 , mean body mass index: 27.1 ± 4.0), participated in this study. The protocol was approved by the Ethics Committee of Escola Superior de Tecnologia da Saúde do Porto (ESTSP). The investigation conforms to the principles outlined in the Declaration of Helsinki.

For general groups inclusion, subjects must be above 45 years old. Exclusion criteria comprised musculoskeletal pathology, neck and/or upper-limb pain, cerebellar, basal ganglia or brain stem lesions, and a Mini Mental State Examination score below 25.

For the post stroke group inclusion, participants must met the additional following criteria: unilateral stroke at the subcortical middle cerebral artery territory, confirmed by neuroimaging; time evolution up to 6 months and a score between 30 and 50 of the Fugl-Meyer Assessment Scale (moderately impaired) (Scheidt et al., 2007). As exclusion criteria were considered: hemispatial neglect; visual (uncorrected), perceptual or cognitive deficits and active range of motion of the contralesional shoulder and elbow joints inferior to 15° (Zackowski et al., 2004);

Post-stroke group's characterization, namely age, gender, height, weight, time post stroke and location of lesion is presented in Table 1.

3.1 Study I – Kinematic Characterization of Reaching in Post-Stroke Subjects

Table 1: Post-stroke group characterization regarding age, gender, weight, height, time post-stroke and location of lesion.

	Post-stroke group								
	A	B	C	D	E	F	G	H	I
Age/ Gender	64/M	57/M	47/F	45/M	45/F	49/M	72/M	53/F	63/M
Weight (Kg)	82	105	70	75	60	72	68	69.3	74
Height (m)	1.70	1.69	1.63	1.75	1.63	1.68	1.65	1.58	1.65
Time post- stroke (years)	1	8	1	1	4	5	2	2	8
Location of lesion	LMCA	RMCA	RMCA	LMCA	LMCA	RMCA	LMCA	RMCA	RMCA

A-I represent each subject; M – male; F – female; LMCA – left medial cerebral artery; RMCA – right medial cerebral artery

Experimental procedures

For kinematic data acquisition, four cameras (Sony Handicam DCR-HC53, Lisboa, Portugal), with a sampling frequency of 50 Hz, were placed 4 m away from the subject, two at the frontal plane and two at a 45° angle between the frontal and the sagittal planes from each shoulder (Vandenberghe et al., 2010). For each limb assessment (dominant/non-dominant of healthy and ipsilesional/contralesional of post-stroke), eight reflective markers were placed in the following landmarks: mid-sternum, acromion (bilaterally), lateral epicondyle of the humerus, ulnar styloid apophysis, third metacarpus and greater trochanter. A reflective marker was also placed at the target (glass).

Each subject was assessed in sitting position without trunk support. Seat height was adjusted to each participant's lower leg length, measured from the lateral line of the knee joint to the ground. At the initial position, 75% of the thigh length was seat supported (Michaelsen et al., 2001). Participants were barefoot. One height adjustable table was placed anteriorly, at the level of each subject's iliac crests. A juice glass (5.5 cm of diameter) was placed on it,

according to each subject's anatomical reaching distance, measured from the acromion to the thumb metacarpophalangeal joint (Reisman et al., 2006; Vandenberghe et al., 2010). Before the beginning of the task, subjects were instructed to position with the following parameters: 0° of flexion/extension/internal rotation of the shoulder; 100° of flexion of the elbow; forearm in pronation; and the palm of the hand resting on thigh.

Two reaching movements were performed, one on the sagittal plane and another considering the scapular plane (30° from the frontal plane). These planes were chosen because the functional reaching movements occur mainly in these planes. When evaluating the movement performed at the sagittal plane, the glass was positioned in front of the ipsilateral shoulder, and when evaluating the scapular plane it was placed, also ipsilaterally, at 30° from the frontal plane. Subjects were instructed, after a verbal cue, to reach and grasp the glass. Three valid repetitions were executed, with an interval of one minute each. All the verbal commands were given equatively and by the same researcher.

Data Processing

APAS Software (Ariel Performance Analysis System, Ariel Dynamics Inc., Canyon, USA), version 12.1.0.10, was used for data analysis. This software allows analyzing data captured from multiple cameras simultaneously, performing 3D biomechanical analysis automatically through the use of specific markers and DLT algorithm (Abdel-Aziz et al., 1971).

Data were digitally low-pass filtered using a second order Butterworth filter with a cutoff frequency of 7 Hz, and analyzed in terms of movement time, hand peak velocity, trunk displacement, elbow extension, shoulder elevation, and movement units. Movement onset and offset were defined as the times at which third metacarpus' tangential velocity exceed or fell below 10% of its maximal value, respectively (Cirstea et al., 2000). Trunk displacement was measured considering the displacement (in cm) of the reflective marker located on the mid-sternum in the sagittal plane. The range of angular elbow extension

during the sequence was analyzed at the time that maximal elbow flexion occurred until the movement offset. Movement units were obtained from the number of velocity peaks (velocity variations of 5% were considered) and consisted in a measure of trajectory smoothness (Konczak et al., 1997).

Statistics

Statistical Analysis was performed using IBM SPSS Statistics software v20 with a significance level of 0.05. Due to the small number of participants (n=9 per group), Mann-Whitney U test was used to compare healthy vs post-stroke groups, and Friedman ANOVA test, with Dunn's test as Post-Hoc, to compare sides and planes within each group. Median and interquartile deviation were used as descriptive statistics (Marôco, 2010).

3.1.3. RESULTS

The following results characterize the kinematic behavior of the ipsilesional limb of post-stroke subjects compared to the dominant limb of the healthy group and the contralesional limb compared to the non-dominant limb. Still, no statistical differences were observed between dominant and non-dominant limbs of healthy subjects (data not shown).

Movement time

The movement time of the ipsilesional limb was significantly longer when compared to the dominant limb of healthy subjects, in both sagittal (1.1 ± 0.5 s vs 0.9 ± 0.3 s, respectively; $p=0.006$) and scapular (1.3 ± 0.7 s vs 0.9 ± 0.2 s, respectively, $p=0.033$) planes (Figure 3A). Similarly, contralesional limb showed an increased movement time when compared with the non-dominant limb of the healthy group, in both sagittal (4.5 ± 3.9 s vs 1.0 ± 0.3 s,

respectively, $p < 0.001$) and scapular (5.8 ± 4.0 s vs 1.0 ± 0.3 s, respectively, $p = 0.001$) planes (Figure 3B).

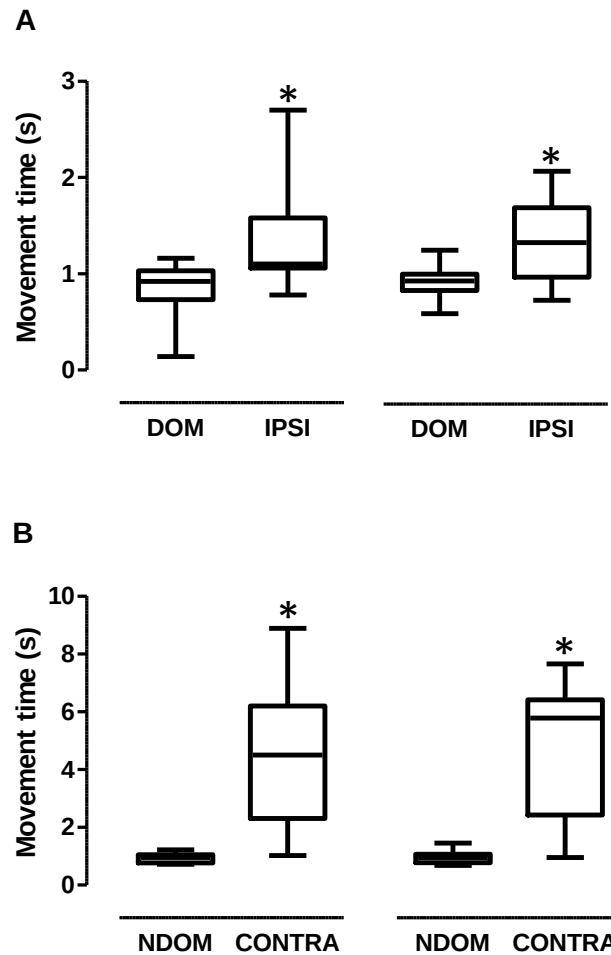


Figure 3: Movement time. The duration of the movement performed in both sagittal and scapular planes are illustrated for the dominant limb of healthy subjects (DOM) vs the ipsilesional limb of post-stroke subjects (IPSI) (A), and for the non-dominant limb of healthy subjects (NDOM) vs the contralesional limb of post-stroke subjects (CONTRA) (B). Columns plot the median and 25th and 75th percentiles; whiskers reveal the min and max values obtained. * $p < 0.05$ represent significant differences between IPSI (A) / CONTRA (B) limbs vs DOM (A) / NDOM (B) limbs, considered as their respective controls.

Peak velocity

When compared the peak velocity of the dominant limb of the healthy group, to the ipsilesional limb of post-stroke subjects, no significant differences were found, at both sagittal (134.4 ± 24.4 cms^{-1} vs 108.0 ± 22.6 cms^{-1} ,

respectively, $p=0.190$) and scapular ($142.4\pm32.6 \text{ cms}^{-1}$ vs $128.2\pm39.5 \text{ cms}^{-1}$, respectively, $p=0.666$) planes of movement (Figure 4A). In contrast, the contralesional limb showed a significantly smaller peak velocity when compared to the non-dominant limb of healthy subjects in both sagittal ($96.3\pm23.0 \text{ cms}^{-1}$ vs $137.8\pm21.2 \text{ cms}^{-1}$, respectively, $p= 0.008$) and scapular ($90.1\pm19.5 \text{ cms}^{-1}$ vs $168.8\pm17.6 \text{ cms}^{-1}$, respectively, $p= 0.001$) planes of movement (Figure 4B).

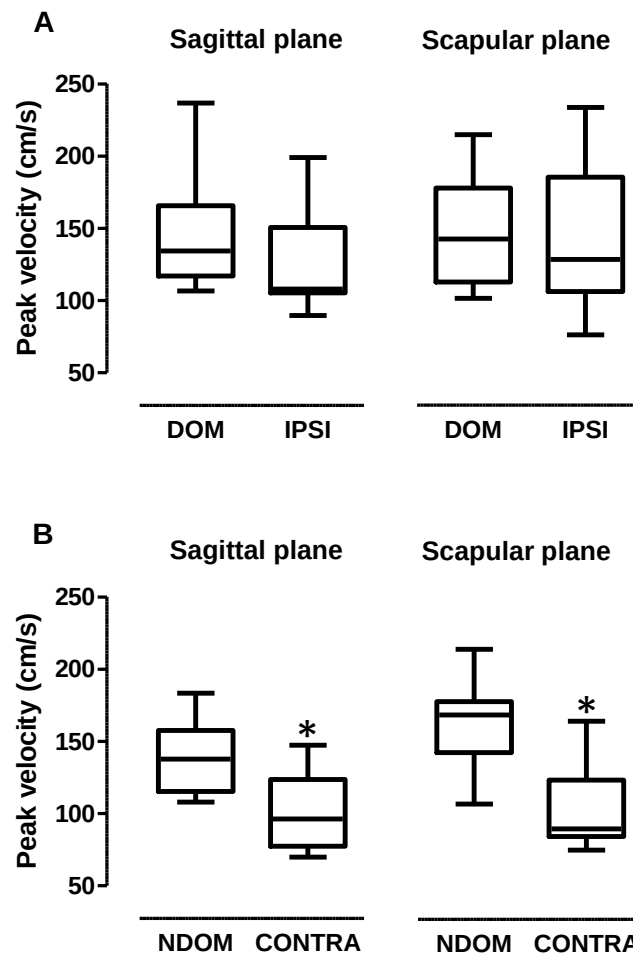


Figure 4: Peak velocity. The peak velocity in both sagittal and scapular planes are illustrated for the dominant limb of healthy subjects (DOM) vs the ipsilesional limb of post-stroke subjects (IPSI) (A), and for the non-dominant limb of healthy subjects (NDOM) vs the contralesional limb of post-stroke subjects (CONTRA) (B). Columns plot the median and 25th and 75th percentiles; whiskers reveal the min and max values obtained. * $p<0.05$ represent significant differences between IPSI (A) / CONTRA (B) limbs vs DOM (A) / NDOM (B) limbs, considered as their respective controls.

Trunk displacement

The ipsilesional limb exhibited an increased trunk displacement, when compared to the healthy group, either in the sagittal (3.6 ± 1.4 cm vs 2.3 ± 1.7 cm, respectively, $p=0.094$) and in the in the scapular plane (3.3 ± 3.2 cm vs 1.9 ± 0.9 cm, respectively, $p=0.04$) being the difference, at this plane, statistically significant (Figure 5A). Significant differences were also found, in both planes, between the contralesional and the non-dominant limbs (6.7 ± 3.2 cm vs $3. \pm 3.8$ cm, respectively, in the sagittal plane, $p= 0.004$; 6.6 ± 7.4 cm vs 1.8 ± 1.5 cm, respectively, in the scapular plane, $p= 0.001$) (Figure 5B).

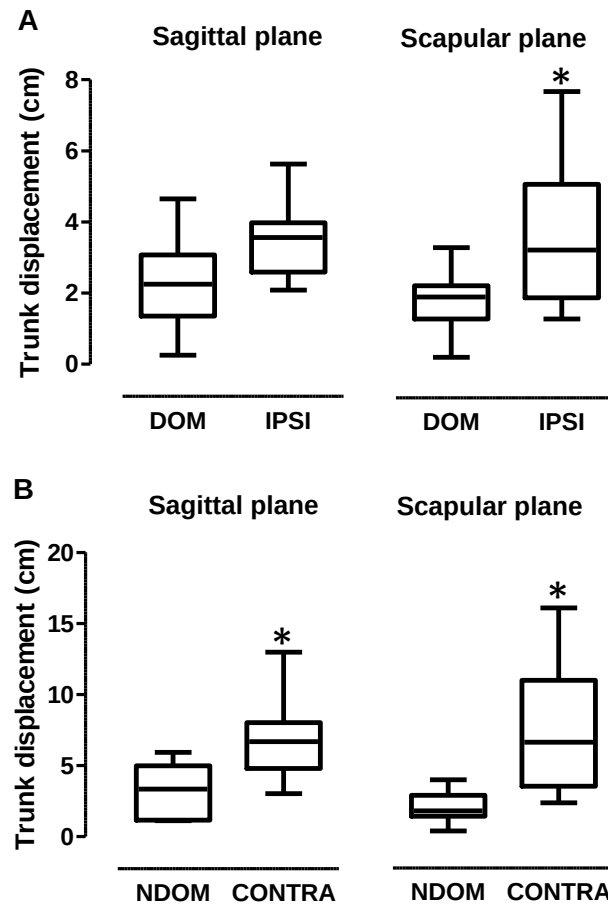


Figure 5: Trunk displacement. The trunk displacement in both sagittal and scapular planes are illustrated for the dominant limb of healthy subjects (DOM) vs the ipsilesional limb of post-stroke subjects (IPSI) (A), and for the non-dominant limb of healthy subjects (NDOM) vs the contralesional limb of post-stroke subjects (CONTRA) (B). Columns plot the median and 25th and 75th percentiles; whiskers reveal the min and max values obtained. * $p < 0.05$ represent significant differences between IPSI (A) / CONTRA (B) limbs vs DOM (A) / NDOM (B) limbs, considered as their respective controls.

Elbow extension

In the sagittal plane of movement, no differences were observed at the elbow extension, between the ipsilesional and the dominant limbs (43.5 ± 16.7 degrees vs 43.5 ± 13.4 degrees, respectively, $p=0.730$). Similarly, in the scapular plane no differences were observed between the ipsilesional limb and the dominant limb (43.0 ± 19.3 degrees vs 44.8 ± 14.1 degrees, respectively, $p=0.796$) (Figure 6A). Statistical significant differences between the contralesional and the non-dominant limbs were observed, either in the sagittal (20.1 ± 10.8 degrees vs 36.9 ± 3.5 degrees, respectively, $p=0.008$) and in the scapular (23.4 ± 30.8 degrees vs 43.3 ± 19.0 degrees, respectively, $p=0.014$) planes of movement (Figure 6B).

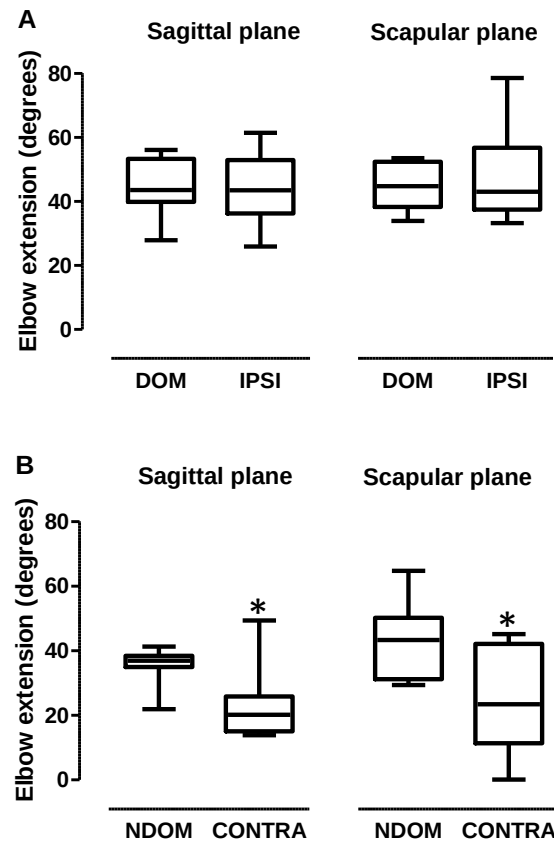


Figure 6: Elbow extension. The elbow extension in both sagittal and scapular planes are illustrated for the dominant limb of healthy subjects (DOM) vs the ipsilesional limb of post-stroke subjects (IPSI) (A), and for the non-dominant limb of healthy subjects (NDOM) vs the contralesional limb of post-stroke subjects (CONTRA) (B). Columns plot the median and 25th and 75th percentiles; whiskers reveal the min and max values obtained. * $p < 0.05$ represent significant differences between IPSI (A) /

CONTRA (B) limbs vs DOM (A) / NDOM (B) limbs, considered as their respective controls.

Shoulder elevation

Interestingly, although variability seems to increase in both ipsilesional and contralesional limbs when compared to their respective controls, dominant (1.3 ± 3.2 cm vs 0.5 ± 0.5 cm – sagittal; 1.0 ± 2.1 cm vs 1.1 ± 1.3 cm - scapular) and non-dominant (2.4 ± 2.9 cm vs 0.9 ± 1.6 cm – sagittal; 2.6 ± 2.9 cm vs 1.4 ± 1.7 cm - scapular) limbs of healthy subjects, no significant differences were detected in both sagittal ($p=0.340$; $p=0.136$, for ipsilesional vs dominant and contralesional vs non-dominant, respectively) and scapular ($p=0.730$; $p=0.222$, for ipsilesional vs dominant and contralesional vs non-dominant, respectively) planes of movement (Figure 7A and B).

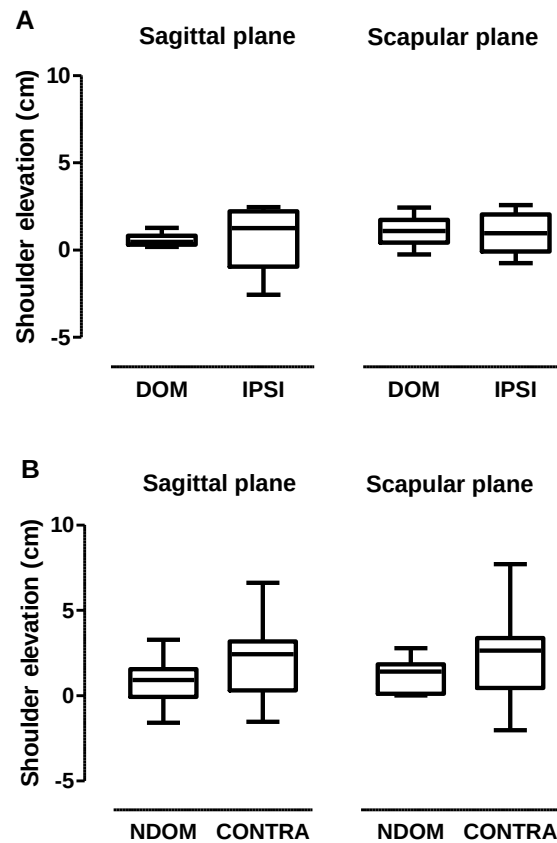


Figure 7: Shoulder elevation. The shoulder elevation in both sagittal and scapular planes are illustrated for the dominant limb of healthy subjects (DOM) vs the ipsilesional limb of post-stroke subjects (IPSI) (A), and for the non-dominant limb of healthy subjects (NDOM) vs the contralesional limb of post-stroke subjects (CONTRA) (B). Columns plot the median and 25th and 75th percentiles; whiskers reveal the min and max values obtained. $*p < 0.05$ represent significant differences between IPSI (A) / CONTRA (B) limbs vs DOM (A) / NDOM (B) limbs, considered as their respective controls.

Movement units

When compared to the dominant limb, the ipsilesional limb revealed more movement units during the gesture execution, either in the sagittal (3.0 ± 0.5 vs 2.0 ± 1.0 , respectively, $p = 0.005$) and the scapular (3.0 ± 2.0 vs 2.0 ± 1.0 , respectively, $p = 0.033$) planes of movement (Figure 8A). Similarly, the contralesional limb showed, when compared to the non-dominant limb, a pronounced increase of the movement units in both sagittal (6.0 ± 3.0 vs

2.0±1.0, respectively, $p<0.001$) and scapular (7.0±3.0 vs 2.0±0.5, respectively, $p<0.001$) planes of movement (Figure 8B).

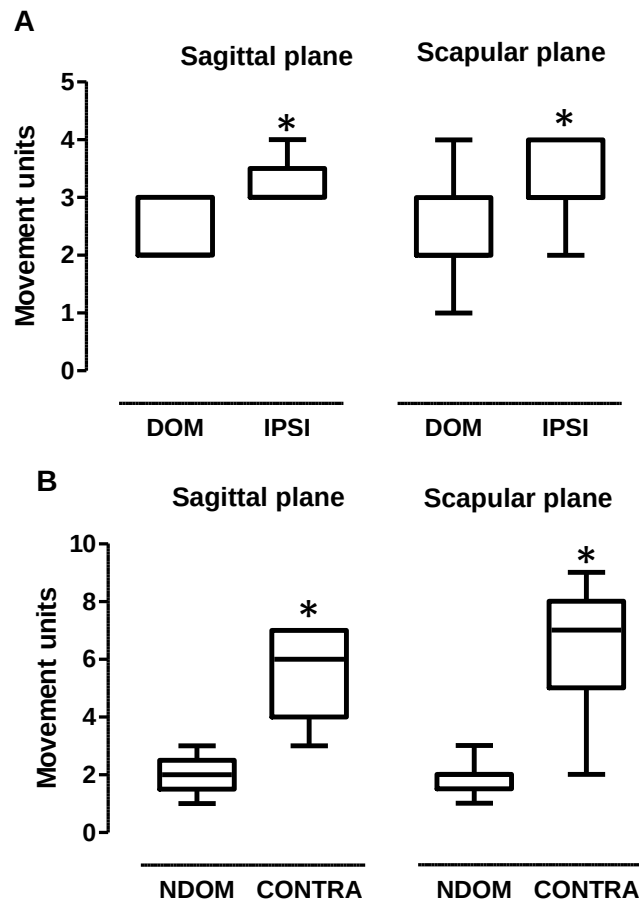


*Figure 8: Movement units. The movement units in both sagittal and scapular planes are illustrated for the dominant limb of healthy subjects (DOM) vs the ipsilesional limb of post-stroke subjects (IPSI) (A), and for the non-dominant limb of healthy subjects (NDOM) vs the contralesional limb of post-stroke subjects (CONTRA) (B). Columns plot the median and 25th and 75th percentiles; whiskers reveal the min and max values obtained. * $p<0.05$ represent significant differences between IPSI (A) / CONTRA (B) limbs vs DOM (A) / NDOM (B) limbs, considered as their respective controls.*

3.1.4. DISCUSSION

In general, when comparing the two groups' performance, results showed that, as expected, post-stroke subjects' motor performance (mostly in contralesional limb) was different from that of healthy group. In fact, similarly to

other researchers, our findings revealed that post-stroke subjects, when performing the functional reaching with the contralesional upper-limb, exhibited a significantly longer movement time (Cirstea et al., 2000); a decreased movement speed (Kamper et al., 2002); increased involvement of the trunk to reach the target (Michaelson et al., 2001; Robertson et al., 2011); decreased active range of elbow extension (Beer et al., 1999; Beer et al., 2004) and increased segmentation (characterized by the presence of multiple peaks in the tangential velocity profile, indicating that the movements were produced by repetitive accelerations and decelerations (Cirstea et al., 2000; Kamper et al., 2002).

The novelty of this study was, however, to explore the ipsilesional limb, to better understand if ipsilateral ventromedial descending pathways influence ipsilesional limb function. Interestingly, significant differences between ipsilesional limb and healthy limb were found. Movement time and movement units, in both planes, were increased when reaching was performed by the ipsilesional limb. Similarly, trunk displacement, when movement was executed at the scapular plane, was higher for the ipsilesional limb. Moreover, descriptive analysis of the remain variables evidences that the ipsilesional limb of post-stroke subjects, often named as “undamaged” limb, exhibits, in general, a poorer performance when compared to healthy subjects (considering the results regarding trunk displacement and shoulder elevation, at the sagittal plane). These findings raise the question on whether this limb may be considered, in terms of movement performance, and specifically related to the presence of compensations, a limb with no post-stroke alterations. Moreover, recent evidence showed that ipsilesional lower-limb, in unilateral post-stroke subjects, seem to be affected as well (Silva, Sousa, Pinheiro, et al., 2012; Silva, Sousa, Tavares, et al., 2012; Sousa et al., 2013). Thus, it seems reasonable to consider the possibility that compensatory movements are also present when the task is performed by the ipsilesional limb.

At this point, questions may be raised about the nature of the excessive trunk displacement exhibited by stroke subjects when performing reaching tasks. In fact, according to some researchers, this excessive trunk displacement is thought to happen as a compensation for the lack of motor functions such as elbow extension (Levin et al., 2004). However, according to motor control knowledge related to the upper-limb function, it is well established that a properly stabilized trunk and scapular muscles, i.e., proximal postural control, is a fundamental prerequisite for an appropriate performance (Massion et al., 1988; Massion, 1992; Massion, 1998). Therefore, it might be possible that the postural control system dysfunction interferes with the ipsilesional proximal stability (trunk and shoulder girdle muscles), necessary for movement execution, affecting the upper-limb performance quality. In fact, after an unilateral lesion of the sub-cortical medial cerebral artery territory, damage can occur not only in the crossed fibers responsible for movement execution in the contralesional limb, but also in the corticoreticular networks, which may have implications with the reticulo-spinal pathways, thus interfering with the neuronal flow to the ipsilesional postural muscles. Given that reticular systems output is related to gamma motoneurons activation, assuring a postural tone both in dynamic and non-dynamic conditions, like sitting, alterations related to a dysfunction at this level can be observed when a functional task is performed in this functional position.

In healthy subjects, we found no significant differences between the dominant and the non-dominant limbs. Similarly, no differences were found between planes, with the exception of the elbow extension when the movement was performed in the sagittal plane. Referring to this, and as stated by Sainburg (2002), the dominant upper-limb had probably evidenced more efficiency in recruiting the elbow muscles, explaining the higher extension range of this joint, for task achievement. Besides this referred difference at the elbow, the overall results seem to suggest that, in general, the handedness did not influence the movement performance. Contrary to these findings, several studies reported differences between dominant and non-dominant arms in controlling limb dynamics (Bagesteiro et al., 2002; Sachlikidis et al., 2007;

Sainburg et al., 2000; Sainburg, 2002). The absence of differences found in this study is possibly related with the nature of the intended task, which does not involve the need for complex manipulative hand skills.

At last, we must take into account that this study is limited by the small number of participants. Given the interquartile deviations found for some movement parameters, developing research studies with a larger sample would be desirable. Despite this, it is important to be aware that gathering a sample as homogeneous as possible within post-stroke population is clearly a challenge, being the main reason for the small number of participants in this study. On the other hand, a larger sample might not solve the large deviations, given that increased variability of movement performance is a characteristic of the post-stroke population.

3.1.5. CONCLUSION

Our findings suggest that post-stroke subjects exhibit compensatory movements in the ipsilesional limb. Instead of considering this motor behavior as merely a result of the deficits in the contralesional side, affecting ipsilesional limb performance as well, we advance with the hypothesis that it is mostly related to the neurological lesion itself, by affecting the postural control system through dysfunctional ipsilaterally descending ventromedial pathways. We are aware that this possibility has significant implications for post-stroke management. Based on these data, we believe that guidelines for neurological rehabilitation intervention must be rethought and targeted for a whole body problem solving approach. Moreover, it reinforces the need of better understanding the basis of compensatory strategies upon movement control systems.

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3.1 Study I – Kinematic Characterization of Reaching in Post-Stroke Subjects

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3.2. STUDY II – CO-ACTIVATION STUDY OF UPPER-LIMB MUSCLES DURING REACHING IN POST-STROKE SUBJECTS: AN ANALYSIS OF IPSILESIONAL AND CONTRALESIONAL LIMBS

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ABSTRACT

The purpose of this study was to analyze the change in antagonist co-activation ratio of upper-limb muscle pairs, during the reaching movement, of both ipsilesional and contralesional limbs of post-stroke subjects, comparing, respectively, to dominant and non-dominant limbs of healthy subjects. Nine healthy and nine post-stroke subjects were instructed to reach and grasp a target, placed in the sagittal and scapular planes of movement. Surface EMG was recorded from latissimus dorsi (LD), sternal head of pectoralis major (PM), anterior (AD) and posterior (PD) segments of deltoid, biceps brachii (BB), brachioradialis (BR), and triceps lateral (TRlat). Reaching movement was divided in two sub-phases, during which antagonist co-activation ratios were calculated for the muscle pairs LD/PM, PD/AD, TRlat/BB and TRlat/BR. Differences between the post-stroke's ipsilesional limb and the dominant limb of healthy subjects were found during the first sub-phase, when the movement was performed in the sagittal plane, for the muscle pair LD/PM ($p<0.05$). Similarly, statistical different co-activation ratios between the post-stroke's contralesional limb and the non-dominant limb of healthy subjects were found for the muscle pair TRlat/BB during the first sub-phase of the reaching movement, when the movement was performed in the sagittal plane ($p<0.05$), and during the second sub-phase, for the muscle pairs LD/PM ($p<0.05$), in the sagittal plane of movement, and PD/AD, in both sagittal ($p<0.05$) and scapular ($p<0.05$) planes of movement. Our findings demonstrate that, in post-stroke subjects, the ipsilesional upper-limb seems to show signs of postural control dysfunction, whereas the contralesional upper-limb seems to have signs of movement dysfunction.

Keywords: stroke; reaching; antagonist co-activation ratio; ipsilesional limb

3.2.1. INTRODUCTION

Disorders of the central nervous system often result in conditioned motor function as a consequence of atypical patterns of muscle recruitment. Besides being the leading cause of persistent neurological impairment, stroke causes seriously functional limitations, being considered a major health problem with enormous economic implications in several countries all over the world (WHO, 2011).

Currently, there are several accepted rehabilitation approaches based on different principles (Tate, 2006). We believe, however, that it is crucial that physiotherapists perform a movement analysis-based clinical reasoning for designing a subject-directed rehabilitation intervention. Therefore, it is an emerging need the understanding the mechanisms related to atypical versus typical movement patterns, so that decisions about the most appropriate rehabilitation strategies can be taken. Moreover, in order to support the clinical reasoning, motor performance assessment should rely on standard and easy applicable instruments. However, standardized clinical motor performance assessment scales are not sensitive enough to the measurement of certain quantitative features (e.g., intersegment coordination, quality and smoothness of movement), and thus not provide accurate information about motor synergies (Patel et al., 2010).

Despite the difficulty of incorporating reliable assessment instruments amongst clinical setting scenarios, surface electromyography (sEMG) seems to represent a valid and relatively easy-to-use tool for motor performance assessment. In fact, signal acquisition through sEMG allows an extensive and in-depth characterization of motor control patterns, which is extremely important to orientate the clinical reasoning process (Hughes et al., 2009; Hughes et al., 2010).

In stroke patients, the contralesional motor deficits have been extensively described (Bobath, 1990; Bourbonnais et al., 1989; Burke, 1988). However, based on the current knowledge of neuroscience about the

neurophysiology of movement organization, ipsilesional deficits should also exist, although these have been less described among the clinical and the research community (Desrosiers et al., 1996; Sunderland et al., 1999). Indeed, in a unilateral stroke, with the brain lesion located at a sub-cortical level (such as the frequently affected internal capsule), it is highly probable that the lesion interferes with the neuronal connection between the motor cortex and the reticular formation, which clearly justifies an ipsilesional postural control dysfunction (Schepens et al., 2004; Schepens et al., 2008). Considering the ventromedial system disposal, which, although bilaterally, presents a predominant ipsilateral projection, the ipsilesional deficits can no longer be ignored. Thus, research about the motor behavior of the ipsilesional upper-limb, should not only address hand's dexterity, but also proximal components (i.e. trunk, shoulder and elbow), which constitutes a still unexplored field.

Given that the major role of the ventromedial system is associated with postural control, it is expected to find signs of dysfunction in stability-related muscles. The inherent specificity of postural control study imposes some demands about the selection of the task and the respective sub-phases, as well as the muscles to be studied. For example, to study the reaching movement it becomes important to assess latissimus dorsi and pectoralis major, as opposed to those mainly related to movement execution, such as deltoid or triceps (Dickstein et al., 2004; Geuze, 2005; Zattara et al., 1988). The importance of the evaluation of postural control muscles during movement tasks is sustained by the evidence that purposeful and orientated distal movement requires the ability to recruit proximal stability (Champion et al., 2009; Shumway-Cook et al., 2007a; Yanga et al., 2002). In this sense, the reach movement can be divided in two sub-phases: a) the first sub-phase, here named as the elbow flexion phase, which includes the period since the movement beginning till the maximum elbow flexion; this phase requires a highly demanding proximal postural control; and b) the second sub-phase, here named as the shoulder flexion phase, starts when the elbow reaches its maximum flexion and ends when the target is reached; this phase is predominantly movement demanding (Figure 9).

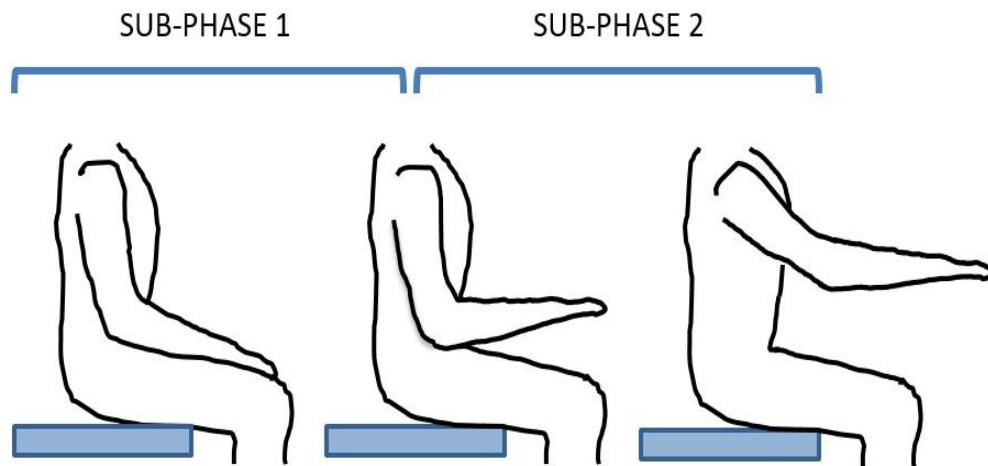


Figure 9: Proposed division of the reaching movement based on postural control demands.

As previously stated, the postural control dysfunction occurring at the ipsilesional side of stroke subjects can only be considered when lesions interfere with the corticoreticular network. At the neuromuscular level, the deregulation of neurophysiologic mechanisms, such as the reciprocal innervation, is one of the alterations that can exist, being expressed with altered co-activation levels between muscle pairs - (antagonist co-activation ratio). Indeed, the mechanism of reciprocal innervation has been highlighted as one of the altered mechanisms following stroke, mainly in the form of high levels of antagonist co-activation ratio (Hammond et al., 1988; Stoeckmann et al., 2009). Despite the large amount of research about co-activation ratios in stroke subjects (Fellows et al., 1994; Higginson et al., 2006; Lamontagne et al., 2002; Lamontagne et al., 2000; Stoeckmann et al., 2009), the study of the behavior of the muscle pairs related to postural vs movement functions has not been explored so far. The researchers developed in this area are mainly focused in an analytical study of shoulder and/or elbow muscle pairs activity, often demonstrating higher levels of co-activation ratios in the contralesional side. However, these studies did not considered the different motor control dimensions (postural control and movement), and because of that, only movement related muscles have been studied (el-Abd et al., 1993; Gowland et al., 1992; Stoeckmann et al., 2009) (Fellows et al., 1994). To the best of our

knowledge, no study has assessed the functional behavior of postural control and movement control related muscles in subjects with postural control and movement control dysfunction, like occurs in post-stroke subjects with lesions at sub-cortical level at the middle cerebral artery (Matsuyama et al., 2004; Silva, Sousa, Pinheiro, et al., 2012; Silva, Sousa, Tavares, et al., 2012; Sousa et al., 2013)

Therefore, the purpose of this study was to analyze the change in antagonist co-activation ratio of upper-limb muscles pairs of either ipsilesional and contralesional limbs of stroke subjects during the reaching movement.

3.2.2. METHODS

Participants

Eighteen subjects, included in two distinct groups (healthy, n=9, mean age: 52.3 ± 4.9 , mean body mass index: 26.1 ± 1.8 ; and post-stroke, n=9, mean age: 55.0 ± 9.6 , mean body mass index: 27.1 ± 4.0), participated in this study. The protocol was approved by the Ethics Committee of Escola Superior de Tecnologia da Saúde do Porto (ESTSP). The investigation conforms to the principles outlined in the Declaration of Helsinki.

For general group's inclusion, subjects must be above 45 years old. Exclusion criteria comprised musculoskeletal pathology, neck and/or upper-limb pain, cerebellar, basal ganglia or brain stem lesions, and a Mini Mental State Examination score below 25.

For the post stroke group inclusion, participants must meet the additional following criteria: unilateral stroke at the subcortical middle cerebral artery territory, confirmed by neuroimaging; a time evolution up to 6 months and a score between 30 and 50 of the Fugl-Meyer Assessment Scale (moderately impaired) (Scheidt et al., 2007). As exclusion criteria were considered: hemispatial neglect; visual (uncorrected), perceptual or cognitive deficits; and active range of motion of the contralesional shoulder and elbow

joints inferior to 15° (Zackowski et al., 2004).

Post-stroke group's characterization, namely age, gender, height, weight, time post stroke and location of lesion is presented in Table 2.

Table 2: Post-stroke group characterization regarding age, weight, height, time post stroke and location of lesion.

	Post-stroke group								
	A	B	C	D	E	F	G	H	I
Age/ Gender	64/M	57/M	47/F	45/M	45/F	49/M	72/M	53/F	63/M
Weight (Kg)	82	105	70	75	60	72	68	69.3	74
Height (m)	1.70	1.69	1.63	1.75	1.63	1.68	1.65	1.58	1.65
Time post- stroke (years)	1	8	1	1	4	5	2	2	8
Location of lesion	LMCA	RMCA	RMCA	LMCA	LMCA	RMCA	LMCA	RMCA	RMCA

A-I represent each subject; M – male; F – female; LMCA – left medial cerebral artery; RMCA – right medial cerebral artery

Instruments

Surface electromyography (sEMG) was recorded using two bioPLUX® (Plux, Portugal) devices with a sampling frequency of 1000 Hz, common mode rejection ratio 110 dB, input impedance greater than 100 MΩ and a 12 bits analog-to-digital signal conversion. The bipolar sensor configuration was selected and auto-adhesive pediatric electrodes were used (Correia et al., 2004; Matias et al., 2006). The sEMG signals were analyzed through the AcqKnowledge Analysis Software version 3.9 (Biopac Systems, Inc., Goleta, USA).

Skin impedance was measured using the Noraxon® Impedance Checker system (Noraxon, Scottsdale, Arizona).

For kinematic data acquisition, four cameras (Sony Handicam DCR-HC53, Lisboa Portugal), with a sampling frequency of 50 Hz were used. APAS Software (Ariel Performance Analysis System, Ariel Dynamics Inc., Canyon, USA), version 12.1.0.10, was used for data analysis. This software allows analyzing data captured from multiple cameras simultaneously, performing 3D biomechanical analysis automatically through the use of specific markers and DLT algorithm (Abdel-Aziz et al., 1971).

Experimental procedures

Each subject was assessed in sitting position without trunk support. Seat height was adjusted to each participant's lower leg length, measured from the lateral line of the knee joint to the ground. At the initial position, 75% of the thigh length was seat supported (Michaelson et al., 2001). Participants were barefoot. One height adjustable table was placed anteriorly, at the level of each subject's iliac crests. A juice glass (5.5 cm of diameter) was placed on it, according to each subject's anatomical reaching distance, measured from the acromion to the thumb metacarpophalangeal joint (Reisman et al., 2006; Vandenberghe et al., 2010). Before the beginning of the task, subjects were instructed to position with the following parameters: 0° of flexion/extension/internal rotation of the shoulder; 100° of flexion of the elbow; forearm in pronation; and the palm of the hand resting on thigh.

Two reaching movements were performed, one on the sagittal plane and another considering the scapular plane (30° from the frontal plane). These planes were chosen because the functional reaching movements occur mainly in these planes. When evaluating the movement performed at the sagittal plane, the glass was positioned in front of the ipsilateral shoulder, and when evaluating the scapular plane it was placed, also ipsilaterally, at 30° from the frontal plane. Subjects were instructed, after a verbal cue, to reach and grasp the glass. Three valid repetitions were executed, with an interval of one minute

each. All the verbal commands were given equatively and by the same researcher.

Surface EMG was recorded from seven trunk and upper-limb muscles, namely the latissimus dorsi (LD), sternal head of pectoralis major (PM), anterior (AD), and posterior (PD) segments of deltoid, biceps brachii (BB), brachioradialis (BR), and triceps brachii lateral head (TRIIlat).

Prior to data collection, the skin was shaved and wiped down with alcohol, after which skin impedance was measured and confirmed less than 5k Ω . Disposable pediatric Ag/AgCl electrodes, with a skin contact surface of 10 mm², and inter-electrode distance of 20 mm, were placed parallel to the muscle fibers and according with SENIAM references, Table 3 (Hermens et al., 2000). Electrode placement was confirmed by voluntary muscle contraction. Ground electrodes were placed over both olecraneums (Correia et al., 2004; Hermens et al., 2000).

Table 3: Anatomical references used to locate the electrodes. Electrode locations were confirmed by palpation of the muscular belly with the subject in the test position.

Muscle	Electrode Placement
LD	One centimetre laterally to the lateral edge of the scapula
PM	Two fingers below the collarbone and at two fingers from the sternum
AD	One finger width distal and anterior to the acromion, in the direction of the line between the acromion and the thumb
PD	Two finger width behind the angle of the acromion, in the direction of the line between the acromion and the little finger
BB	On the line between the medial acromion and the fossa cubit at 1/3 from the fossa cubit
BR	Most prominent bulge of the muscle
TRIIlat	At 50 % on the line between the posterior crista of the acromion and the olecranon at 2 finger widths lateral to the line.
Ground Electrode	Both olecraneums

In the present study, kinematic analysis was only used to assess movement onset and offset, as well as to assess maximum elbow flexion. The selected acquisition setup involved the placement of the cameras at a 4 m distance from the subject, two in the frontal plane and two at a 45° between the frontal and the sagittal planes from each shoulder (Vandenberghe et al., 2010).

The EMG and kinematic data were synchronized by a simultaneous trigger input signal (LED).

Data processing

Kinematic data was digitally low-pass filtered using a second order Butterworth filter with a cutoff frequency of 7 Hz, and analyzed in terms of hand peak velocity and maximum elbow flexion. Movement onset and offset were defined as the times at which third metacarpus' tangential velocity exceeded or fell below 10% of its maximal value, respectively (Cirstea et al., 2000). Maximum elbow flexion was defined as the lowest angle between the arm and forearm segments.

The EMG data was offline processed with AcqKnowledge 3.9.0 software (Biopac Systems, Inc., California, USA). Signals were band-pass filtered at 20-500 Hz, amplified and root-mean-square (RMS) processed for consecutive segments of 100 ms. Muscular onset was determined as the time when the EMG activity exceeded the baseline for three standard deviations, for a minimum period of 50 ms (Hodges et al., 1996).

The reach movement was divided into two sub-phases, using the kinematic data. The first sub-phase was defined as the interval between movement onset until maximum elbow flexion, in this sub-phase muscles of shoulder girdle act to maintain postural stability, while muscles of the elbow joint act to produce movement of the distal segments. The second sub-phase corresponds to the interval between maximum elbow flexion until movement offset, where shoulder girdle and elbow muscles act to produce upper-limb

forward displacement. In each sub-phase, the antagonist co-activation ratios of the muscle pairs (LD/PM, PD/AD, TRlat/BB, TRlat/BR) were evaluated. The antagonist co-activation ratio was calculated according to (Kellis et al., 2003):

$$C(\%) = \frac{\text{antagonist activity}}{\text{agonist} + \text{antagonist activity}} \times 100$$

This approach provides an estimate of the relative activation of the pair of muscles, as well as the magnitude of the co-activation.

Considering that differences in upper-limb motor patterns have been demonstrated between dominant and non-dominant limbs, and that post-stroke subjects tend to use the ipsilesional limb as dominant limb, the values obtained in ipsilesional limb were compared to those obtained in dominant limb while the values obtained in the contralesional limb were compared to those obtained in non-dominant limb (Sainburg et al., 2000; Sainburg et al., 2004; Sainburg, 2002).

Statistics

Statistical Analysis was performed using IBM SPSS Statistics software v20 with a significance level of 0.05. Due to the small number of participants (n=9 per group), Mann-Whitney U test was used to compare healthy vs post-stroke groups, and Friedman ANOVA test, with Dunn's test as Post-Hoc, to compare sides and planes within each group. Median and interquartile deviation were used as descriptive statistics (Marôco, 2010).

3.2.3. RESULTS

The following results characterize the antagonist co-activation ratios of the muscle pairs LD/PM; AD/PD; TRlat/BB and TRlat/BR of the ipsilesional limb of post-stroke subjects compared to the dominant limb of the healthy group and the contralesional limb compared to the non-dominant limb. Still, no statistical differences were observed between dominant and non-dominant limbs of healthy subjects (data not shown).

Antagonist co-activation ratios in the ipsilesional limb of post-stroke subjects in the first sub-phase of the reaching movement

In the first sub-phase of the reaching movement, the antagonist co-activation ratio of the muscle pair LD/PM was significantly different between the post-stroke's ipsilesional and the dominant limb of healthy subjects, when the movement was performed on the sagittal plane ($p=0.04$). Conversely, on the scapular plane of movement no statistical differences ($p>0.05$) were observed. The antagonist co-activation ratios of the other muscle pairs (PD/AD, TRlat/BB and TRlat/BR) did not evidenced a statistical different ($p>0.05$) behavior between both groups (Table 4).

Antagonist co-activation ratios in the contralesional limb of post-stroke subjects in the first sub-phase of the reaching movement

In the first sub-phase of the reaching movement, the contralesional limb showed a significant increase of the antagonist co-activation ratio of the muscle pair TRlat/BB when the movement was performed on the sagittal plane ($p=0.02$). Conversely, no significant differences ($p>0.05$) of the antagonist co-activation of the muscle pairs LD/PM, PD/AD and TRlat/BR were detected between the contralesional limb of post-stroke subjects and the non-

dominant limb of healthy subjects for both sagittal and scapular planes (Table 4).

Table 4: Antagonist co-activation ratios in the first sub-phase of reach movement. Median values and interquartile range of the co-activation ratio in both sagittal and scapular planes are presented for the dominant limb of healthy subjects vs the ipsilesional limb of post-stroke subjects and the non-dominant limb of healthy subjects vs the contralesional limb of post-stroke subjects, for LD/PM , PD/AD, TRIlat/BB and TRIlat/BR muscle pairs.

		Median (Interquartil Range)			Median (Interquartil Range)		
		Healthy dominant limb	Ipsilesional limb	p-value	Healthy non- dominant limb	Contralesional limb	p-value
Sagittal plane	Muscle pairs						
	LD/PM	57.7(±11.4)	46.0(±8.6)	0.04	46.1(±9.7)	54.1(±8.2)	NS
	PD/AD	21.0(±9.7)	23.7(±7.5)	NS	20.7(±11.7)	39.8(±16.2)	NS
	TRIlat/BB	41.8(±12.0)	42.4(±14.3)	NS	30.6(±6.48)	46.4(±11.2)	0.02
	TRIlat/BR	35.0(±7.6)	26.5(±14.1)	NS	34.9(±21.9)	54.0(±20.1)	NS
Scapular plane	Muscle pairs						
	LD/PM	56.7(±8.0)	56.7(±11.6)	NS	54.3(±10.3)	59.0(±4.6)	NS
	PD/AD	41.0(±11.9)	36.3(±18.9)	NS	31.8(±21.4)	35.1(±18.5)	NS
	TRIlat/BB	47.0(±12.3)	42.3(±12.3)	NS	40.8(±8.3)	46.0(±4.4)	NS
	TRIlat/BR	32.9(±10.7)	27.9(±13.0)	NS	34.7(±18.8)	55.5(±20.4)	NS

Antagonist co-activation ratios in the ipsilesional limb of post-stroke subjects in the second sub-phase of the reaching movement

In the second sub-phase of the reaching movement, no significant differences ($p>0.05$) were observed between the ipsilesional limb of post-stroke subjects and the dominant limb of the healthy group in all of the studied muscle pairs, namely LD/PM, PD/AD, TRIlat/BB and TRIlat/BR (Table 5).

Antagonist co-activation ratios in the contralesional limb of post-stroke subjects in the second sub-phase of the reach movement

In the second sub-phase of the reaching movement, differences between the contralesional limb of post-stroke and non-dominant limb of healthy subjects were observed in the antagonist co-activation ratios of the muscle pairs LD/PM ($p=0.019$), in the sagittal plane of movement, and of the PD/AD pair, in both sagittal ($p=0.008$) and scapular ($p=0.04$) planes of movement. The other analyzed muscle pairs, TRlat/BB and TRlat/BR showed no statistical differences ($p>0.05$) (Table 5).

Table 5: Antagonist co-activation ratios in the second sub-phase of reach movement. Median values and interquartile range of the co-activation ratio in both sagittal and scapular planes are presented for the dominant limb of healthy subjects vs the ipsilesional limb of post-stroke subjects and the non-dominant limb of healthy subjects vs the contralesional limb of post-stroke subjects, for LD/PM , PD/AD, TRlat/BB and TRlat/BR muscle pairs.

		Median (Interquartil Range)			Median (Interquartil Range)			
		Healthy dominant limb	Ipsilesional limb	p-value	Healthy non- dominant limb	Contralesional limb	p-value	
Sagittal plane	Muscle pairs	LD/PM	45.5(±14.4)	45.3(±10.8)	NS	42.6(±9.0)	56.6(±10.7)	0.019
		PD/AD	7.2(±3.6)	11.0(±4.0)	NS	8.2(±2.0)	30.6(±8.8)	0.008
		TRlat/BB	51.9(±10.2)	46.2(±14.9)	NS	59.9(±7.6)	53.2(±14.8)	NS
		TRlat/BR	45.0 (±7.7)	58.9(±14.8)	NS	58.2(±13.0)	46.2(±17.2)	NS
Scapular plane	Muscle pairs	LD/PM	55.2(±9.0)	53.9(±9.7)	NS	53.6(±6.1)	58.9(±8.1)	NS
		PD/AD	12.6(±4.5)	14.7(±4.2)	NS	13.9(±5.7)	26.6(±7.5)	0.04
		TRlat/BB	57.3(±15.9)	43.6(±17.6)	NS	59.7(±7.2)	48.5(±10.6)	NS
		TRlat/BR	55.2(±14.5)	60.6(±11.5)	NS	60.3(±13.4)	50.6(±16.9)	NS

3.2.4. DISCUSSION

Antagonist co-activation ratio in the ipsilesional limb of post-stroke subjects

In this study we demonstrated that the ipsilesional limb of post-stroke subjects shows an altered antagonist co-activation ratio of the LD/PM muscle pair in the first sub-phase of the reaching movement, when performed in the sagittal plane. Moreover, no significant differences were observed between the ipsilesional limb of post-stroke subjects and the dominant limb of healthy subjects in the second sub-phase of the movement, in both sagittal and scapular planes. These findings are in agreement with our postulated hypothesis, i.e., that the ipsilesional limb of post-stroke subjects presents a motor dysfunction of postural muscles. Given that the first sub-phase of the reaching task imposes a higher demand of the proximal postural control, in relation to the second sub-phase that imposes higher demands in terms of proximal mobility, the different behavior between the ipsilesional side of stroke subjects and healthy subjects may be explained by the dysfunctional neuronal systems that present mostly an ipsilateral disposal/projection. Moreover, the fact that stroke subjects evidenced sub-cortical lesions compatible with alterations of the cortical-reticular circuits reinforces this possibility. Concerning the upper-limb analysis, little or no evidence corroborant with these findings was found. On the other hand, regarding the lower-limb, atypical antagonist co-activation ratios in the ipsilesional limb were already reported, but causes were attributed to a compensatory mechanism, rather than resulting from the lesion itself (Lamontagne et al., 2000). Recently, an altered antagonist co-activation ratio was found in the ipsilesional lower-limbs of stroke subjects, an effect that was attributed to a possible dysfunction of ipsilaterally-descending pathways (Silva, Sousa, Tavares, et al., 2012; Sousa et al., 2013)

The fact that, when the reaching movement was performed in the scapular plane, the antagonist co-activation ratio of the ipsilesional limb evidenced a similar behavior when compared to the healthy subjects, might be

explained by the influence of scapula's alignment in the mechanical efficiency of proximal postural control for reaching. As stated by Kibler (1998), in this particular alignment there is an enhanced biomechanical relation between the scapula and the thoracic wall, which contributes to improve postural control function and, thus, imposes less challenge to LD/PM muscle pair. This perspective about the supremacy of the scapular plane of movement for stability muscular recruitment is also hypothesized by Matias et al. (Kibler, 1998; Matias et al., 2006).

Considering that: 1) the second sub-phase of the reaching movement is more mobility-demanding rather than stability-demanding; 2) the fact that the differences between the ipsilesional limb stroke subjects and the dominant limb of healthy subjects in the behavior of the LD/PM muscle pair were no longer observed in the second sub-phase of the movement; and 3) that the muscle pairs whose major role is mobility did not show significant differences between the ipsilesional limb of stroke subjects when compared to the dominant limb of healthy subjects; strengthen the idea that the ipsilesional limb presents postural control deficits.

Antagonist co-activation ratio in the contralesional limb of post-stroke subjects

Concerning the analysis of antagonist co-activation ratios at the contralesional side, our results are in agreement with the widespread scientific evidence that stroke subjects exhibit atypical co-activation levels between muscle pairs, when compared to healthy subjects (Higginson et al., 2006; Lamontagne et al., 2002; Lamontagne et al., 2000). However, it is important to explore this overall tendency to higher co-activation levels, relating the role of the muscle pairs according to the movement sub-phase. So, at the first sub-phase of the movement, statistical differences between groups were only observed in the muscle pair TRlat/BB, which is considered to be the mobility pair for the elbow joint. Indeed, at this sub-phase, the elbow flexion demands the co-activation of these muscles (flexors/extensors), which is, in these participants, altered. This finding may be explained by the lesion at the

corticospinal system, which influences the activity of agonist muscles mainly related with voluntary movement. Since impairment of this system is associated to lower muscle activation capacity during movement tasks, the increased antagonist co-activation ratio can be sustained by this influence.

When analyzing the second sub-phase, and according with the above stated, it is important to understand that, since at this sub-phase, the shoulder is the joint which contributes the most to provide the upper-limb displacement towards the goal, the muscles at this joint need to be considered mainly mobility orientated. So, statistical differences were only observed in the muscle pairs LD/PM (at the sagittal plane) and PD/AD (at both planes). It is important to highlight that although proximal muscles frequently assume a stability role, the reaching gesture incorporates continuous shifts in their roles, according to the upper-limb's segment presenting higher mobility.

Limitations

Despite, like other authors (Lamontagne et al., 2000), we opted to use absolute EMG levels, this methodological decision has as drawback the fact that, as we did not measure the thickness of the subcutaneous fat layer, we cannot guarantee that this variable did not influenced the co-activation levels obtained. Nevertheless the EMG normalization in post-stroke subjects can be questionable given the abnormal EMG pattern frequently exhibited by these subjects. As a consequence, the EMG normalization in post-stroke subjects can lead to distortion of co-activation values and to higher variability (Yang et al., 1984).

Clinical implications

These results should be taken into account in the rehabilitation field, i.e., clinicians should be aware to the fact that the ipsilesional side of stroke subjects may also present a motor control dysfunction. For this reason ipsilesional side of stroke subjects should not be overlooked and involved in the rehabilitation strategy.

On the other hand, the possible adverse influence of the atypical behavior found in the ipsilesional side (regarding postural control function) over the contralesional side has not yet been fully explored. The pertinence of such (to be addressed in future research) is based on the knowledge that the type II fibers present bilateral connections, justifying thus, the possible interdependence between both sides of the stroke subjects (Jankowska et al., 2005).

3.2.5. CONCLUSION

Our findings demonstrate that, in post-stroke subjects, the ipsilesional upper-limb might show signs of postural control dysfunction, whereas the contralesional upper-limb might have signs of movement dysfunction.

Although further research is still needed, the global motor dysfunction after an unilateral brain lesion has been gaining evidence.

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3.3. STUDY III – ANTICIPATORY POSTURAL ADJUSTMENTS OF REACHING WHILE SITTING: AN ANALYSIS OF THE CONTRALATERAL BODY SIDE TO MOVEMENT EXECUTION IN POST-STROKE SUBJECTS

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ABSTRACT

A delay in anticipatory postural adjustments (APAs) ipsilaterally to movement execution seems to occur in post-stroke subjects. However, there is strong evidence suggesting that postural control pathways descend contralaterally to movement execution, i.e., ipsilaterally to the planning cortical areas. Therefore, the goal of this study was to investigate the activation timings (the temporal parameter of anticipatory postural adjustments (APAs)) of scapular/upper-trunk postural muscles, during reaching of the contralateral upper-limb. Eight healthy and seven post-stroke subjects were instructed to reach a target independently with both limbs. Surface EMG was recorded from the upper trapezius (UP), the inferior trapezius (IT) and the latissimus dorsi (LD) muscles. When reaching was performed with the ipsilesional upper-limb of post-stroke subjects and with the dominant upper-limb of healthy subjects, UT, IT and LD muscles showed no statistical different activation timings ($p = 0.520$, $p = 0.776$ and $p = 0.661$, respectively). When the reaching movement was performed with the contralesional and with the non-dominant upper-limbs, the post-stroke group showed a significant delay in the activation timing of the IT and LD muscles, when compared to the healthy group ($p = 0.017$ and $p = 0.031$, respectively); the UT showed no significant differences ($p = 0.500$). These results suggest that when movement is performed with the contralesional upper-limb of post-stroke subjects, a delay in the activation timing of contralateral IT and LD muscles seems to occur, showing that APAs are dysfunctional in the ipsilesional upper-trunk. When movement is performed with the ipsilesional upper-limb, the contralateral UT, IT and LD muscles seem to activate appropriately.

Keywords: Anticipatory postural adjustments, ipsilesional body side, scapular/upper-trunk postural muscles, reaching.

3.3.1. INTRODUCTION

Movement and postural control are two fundamental and interconnected aspects of motor control (Massion et al., 1988), whose proper coordination allows smooth and goal-directed movement, with few perturbations constraints (Guigon, 2010). During a voluntary complex multijoint task, such as reaching, the ability to maintain a reference frame of external- and internal-guided disturbances is one of the crucial aspects that contribute to the skillfully motor action (Massion, 1992; Massion, 1998). Considering that voluntary movements can be overviewed as self-inflicted postural disturbances (Aruin, 2002), the resultant skillful output has to rely on the ability of central nervous system (CNS) to predict those perturbations and minimize them with anticipatory postural adjustments (APAs).

APAs can be divided into preparatory (pAPA, occurring prior to movement) and accompanying (aAPA, occurring during the movement) postural adjustments. Both responses are considered anticipatory in nature because they are based in a feedforward fine-tuned modulation rather than by feedback mechanisms (Aruin, 2002; Schepens et al., 2004). Though consensus about the timing of anticipatory postural activity is still lacking (Bertuccio et al., 2013; Lee et al., 2013; Santos et al., 2010), it has been described that APAs should occur at least between 150 ms prior to movement onset until 50 ms after its initiation (Aruin et al., 1996; Aruin et al., 1995; Bouisset et al., 1987; Massion, 1992).

Although movement execution, such as reaching, strongly involves cortical areas, the neural circuitries that convey the needed postural control (stability) for the movement (mobility) involve the pontomedullary reticular formation, which main goal is the preparation of postural adjustments (Lalonde et al., 2007; Schepens et al., 2004; Schepens et al., 2008). Electrophysiological and anatomical studies have shown that neurons of the pontomedullary reticular formation, acting in the axial and proximal muscles, descend through the reticulospinal system, influencing muscle's activity bilaterally (Rothwell, 2012; Schepens et al., 2004; Schepens et al., 2008).

Interestingly, during the upper-limb function, pontomedullary reticular formation seems to predominantly influence the contralateral side of movement execution, i.e., ipsilaterally to the motor cortical areas that planned the movement (Matsuyama et al., 2004). This knowledge is of great importance, particularly when movement reorganization is intended after neurological disorders. Despite some evidence demonstrating that post-stroke subjects exhibit deficits in postural control, most frequently due to the delay and/or abolishment of APAs in the contralesional side, most studies have been focused on the analysis of lower trunk and/or leg postural muscles behavior during movement performed with the ipsilesional upper-limb (Garland et al., 1997; Horak et al., 1984; Slijper et al., 2002). However, given that pontomedullary reticular formation projects bilaterally, one should expect that postural control dysfunction might occur in the ipsilesional side as well. Furthermore, an appropriate postural control of the contralateral hemitrunk seems to be necessary for an efficient movement of the contralateral limb (Schepens et al., 2006). Though one study has been focused on bilateral APAs during reaching of both upper-limbs, it did not consider the performance of the task, i.e., the movement onset was given by muscle activation (Dickstein et al., 2004), which can be affected in post-stroke subjects, thereby allowing for misunderstandings. Therefore, we aimed at investigating the activation timings (temporal parameter of APAs) of scapular/upper-trunk postural muscles, during reaching in the contralateral side to movement execution.

3.3.2. METHODS

Participants

Fifteen subjects, included in two distinct groups (healthy, $n=8$, mean age of 52.3 ± 6.2 years, and mean body mass index of $29.7 \pm 3.6 \text{ Kg/m}^2$; and post-stroke, $n=7$, mean age of 59.3 ± 6.2 years, and mean body mass index of $25.5 \pm 2.7 \text{ Kg/m}^2$), participated in this study. This investigation was approved by the

Ethics Committee of Escola Superior de Tecnologia da Saúde do Porto (ESTSP) and conforms the principles outlined in the Declaration of Helsinki.

In both groups were only included subjects over 45 years old. Exclusion criteria comprised musculoskeletal pathology, neck and/or upper-limb pain, cerebellar, basal ganglia or brain stem lesions, and a Mini Mental State Examination score below 25. For the post-stroke group's inclusion, participants followed the additional criteria: an unilateral stroke in the subcortical middle cerebral artery territory, confirmed by neuroimaging; an evolution time over 6 months; and a score between 30 and 50 of the Fugl-Meyer Assessment Scale (moderately impaired) (Scheidt et al., 2007). As exclusion criteria to the post-stroke group were considered: hemispatial neglect; visual (uncorrected), perceptual or cognitive deficits; and active range of motion of the contralesional shoulder and elbow joints inferior to 15° (Zackowski et al., 2004). The post-stroke group is briefly characterized in Table 6.

Table 6: Characterization of the post-stroke group regarding age, gender, weight, height, post-stroke time evolution and affected artery

	Post-stroke group						
	A	B	C	D	E	F	G
Age/ Gender	50/F	54/F	63/M	62/M	59/F	69/M	58/M
Weight (Kg)	71	80	105	82	72	80	85
Height (m)	1.57	1.58	1.69	1.70	1.65	1.71	1.73
Time evolution (years)	3	4	10	2	2	1	4
Affected artery	RMCA	LMCA	RMCA	LMCA	RMCA	RMCA	RMCA

A-I represent each subject; M – male; F – female; LMCA – left medial cerebral artery; RMCA – right medial cerebral artery

Instruments

Surface electromyography (sEMG) was recorded using two bioPLUX® (Plux, Portugal) devices with a sampling frequency of 1000 Hz, common mode rejection ratio 110 dB, input impedance greater than 100 MΩ and analog channels with 12 bits. The bipolar sensor configuration was selected and auto-adhesive pediatric electrodes were used (Correia et al., 2004; Matias et al., 2006). The sEMG signals were analyzed through the AcqKnowledge Analysis Software version 3.9 (Biopac Systems, Inc., Goleta, USA).

Skin impedance was measured using the Noraxon® Impedance Checker system (Noraxon, Scottsdale, Arizona).

For kinematic data acquisition, a four cameras Qualisys Motion Capture System (sampling frequency of 100 Hz) was used. Qualisys Track Manager (QTM) Software (Qualisys, Sweden) was used for data analysis. QTM kinematic analysis was synchronized with the sEMG.

Experimental procedures

Each subject was assessed in sitting without trunk support. Seat height was adjusted to each participant's lower-limb length, measured from the knee joint to the ground. In the initial position, 75% of the thigh length was seat supported (Michaelsen et al., 2001). Participants were barefoot. Subjects were instructed, after a verbal cue, to reach and grasp a 0.5 L plastic water bottle, which was placed in the scapular plane, at mid-sternum height, according to the anatomical reaching distance of the hand, using the measured distance from the acromion to the metacarpophalangeal joint of the thumb (Reisman et al., 2006; Vandenberghe et al., 2010). Subjects started the task with approximately 0° of flexion/extension/internal rotation at the shoulder, approximately 100° of flexion at the elbow with forearm in pronation, and the palm of the hand resting on thigh. Three valid repetitions of the task were recorded, separated by one minute rest period. All the verbal commands were given equitatively and by the same researcher.

Surface EMG was recorded from the upper trapezius (UP), inferior trapezius (IT) and latissimus dorsi (LD), bilaterally. Prior to data collection, the skin was shaved and wiped down with alcohol, after what skin impedance was measured and confirmed less than 5 k Ω . Disposable pediatric Ag/AgCl electrodes with a skin contact surface of 10 mm² and inter-electrode distance of 20 mm were placed parallel to the muscle fibers and according to SENIAM references (Hermens et al., 2000). Electrode placement was confirmed by voluntary muscle contraction. Ground electrodes were placed over the olecraneums (Correia et al., 2004; Hermens et al., 2000). For each limb's assessment, five reflective markers were placed in the following landmarks: mid-sternum, acromion (bilaterally), lateral epicondyle of the humerus and ulnar styloid apophysis. A reflective marker was also placed in the target.

Data processing

Kinematic data was digitally low-pass filtered using a second order Butterworth filter with a cutoff frequency of 6 Hz, and analyzed in terms of hand's peak velocity (through ulnar marker), allowing the extraction of the movement onset, that was visually determined and posteriorly confirmed through the analysis of the velocity curve and extracted numeric data.

The EMG data was processed offline with AcqKnowledge 3.9.0 software (Biopac Systems, Inc., California, USA). Signals were band-pass filtered at 20-500 Hz, amplified and root-mean-square (RMS) processed for consecutive segments of 100 ms. Muscular onset was determined as the time when the EMG activity exceeded the mean baseline activity (measure 500 ms to 450 ms before the event) for two standard deviations, for a minimum period of 50 ms (Hodges et al., 1996); for each subject it was considered the average value obtained by the difference between the time of the EMG onset of the UT, IT and LD and the movement onset of the three performed trials.

Statistics

Statistical analysis was conducted using IBM SPSS Statistics software v20 with a significance level of 0.05. Given that variables followed a normal distribution (Shapiro-Wilk test), t-test was used to compare post-stroke to healthy subjects. Mean and S.E.M. were used as descriptive statistics.

3.3.3. RESULTS

The following results show the activation timings of the contralateral scapular/upper-trunk postural muscles (upper trapezius, inferior trapezius and latissimus dorsi), during reaching movement performed with the ipsilesional limb of post-stroke subjects compared to the dominant limb of healthy subjects (Figure 10) and with the contralesional limb of post-stroke subjects compared to the non-dominant limb of healthy subjects (Figure 11). Still, no statistical differences were observed between dominant and non-dominant limbs of healthy subjects (data not shown).

Activation timing of contralateral trunk muscles during reaching movement performed with the ipsilesional limb of post-stroke subjects vs dominant limb of healthy subjects

The activation timings of UT (7.5 ± 85.7 ms vs 68.3 ± 42.7 ms, Figure 10A), IT (-7.8 ± 71.8 ms vs 14.1 ± 32.5 ms, Figure 10B) and LD (-57.1 ± 97.6 ms vs -15.2 ± 20.4 ms, Figure 10C) muscles in post-stroke and healthy subjects, respectively, showed no statistical differences ($p = 0.520$ for UT, $p = 0.776$ for IT, and $p = 0.661$ for LD) when the reaching movement was performed with the ipsilesional and the dominant upper-limbs.

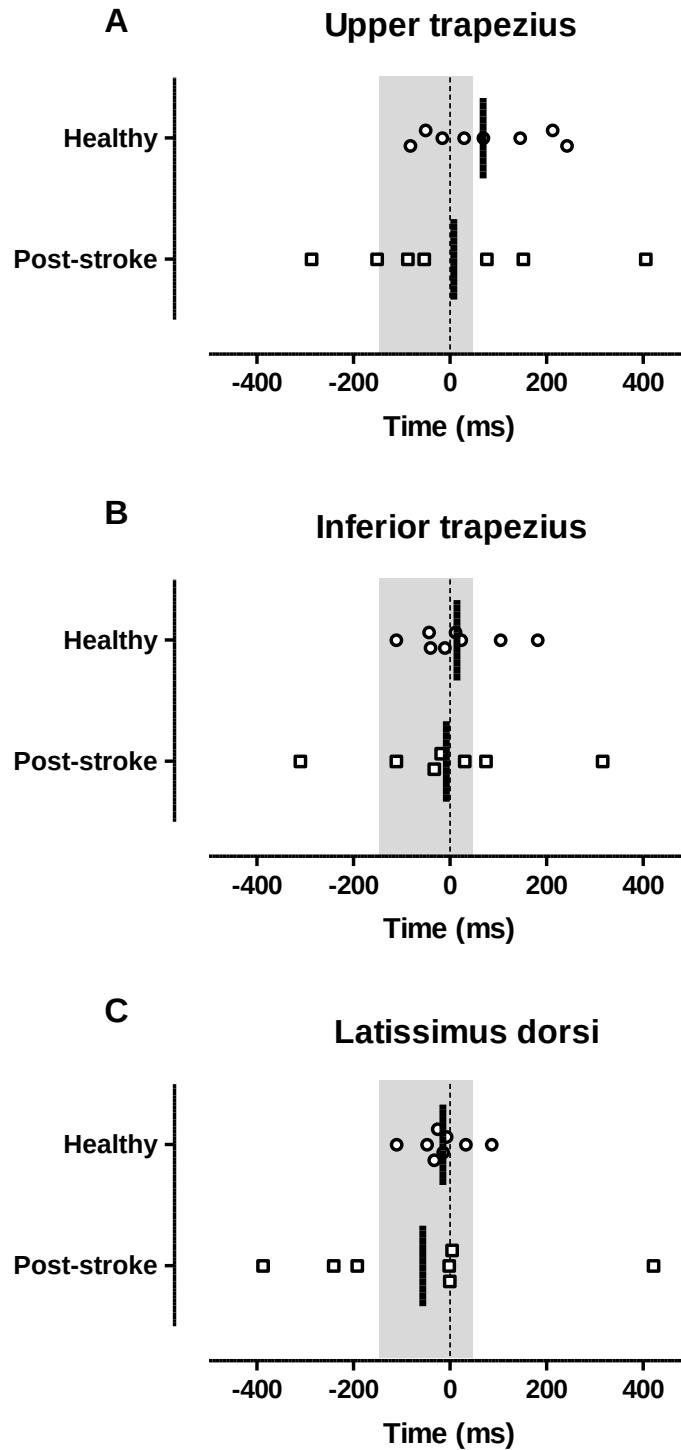


Figure 10: Activation timing of contralateral scapular/upper-trunk muscles during reaching movement of the ipsilesional upper-limb of post-stroke subjects and the dominant upper-limb of healthy subjects. The activation timings are illustrated for upper trapezius (A), inferior trapezius (B) and latissimus dorsi (C) muscles. Open squares represent muscle activation timing of each post-stroke subject, whereas open circles represent muscle activation timing of healthy subjects; bold vertical lines represent the mean values of both groups. Time zero indicates movement initiation. The interval that shows APAs is marked in gray.

Activation timing of contralateral trunk muscles during reaching movement performed with the contralesional limb of post-stroke subjects vs non-dominant limb of healthy subjects

When the reaching movement was performed with the contralesional upper-limb of post-stroke subjects and with the non-dominant upper-limb of healthy subjects, no statistical differences between groups were found in the activation timing of the contralateral UT ($p = 0.500$, Figure 11A). Conversely, the activation timings of the contralateral IT and LD were significantly different between groups ($p = 0.017$ and $p = 0.031$, respectively). In these muscles, the post-stroke group showed a significant delay in the activation timing when compared to the healthy group (96.1 ± 41.2 ms vs -25.2 ± 20.6 ms and 167.0 ± 64.7 ms vs 9.5 ± 23.4 ms, respectively for the IT and LD) (Figure 11B and C).

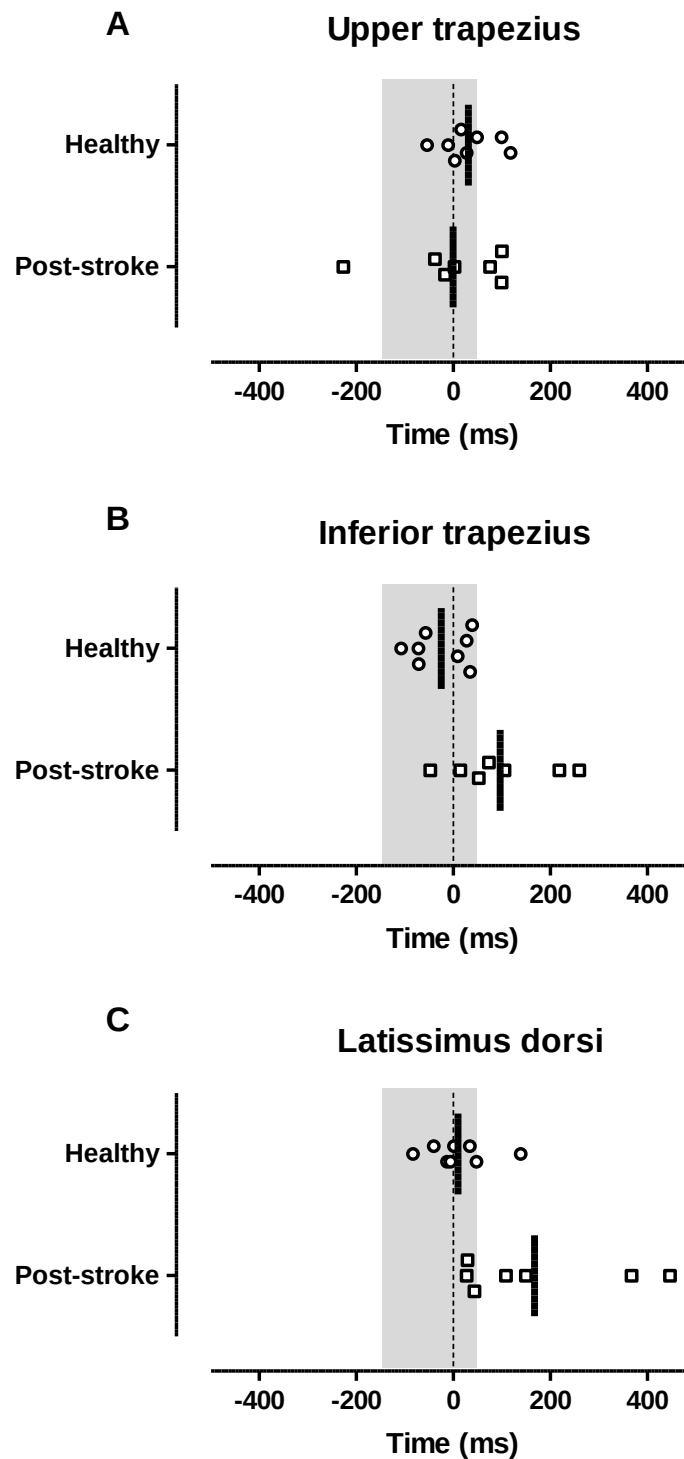


Figure 11: Activation timing of contralateral scapular/upper-trunk muscles during reaching movement of the contralesional upper-limb of post-stroke subjects and the non-dominant upper-limb of healthy subjects. The activation timings are illustrated for upper trapezius (A), inferior trapezius (B) and latissimus dorsi (C) muscles. Open squares represent muscle activation timing of each post-stroke subject, whereas open circles represent muscle activation timing of healthy subjects; bold vertical lines represent the mean values of both groups. Time zero indicates movement initiation. The interval that shows APAs is marked in gray.

3.3.4. DISCUSSION

Efficient movement of a body segment must be associated with a previous postural muscle pattern activation (at least 150 ms prior to movement onset until 50 ms after its initiation) to prevent perturbations derived from the action of the mobilizing muscles.

Although it seems that volitional movement demands an axial postural control response also in the contralateral side to movement execution (Matsuyama et al., 2004; Schepens et al., 2006; Schepens et al., 2008), few studies have, so far, focused on this relevant motor control aspect. To our knowledge, few studies addressed this issue, and its focus was in lower-limbs (Silva, Sousa, Pinheiro, et al., 2012; Silva, Sousa, Tavares, et al., 2012). Moreover, a recent study focused on lower-limb's function suggested that the ipsilesional postural control deficits seen in post-stroke subjects negatively influence the performance of the contralesional lower-limb (Sousa et al., 2013). These findings are supported with the current knowledge of the neurophysiological basis of motor control, which indicates that movement execution foresees parallel circuitries based on a predominantly contralateral movement control (dorsolateral system) and a predominantly ipsilateral postural control (ventromedial system) (Rothwell, 2012). Therefore, we should expect that, in post-stroke subjects, the ipsilesional hemitrunk might influence contralesional upper-limb's function, which can ultimately have a significant impact in the design of rehabilitation interventions. Interestingly, our results are in agreement with our hypothesis, showing that activation timings of IT and LD muscles, which are stabilizing muscles of the scapula, are delayed in the ipsilesional hemitrunk of post-stroke subjects, comparing to healthy subjects, when reaching movement was performed with the contralateral upper-limb. Conversely, the activation timings of the contralateral UT, IT and LD muscles were not significantly different when reaching was performed with the ipsilesional upper-limb of post-stroke subjects vs the dominant upper-limb of healthy subjects. Though it might seem that these findings contrast with the results found in other studies (Garland et al., 1997; Hedmann et al., 1997;

Horak et al., 1984; Slijper et al., 2002; Stevenson et al., 1996), which describe impairments in temporal parameters of APAs also in the contralesional side of the body, i.e., ipsilaterally to contralesional upper-limb's movement, we believe that these differences might be due to the performed tasks and their underlying neural circuits. In other words, in those studies, APAs were analyzed when the movement was performed with the ipsilesional limb (Garland et al., 1997; Horak et al., 1984; Slijper et al., 2002), whereas we studied APAs behaviors accordingly to each limb movement. Therefore, when movement is performed with the contralesional limb, given that both the ipsilesional pontine and medullary reticular nucleus might be dysfunctional, their correspondent pontinereticulospinal and medullaryreticulospinal pathways (which, although bilaterally, are mainly ipsilateral and contralateral, respectively (Matsuyama et al., 2004) might trigger bilaterally dysfunctional APAs. On the other hand, when movement is performed with the ipsilesional limb, given that both the contralesional pontine and medullary reticular nucleus are unaffected by the lesion, their correspondent pontinereticulospinal and medullaryreticulospinal pathways might trigger appropriate APAs or, ultimately, negligible less efficient APAs (see Figure 12 for schematic representation). Therefore, it might be questionable if the impairment of APAs seen by other others in the contralesional hemitrunk when ipsilesional upper-limb moves (Garland et al., 1997; Horak et al., 1984; Slijper et al., 2002) is related to the neurological lesion itself or a consequence of a biomechanical impairment due to viscoelastic adaptations of the soft tissue secondary to the lack of activity. Also, studying postural responses having as a reference for the movement initiation the activity of a theoretical prime mover may raise some questions, especially in post-stroke subjects, since impairments in muscle activation are highly probable and the theoretical pattern of muscle recruitment may be altered (Dickstein et al., 2004).

3.3 Study III – Anticipatory Postural Adjustments of Reaching while Sitting

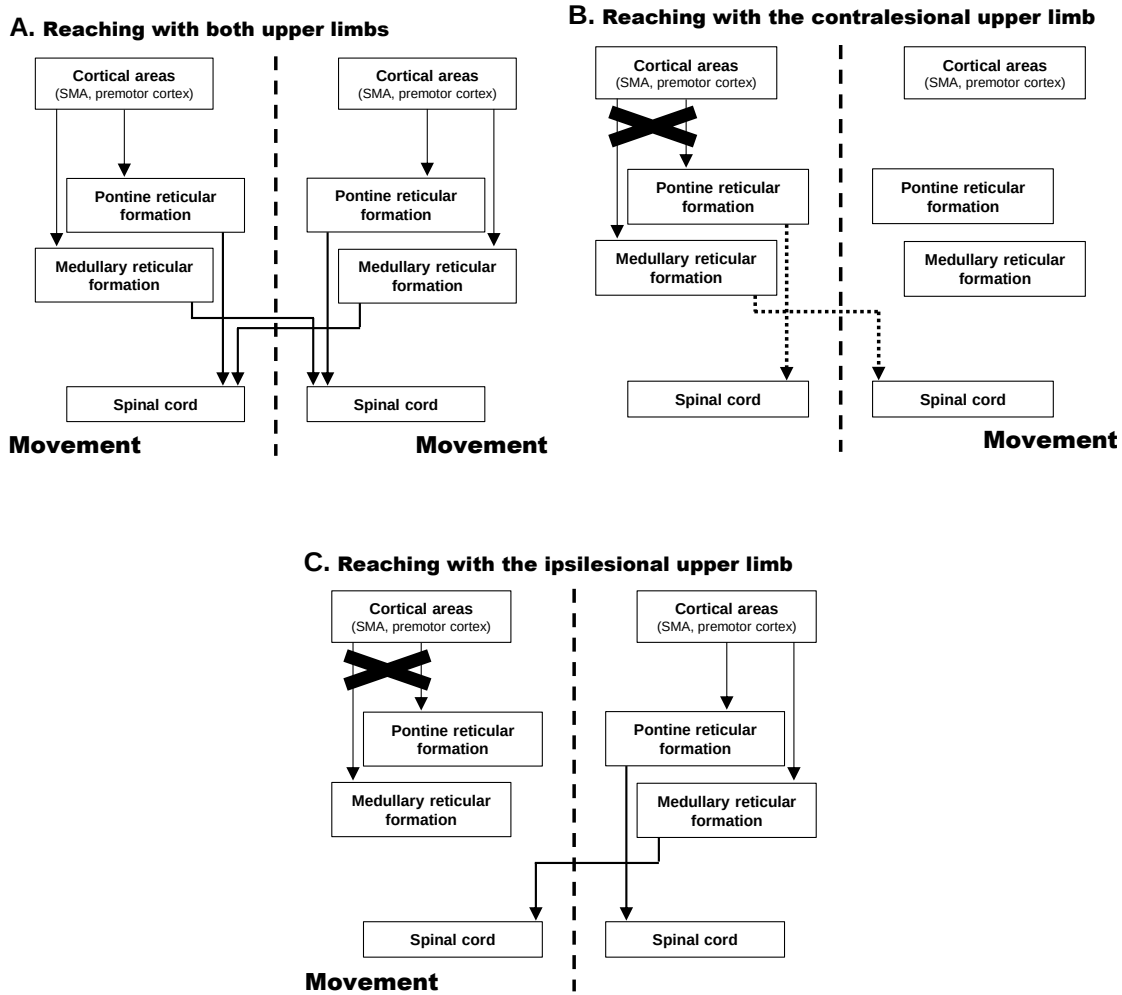


Figure 12: Schematic representation of a proposed simplified model for global planning of postural control during the reaching movement of upper-limbs. Panel A illustrates a schematic organization of the predominantly circuits for postural control in healthy subjects during reaching with both upper-limbs. Panels B and C represent reaching with the contralesional and the ipsilesional limbs, respectively, in post-stroke subjects in which corticoreticular projections were affected.

Thus, we conclude that our findings are not contradictory to literature; the differences rely on the circuits that underlie the tasks.

Furthermore, the fact that the UT muscle showed no differences between post-stroke and healthy subjects when movement was performed with the contralesional upper-limb and the non-dominant limb might be explained by a compensatory activity of this muscle in such conditions.

Taken these findings together, we hypothesize that when movement is performed with the contralesional upper-limb, postural control deficits might occur both ipsilaterally and contralaterally to the movement, whereas when movement is performed with the ipsilesional upper-limb, postural control should occur appropriately both ipsilaterally and contralaterally to the movement (if there are no changes in the biomechanical dynamic). Further research, however, is required to better understand the relative contribute of ipsilateral and contralateral postural control (relatively to movement execution).

3.3.5. CONCLUSION

Our results suggest that when movement is performed with the contralesional upper-limb of post-stroke subjects, a delay in the activation timing of contralateral IT and LD muscles seems to occur, showing that APAs are dysfunctional in the ipsilesional upper-trunk. When movement is performed with the ipsilesional upper-limb, the contralateral UT, IT and LD muscles seem to activate appropriately, suggesting no deficits in APA's recruitment.

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3.4. STUDY IV – ANTICIPATORY POSTURAL ADJUSTMENTS OF REACHING WHILE STANDING: AN ANALYSIS OF THE CONTRALATERAL BODY SIDE TO MOVEMENT EXECUTION IN POST-STROKE SUBJECTS

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ABSTRACT

The goal of this study was to investigate the activation timings (temporal parameter of APAs) of scapular/upper-trunk postural muscles of post-stroke subjects, during standing reaching in the contralateral side to movement execution. Eight healthy and seven post-stroke subjects were instructed to reach a target, placed in the scapular plane of movement, with the dominant and non-dominant vs the ipsilesional and contralesional upper-limbs, respectively. Surface EMG was recorded from the upper trapezius (UP), inferior trapezius (IT) and latissimus dorsi (LD), bilaterally. Movement onset was determined through hand's peak velocity and muscle activity onset was considered the value obtained by the difference between the time of the EMG onset of the UT, IT and LD and the movement onset. When the reaching movement was performed with the ipsilesional upper-limb of post-stroke subjects and with the dominant upper-limb of healthy subjects, the activation timings of contralateral UT, IT and LD muscles fitted into the time window considered for APAs and no statistical differences between groups were observed ($p= 1.000$, $p= 0.418$ and $p= 0.908$, respectively). When the reaching movement was performed with the contralesional and with the non-dominant limbs, no statistical differences between groups were found ($p= 0.366$, for the UT; $p= 0.302$, for the IT and $p= 0.606$, for the LD). Nevertheless, in this case a delay in the activation timings of the ipsilesional UT and IT muscles was observed in post-stroke subjects once they were out of the considered interval for APAs. Concluding, when standing reaching is performed with the contralesional and the non-dominant upper-limbs of MCA post-stroke and healthy subjects, respectively, delayed activation timings of the ipsilesional UT and IT muscles seem to occur.

Keywords: Anticipatory postural adjustments, ipsilesional body side, scapular/upper-trunk postural muscles, standing reaching.

3.4.1. INTRODUCTION

Movement efficiency is highly dependent on the ability to generate anticipatory postural adjustments (APAs) (Massion et al., 1988; Massion, 1992; Massion, 1998). In post-stroke subjects, an atypical behavior of APAs may contribute to the observed movement deficits, as well as to the presence of compensatory strategies, often recruited in order to accomplish functional tasks, like reaching (Champion et al., 2009). Indeed, extensive research has reported an atypical movement performance during this upper-limb gesture in post-stroke subjects, which may be related to the inability of maintaining a reference frame during external and internal disturbances, interfering with the production of a skillful motor action (Massion, 1992; Massion, 1998). Furthermore, it is important to highlight that postural adjustments modulation are intrinsically dependent on the postural set selected to the task performance, being expected changes in muscle response patterns according to different body configurations (Aruin et al., 1998; Aruin et al., 2003). For instance, considering the positions of sitting versus standing, clear differences in the biomechanics of both postures are observed. Comparing to sitting, in standing, the considerably smaller base of support and the higher position of the center of mass contribute to a bigger challenge to the task of preserving the center of mass projection within the limits of the base of support (Li et al., 2007). Moreover, the vestibular system is significantly more active in standing than in sitting, which may contribute to a different APAs behavior between these two positions (Haines, 2002).

While some studies reported that, in sitting, APAs were generally absent (Moore et al., 1992; van der Fits et al., 1998; Yoshida et al., 2008), justifying that an inherent stable position does not demand for APAs generation, others (Aruin et al., 2003; Silva et al., not published), including a study conducted by this research team showed postural muscle activity compatible with APAs, either in healthy and post-stroke subjects. Similarly to the controversial results found in sitting position, evidence reporting APAs behavior in standing is also controversial, particularly amongst post-stroke subjects (Garland et al., 1997;

Horak et al., 1984; Kusoffsky et al., 2001; Slijper et al., 2002). Indeed, while, as stated by Aruin (2002), APAs generation may be a trivial task for the central nervous system (CNS) of a healthy person, those committed with neurological disorders, like stroke, may have to face challenging conditions, especially in less stable positions, like standing, in order to counteract the effects of self-triggered and imposed disturbances. In fact, for post-stroke subjects, standing position may represent per se an enormous challenge, limiting the ability to actively engage into functional activities. Standing reaching, basis of several functional tasks, is an obvious example of the above referred (Kusoffsky et al., 2001). According to this, and considering the contradictory evidence about the relationship between APAs behavior and the stability demands of the postural task (Aruin et al., 1998; Aruin et al., 2003), the assessment of such seems quite pertinent, in order to orientate clinical intervention decisions within rehabilitation scenarios. Moreover, the knowledge about pontine reticular formation influencing predominantly the contralateral side of movement execution, i.e., ipsilaterally to the motor cortical areas that planned the movement (Matsuyama et al., 2004), still needs further research, since studies addressing this issue are still scarce, and mostly related with lower-limb's function (Silva, Sousa, Pinheiro, et al., 2012; Silva, Sousa, Tavares, et al., 2012; Sousa et al., 2013). Therefore, we aimed at investigating the activation timings (temporal parameter of APAs) of scapular/upper-trunk postural muscles of post-stroke subjects, during standing reaching, in the contralateral side to movement execution.

3.4.2. METHODS

Participants

Fifteen subjects, included in two distinct groups (healthy: n=8, mean age of 52.3 ± 6.2 years and mean body mass index of 29.7 ± 3.6 kg/m²; and post-stroke: n=7, mean age of 59.3 ± 6.2 years and mean body mass index of

$25.5 \pm 2.7 \text{ kg/m}^2$), participated in this study. The protocol was approved by the local Ethics Committee and conforms to the principles outlined in the Declaration of Helsinki.

In both groups were only included subjects over 45 years old. Exclusion criteria comprised musculoskeletal pathology, neck and/or upper-limb pain, cerebellar, basal ganglia or brain stem lesions, and a Mini Mental State Examination score below 25. For the post-stroke group's inclusion, participants followed the additional criteria of: an unilateral stroke at the subcortical middle cerebral artery territory, confirmed by neuroimaging; an evolution time over 6 months; and a score between 30 to 50 of the Fugl-Meyer Assessment Scale (moderately impaired) (Scheidt et al., 2007). As exclusion criteria to the post-stroke group were considered: hemispatial neglect; visual (uncorrected), perceptual or cognitive deficits; and active range of motion of the contralesional shoulder and elbow joints inferior to 15° (Zackowski et al., 2004). The post-stroke group is briefly characterized in Table 7.

Table 7: Characterization of the post-stroke group regarding age, gender, weight, height, post-stroke time evolution and affected artery

	Post-stroke group						
	A	B	C	D	E	F	G
Age/ Gender	50/F	54/F	63/M	62/M	59/F	69/M	58/M
Weight (Kg)	71	80	105	82	72	80	85
Height (m)	1.57	1.58	1.69	1.70	1.65	1.71	1.73
Time evolution (years)	3	4	10	2	2	1	4
Affected artery	RMCA	LMCA	RMCA	LMCA	RMCA	RMCA	RMCA

A-I represent each subject; M – male; F – female; LMCA – left medial cerebral artery; RMCA – right medial cerebral artery

Instruments

Surface electromyography (sEMG) was recorded using two bioPLUX® (Plux, Portugal) devices with a sampling frequency of 1000Hz, common mode rejection ratio 110 dB, input impedance greater than 100 MΩ and analog channels with 12 bits. The bipolar sensor configuration was selected and auto-adhesive pediatric electrodes were used (Correia et al., 2004; Matias et al., 2006). The sEMG signals were analyzed through the AcqKnowledge Analysis Software version 3.9 (Biopac Systems, Inc., Goleta, USA).

Skin impedance was measured using the Noraxon® Impedance Checker system (Noraxon, Scottsdale, Arizona).

For kinematic data acquisition, a four cameras Qualisys Motion Capture System (sampling frequency: 100Hz) was used. Qualisys Track Manager (QTM) Software (Qualisys, Sweden) was used for data analysis. QTM kinematic analysis was synchronized with the sEMG.

Experimental procedures

Each subject was assessed standing barefoot, with feet slightly apart, and upper-limbs alongside the body, shoulder in neutral alignment, elbow in extension, forearm and wrist in neutral position. Subjects were instructed, after a verbal cue, to reach and grasp a 0.5 l plastic water bottle, which was placed in the scapular plane, at mid-sternum height, according to the anatomical reaching distance of the hand, using the measured distance from the acromion to the metacarpophalangeal joint of the thumb (Reisman et al., 2006; Vandenberghe et al., 2010). Three valid repetitions of the task were recorded, separated by one minute resting period. All the verbal commands were given equitatively and by the same researcher.

Surface EMG was recorded from the upper trapezius (UP), lower trapezius (LT) and latissimus dorsi (LD), bilaterally. Prior to data collection, the skin was shaved and wiped down with alcohol. Thirty seconds after, skin impedance was measured and confirmed less than 5 kΩ. Disposable pediatric

Ag/AgCl electrodes, with a skin contact surface of 10 mm² and inter-electrode distance of 20 mm, were placed parallel to the muscle fibers and according with SENIAM references (Hermens et al., 2000). Electrode placement was confirmed by voluntary muscle contraction. Ground electrodes were placed over the olecraneums (Correia et al., 2004; Hermens et al., 2000). For each limb assessment, five reflective markers were placed in the following bodymarks: mid-sternum, acromion (bilaterally), lateral epicondyle of the humerus and ulnar styloid apophysis. A reflective marker was also placed at the target.

Data processing

Kinematic data was digitally low-pass filtered using a second order Butterworth filter with a cutoff frequency of 6 Hz, and analyzed in terms of hand's peak velocity (through ulnar marker), allowing the extraction of the movement onset, that was visually determined and posteriorly confirmed through the analysis of the velocity curve and extracted numeric data. The EMG data was offline processed with AcqKnowledge 3.9.0 software (Biopac Systems, Inc., California, USA). Signals were band-pass filtered at 20-500 Hz, amplified and root-mean-square (RMS) processed for consecutive segments of 100 ms. Muscle onset was determined as the time when the EMG activity exceeded the baseline activity (measure 500 ms to 450 ms before the event) for two standard deviations, for a minimum period of 50 ms (Hodges et al., 1996). To assess the temporal parameter of APAs, the timing of the EMG activity onset consisted in the average value obtained by the difference between the time of the EMG onset of the UT, LT and LD and the movement onset in the three trials.

Statistics

Statistical Analysis was conducted using IBM SPSS Statistics software v20 with a significance level of $\alpha = 0.05$. Given that variables did not follow a normal distribution, Mann-Whitney U test was used to compare healthy and

post-stroke subjects. Median and interquartile deviation were used as descriptive statistics.

3.4.3. RESULTS

The following results show the activation timings of the contralateral scapular/upper-trunk postural muscles (upper trapezius, inferior trapezius and latissimus dorsi), during reaching movement performed with the ipsilesional limb of post-stroke subjects compared to the dominant limb of healthy subjects (Figure 13) and with the contralesional limb compared to the non-dominant limb (Figure 14). Still, no statistical differences were observed between dominant and non-dominant limbs of healthy subjects (data not shown).

Activation timing of contralateral trunk muscles during reaching movement performed with the ipsilesional limb of post-stroke subjects vs dominant limb of healthy subjects

The activation timings of UT (Figure 13A), IT (Figure 13B) and LD (Figure 13C) muscles in post-stroke and healthy subjects, showed no statistical differences ($p = 1.000$, $p = 0.418$ and $p = 0.908$, respectively) when the reaching movement was performed with the ipsilesional and the dominant limbs. For both groups, medians of the activation timings fitted within the defined interval of APAs.

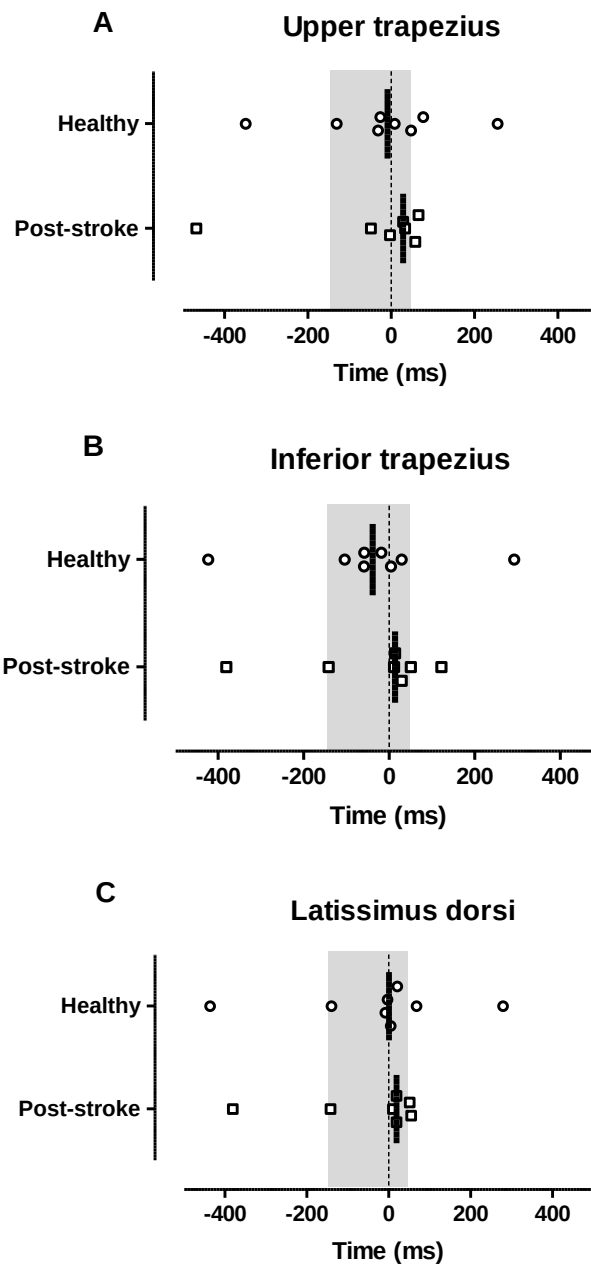


Figure 13: Activation timing of contralateral scapular/upper-trunk muscles during reaching movement of the ipsilesional upper-limb of post-stroke subjects and the dominant upper-limb of healthy subjects. The activation timings are illustrated for upper trapezius (A), inferior trapezius (B) and latissimus dorsi (C) muscles. Open squares represent muscle timing of each post-stroke subject, whereas open circles represent muscle timing of healthy subjects; bold vertical lines represent the mean values of both groups. Time zero indicates movement initiation. The interval that shows APAs is marked in gray.

Activation timing of contralateral trunk muscles during reaching movement performed with the contralesional limb of post-stroke subjects vs non-dominant limb of healthy subjects

When the reaching movement was performed with the contralesional upper-limb of post-stroke subjects and with the non-dominant upper-limb of healthy subjects, no statistical differences between groups were found in the activation timing of the contralateral UT ($p = 0.366$, Figure 14A), contralateral IT ($p = 0.302$, Figure 14B) and contralateral LD ($p = 0.606$, Figure 14C).

Despite the likewise ipsilesional vs dominant limb absence of statistical significant differences, in this case it was possible to observe that both UT and IT muscles of the post-stroke subjects were predominantly activated after the interval considered as APAs, which represents a clinical significant. Similarly, the LD muscle showed a borderline pattern.

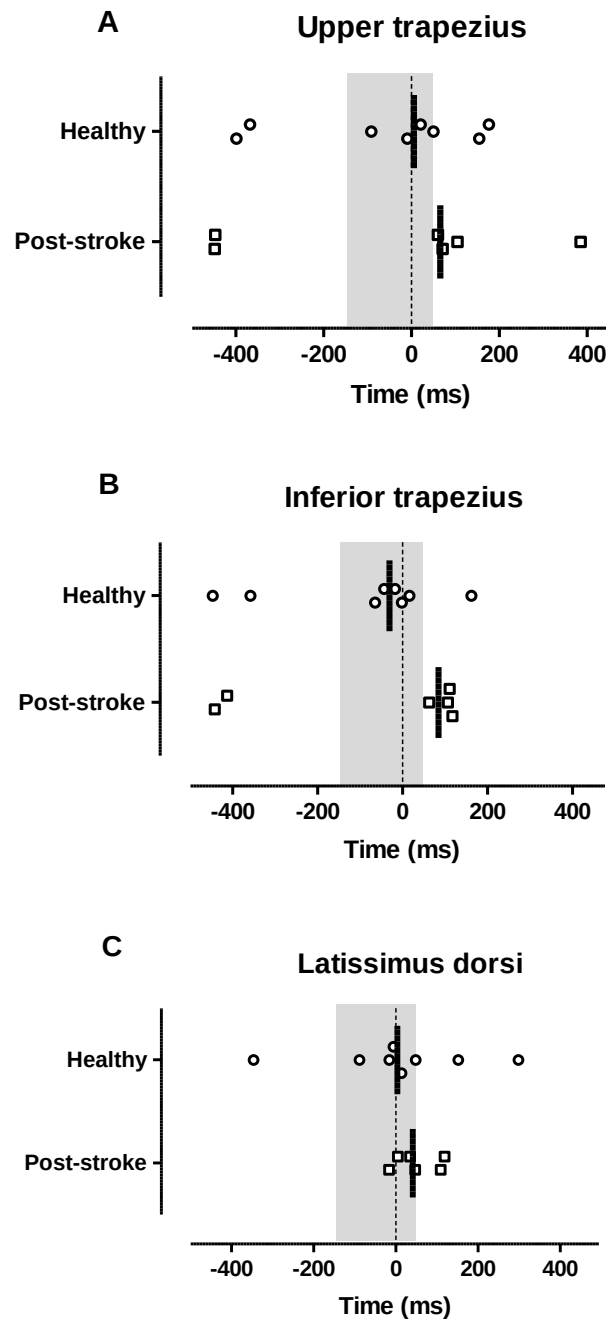


Figure 14: Activation timing of contralateral scapular/upper-trunk muscles during reaching movement of the contralesional upper-limb of post-stroke subjects and the non-dominant upper-limb of healthy subjects. The activation timings are illustrated for upper trapezius (A), inferior trapezius (B) and latissimus dorsi (C) muscles. Open squares represent muscle timing of each post-stroke subject, whereas open circles represent muscle timing of healthy subjects; bold vertical lines represent the mean values of both groups. Time zero indicates movement initiation. The interval that shows APAs is marked in gray.

3.1.1. DISCUSSION

The delay or even suppression of APAs generation in unstable conditions are referred to as a protective CNS strategy, given that, in such conditions, APAs could act as a potential source of perturbation and, thus, contribute to additional posture destabilization (Aruin et al., 1998). As standing is a highly demanding position regarding to postural control function, the performance of functional tasks in this position is often considered a challenge for post-stroke subjects, since a fine-tuned interplay between systems responsible for movement execution and for posture control is required (Berrigan et al., 2006). In fact, post-stroke subjects frequently exhibit difficulties at this point, which are expressed in some scientific research as impaired APAs organization, mainly at the contralesional body side (Garland et al., 1997; Horak et al., 1984; Slijper et al., 2002).

Despite the narrow base of support of standing position, in this study we showed that, when movement was performed with the ipsilesional upper-limb of stroke subjects, the contralesional trunk muscles UT, IT and LD exhibited activation timings within the time window defined for APAs (i.e. between -150 ms prior to movement onset, until 50 ms after its initiation). Moreover, no statistical significant differences seem to occur between post-stroke and healthy subjects when movement is performed with the ipsilesional and the dominant upper-limbs, respectively. Interestingly, similar results were found when subjects performed reaching in sitting position (Silva et al., not published). Conversely, and though no statistical differences were observed between post-stroke and healthy subjects when movement was performed with the contralesional and the non-dominant upper-limbs, respectively, the activation timings of the UT and IT muscles of post-stroke subjects were delayed and out of the APAs period, which represents a clinical significance. The LD muscle showed a borderline profile, suggesting that further research is needed to clarify its pattern. Altogether, these results fit with the hypothesis that post-stroke subjects with MCA territory lesions might exhibit a dysfunction of the postural control system, particularly of APAs behavior in the ipsilesional

body side (when movement is performed with the contralesional upper-limb). This assumption is based on the fact that sub-cortical MCA lesions have a strong probability of interfering with the corticoreticular network, which, in turns, may interfere with the reticulospinal tract function, whose disposal is mostly ipsilateral (from the pontine nucleus) (Schepens et al., 2006; Schepens et al., 2004; Schepens et al., 2008).

These findings are in agreement with previous evidences about this topic, but in relation to the lower-limb's behavior (Silva, Sousa, Pinheiro, et al., 2012; Silva, Sousa, Tavares, et al., 2012), which also discuss the nature of the observed neuromuscular atypical behavior in the ipsilesional limb as a dysfunction of the postural control system, refuting the widespread idea that the deficits found in this limb result from a compensatory mechanism related to the deficits in the contralesional limb (Lamontagne et al., 2000). Interestingly, recent research suggested exactly the opposite, i.e. the ipsilesional limb seems to negatively affect the contralesional limb (Sousa et al., 2013).

Concluding, when standing reaching is performed with the contralesional and the non-dominant upper-limbs of MCA post-stroke and healthy subjects, respectively, delayed activation timings of the ipsilesional UT and IT muscles seem to occur. However, to the best of our knowledge, it remains to clarify how vestibular system may influence the behavior of APAs by varying the initial position of the task. Therefore, we believe that this issue deserves further research with relevant clinical impact, since alternative paths for neuronal activity organization may be selected.

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CHAPTER 4

DISCUSSION, CONCLUSIONS

AND FUTURE WORK

4.1. GLOBAL DISCUSSION

Considering the current neurosciences knowledge about motor system's organization and neuronal disposal, namely the ventromedial system, which, although bilaterally, presents predominantly an ipsilateral projection (Schepens et al., 2006; Schepens et al., 2004; Schepens et al., 2008), ipsilesional deficits resulting from the lesion itself should be considered. Indeed, in a unilateral stroke, with the brain lesion located at a sub-cortical level (such as the frequently affected internal capsule), it is highly probable that the lesion interferes with the neuronal connection between the motor cortex and the reticular formation, which clearly justifies an ipsilesional postural control dysfunction. Moreover, recent research has highlighted the presence of an atypical neuromotor behavior in the ipsilesional lower-limb (Silva, Sousa, Pinheiro, et al., 2012; Silva, Sousa, Tavares, et al., 2012; Sousa et al., 2013). Based on these assumptions, during this investigation we intended to assess postural control function in both the ipsilesional and contralesional body sides of post-stroke subjects, during reaching performance, hypothesizing that signs of postural control dysfunction would be found, also in the ipsilesional side. Although there has already been some evidence reporting a dysfunctional motor behavior in the ipsilesional upper-limb of post-stroke subjects, it is mostly focused on hand dexterity and essentially related with the ipsilateral projection of the corticospinal tract (Nowak, 2008; Yarosh et al., 2004). However, such an assumption lacks validity, since the functional role of this system in adulthood it is not quite clear (Martin, 2005). Indeed, research concerning this matter has demonstrated that the ipsilateral projection of the corticospinal tract is quite predominant in an immature CNS, while mature systems exhibit predominantly contralateral projections (Martin, 2005). Other researchers have also reported an altered behavior of the ipsilesional lower-limb, but attributed the alterations to a compensatory mechanism resulting from the behavior of the contralesional limb (Higginson et al., 2006; Lamontagne et al., 2002; Lamontagne et al., 2000).

From a biomechanical point of view, the results presented and discussed in paper 1 showed that when the movement was performed with the ipsilesional limb, post-stroke subjects exhibited a significantly increased trunk displacement in the scapular plane, and a longer movement time as well as more movement units in both sagittal and scapular planes. According to Murphy et al. (2011) these three variables (movement time, number of movement units and trunk displacement) represent the key elements of movement performance and compensatory movement pattern. Therefore, the referred results may suggest that post-stroke subjects exhibit compensatory movements not only associated with contralesional limb movement, but also with the ipsilesional. Instead of considering this motor behavior as merely a result of the deficits in the contralesional side, affecting ipsilesional limb performance as well, like Higginson et al. (2006), Lamontagne et al. (2002) and Lamontagne et al. (2000) stated in relation to the lower-limb, we propose that this finding is mostly related to the neurological lesion itself, by affecting the postural control system through dysfunctional ipsilaterally descending ventromedial pathways. In fact, as already mentioned, after an unilateral lesion of the sub-cortical medial cerebral artery territory, damage can occur not only in the crossed fibers responsible for movement execution in the contralesional limb, but also in the corticoreticular networks, which may have implications with the reticulospinal pathways, thus interfering with the neuronal flow to the ipsilesional postural muscles (Gjelsvik, 2007; Matsuyama et al., 2004; Schepens et al., 2006). Moreover, descriptive analysis of the remain variables evidences that the ipsilesional limb of post-stroke subjects, often named as “undamaged” limb, exhibits, in general, a poorer performance when compared to healthy subjects. Similarly, the study of the antagonist co-activation ratios of both limbs of post-stroke subjects (paper 2), which was conducted under the hypothesis that, after a stroke in the MCA territory, there might be an ipsilesional postural muscle pair deregulation, revealed that when the reaching was performed with the ipsilesional limb, an altered antagonist co-activation ratio was present in the stability muscle pair (LD/PM) in the movement sub-phase where stability demands were higher (first sub-phase), while in the

second sub-phase, which is more mobility-demanding, this was no longer evident. These findings, together with the results concerning the mobility muscle pairs, which did not show significant differences between post-stroke and healthy subjects, strengthen the idea that the ipsilesional limb presents postural control deficits.

The altered movement kinematics related to postural control dysfunction and altered postural muscle pairs antagonist co-activation ratios in the ipsilesional side, during reaching movement, are novel aspects within the post-stroke motor characterization since, to the best of our knowledge, there are any scientific papers reporting these issues. Given that these findings were suggestive of a postural control dysfunction during the movement execution, the need to explore postural control mechanisms prior to movement onset, which is a relevant feature of overall postural control system, namely through the APAs study, justified the design of paper 3. Since assessing whether or not postural muscle activity qualifies as anticipatory requires the comparison of their activity onset to a temporal event, defined as time 0 (T_0), we selected, movement initiation by a kinematically reference event (Berg et al., 2012) instead of the most common used event, which is the activity onset of the muscle(s) involved in the focal movement, i.e., the prime mover(s) (Rosenbaum, 2011). The justification for such was related with some reported evidence that during tasks performance subjects may use different muscle strategies, despite identical execution instructions were given (van der Fits et al., 1998). Indeed, this study found that, although subjects were identically instructed to perform a pointing task, half of them used the deltoid as prime mover, while the other half used the biceps brachii. The authors highlighted that the presence of two different strategies affected the postural adjustments greatly; having its main effects on their temporal characteristics, and suggested that kinematic recordings would be desirable to detect movement displacements.

Based on the findings by van der Fits et al. (1998), Dickens et al. (2004), whose study aim was to assess APAs in post-stroke subjects, selected

as arm prime movers both the deltoid and the biceps brachii (Dickstein et al., 2004). However, considering that subject-specific strategies reflect the ability of the CNS to generate different motor patterns, despite identical goals are achieved, no guarantees can be given that post-stroke subjects use only deltoid or biceps brachii as arm prime movers. Indeed, there is enough evidence to support the fact that upper-limb movement variability increases following stroke (Cirstea et al., 2000; Reinkensmeyer et al., 2003; Thies et al., 2009). Moreover, clinical evidence suggests that this variability is expressed in the use of different patterns of movement initiation, recruiting, for example, such different muscles as the upper trapezius, pectoralis major, or even posterior deltoid, even when the intended task demands for upper-limb flexion. These assumptions supported the methodological decision of selecting movement kinematics as the T0 event, and thus as the reference event for postural muscles activity onset. The results of this paper (paper 3) shown that activation timings of inferior trapezius and latissimus dorsi muscles, which are stabilizing muscles of the scapula, are delayed in the ipsilesional hemitrunk of post-stroke subjects, comparing to healthy subjects. These findings are in agreement with the hypothesis underlying this investigation, since it was expected, according to neurophysiological data, that when movement was performed with the contralesional limb, given that both the ipsilesional pontine and medullary reticular nucleus might be dysfunctional, their correspondent pontine reticulospinal and medullary reticulospinal pathways (which, although bilaterally, are mainly ipsilateral and contralateral, respectively (Matsuyama et al., 2004) might trigger bilaterally dysfunctional APAs. Therefore, it might be questionable if the impairment of APAs seen by others in the contralesional hemitrunk when ipsilesional upper-limb moves (Garland et al., 1997; Horak et al., 1984; Slijper et al., 2002) is related to the neurological lesion itself or a consequence of a biomechanical impairment due to viscoelastic adaptations of the soft tissue secondary to the lack of activity.

The results of papers 1, 2 and 3 contributed to new insights on the relationship between postural control and upper-limbs movement in post-stroke subjects, when functional tasks are performed in sitting position. However, a

great percentage of these subjects regain locomotor function, although presenting gait deficits (Hornby et al., 2008) and, thus, the investigation of postural control function during task performance in standing is quite pertinent. Therefore, since postural adjustments modulation are intrinsically dependent on the postural set, and changes in muscle response patterns according to different body configurations may occur, we intended to verify if the dysfunctional behavior found in sitting position, in the ipsilesional body side, would still be present when the task was performed in standing. Also, we intended to assess if post-stroke subjects who exhibit, in sitting, postural adjustments compatible with APAs in the contralesional body side, would still present them in standing position, given that results about this are still highly controversial (Garland et al., 1997; Horak et al., 1984; Kusoffsky et al., 2001; Slijper et al., 2002). The results showed, once more, the presence of an atypical motor behavior concerning the postural control function, in the ipsilesional body side, which reinforces the overall results found throughout this study.

It is important to reinforce that the fact that all participants sustained sub-cortical lesions, thus with high probability of impairment of the neuronal flow from motor cortex areas to the reticular formation, may have contributed to the consistency of the results along the different studies, and in our point of view this methodological option strengthens the contribution of this research to the intended goals. Moreover, the results consistencies, which reveal the presence of a motor dysfunction in both body sides of post-stroke subjects, allow the discussion of the rehabilitation principles, within this clinical area. Indeed, it might be reasonable to question the validity of those therapeutic approaches that emphasize the motor paresis in the contralesional body side, disregarding the importance of the postural control function in the overall muscular activity organization for movement production. Therefore, it seems imperative that therapeutic decisions contemplate this knowledge, and both post-stroke subject's body sides be assessed, so that the interdependence between postural control and movement execution, can be potentiated for

better rehabilitation outcomes. Additionally, during research studies, as for example biomechanical studies, these considerations should also be present.

4.2. CONCLUSIONS

Concluding, our findings suggest that post-stroke subjects exhibit a postural control dysfunction in the ipsilesional body side. Instead of considering this motor behavior as merely a result of the deficits in the contralesional side, affecting ipsilesional side performance as well, we consider that it is mostly related to the neurological lesion itself, by affecting the postural control system through dysfunctional ipsilaterally descending ventromedial pathways. In fact, these stroke subjects presenting lesions located at the MCA territory evidenced alterations in the postural neuronal systems with mainly an ipsilateral disposal and, consequently, exhibited a dysfunctional postural control, also at the ispilesional side.

We are aware that this possibility has significant implications for post-stroke management. Based on these data, we believe that guidelines for neurological rehabilitation intervention must be rethought and targeted for a whole body problem solving approach. Accordingly, the connection between postural control systems (ventromedial systems) and movement performance systems (dorsolateral systems) must be considered not only within intervention programs (physiotherapy and physical activity programs), but also within biomechanical studies.

In summary, although the assumption of the overall involvement after a unilateral brain lesion is systematically gaining evidence, further research is still needed.

4.3. FUTURE WORK

The findings achieved with this study allowed some breakthroughs regarding post-stroke subject's motor behavior, specifically in the ipsilesional body side. However, more insights can be obtained with the conduction of further research, namely, the assessment of post-stroke subjects with brain lesions located at other artery territories, aiming to understand if global motor commitment is also present. Besides, the evaluation of subjects in an acute/subacute stage, rather than the chronic one, might allow the confirmation of the dysfunctional behavior of the ipsilesional body side, since the possible influence of biomechanical compensatory strategies is less likely to occur. Also pertinent is the selection of different upper-limb functional tasks and the integration of the grasping component in the assessment protocol.

At last, developing research where the role of the physiotherapy intervention can be accurately understood is a main area of future investigation.

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