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Proximal arm non-use in post-stroke individuals

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Sous la direction du Pr Isabelle LAFFONT et Pr Denis MOTTET

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The 10th century physician, Khalaf Albucasis,

Described as the “father of modern surgery”

Inspired me to pursue science.

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ARAT: Action research arm test

AAUT: Actual amount of Use Test

BART: Bilateral Arm Research Test

BB: Box and Blocks test

C: CMS20s®

CI: Compensation index

CIMT: constraint induced movement therapy

FM: Fugl Meyer

fNIRS: functional near-infrared spectroscopy

FES: Functional Electrical Stimulation

K: Kinect®

M_{PAU}: Maximal proximal arm non-use

MAL: Motor Activity Log

MT: Movement Time

NVP: Number of velocity peaks

PANU: Proximal arm non-use

PAU: Proximal arm use

RPS: Reaching performance scale

S_{PAU}: Spontaneous proximal arm use

SD: Standard deviation

STRIVE: Stroke interactive virtual therapy

UL: Upper limb

WMFT: Wolf Motor Function Test

INTRODUCTION

Stroke is the leading cause of long-term disability in industrialized nations with approximately 80% of people who survive a stroke experiencing some form of motor disability. Up to 85% of post-stroke individuals have hemiparesis that affects the upper limb (UL) of one side (Jones, 2017), which results in a reduced ability to use the paretic UL during activities of daily living (van Kordelaar et al., 2012b) and may lead to permanent disability (Cirstea and Levin, 2000; Nakayama et al., 1994). Although 80% of people who survive a stroke relearn to walk (Friedman, 1990), less than 50% recover a functional UL particularly hand reaching (Nakayama et al., 1994), which makes recovery of UL function a real challenge in rehabilitation.

A common response to this loss of UL function of the paretic side after a stroke is to learn compensatory strategies of using the non-paretic UL for functional tasks such as reaching (Nakayama et al., 1994; Taub et al., 2014). Another way to compensate is to develop new movement strategies to cover the specific deficits of the paretic UL. One of the most common compensatory movements is the recruitment of excessive trunk flexion (self-taught compensatory behaviour) when reaching with the paretic UL (Cirstea and Levin, 2000; Levin et al., 2002; Roby-Brami et al., 1997, 2003). Trunk compensation during reaching can be “mandatory” or adaptive for severe UL deficits, and “non-mandatory” or maladaptive for mild to moderate post-stroke individuals who have recovered enough paretic UL function, specifically active motion of elbow extension and shoulder flexion. However, motor recovery is defined as the return of a more normal movement pattern or reductions in movement impairment, that is to mean use of shoulder-elbow motion during a reaching task (Jones, 2017). In addition, long-term use of the maladaptive trunk compensation may lead to suboptimal motor recovery, pain and orthopaedic conditions of the paretic UL. Consequently, there is a necessity to quantify this non-mandatory/maladaptive trunk compensation in order to facilitate recovery of UL function.

In this thesis it was reasoned that non-mandatory/maladaptive trunk compensation during reaching reflects a form of arm non-use (i.e., shoulder-elbow non-use), which we termed proximal arm non-use (PANU). The ability to quantify proximal arm non-use may allow to differentiate mandatory and non-mandatory trunk compensation in seated reaching. Measuring the proximal arm non-use likely allows therapists to guide post-stroke individuals to appropriate rehabilitation training of UL motor function through reducing maladaptive trunk compensatory movements and thereby reducing the proximal arm non-use by increasing shoulder (flexion) and elbow (extension) use.

1 CHAPTER 1 – REVIEW OF LITERATURE

1.1 Stroke and upper-limb disability

1.1.1 Stroke

There were more than 25 million stroke survivors worldwide in 2013 (Feigin et al., 2015), and this population is predicted to reach 70 million by 2030 (Feigin et al., 2014). Furthermore, stroke is the leading cause of long-term disability and even in the chronic stage (> six months post stroke), upper limb (UL) paresis is still present in approximately 50-75% of survivors (Kwakkel et al., 2003; Parker et al., 1986). Thus, functional motor deficit of the UL is one of the most common and challenging sequelae following a stroke. Due to its implication in everyday activities, UL motor deficit limits the post-stroke individuals' autonomy in daily life activities and may induce persistent disability (Cirstea and Levin, 2000; Nakayama et al., 1994).

1.1.2 Upper limb motor deficits after a stroke

Post-stroke motor impairments, such as arm weakness and spasticity are the most common and important sequelae of stroke, which diminish UL movement capacity (Jones, 2017; Li, 2017; McCrea et al., 2002). In this post stroke sequale (see Figure 1.1), weakness and spasticity, which are the main signs of upper motor neuron lesion after a stroke, lead to non-use of the paretic UL muscles at a short length. When these muscles are shortened for a prolonged time, secondary biomechanical changes occur within the muscle that lead to contracture, and finally to a reduced range of movement that impairs UL function (Sheean, 2002). Although it has be shown that both arms are affected following a stroke lesion (Metrot et al., 2013), UL movement deficits are more pronounced in the limb contralateral to the side of the stroke lesion, which is explained by the predominant cerebral control of contralateral limb movements (Cirstea and Levin, 2000). In this thesis, the more affected UL will be called the paretic UL and the less affected will be called the non-paretic UL.

Paresis or muscle weakness may be the major impairment underlying the functional disability of the paretic UL (McCrea et al., 2002). Thereotically, paresis is described as a decreased ability to volitionally activate motor units. Poor voluntary motor control following a stroke means that sets of muscles cannot be activated appropriately, coordinated nor activated with sufficient force. Clinically, weakness is the term generalled used and is defined as the inability of the motor system to produce and maintain the force necessary for a given static movement or effort.

Spasticity is considered to be a complex multidimensional disorder following a stroke that incorporates neural (i.e, hyperactivity of the stretch reflex depending on stretching speed) and muscular (i.e, increased muscle stiffness) components (McCrea et al., 2002). Spasticity was traditionally believed to be the largest cause of loss of selective UL motor control and function and thus inhibiting spasticity was the focus of rehabilitation sessions (Bobath, B., 1990). Nowadays, reducing UL weakness is the focus of rehabilitation but management of spasticity to facilitate the motor recovery is still a clinical challenge (Li, 2017).

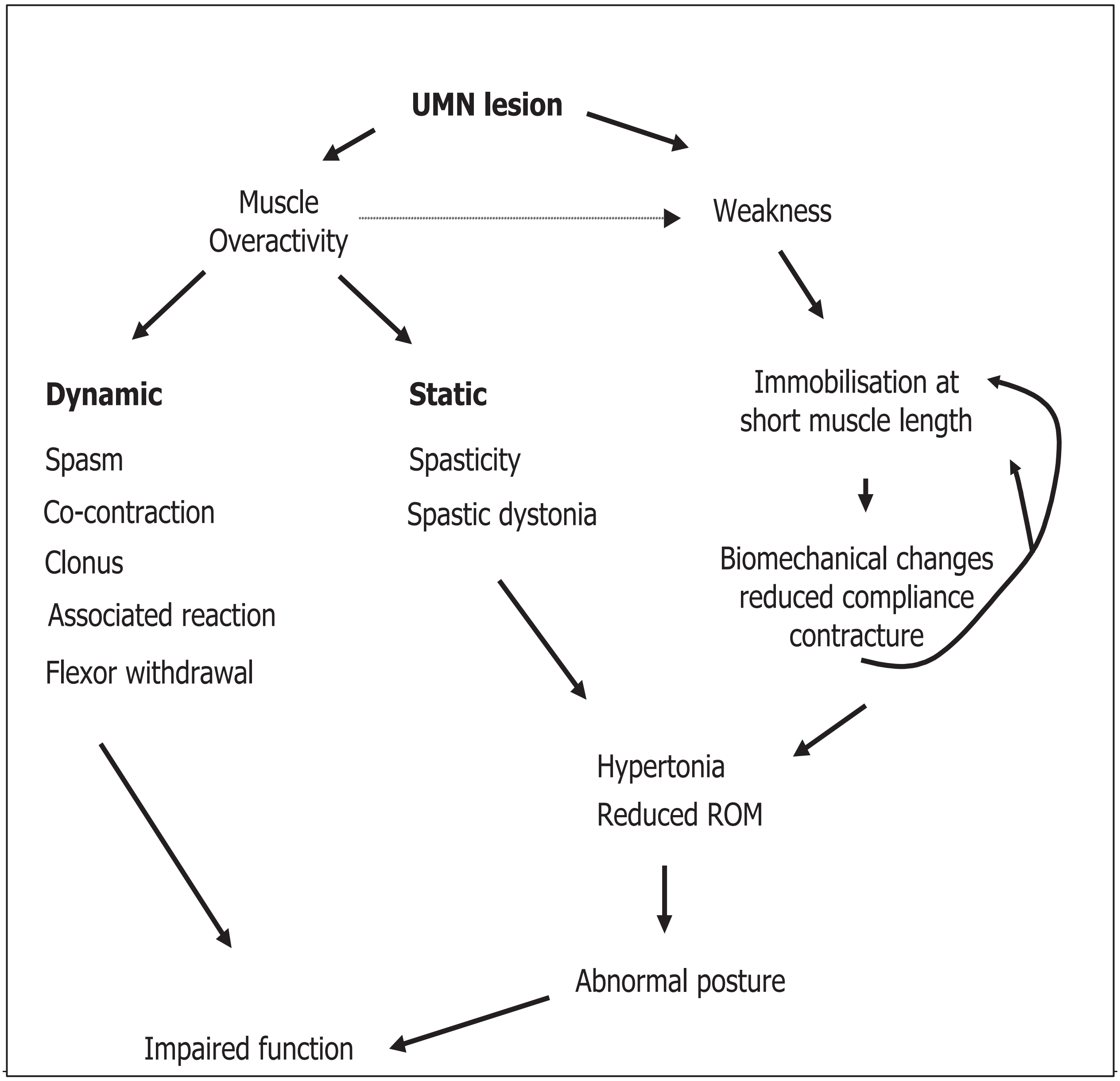

Figure 1.1: An overview of the sequale leading to impaired paretic upper limb function following an upper motor neurone (UMN) lesion after a stroke (adapted from Sheean, 2002).

1.2 Upper limb reaching movements

1.2.1 Normal upper limb reaching movements

Reaching is a complex multi-joint UL task that involves coordinating the arm through space so that the hand can interact with the environment in a purposeful aimed movement (Georgopoulos, 1986; Pain et al., 2015). The ability to reach a target and interact with the surrounding environment is an important element in daily life activities such as self-grooming, food preparation, and housecleaning. This thesis will focus on the transport phase of reaching, which is defined from the start of the movement from elbow flexed resting position until the object is reached by the hand, excluding grasping strategy (Levin et al., 2004).

a) Shoulder-elbow coordination during reaching

In healthy individuals, reaching is characterized by a straight or near curved trajectory of the hand and a smooth bell-shaped velocity profile with an approximate peak speed at the midpoint between the start and end position (McCrea et al., 2002). To produce a straight hand trajectory, coordination of both the shoulder and elbow joints is needed with shoulder–elbow coordination being typically characterized by tightly coupled angular velocities during reaching movements with peak velocity reached at the same time (McCrea et al., 2002).

Coordination is defined as “the organization of the different elements of a complex body or activity so as to enable them to work together effectively” (Shirota et al., 2016). In the context of motor coordination this definition boils down to the concept of motor synergy, which represents the ensemble of muscles that are activated in a cooperative way to achieve a specific motor task (see section 1.2.1.c). Therefore, the musculoskeletal system is considered redundant in the context of coordination (Bernstein, 1967), whereby there are potentially many ways to combine the movements of each joint to accomplish a motor task (Cirstea and Levin, 2000). This natural excess of motor strategies permits the possibility of a large number of inter joint coordination combinations and an infinite number of paths, which needs to get the end effector to consistently arrive at the target (McCrea et al., 2002).

The elbow-shoulder coupling represents a partial solution to the redundancy problem (Levin et al., 2015). In the healthy motor system, synergies have been based on the ability to produce abundant joint movement combinations to accomplish the same motor goal (i.e., “motor equivalence”). Controlling the movement of the UL to achieve a goal, such as reaching for an object, is challenging because the motor system requires to coordinate many muscles acting on many joints in the kinematic chain. The motor system might simplify the control of reaching through the combination of muscle synergies with coordinated recruitment of groups of muscles (d'Avella and Lacquaniti, 2013). As indicated in the previous section, the multitude of ways that one motor task can be performed is an example of the concept of redundancy of the motor system. Thus, although reducing the number of joints can help the motor system to select a unique trajectory and adequate inter-joint coordination among several possibilities, another partial solution is the use of movement synergies (Bernstein, 1967).

b) Trunk involvement during reaching within and beyond arm's length.

Targets within reaching distance are defined as the length of the extended arm from the shoulder axilla to the wrist (Levin et al., 2002). Reaching to a target within arm's length in healthy individuals involves mainly the shoulder and elbow joints working together as a coordinated mechanical system to accurately place the hand in a desired position (Figure 2.4) (McCrea et al., 2002). Healthy individuals use minimal trunk displacement for reaching to targets within arm's length (Levin et al., 2002), however reaching a target beyond arm's length requires the recruitment of additional trunk movement is necessary (Kaminski et al., 1995; Levin et al., 2002). Therefore, reaching to targets beyond arm's length involves movements at the shoulder-elbow joints, as well as the trunk (McCrea et al., 2002), where the trunk assumes a more dynamic role, as it becomes part of the kinematic chain to extend the maximum reaching distance (Pain et al., 2015; Rossi et al., 2002).

The threshold limit for the involvement of the trunk in the reaching kinematic chain is usually shorter than the anatomical maximal length of the UL and may vary with the task condition instruction (Ma and Feldman, 1995) and pathological situations such as following a stroke, developed in the next section (Fayad et al., 2008; Levin et al., 2002), this will be developed in the next section (1.2.2). Taken together, in healthy subjects, in addition to the specific shoulder-elbow joint movements of the UL, the trunk also plays an important role in hand reaching tasks to ensure postural stabilization as well as to extend the reach of the UL when grasping objects at a greater distance than that corresponding to the arm length (Jones, 2017; Saling et al., 1996).

1.2.2 Post-stroke upper limb reaching movements

When reaching after a stroke, individuals have prolonged movement times and have difficulty making smooth and accurate movements with the paretic UL (Jones, 2017; Levin, 1996). When a post-stroke individual attempts to move the paretic UL, the natural reaction of the motor system is to compensate with the available motor strategies (Cirstea et al., 2003; Cirstea and Levin, 2000; Dancause et al., 2002; Levin, 1996; McCrea et al., 2002). Well-coordinated UL reaching movements are a characteristic feature of a well-developed motor system as presented in the previous section (1.2.1), and deviation from a straight hand trajectory is primarily caused by reduced coordination of the shoulder and elbow joint movements (Shirota et al., 2016). Levin's team (Levin, 1996) showed that the most important feature in post stroke individuals reaching performance is the alteration of the interjoint coordination between the shoulder and elbow of the paretic UL. Inter-joint coordination patterns are modified with movements appearing to be made in stereotypical patterns, which are less flexible than in healthy subjects (Cirstea et al., 2003; Cirstea and Levin, 2000; Levin, 1996; Michaelsen et al., 2001).

a) Abnormal/pathological synergy - stereotype

Pathological motor synergies may be defined as stereotyped movements of the entire limb that reflect loss of independent joint control limiting the post-stroke individual to coordinate their joints for any task. Occurrence of a pathological UL stereotype has been regarded as a compensatory strategy developed by the motor system when trying to move the paretic UL (Bobath, B., 1990). Paretic UL stereotyped movement pattern during reaching primarily consists of a gross flexor stereotypted movement (Figure 1.2), characterized by simultaneous abduction and internal rotation of the shoulder, elbow flexion with pronation or supination and wrist and finger flexion (Twitchell, 1951).

Figure 1.2. A typical "flexor stereotype" in post-stroke individuals; the shoulder is medially rotated, the elbow is flexed, the forearm is pronated and the wrist and fingers are flexed (Mayer et al. 1997).

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Fractionation of movement is the ability to voluntarily move one segment independently of other segments. Post-stroke individuals present "motor stereotypes" which are characteristic of a loss of the ability to fractionate movement (e.g. inadvertent shoulder flexion during instructed or voluntary elbow flexion). A reduced ability to fractionate movement can limit UL function because fractionation of movement is essential for skilled UL motor control.

In agreement with Bernstein's theory of human movement behaviour, the most fundamental solution of a lesioned motor system to the problem of controlling coordination during reaching consists of reducing the number of independent elements to be controlled (i.e., joint). By locking the elbow in a stereotype pattern during reaching thus enables the post-stroke individual to compensate for the weakness of the paretic elbow musculature. Obviously, the stereotype dependent reaching movements with the UL may be seen as an adaptive mechanism that facilitates functionality by (1) reducing the joints and hence the complexity of movement control and (2) compensating for the muscle weakness at the distal UL that can be controlled with less accuracy.

b) Trunk involvement during reaching within arm's length

Development of trunk compensation for reaching within arm's length

In order to be able to achieve a reaching task, in the presence of deficits of the paretic UL, post-stroke individuals use trunk compensatory movement (adaptive coordination) for reaching to compensate for a lack of active motion in shoulder-elbow joints (Cirstea and Levin, 2000; Roby-Brami et al., 2003). This disruption in shoulder-elbow coordination persists partly as a result of the development of trunk compensation (trunk flexion) (Jones, 2017). In fact, contrary to healthy individuals, some post-stroke individuals recruit their trunk even for reaching a target placed within the reach of the UL (Figure 1.3) (Levin et al., 2002; Roby-Brami et al., 1997), which is to compensate for limited arm extension (Figure 1.4) and stability using movements of the trunk (Jones, 2017). In fact, the increased involvement of the trunk is significantly correlated with the decrease in elbow extension and decrease of shoulder flexion (Jones, 2017).

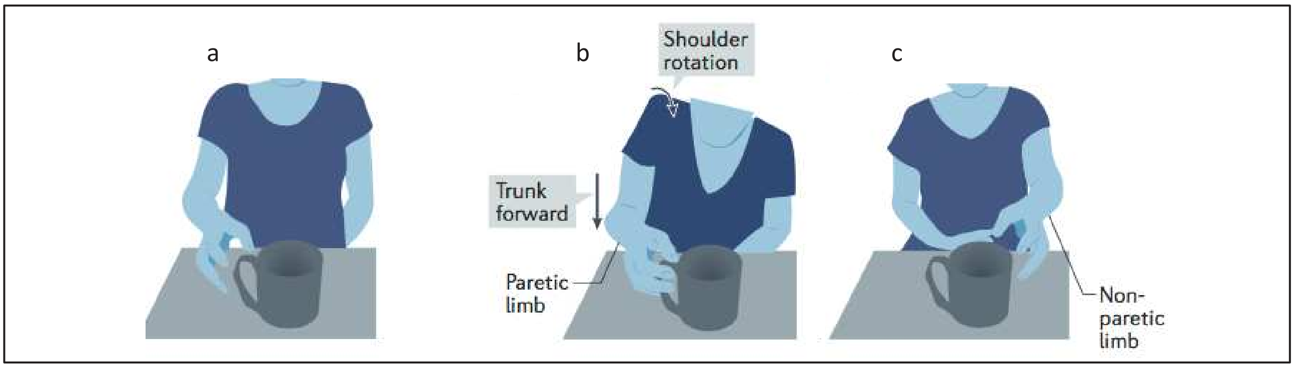


Figure 1.3. Illustrations of compensatory movement strategies for upper limb reaching. a) typical upper limb reaching movement in healthy individuals, b) reaching with the paretic upper limb after a stroke, forward trunk and shoulder displacement and rotation compensate for the diminished control of more-distal movements, c) more commonly, the non-paretic side is used for unimanual task which may result in arm non-use phenomenom of the paretic upper limb (adapted from Jones, 2017).

Levin et al. (Levin et al., 2002) showed that, like in healthy subjects, when trunk motion is involved in reaching movements made by post-stroke individuals, it begins before and ends after hand motion, which shows that it is fully integrated in the movement. Therefore, the pattern of the relative arm and trunk displacement for reaches to close targets for post-stroke individuals is similar to that observed in healthy individuals reaching to far targets.

Trunk compensation is likely to begin whenever a stroke survivor first attempts to perform an activity with the paretic UL in the normal way that they did before the stroke, at which point it becomes evident that the normal way no longer works (Jones, 2017) That is, trunk compensation can be expected to begin with the resumption of movement very early after stroke, but the process of becoming adept in the new ways of moving involves motor skill learning. Even long after the stroke event, new compensatory movement patterns can be developed in response to motor training (Jones, 2017).

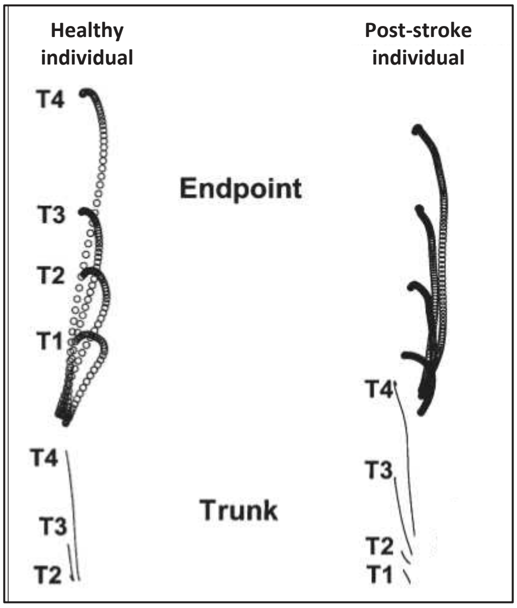


Figure 1.4. Representative hand endpoint (circles) and trunk (lines) trajectories for one healthy participant and one post-stroke participant: T1 for the closest target to T4 for the furthest target. When the healthy participant made reaches to target 1 and 2 there was no trunk movement to T1 and a little movement to T2 (bottom left). However, the post-stroke participant used significantly more trunk movement for reaches to all targets and especially to targets 1 and 2 (bottom right) (From Levin et al., 2002).

Mechanism(s) for the recruitment of the trunk during reaching within arm's length

The excessive recruitment of the trunk in post-stroke individuals during reaching can be explained by several mechanisms.

For example, the inability to extend the UL may be limited by weakness of the agonist muscles of the shoulder (anterior deltoid), and elbow (triceps brachii) joints and/or by the excessive antagonist muscle activation of the elbow (biceps brachii) joint. The motor system may exploit the redundancy of the motor system, such that lost elements of the motor pattern (shoulder flexion-elbow extension) are substituted by new elements (trunk flexion) to achieve the functional goal. This adaptation post-stroke may be due to neural plasticity during recovery. For Takeuchi and Izumi, compensatory movements contributes to “maladaptive plasticity” (Takeuchi and Izumi, 2012a). The use of trunk compensation to extend the UL might shape the maladaptive plasticity interfering with plasticity, which could support greater range of elbow joint. The persistence of trunk compensation may be due to experience dependent plasticity (Jones, 2017).

The greater trunk use during reaching could also be due to the decrease in the ability to make isolated movements with the paretic UL (relative to the immobile trunk) that could be seen as an abnormal stereotype. Thus, an unsuccessful attempt to produce a movement in a joint/limb (such as the elbow-shoulder joints of the paretic UL) leads to the involuntary movement of another connected segment (such as the trunk), producing a stereotypical movement of fixed motion, securing the elbow in a flexion stereotype position (Bobath, B., 1990). Evidence for this flexion stereotype movement has been shown by post-stroke individuals who seem to control the movement proximally at the trunk and shoulder level, while simultaneously freezing the elbow, wrist and hand in a pre-adjusted mid-position during the transport phase of the reaching task (Kwakkel et al., 2004). The additional trunk recruitment might replace the lack of shoulder (flexion/adduction) and elbow (extension) movement and provide more stability.

Lower threshold for activation of the trunk musculature than paretic UL musculature could be another mechanism, since the control of the trunk is bilaterally organised and consequently less affected by a hemiparetic stroke than the paretic UL. In fact, following a stroke, there is a relative preservation of the trunk musculature by greater ipsilateral corticospinal projections to motor neurons controlling the proximal muscles compared to the distal muscles as well as by the bilateral innervation of the trunk musculature (Carr et al., 1994), possibly causing greater involvement of the trunk with the UL (Cirstea and Levin, 2000). Some arguments are in favour of an adaptive strategy, since the direction of the trunk movement seems to be appropriate to the intended direction, and its amplitude would be controlled in gradation, depending on the distance of the object. In addition, the movement of the trunk begins before the movement of the hand (Levin et al., 2002; Roby-Brami et al., 1997).

Another explanation for the trunk use may be the anticipated need by the motor system to preserve hand trajectory smoothness or to limit movement errors (Cirstea and Levin, 2000). The interactions between components involved in reaching are likely to be highly elaborate to produce smooth endpoint movement (Kaminski et al., 1995) an thus the trunk may be recruited in order to preserve trajectory smoothness even in the presence of a disrupted shoulder-elbow coordination

(Levin, 1996). In a study using four targets placed at different distances (two within and two outside the arm length), Levin et al. (2002) demonstrated that the relative contribution of trunk displacement to hand displacement was greater in people with hemiparesis compared to the control group. However the coordination between the movements of the arm and the trunk was preserved. This study, as well as others (Archambault et al., 1999; Roby-Brami et al., 1997) have consistently shown a relative preservation of the trajectory of the hand during reaching movements. Thus, rather than a pathological stereotype arising from the stroke lesion, trunk movement could be a strategy used by the motor system after a stroke in order to preserve the trajectory of the hand despite the presence of abnormal coordination between shoulder and elbow movements (Levin, 1996). The possibility that the involvement of the trunk may be related to the need to adopt a more frontal hand posture for grasping as has been observed in some post-stroke individuals (Roby-Brami et al., 1997).

Mandatory/adaptive and non-mandatory/maladaptive trunk compensation during reaching

Despite the UL impairments after stroke, even individuals with the most severe motor impairments can reach into all parts of the workspace with their paretic UL (using trunk flexion) and non-paretic UL (arm non-use developed in section 1.3.3). In a reaching task, the trunk compensation is considered mandatory when the post-stroke individual has not recovered motor control of the paretic UL (shoulder flexion and elbow extension). Therefore, the trunk compensation could be the best option for those with the most-severe impairments, such that the trunk compensation is mandatory to achieve the reaching task.

Post-stroke individuals who have preserved/recovered functional capacity of their paretic UL, can persist in using "non-mandatory" trunk compensation to perform reaching tasks in everyday life activities (Dromerick et al., 2006). However, the strategies of relying on proximal body movements (trunk flexion) instead of proximal arm movements (shoulder flexion-elbow extension) can encourage the non-use of any residual UL capacity for better overall functionality (Alaverdashvili, 2008; Jones, 2017; Levin et al., 2015; Michaelsen et al., 2001). This non-mandatory trunk compensation is well shown by well-recovered post-stroke individuals who do not use their UL in activities of daily living. In fact, reaching deficits in well-recovered post-stroke individuals are not as apparent because these post-stroke individuals regain high levels of motor control (low impairment) and function in their paretic UL. However, follow-up studies of well-recovered post-stroke individuals have revealed that these individuals are not using their paretic UL to the full extent expected of them in activities of daily living and also report feeling less confidence in using their UL (Rand and Eng, 2012).

1.2.3 Summary

Despite the fact that post-stroke individuals with hemiparesis are capable of reaching targets placed in front of them within arm's length, kinematic analysis indicates that coordination between the elbow and the shoulder during these movements is compromised. Therefore, this section has provided evidence on the active role of the trunk during reaching tasks as a compensatory mechanism between the trunk and the arm to maintain the trajectory of the hand. The trunk compensation can be mandatory for severe deficits and non-mandatory for mild to moderate deficits.

1.3 Evaluation of paretic UL recovery versus trunk compensation

Improvement after stroke is considered as « True (neurological) recovery » when reflecting the return or restitution (or repair) of body functions (or reduction of impairments), which results in the reappearance of the same end effectors during task performance (Krakauer et al., 2012). There are strong indications that motor recovery after stroke occurs to a large extent through behavioural compensation, rather than via processes of true recovery alone (Kwakkel et al., 2004)

As explained in the previous section, one typical compensatory strategy used by post-stroke individuals is the use of the trunk to compensate for a shoulder-elbow joint motion deficit of the paretic UL (Roby-Brami et al., 1997). This is represented by post-stroke individuals moving the trunk to bring the hand to the target instead of flexing the shoulder and extending the elbow. This self-taught trunk compensatory strategy is likely to aid in achieving functional reaching tasks of daily living (Cirstea and Levin, 2000) which is mandatory for severe deficits and non-mandatory for mild-to moderate deficits.

A problem in studies evaluating clinical outcomes is that the term 'recovery' is used to describe clinical improvements without differentiating between the different processes involved (Floor et al., 2013). It is essential to be explicit when talking about the definition of recovery, and to refer to the different levels of the International Classification of Functioning, Disability and Health (ICF) as suggested by Levin and colleagues (Levin et al., 2009). In the most recent version of the ICF framework put forward by the World Health Organisation human functioning is described at three levels (World Health Organization, 2001) —1) the body or body part, 2) the whole person, and 3) the whole person in relation to his/her social context (Figure 1.5 and Table 1.1). Outcome measures may be assessed at any of these levels—i) Body Function/Structure (formerly referred to as impairment); ii) Activities (refers to the whole person—formerly referred to as disability) and iii) Participation (referred to as contextual factors within the ICF). Activity level is subdivided into capacity and performance (Lemmens et al., 2012). Activity and Participation are affected by environmental and personal factors (Salter et al., 2005).

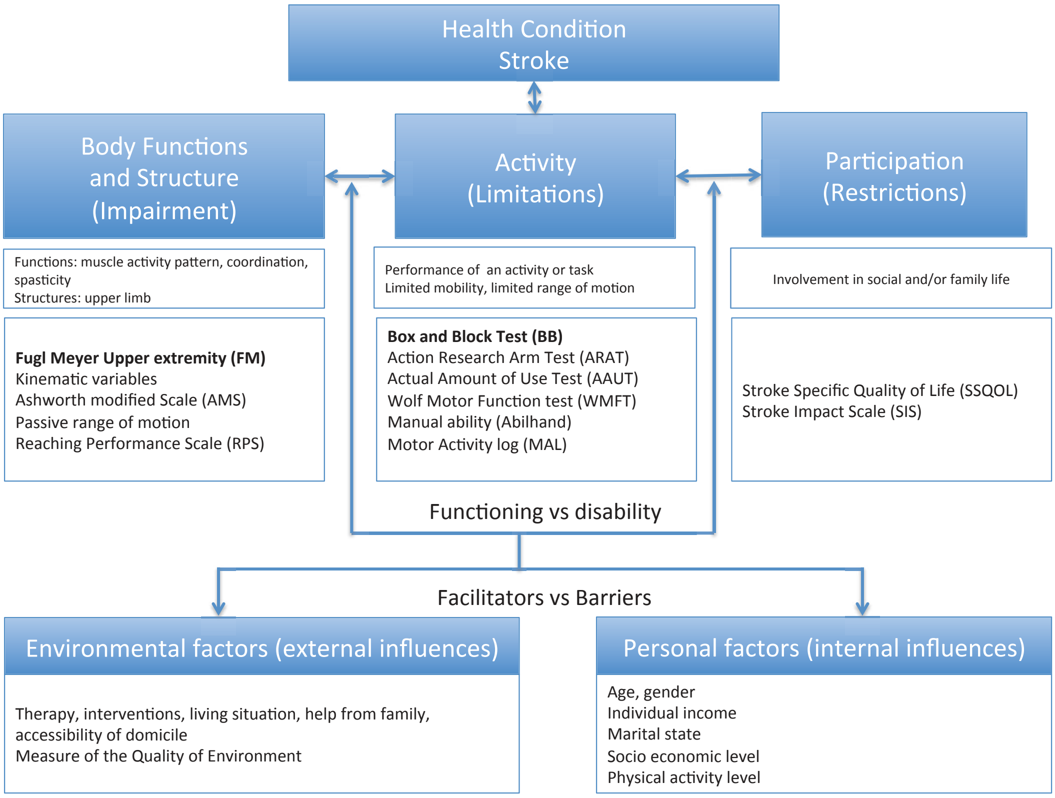


Figure 1.5. International Classification of Functioning levels and subdivisions for stroke (Adapted from Levin et al 2009; Langhorme et al 2011; Lemmens et al., 2012; Salter et al. 2013 and Calvalhopinto et al., 2016).

In this thesis, in order to keep an international language and standard for measurement, the ICF framework was chosen to classify the motor consequences of stroke at two levels: 1) Impairment level (aimed at Body Function/Structure), and 2) Function level (aimed at skills, task execution and activity completion). Figure 1.5 shows a number of clinical scales that are commonly used to measure the level of UL motor impairment and function. Impairment scales, such as the Fugl Meyer (FM) measure specific motor aspects that may limit but are not related to task accomplishment (spasticity, strength, isolated joint motion), whereas functional scales such as the Box and Blocks (BB) test measure the level of task success (reaching, grasping, moving blocks). .

Functional gains, however, can occur even in the absence of true paretic UL motor recovery (i.e., lost motor patterns such as elbow extension and shoulder flexion have not returned). For example, with intensive task-oriented training, post-stroke individuals with poor paretic UL motor recovery may improve movement speed and precision by recruiting the trunk instead of using elbow extension and shoulder flexion (Levin et al., 2009). Finally, to distinguish recovery and compensation, we used the Levin's (Levin et al., 2009) definitions of motor recovery and motor compensation in order to clarify terminology used in the literature.

Table 1.1. Definitions International Classification of Functioning terms.

Term	Definition	References
Health condition level	Variables about health status and assistance received from the health-care unit. Recovery: *Restoring function in neural tissue that was initially lost after injury.* May be seen as reactivation in brain areas previously inactivated by the circulatory event. Although this is not expected to occur in the area of the primary brain lesion, it may occur in areas surrounding the lesion (penumbra) and in the diaschisis. Compensation: *Neural tissue acquires a function that it did not have prior to injury.* May be seen as activation in alternative brain areas not normally observed in nondisabled individuals.	Calvalhopinto et al., 2016 Levin et al, 2009 Levin 2009
Body function/ structure level (Impairment)	Physiological functions of body systems including psychological. Structures are anatomical parts or regions of their bodies and their components. Impairments are problems in body function or structure. Recovery: *Restoring the ability to perform a movement in the same manner as it was performed before injury.* This may occur through the reappearance of premorbid movement patterns during task accomplishment (voluntary joint range of motion, temporal and spatial interjoint coordination, etc). Compensation: *Performing an old movement in a new manner.* May be seen as the appearance of alternative movement patterns (ie, recruitment of additional or different degrees of freedom, changes in muscle activation patterns such as increased agonist/antagonist coactivation, delays in timing between movements of adjacent joints, etc) during the accomplishment of a task.	Salter et al., 2013 Levin et al., 2009 Jones, 2017 Levin 2009
Activity level (Disability)	The level of execution of meaningful tasks by an individual. The execution of a task by an individual. Limitations in activity are defined as difficulties an individual might experience in completing a given activity. Recovery: *Successful task accomplishment using limbs or end effectors typically used by nondisabled individuals.* Compensation: *Successful task accomplishment using alternate limbs or end effectors.* For example, opening a package of chips using 1 hand and the mouth instead of 2 hands.	Salter et al., 2013 Levin et al., 2009 Levin et al., 2009
Capacity	The highest possible level of functioning of a person in a given domain at a given moment, measured in a standardized environment.	
Perceived performance	The level of functioning subjectively experienced by a person in a given domain at a given moment in his/her current environment.	Lemmens et al., 2012
Actual performance	The objectively detectable level of functioning of a person in a given domain at a given moment in his/her current environment.	
Amount of use	How often (frequency) or how much (quantity) the arm-hand is used.	Lemmenset al., 2012
Quality of use	The quality with which the arm-hand is used during tasks or movements.	Lemmens et al., 2012
Participation level (Handicap)	Involvement of an individual in a life situation. Restrictions to participation describe difficulties experienced by the individual in a life situation or role.	Salter et al., 2013

1.3.1 Evaluation of paretic UL recovery versus trunk compensation at the impairment level

a) Clinical evaluations of paretic upper limb impairment

Manual muscle testing: Assessment of weakness

Clinically, weakness results in slower, less accurate, and less efficient movements compared to those in healthy individuals (Lang et al., 2013). Weakness (paresis) may be quantified in terms of range of active joint motion and muscle strength as the ability of the post-stroke individuals to perform movements of individual joints or groups of adjacent joints (Levin et al., 2009). Manual muscle testing of the UL by lateral extension can be used to assess the range of active shoulder and elbow joint motion.

Modified Ashworth scale: Assessment of spasticity.

The presence or absence of resistance to passive range of motion associated with spasticity can be assessed by the Modified Ashworth Scale - MAS (Bohannon and Smith, 1987). In the MAS, the therapist flexes as fast as possible the elbow to assess the triceps brachii muscle and vice versa for extending the elbow to assess the biceps brachii msucle. The sensation of resistance while moving the joint passively through its range of motion, and the degree of resistance is classified (McCrea et al., 2002).

The Fugl Meyer.Assessment of upper limb fractionation of movement:

The FM is a stroke-specific performance-based impairment measure (Fugl-Meyer et al., 1975; Gladstone et al., 2002) that provides assesment of several types of UL impairement (increase of muscle tone, lack of range of motion, decrease of fractionation of UL movements, and voluntary motor control). The UL subsection of the FM assesses the ability of the subject to make isolated movements within and out of pathological stereotype patterns. The UL section has 33 items including: movement observation, reflex testing, grasp testing and coordination. A three point scale from 0 (unable to perform) to 2 (able to perform) totaling 66 for the UL portion (Lang et al., 2013). This assessment includes an evaluation of muscle tone, range of motion, tendon reflexes, and the performance of proximal (/42) and distal (/24) voluntary movements of the paretic UL. A maximum score of 66 indicates normal UL structure. At the impairment level, FM demonstrated the strongest level of measurement quality and clinical utility (Alt Murphy et al., 2015).

b) <u>Reaching Performance Scale (RPS): Distinction between recovery and compensation</u>

Although the different impairment scales may offer the clinician an appreciation of UL impairment level, they lack quantitative control and measurement and moreover neither of them can distinguish recovery from compensation (Alaverdashvili, 2008; Cirstea and Levin, 2000; Levin et al., 2009). To our knowledge, the Reaching Performance Scale (RPS) (Levin et al., 2004) is the only quantitative evaluation method of trunk compensation at the impairment level. In fact, the RPS evaluates UL and trunk movement quality while reaching and grasping for an object placed close to and far away from the body of the seated subject. Six components are scored: trunk displacement, movement smoothness, shoulder and elbow movements, quality of prehension and the overall accomplishment of the task. A score of 18/18 is indicative of a smooth reaching movement without trunk compensatory movements.

1.3.2 Evaluation of paretic UL recovery versus compensation at the function level

At the function level, recovery requires that the task is performed using the same body part and joints in the same movement patterns typically used by non-disabled / healthy individuals (Floor et al., 2013; Levin et al., 2009); while capacity is defined as the highest level of functioning (Lemmens et al., 2012). Most frequently cited assessments of recovery are presented in Figure 1.5.

a) Clinical evaluations of paretic upper limb function

Box and Block Test of upper limb functional capacity

The Box and Block test (BB) test is as a functional measure of UL capacity, which is designed to be a quick and easy to administer assessment. BB quantifies UL function limitations by a post-stroke individual 's ability to grasp, transport, and release small blocks with their hand (Mathiowetz et al., 1985). Individuals are asked to move as many one-inch blocks across the centre of the test box in one minute. Better function is indicated by a higher number of blocks moved with the score being compared to established norms or to non-paretic UL (Lang et al., 2013). A recent review reported that the BB Test is best assessment at the function level having the strongest level of measurement quality and clinical utility (Alt Murphy et al., 2015).

Wolf Motor Function Test of upper limb functional capacity

The Wolf Motor Function Test – WFMT (Wolf et al., 2001) measures the movement quality including the configuration of the examined UL and measurement of compensatory movements (Shishov et al., 2017; Subramanian et al., 2010). The WMFT quantifies UL motor ability through 15 timed and functional tasks, which yields two scores: 1) a functional ability score quantifying quality of performance, and 2) a timed score quantifying speed of performance in seconds (Levin et al., 2009). The 15 tasks are arranged in order of complexity and progress from proximal to distal joint involvement that test total UL movement and movement speed, and require few tools and minimal training for test execution (Wolf et al., 2001). The main problem with the WMFT is the time required to complete all items of the assesmment, which can take up to 1 hour.

b) Distinction between recovery and compensation at the function Level

At the Function level, both situations i.e., recovery and compensation mean that post-stroke individuals are able to accomplish the task, but they differ greatly in the way the task is performed, in terms of quality of motor function (Floor et al., 2013). Most of UL functional assessments concerned with the ability to achieve a task treat all the physiological structures and possible impairments as a black box, scoring function on a “can” or “cannot” basis. However, the post-stroke individual can get a perfect score for accomplishing the task using trunk compensatory strategies if the scale does not mention how the task is performed. In fact, an activity may be successful or partially successful using compensatory motor strategies at impairment level (Forward displacement of the trunk) but such scales do not provide information on specific strategies used (Levin et al., 2009). Therefore, these assessments fail to provide valuable information about the strategies and mechanisms underlying abnormal reaching (McCrea et al., 2002). However, other scales allow for a partial score to be given if the task is partially completed or done too slowly or with difficulty. For example, the WFMT can be used to distinguish between recovery and compensation in terms of function motor outcome (Levin et al., 2009). Most clinical outcome measures of the paretic UL function do not account for trunk involvement in their final scoring system. An example is the BB test where the final score is based only on the accomplishment of the task (Floor et al., 2013). This also indicates that without quantifying the quality of task performance, it is not possible to distinguish restitution of function as a result of neurological repair from compensation strategies, especially when post-stroke individuals are using the same end effectors to accomplish the specific task (Floor et al., 2013; Levin et al., 2009). Therefore, this assessment fail to provide valuable information about the strategies and mechanisms underlying abnormal reaching (McCrea et al., 2002). However, the WFMT can be used to distinguish between recovery and compensation in terms of function motor outcome (Levin et al., 2009)..

Current clinical measures of UL impairment (e.g., FM test) and function (e.g., BB test) may not capture the non-mandatory trunk compensation of well-recovered post-stroke individuals. Over time, with continued use of the trunk compensation during paretic UL movements there is a risk of losing more UL function because non-use of the paretic UL can cause further muscular and neurological deterioration following the principle of « use it or lose it », leads to a non-mandatory or maladaptive trunk compensation scenario.

1.3.3 Evaluation of arm non-use

It should be noted that outcomes of capacity measures and UL use measures may differ strongly; e.g,. the highest level of functioning versus functioning in activities of daily living. The preference given to compensatory strategies, when non-compensatory strategies are possible, defines the arm non-use phenomenon (Taub et al., 2006). The arm non-use of the paretic UL is the difference between what a patient can do when requested to do it, and what the patient actually does spontaneously (Han et al., 2013; Sterr et al., 2002). Lemmens et al. showed that although information about the highest level of functioning (capacity) may be very useful, it does not reveal valid information about the functioning of a post-stroke individual in daily life (how they use the UL in home environments, see Figure 1.6). It is well known that a large difference may exist between capacity and arm use (Lemmens et al., 2012). Four years after stroke, 67% of the post-stroke individuals experience the non-use or disuse of the paretic UL as a major problem, whereas only 6% of the post-stroke individuals are satisfied with their arm-hand function (Lemmens et al., 2012).

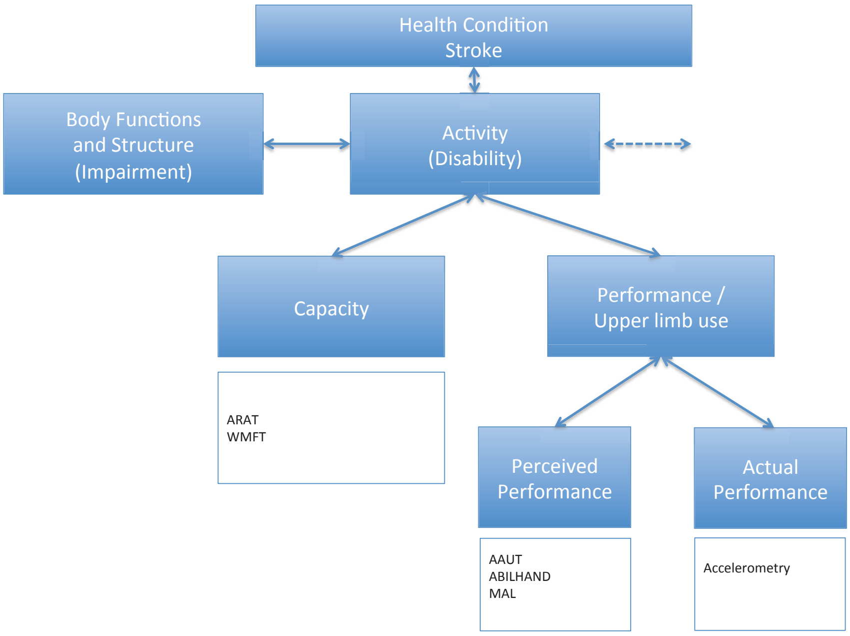


Figure 1.6. Stroke specific subdivisions of upper limb use at the activity level (adapted from Lemmens et al., 2012).

a) <u>Evaluation of global paretic arm non-use (difference between capacity and use)</u>

Arm non-use: Definitions in ICF

The arm non-use is usually defined as the difference between the UL capacity and UL use with the measurement of capacity being objective, while the measurement of UL use can be objective (Actual arm use) or subjective (perceived arm use), see Table 1.1 and Figure 1.6. When assessing arm use, two kinds of instruments are available. On the one hand, questionnaires can be used to measure perceived arm use and on the other hand, actual arm-use can be measured by direct and objective assessment in real-life situations (Lemmens et al., 2012).

Capacity is defined as the highest level of functioning (Lemmens et al., 2012) and many studies evaluate the UL capacities of their subjects using functional tests (Kitago and Krakauer, 2013) that often include more complicated movements with multiple degrees of freedom, resemble real-life activities, and are categorized under the “activities” domain of the ICF classification (Shishov et al., 2017; Sivan et al., 2011).

Questionnaires used to assess “perceived arm-use” take the perspective of the post-stroke individual into account, which may be desirable but also has disadvantages. These questionnaires rely on recall and valid reporting of the post-stroke individual. (e.g., Motor Activity log - MAL).

Actual arm-use can be measured by direct and objective assessment of activities of daily living. For example, Actual Amount of Use Test (AAUT) measures the spontaneous use of the paretic UL in daily life activities

Clinical evaluations of arm non-use

Using classical clinical tests (see Table 1.2), one can extract the non-use of the paretic UL can be extracted from the difference between the Wolf Motor Function Test (WMFT) and the Motor Activity Log (MAL) (Taub et al., 2006). Another method compares the spontaneous use of the paretic UL in daily life activities (AAUT and MAL) with the ability of the paretic UL to perform the same tasks when requested to do so (Sterr et al., 2002).

Instrumental evaluation of arm non-use

Although these previous subjective clinical scales may offer the clinician an appreciation of paretic arm non-use and impairment, more detailed kinematic analysis of motor patterns during functional tasks would provide quantative even more important information about movement strategies and motor compensations. The Bilateral Arm Reaching Test (BART) is an instrumental method (kinematic analysis, see Table 1.2) that quantifies the paretic arm non-use by comparing the hand reaching in a spontaneous hand choice condition and in constrained use condition (Han et al., 2013).

Table 1.2. Measures of paretic arm non-use

References	Type of paretic arm non-use	Calculation of the paretic arm non-use	Forbidden movements	Allowed compensations
(Taub et al., 2006)	Global (Versus Non-paretic arm)	$_{normalized}$WFMT- $_{normalized}$ MAL	None	All
(Sterr et al., 2002)	Global (Vs Non-paretic arm)	$_{forced}$AAUT - $_{spontaneous}$ AAUT	None	All
(Han et al., 2013)	Reaching (Vs Non-paretic arm)	$_{forced}$BART - $_{spontaneous}$ BART	Trunk	Non-paretic arm
PANU method	Reaching (Vs trunk use)	$_{forced}$ PAU - $_{spontaneous}$ PAU	Non-paretic arm	Trunk

WFMT = Wolf Motor Function Test; MAL = Motor Activity log; AAUT = Actual Amount of Use Test; BART = Bilateral Arm Reaching Test; PAU = Proximal Arm Use; PANU = Proximal Arm Non-Use. In all cases, the arm non-use of the paretic upper limb is the difference between a forced-use condition and a spontaneous-use condition. Taub et al.(Taub et al., 2006) used the normalisation of two different assessments (WMFT – MAL), but the others used the same assessments for the forced and spontaneous scores.

b) Development and assessment of Proximal Arm Non-Use

Development of proximal arm non-use following a stroke

The mechanism(s) of excessive trunk recruitment during reaching by the paretic UL were discussed in the previous section, which suggests this compensatory behaviour may be an adaptation of the motor system during early recovery from stroke, to obtain a short-term reduction of the disability (Levin et al., 2002; Roby-Brami et al., 1997) However, this trunk compensation may be maladaptive and detrimental in the long term since, by providing an alternative method for the hand to reach an object, the system is less motivated to use a solution requiring recovery of lost movement elements (such as elbow extension or shoulder flexion). Previous studies have shown that hemiparetic post-stroke individuals with poor initial recovery use more compensatory trunk movement during reaching, but that during the course of recovery or training, those who achieve better UL function use more elbow extension and shoulder flexion while decreasing trunk movement (Cirstea and Levin, 2000; Roby-Brami et al., 1997)

Evaluation of proximal arm non-use during reaching using kinematic analysis

Outside of the laboratory, increased reliance on the non-paretic hand is a dominant stategy (Jones, 2017). In the laboratory, stroke survivors who are not told which hand to use to reach for objects will typically perform unimanual tasks with the non-paretic UL. In the same way, even when stroke survivors are restricted to use the paretic UL and are not instructed to not use trunk compensation, they will typically perform reaching tasks with their paretic UL by using forward displacement of the trunk instead of using shoulder flexion and elbow extension (see Figure 1.3). Although as explained in the previos section, mandatory compensatory trunk movements may help post-stroke individuals perform tasks in the short term, the use of trunk compensation may lead to long-term disability such as reduced range of joint motion and pain (Ada et al., 1994). Also, permitting the use of trunk compensation could lead to a pattern of arm non-use, limiting the capacity for some gains in motor function of the paretic UL (Levin et al., 2009).

Several methods can assess arm non-use when given the chance of using eiher the paretic or non-paretic UL (Table 1.2) and such quantification is important because arm non-use is suspected to be detrimental to true recovery (Roby-Brami et al., 2003; van Kordelaar et al., 2012b). However no assessments measure proximal arm non-use within the paretic arm itself (i.e., shoulder – elbow non-use).

Non-use at the level of the paretic shoulder and elbow is expressed through excessive and non-mandatory trunk movements while reaching towards a target. In seated reaching, compensation with the trunk is the negative picture of the proximal arm non-use, which is suspected to limit the recovery of 'near-to-healthy' motor patterns of the paretic UL (Jeyaraman et al., 2010; Levin et al., 2009; Roby-Brami et al., 2003). In fact, shoulder-elbow non-use (i.e, proximal arm non-use) may not be targeted in rehabilitation because it is not being measured with current clinical tests. Tests such as the FM and BB that measure paretic UL impairment and function, respectively, may not have the sensitivity to detect the shoulder-elbow non-use, maladaptive trunk compensation during the reaching.

Evaluations distinguishing recovery and compensation

Kinematic movement quality measures are valid and sensitive for recognizing UL impairments of post-stroke individuals performing reach-to-grasp tasks (Subramanian et al., 2010). Moreover Kinematic variables are suggested to be valid for differentiating compensation from recovery and for measurement of UL impairment (Shishov et al., 2017; Subramanian et al., 2010). For example, Roby-Brami and colleagues showed that reaching movements are characterized by spatiotemporal incoordination between the arm and the trunk (Roby-Brami et al., 1997). Their study indicated that post-stroke individuals use a new pattern of coordination represented by more trunk recruitment during reaching.

1.3.4 Summary

The non-mandatory or maladaptive trunk compensation during reaching reflecting the non-use of the shoulder and elbow defined, as proximal arm non-use has never been measured. However, objective kinematics to measure it could give access to distinguish paretic UL recovery from compensation. Even if there are no current assessment methods of proximal arm non-use in clinical practice, the therapists and researchers are already trying to find therapy to counteract the maladaptive trunk compensation, which will be developed in the next section.

1.4 Rehabilitation of the paretic to counteract maladaptive trunk compensation

1.4.1 Aim of rehabilitation of the paretic upper limb

Rehabilitation, by definition, aims at enabling people experiencing or likely to experience disability, to achieve and maintain optimal functioning in interaction with the environment (Shirota et al., 2016). Measurement at the impairment and function is essential to understand the response to treatment at each level, but equally to begin to understand relationships between levels (e.g., impairment and function). A selection of outcome measures at each level must be used in order to evaluate the level of impact of any rehabilitation treatment (Levin et al., 2009). For example, a reduction in impairment (FM) may or may not result in improved function (BB) of the UL.

1.4.2 Trunk restraint or forced-use of the paretic upper limb

Wolf et al. (1989) showed that arm non-use can be reversed through application of a forced use of paretic UL paradigm (Wolf et al., 1989). Shoulder-elbow coordination in the paretic UL can be improved simply by preventing compensatory trunk motion and also through rehabilitation. In fact, Michaelsen et al. (Michaelsen et al., 2001) demonstrated that moderate to mild impaired post-stroke individuals are actually able to produce greater elbow extension during reaching than they use spontaneously. If trunk motion is restrained, coordination between the elbow and shoulder improves. This unused motor capacity (i.e., shoulder-elbow use or coordination) can be enhanced and generalised into daily activities through a period of training with trunk restraint (Michaelsen et al., 2006; Michaelsen and Levin, 2004).

Recovery of isolated reaching ability after training programmes incorporating different forms of trunk restraint or feedback on excessive trunk use has been characterized by decreased maladaptive trunk compensation and improved UL kinematics (Levin et al., 2015). Trunk restraint has been proposed as a method of restraining the maladaptive trunk movements that can arise post-stroke, while encouraging the recovery of normalized reaching patterns and function (Pain et al., 2015). In fact, Trunk restraint, in combination with strengthening and task-oriented approaches, has been shown to improve dissociation between the trunk, shoulder and elbow when reaching targets within arm's length. By restraining excessive trunk movement, it has been suggested that "Trunk Restraint" encourages shoulder and elbow movements that are not spontaneously recruited in the stroke population (Pain et al., 2015). To provide trunk restraint, a clinician might consider the use of a harnessing device to provide physical restraint, auditory, visual cues to encourage self-restraint, or a combination of both.

a) Physical restraint: Harnessing device for trunk / strap

When time and staffing resources are limited, a physical restraint (Figure 1.7) may be appropriate for post-stroke individuals' reaching exercises within arm's length. The method of physical restraint such as a strap (Bang et al., 2015) or a harness (Alankus and Kelleher, 2015) or seat belt (Park et al., 2016) are types of restraints that may prevent anterior trunk flexion, while others may prevent anterior/lateral flexion and rotation of the trunk, as well as compensatory scapular elevation.

Figure 1.7. Trunk restraint by a harness during reaching training (De Oliveira et al., 2015).

b) Wearable system

Ranganathan et al., (Ranganathan et al., 2017) developed a wearable sensor system that is capable of detecting compensatory trunk movements in a wide range of UL activities. The wearable system consists of 3 wearable devices that are mounted on the trunk, UL and forearm segments (Figure 1.8). Each device consists of a 3-axis accelerometer and a 3-axis gyroscope, which was used to measure the acceleration and angular velocity of these segments during movement. In addition a small vibrotactor placed on the UL, which can be used to produce a small "buzz" whenever a trunk compensatory movement is detected.

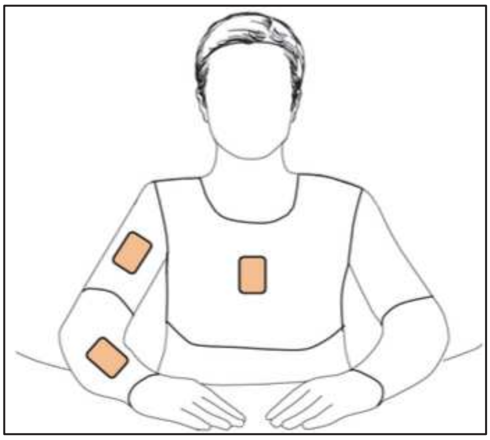


Figure 1.8. Wearable devices during reaching task (Raghanatan et al., 2017).

Alankus and Kelleher (Alankus and Kelleher, 2015) used Wii remotes as inexpensive sensors to detect exercice and trunk compensation. A Wii remote on the UL with a commercial arm strap and a Wii remote on the torso with a lab made harness (Figure 1.9). They, also, developed a game that meaningfully uses UL exercise and trunk compensation as inputs, and use incentives and disincentives to reduce compensation.

Figure 1.9. Harness detecting trunk compensation (Alankus et al, 2015)
.

c) Auditory feedback

A second method of trunk restraint is the use of pressure sensors, which provide an auditory feedback signal when the trunk moves away from the back of a chair. This method cues the individual to engage in self-restraint of the trunk, while encouraging paretic UL range to achieve the reaching goal. Auditory cues provided as the subject practices varying degrees of self-restraint (i.e. during Bobath-based treatment). The sensory feedback provided from the restraint may also provide cognitive awareness of the compensatory trunk activity and promote a conscious effort to recruit latent shoulder and elbow activity (Pain et al., 2015).

d) Augmented visual feeback using Kinect-based motion analysis and force feedback using robotics

Valdés et al (Valdés et al., 2017) used augmented visual feedback delivered through a computer monitor, and force feedback through two robotic devices. Trunk compensation was measured by Kinect v2 motion tracking camera.

e) Direct hands-on

When resources permit to emply a therapist, a direct hands-on approach can enable the therapist to manually and verbally provide the required restraint as the patient reaches to different directions, distances and heights. A hands-on approach will also allow the therapist to grade the amount of external restraint

f) Self trunk restraint

Michaelsen et al. (2001) showed that mildly impaired individuals, who do not demonstrate pronounced post-stroke stereotypes, might have a greater potential to learn self-restraint while practicing reaching tasks that target speed and dexterity. As a result, clinicians can vary the method of trunk restraint based on their subject's level of impairment. Trunk restraint appears to be a simple and cost-effective adjunct to stroke interventions, which can potentially improve range of motion and kinematics at the impairment level.

Finally, in deciding when and how to incorporate trunk restraint into clinical practice, a clinician must consider the method of trunk restraint, the severity of neurological impairment, the postural demands of a task, the potential development of alternate compensatory movements, and the functional goals of the patient (Pain et al., 2015). Given that the post-stroke individuals consider that the ‘‘use of the arm in everyday tasks’’ as a primary factor in their paretic UL recovery, it is also important to evaluate how this potential reduction in impairment translates into activity.

1.5 Summary

Post-stroke subjects using maladaptive trunk compensation during reaching need specific rehabilitation. Specific programmes would be provided with “forced-use” of shoulder and elbow motility with the goal to increase the functional use of the paretic UL in real life without the constraints of a lab environment. In this goal, it is important to differentiate subjects for whom trunk compensation is the sole choice to perform a reaching task (i.e., mandatory trunk compensation) and those post-stroke individuals with a potential capacity (reserve) of shoulder-elbow hidden by non-mandatory/maladaptive trunk compensation movements. In this second case, the non-mandatory/maladaptive compensation reflects the shoulder-elbow non-use that is highly suspected to be detrimental to functional recovery, which is the primary goal of the thesis to objectively quantify using motion analysis technologies (Chapter 2 and 3) and then to counteract (chapter 4).

The aims of this thesis were to i) develop an instrumental method using objective motion analysis to quantify the proximal arm non-use during a seated reaching task (PANU score) (Chapter 2), ii) use the PANU scores to determine the level of recovery of the paretic UL in post-stroke individuals and compare PANU score to clinical metrics of UL impairment (Fugl Meyer test) and function (Box and Block test) (Chapter 2), iii) develop and validate a simple marker-less based motion analaysis method (Kinect) to quantify the proximal arm non-use (Chapter 3), and iv) determine the applicability of implementing PANU scores in Kinect based virtual reality UL rehabilitation (Chapter 3 & 4).

The thereotical section of this dissertation (Chapter 1) consists of a literature review to introduce the general subject and includes the prevalence and UL disability following a stroke, a behavioral description of post-stroke versus healthy reaching movements, the assessment of paretic UL recovery versus compensation, and the specific rehabilitation of arm non-use.

Then, the dissertation is divided in 2 parts: an experimental section to present PANU score as a diagnostic and assessment tool (Chapter 2 &3) and a review to approach the use of PANU score in a treatment (chapter 4). In Chapter 2, I propose a novel arm non-use assessment of the paretic UL itself: the shoulder-elbow non-use during a seated reaching task, which is an objective method to quantify the amount of proximal arm non-use in post-stroke individuals using a 3D motion analysis system (CMS20s, Zebris). PANU scores are based on the respective amount of trunk displacement compared to hand displacement, defined in two conditions: spontaneous arm use vs. trunk self-restrained arm use. Chapter 3 develops and validates a more widely available marker-less Kinect based motion analysis system against the standard CMS20s system to quantify the proximal arm non-use. Chapter 4 is a review of innovative technologies of UL rehabilitation particularly using Kinect based virtual reality in order to determine the possible rehabilitation criteria to counteract the proximal arm non-use in order to achieve optimal UL motor recovery.

In the final Chapter 5 the specific interest of the proximal arm non-use in paretic UL rehabilitation (diagnosis and treatment) is evaluated in a general discussion/conclusion.

In the next chapter, an instrumental methodology was developed to quantify the shoulder-elbow non-use or proximal arm non-use (PANU score). The next study is a validation of the PANU score in post stroke individuals.

2 CHAPTER 2 – PROXIMAL ARM NON-USE WHEN REACHING AFTER A STROKE

K.K.A. Bakhti, D. Mottet, N. Schweighofer, J. Froger, I. Laffont.

Proximal arm non-use when reaching after stroke.

Neurosciences Letters.

Abstract

After a stroke, many people "cannot and do not" use their paretic upper limb. With recovery, some people "can but do not" use their paretic upper limb and this non-use should be counteracted with specific rehabilitation.

The aim of the study was to quantify one aspect of the non-use: proximal arm non-use when reaching within one's arm length in 45 post-stroke and 45 age matched controls. Arm use refers to the contribution of the shoulder and elbow motion to the hand movement towards the target. Proximal arm non-use is calculated as the ratio of the difference between spontaneous arm use and maximal arm use.

We found that proximal arm non-use has very good test-retest reliability, does not depend on time since stroke, increases with impairment (Fugl-Meyer) and loss of function (Box & Block), and most importantly, that 61% of patients with lower impairment (Fugl-Meyer >28/42) exhibit proximal arm non-use.

We conclude that quantifying proximal arm non-use in post-stroke individuals provides novel information that complements routine clinical measures. It is likely that proximal arm non-use quantifies one aspect of the motor reserve that therapists can target in patient specific rehabilitation programs.

Key Words:

Kinematic analysis; non-use; reaching; stroke; upper-limb

2.1 Introduction

About 80% of stroke survivors suffer a reduced ability to use their paretic upper limb, and this is a challenge for therapists. Among people with stroke, some “can but do not” use the paretic arm, to paraphrase the title of the first paper that discussed this non-use phenomenon, and this non-use should be counteracted with specific rehabilitation.

The most classical form of non-use after stroke is the non-use of the paretic arm in daily life. Individuals post-stroke often under-use their paretic arm, and compensate for this with excessive use of the non-paretic arm (Taub et al., 2006). Using clinical tests, therapists can detect the non-use of the paretic arm by comparing the spontaneous use of the paretic arm in daily life activities (Actual Amount of Use Test or the Motor Activity Log) with the maximal use of the paretic arm when requested to do so in clinical settings (Sterr et al., 2002). Using a bilateral arm choice test, in which one reaches 100 targets at various distances and directions, researchers can quantify the non-use of the paretic arm by subtracting its probability of use in a spontaneous choice condition from the probability of its use when forced to do so (Han et al., 2013). From the previous measures, it comes that the non-use is not a mere measure of use, but a difference in use. Non-use is the result of the comparison of spontaneous use and maximal use (Sterr et al., 2002), and it is quantified as maximal use minus spontaneous use (Han et al., 2013), patient by patient.

Besides paretic arm non-use, a prevalent form of non-use occurs during reaching movements with the paretic arm. Individuals post-stroke often under-use shoulder and elbow joints when reaching within one’s arm length, and compensate with excessive trunk movements (Cirstea and Levin, 2000; Levin et al., 2002; Roby-Brami et al., 2003). Proximal arm non-use is the persistence of such under-use of shoulder and elbow joints for patients with sufficient recovery of arm function. As with all non-use measures, proximal arm non-use is the result of the comparison of spontaneous use and maximal use, which entails two measurements of proximal arm use (Taub et al., 2006). In the specific case of seated reaching, trunk compensation can inform about proximal arm use, because the hand is the end effector of the kinematic chain formed by the trunk, the arm and the forearm (Robertson and Roby-Brami, 2011): patients can compensate for under-use of one joint with over-use of another joint, within certain limits. Using clinical tests, therapists can identify trunk compensation and its counterpart in terms of under-use of shoulder and elbow joints. The Reaching Performance Scale, in which the therapist visually decomposes the reaching movement into its sub-elements, is best suited for that (Levin et al., 2004). Using kinematic analysis in a seated reaching movement, researchers can quantify trunk compensation, as well as shoulder and elbow joint contributions (Subramanian et al., 2010). In fine, proximal arm non-use will be given by comparing the spontaneous use of the arm with the maximal use of the arm.

Though measuring proximal arm non-use seems doable, it received little attention up to now, most likely because researchers focused on only measuring trunk compensation per se (Levin et al., 2002; Robertson and Roby-Brami, 2011; Roby-Brami et al., 2003; van Kordelaar et al., 2012a). From a rehabilitation point of view, because paretic arm non-use can persist at various stages of impairment (Taub et al., 2006), measuring proximal arm non-use is important to distinguish recovery from compensation (Levin et al., 2009) and to quantify the amount of shoulder and elbow movements that a post-stroke individual can relearn to use over therapy (Michaelsen et al., 2006).

In this study, we aimed to quantify proximal arm non-use when reaching within one's arm length in a seated position, for patients post-stroke and for healthy age-matched individuals. We use kinematic analysis to define a score of proximal arm non-use (PANU score), assess test-retest reliability and relation to arm function (Box & Block Test) and impairment (Fugl-Meyer). First, we hypothesize that PANU score will be higher for the paretic hand than for the non-paretic hand or for control participants. Second, we hypothesize that PANU score will be strongly related to function and weakly related to impairment, because paretic arm non-use can persist at various stages of impairment (Taub et al., 2006).

2.2 Methods

2.2.1 Participants

After preliminary tests to estimate effect size, a total of 45 people who had suffered a stroke (29 men, 16 women) participated in the study. In addition, 45 age-matched participants with no neurological or orthopedic disease were recruited (Table 2.1). For individuals post-stroke, the inclusion criteria were: first supratentorial hemorrhagic or ischemic cerebral vascular accident; anytime after the cerebral vascular accident; either left or right affected hemisphere; aged ≥18 and ≤ 90; able to carry out a seated forward reaching task with the paretic arm without trunk compensation (see details of reaching task in Figure 2.1); had health insurance. Exclusion criteria were: severe cognitive disorders (Mini Mental Status Examination score < 24); severe aphasia with impaired comprehension (Boston Disability Aphasia Quotient < 4/5); strong neglect (Bell's test > 15 bells). Out of 68 patients screened for inclusion, 16 could not achieve the hand-reaching task with their paretic arm, 5 could not perform the reaching task without excessive trunk compensation, and 2 had too much spasticity. That left 45 patients included in the analysis.

The Ethics Committee of Nimes approved the study protocol (N°ID-RCB: 2014-A00395-42, Clinical Trial: NCT02326688). The research was carried out in two Physical and Rehabilitation Medicine Departments. All participants provided written consent before inclusion. Participants were not informed about the precise aim of the study to minimize bias.

Table 2.1. Demographic and clinical characteristics of the post-stroke (N=45) and control participants (N=45).

Domain		Patients Median (IQR) or Count (%)	Controls Median (IQR) or Count (%)
Gender	Women Men	16 (36%) 29 (64%)	26 (58%) 19 (42%)
Age (Years)		58 (21)	58 (20)
Hand Dominance	Right Left Ambidextrous	40 (89%) 4 (9%) 1 (2%)	42 (93%) 3 (7%)
Side of stroke	Right Left	16 (36%) 29 (64%)	
Aetiology	Haemorrhagic Ischemic	18 (40%) 27 (60%)	
Localisation	Middle cerebral artery Other	17 (38%) 28 (62%)	
Delay post-stroke (Months)		8 (31)	
Fugl-Meyer Assessment (/42)		29 (12,5)	
Box & Block Test (%)		21 (29)	

2.2.2 Experimental setup

The movements of the hand and of the trunk were recorded during a seated reaching task with a CMS 20s system (Zebris Medical GmbH, Isny, Germany). Sensors were placed at the head of the second metacarpal of each hand and at the middle of the sternum. Sampling frequency was 50 Hz and spatial accuracy was better than 1.5 mm. The participant's back was against the backrest of the chair and both feet were on the floor. The initial hand position was on the middle edge of the table in front of the participant's navel, with fingers of the two hands drawn on the table. The height of the table was modified in accordance with the height of the sitting participant.

2.2.3 Procedure

Participants had to reach a cone (17 cm high, 7.2 cm base diameter, 3 cm upper diameter) placed on the table in front of them just within the anatomical reaching distance for the hand (Levin et al., 2002). This task was always performed 5 times with one hand (paretic hand for patients, and right hand for controls), then 5 times with the other hand. The pace was self-selected. In the spontaneous arm use condition, after a "go" signal, the participant was free of constraint and reached the cone in a spontaneous manner. In the maximal arm use condition (Figure 2.1), the therapist explicitly informed the participant to self-minimize trunk movement so to “force” the patient to maximize arm use. The light touch by the therapist served as an external feedback to maximally use shoulder and elbow active motion to reach the cone (Shaikh et al., 2014). Mandatory and thus “non avoidable” trunk movements for task success were allowed (Levin et al., 2015). The total measurement session lasted about ten minutes. The same assessor evaluated each participant twice (24h between the two assessments).

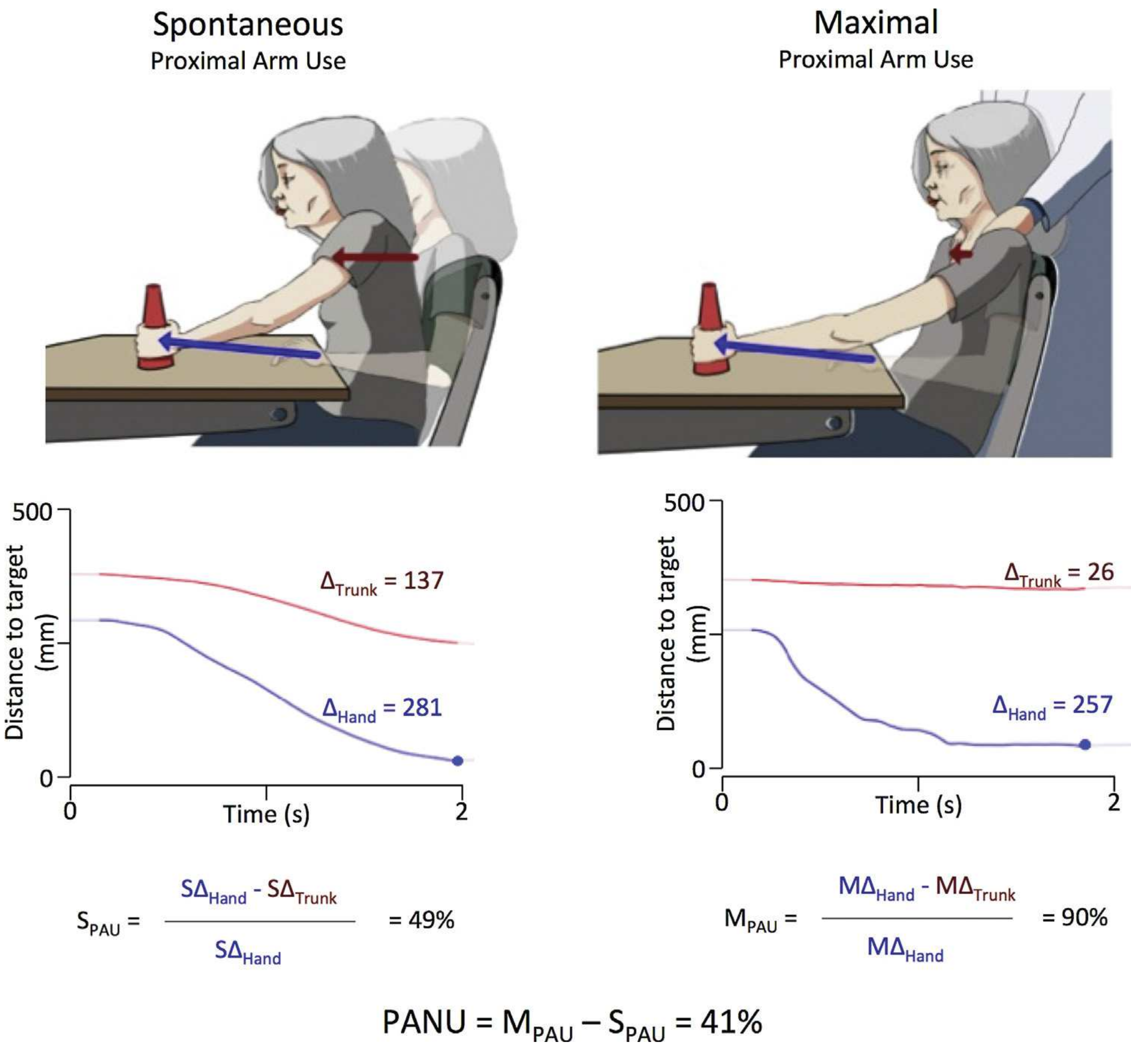


Figure 2.1. Experimental setup and an example of high Proximal Arm Non-Use (PANU) on the paretic side of a post-stroke individual. In the left and right panels, the upper panel illustrates the experimental setup and the graph below shows the corresponding distance to the target (mm) as a function of time (s). The blue line represents the hand movement and the red line represents the trunk movement. Δ_{Trunk} and Δ_{Hand} are the changes in distance to the target due to the reaching. Proximal arm use (PAU) in the two conditions (spontaneous-use S_{PAU}, maximal-use M_{PAU}) is computed from Δ_{Trunk} and Δ_{Hand} following the equation below each panel. PANU score is calculated as M_{PAU} (right panel) minus S_{PAU} (left panel).

2.2.4 Kinematic analysis

During seated reaching, the hand is the end effector of the kinematic chain formed by the trunk, upper arm and forearm (Robertson and Roby-Brami, 2011). Moreover, when reaching at a target, the Euclidian distance from the hand to the target defines the so-called “task space”, which summarizes the subspace that ensures task success (Mottet et al., 2001). In the task space, the displacement of the hand is the sum of the trunk, shoulder, and elbow movements. As a consequence, proximal arm use was computed from the 3D Euclidian distance from the hand to the target (Figure 2.1).

In a first step, the start and the end of each reaching movement were determined. The start of the movement was defined when velocity in task space became positive and stayed positive up to peak velocity. The end of the movement was defined when the distance to the target was minimal. Then, the change in distance to the target during the reaching movement was measured, for the trunk and for the hand (Δ_{Trunk} and Δ_{Hand} in Figure 2.1). Finally, using Δ_{Trunk} and Δ_{Hand}, proximal arm use (PAU) was computed, which was equal to hand movement minus trunk movement relative to hand movement (equation in Figure 2.1) and refers to the contribution of the arm to the hand movement toward the target.

In a second step, PANU score was computed as the difference in arm use between the spontaneous arm use (S_{PAU}) condition and the maximal arm use (M_{PAU}) condition (i.e., PANU = $M_{PAU} – S_{PAU}$, see details in Figure 2.1).

Finally, PANU score was calculated for the paretic and the non-paretic hand, and for the right and left hand in the control group, using the median of the 5 reaching movements in each condition.

2.2.5 Clinical assessments

The patient’s upper limb sensorimotor impairment was assessed with the upper limb proximal Fugl-Meyer score, allowing a maximal score of 42 (Fugl-Meyer et al., 1975). The patient’s upper limb functional capacity was assessed using the Box & Block test, with scores expressed as the number of blocks transferred using the paretic arm compared to the non-paretic arm (Mathiowetz et al., 1985). Data are summarized in Table 2.1.

2.2.6 Statistical Analysis

In all analyses, the significance level was set to $\alpha = 0.01$. A Shapiro-Wilk test indicated that patient’s data often departed from a normal distribution. As a consequence, the effects of the four experimental conditions (Patient-Paretic, Patient-Non-paretic, Control-Right, Control-Left) were assessed using non-parametric methods (Hollander et al., 2014). The non-parametric Spearman correlation coefficients were used to assess the relationship between the PANU scores on the paretic side and arm impairment (proximal Fugl-Meyer score), arm function (Box & Block test) and time since stroke. We also used Spearman correlation to measure the reliability of PANU scores assessed between day 1 and day 2, in patients and controls. With the Bland & Altman graphical method (Bland and Altman, 1999), we found that the PANU difference values (retest minus test) were normally distributed so that we report the mean ± standard deviation.

2.3 Results

2.3.1 Proximal arm non-use is reliably assessed on test-retest

The test-retest analysis using the Spearman correlation coefficient indicated that PANU measurements were very reliable for the Patient-Paretic condition (rs = .82, p = .0000), but less for the other conditions (Patient non-paretic: rs = .53, p = .0001; Control right: rs = .66, p = .0000 and left: rs = .65, p = .0000).

Using the Bland & Altman graphical method (Bland and Altman, 1999), we found that the bias in PANU score was: -2.62 ±7.24, 0.96 ±3.37, 0.38 ±1.59 and -0.35 ±1.38, respectively for the Patient-Paretic, Patient-Nonparetic, Control-Right, Control-Left hand conditions. As illustrated in Figure 2, the PANU difference values between test and retest were closer to zero and less variable for the control participants and the non-paretic hand, in comparison to the paretic hand.

Overall, these results indicate that the PANU assessment was very reliable for the paretic hand, yet with a constant bias towards lower values on the retest one day later.

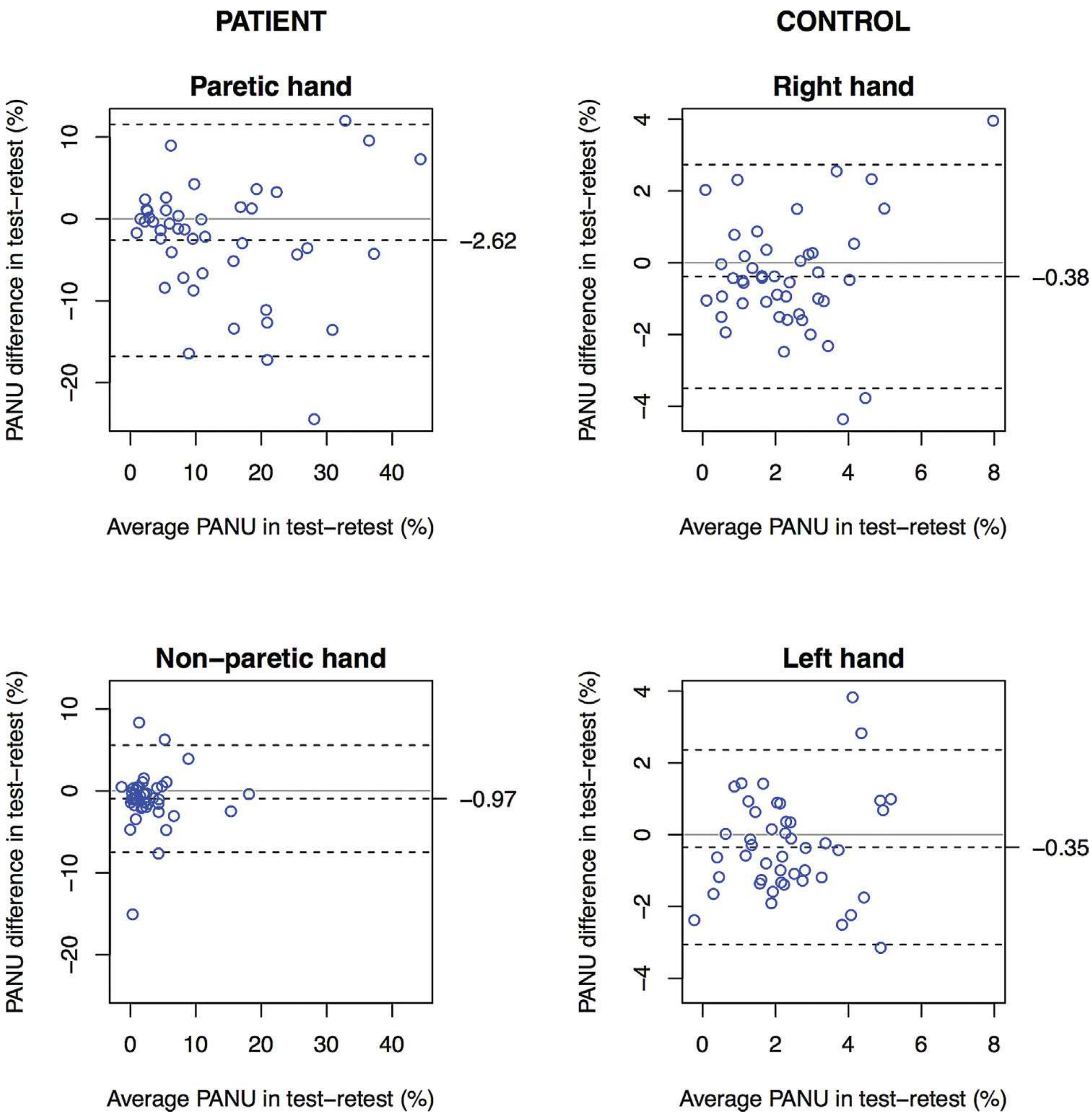


Figure 2.2. Bland-Altman plots of the repeatability of the measure of proximal arm non-use (PANU). Note the difference in scale for the post-stroke participants (left panels) and for healthy participants (right panels). The number on the right of each graph is the mean PANU difference from test to retest.

2.3.2 Proximal arm non-use is higher for the paretic hand

A Kruskal-Wallis H test showed a significant difference in PANU scores between hand conditions ($\chi^2(3) = 54.90$, $p = 0.000$), with a mean rank of 140.19 for Patient-Paretic, 76.19 for Patient-Nonparetic, 73.03 for Control-Right and 72.68 for Control-Left. Post-hoc comparisons using Mann-Whitney U tests (interpreted with Bonferroni corrections) indicated that PANU was higher in Patient-Paretic than in the other 3 conditions (Patient-Nonparetic: U = 308, p = .0000; Control-Right: U = 245, p = .0000; Control-Left: U = 248.5, p = .0000) which did not differ significantly from one another (Patient-Nonparetic vs. Control-Left: U = 981.5, p = .4012; Patient-Nonparetic vs. Control-Right: U = 985, p = .4122; Control-Right vs. Control-Left: U = 1004, p = .4727). Therefore, in agreement with our first hypothesis, the median Patient-Paretic PANU score of 11.7% was significantly higher than in the other conditions, where median PANU scores were similar for the Patient-Nonparetic (2.4%), Control-Right (2.5%) and Control-Left (2.3%) conditions (see Figure 2.2).

In healthy participants, 99 percent of the PANU distribution lied between -0.5 and 6.5%. This value of 6.5% was considered as a threshold of significant difference from the control group. On the paretic side of participants post-stroke, 99 percent of the PANU distribution lied between 1.3 and 40.5%, with 69% of participants with a PANU value higher than in the control group.

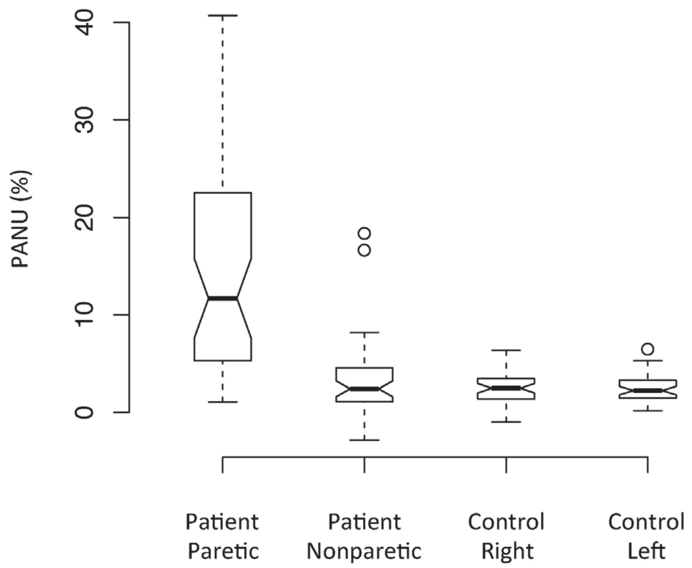


Figure 2.3. Proximal arm non-use (PANU) for post-stroke and control participants. The boxplot represents proximal arm non-use (PANU) for the paretic and non-paretic hand of post-stroke participants (Patient Paretic; Patient Nonparetic) and for the left and right hand of age-matched control participants (Control Right; Control Left). The box represents the interquartile range of PANU scores with the internal horizontal line representing the median score. The “whiskers” extend to the highest and lowest (non-outliers) values. The circles indicate outliers.

2.3.3 Proximal arm non-use relations with clinical assessments

PANU scores were not significantly related to the time since stroke (rs = −0.26, p = .0897). Higher PANU scores were related to lower proximal Fugl-Meyer scores (rs = -0.51, p = .0004) and to lower Box and Block scores (rs = -0.69, p = .0000) scores. Box and Block and Fugl-Meyer scores were related (rs = 0.63, p = .0000). All in all, PANU scores were strongly related to hand function

(Box and Block test), and moderately related to sensorimotor impairment (Fugl-Meyer score). Therefore, confirming our second hypothesis, PANU score increased with loss of function and less so with sensorimotor impairment.

In addition, among the 23 post-stroke individuals with high proximal Fugl-Meyer score (> 28/42), 14 were found with PANU > 6.5% (where 6.5% was the 99^{th} percentile of PANU distribution in controls). Hence, 61% of the less impaired post-stroke individuals had proximal arm non-use.

2.4 Discussion

In the present work, we quantified proximal arm non-use in people post-stroke when reaching within one's arm length in a seated position. The score of proximal arm non-use (PANU score) was obtained from the difference between the spontaneous use of the arm and the maximal use of the arm. We found that PANU has very good test-retest reliability, does not depend on time since stroke, increases with impairment (Fugl Meyer) and loss of function (Box & Block Test), and most importantly, that 61% of patients with lower impairment (Fugl-Meyer >28/42) exhibit proximal arm non-use.

2.4.1 Proximal arm non-use measures functional motor reserve

Proximal arm non-use quantifies the amount of shoulder and elbow movements that a post-stroke individual does not use spontaneously, but can use when forced to do so. Therefore, PANU measures what a person mobilizes in order to increase "near-to-healthy" recovery of paretic arm function (Jeyaraman et al., 2010) that is, the "functional motor reserve" available to improve reaching movements. Generally speaking, the concept of reserve captures the ability to perform the same task with a damaged central nervous system, provided that damage to the basic control centers remain below a critical threshold (Stern, 2009). Here, we focus on the motor expression of the reserve (Palmer et al., 2009). In the maximal arm use condition, patients have no option but to recruit the motor reserve of their paretic arm to complete the task (i.e., they recruit as much shoulder flexion and elbow extension as available). From a rehabilitation point of view, measuring proximal arm non-use is important because it can reveal an "unused potential" of the paretic arm after a stroke (Sunderland and Tuke, 2005), with therapeutic consequences (Michaelsen et al., 2006).

2.4.2 Proximal arm non-use complements classical clinical assessments

The significant negative correlations of the PANU scores with the Fugl-Meyer and the Box & Block scores were expected. Because a higher PANU score implies higher trunk compensation (Figure 1), and because trunk compensation increases with impairment and loss of function (Cirstea and Levin, 2000; Nakayama et al., 1994; Roby-Brami et al., 2003), it is logical that higher impairment and lower function result in higher non-use (Taub et al., 2006), hence higher PANU. However, although PANU provides information related to the Fugl-Meyer and the Box & Block tests, PANU goes beyond the clinical assessment of arm deficit and function. The fact that 61% of the less impaired patients (Fugl-Meyer >28/42) exhibit proximal arm non-use indicates that PANU score provides novel information, which can help therapists to better personalize the strategy of post-stroke rehabilitation.

First, PANU score directly informs about the non-use, and it focuses on the non-use phenomenon *intrinsic* to the paretic upper limb. Measures of non-use are important to complement clinical assessments and organize the therapeutic strategy (Han et al., 2013; Taub et al., 2006). PANU method provides an objective quantification of the functional motor reserve, patient by patient. For a therapist, PANU method directly quantifies the potential of progress that one can expect with specific rehabilitation to promote arm use (Jeyaraman et al., 2010). Measuring PANU could help therapists deciding which patients would best benefit from specific rehabilitation targeting the use of shoulder and elbow (Jeyaraman et al., 2010; Taub et al., 2006). Throughout the course of treatment, the PANU measure could complement conventional clinical assessments to monitor post-stroke upper limb recovery and better evaluate treatment efficacy.

Second, PANU method is fast and easy to quantify. Obtaining a PANU score takes about 10 minutes per patient, and the score is more fine-grained and objective than clinical assessments such as the Fugl-Meyer or Box & Block tests. Moreover, training a therapist to score PANU requires only 15 minutes.

All these make PANU a useful measure to complement classical clinical assessments of the upper arm after a stroke.

2.4.3 Limitations

First, measuring PANU currently necessitates a 3D movement capture system, making the method more suitable for research centers or large hospitals, although, in the future, low-cost movement capture systems from the video game industry could make the method more accessible (Mobini et al., 2015).

Second, PANU method remains to be compared to other methods to assess arm non-use after a stroke (Han et al., 2013; Sterr et al., 2002; Taub et al., 2006). This impedes any generalization of its validity as a generic measure of the non-use. However, because forward reaching is the building block of many upper limb activities, it is likely proximal arm non-use co-varies with non-use in a larger variety of upper limb activities.

Third, measurement of arm use were set after summarizing all body movements in one dimension that represents task space (Mottet et al., 2001). This approach does not allow to assess arm joint rotations, scapular rotations or trunk rotations, and their synergistic organization during reaching (Levin et al., 2015; van Kordelaar et al., 2012a).

Finally, sensitivity of PANU scores to change remains to be evaluated by future work.

2.5 Conclusion

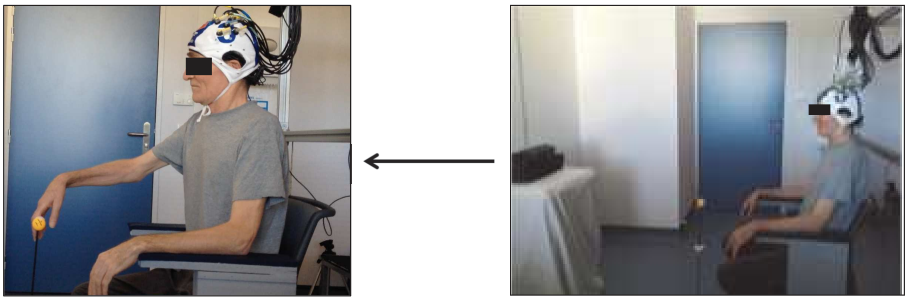
The low rate of recovery of upper limb function post-stroke is a considerable challenge for therapists. Individualized assessment can help determining the best rehabilitation protocol for each patient. Here, we quantified one aspect of the non-use in people post-stroke: proximal arm non-use when reaching within arm's length in a seated position. We found that a high score of PANU identified the patients with a potential functional reserve of arm use. Consequently, we propose that PANU scores be used to select patients for specific rehabilitation programs focusing on the "forced-use" of shoulder and elbow movements as well as to monitor the recovery of upper limb post-stroke.

2.6 Perspectives

Analysis of possible brain correlates of the proximal arm non-use

This part presents a case study I did with two post-stroke individuals to evaluate the possible brain correlates of the proximal arm on-use using non-invasive near-infrared spectroscopy (fNIRS) neuroimaging (Bakhti et al., 2016).

Two post-stroke individuals (52 years old, ischemic middle cerebral artery), one right handed with a right hemisphere lesion (4m post-stroke; BB score: 61/1) and the other left handed with a left hemisphere lesion (6m post-stroke; BB score: 23/73) were required to perform a series of seated reaching movements with their paretic, non-paretic, and both arm(s) using a blocked design (3 blocks, 20s task and 20s rest) in a free and then in a forced arm use (trunk restrained) condition allowing to compute the percentage of proximal arm non-use (see Fig. 2.4 for the experimental setup).



Right Hand (paretic) task **Rest position**

Figure 2.4 Experimental setup. Markerless recording of hand and trunk kinematics using the Kinect (Medimoov, NaturalPad, France), and the 8 channel Octamon (prefrontal cortex-PFC region) and 16 channel Oxymon (sensorimotor cortex-SMC region) fNIRS (functional near-infrared spectroscopy) systems (Artinis Medical Systems, The Netherlands) to measure brain activation during the seated hand reaching to a target (ball).

For the subject with the left hemisphere lesion (right paretic arm) the PANU score was 3.5% for the Paretic arm (0.3% for the non-paretic arm, and 6.5% for both arms). This patient had a large deficit in their paretic arm function, which resulted in trunk movements both in the free-use and forced-use condition, and thus did not show a proximal arm non-use effect. For the subject with the right hemisphere lesion (left paretic arm) the PANU score was 13% for the Paretic arm (30% for both hands, and 1% for non-paretic arm). For this patient, we found differences in activation of the prefrontal cortex (PFC) and sensorimotor cortex (SMC) regions, between the free-use and forced-use conditions (Figure 2.5).

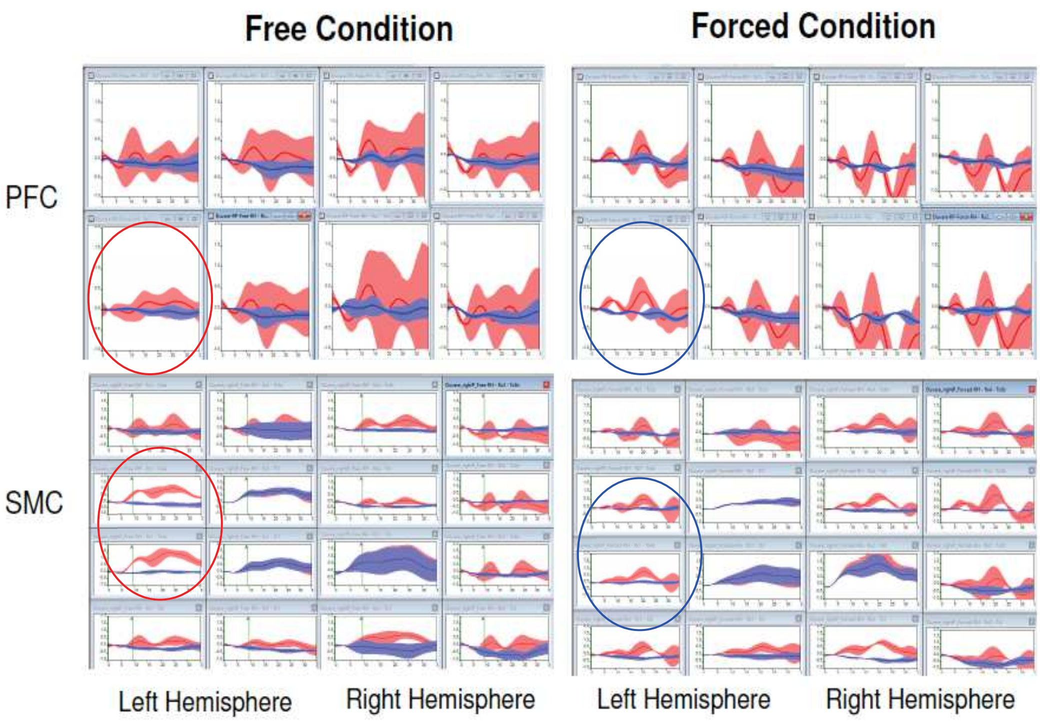


Figure 2.5 fNIRS-derived brain activation (time course of oxy [red line] and deoxy [blue line] hemoglobin) of the right hemisphere lesion post-stroke individual during left paretic arm seated reaching in the free-use and forced-use condition.

This pilot study has shown for the first time that fNIRS neuroimaging could be used in clinical settings to determine brain activation changes as a function of the proximal arm non-use of the paretic arm after a stroke. However, further investigations are necessary to go beyond the present proof of concept.

2.7 Summary

The PANU method was validated in the first study and the PANU scores reliably quantifies a motor reserve of shoulder-elbow movements. The PANU score could be used to follow the recovery of post-stroke individuals and to evaluate the efficacy of a treatment such as FM. The PANU score could also be used in research to try to uderstand the neural correlates with arm non-use.

The PANU score was measured in this study by an objective marker-based movement analysis device (Zebris CMS20s), which is quite expensive and thus more applicable to research intensive clinics. How is it possible to use this PANU score routinely and more widely? The next chapter validates a marker-less motion capture system (Kinect) that is a low-cost system ideal for routine clinical applications.

3 CHAPTER 3 – VALIDATION OF A KINECT-BASED SYSTEM TO QUANTIFY PROXIMAL ARM NON-USE AFTER A STROKE

This chapter is in preparation:

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Validity of a kinect-based system to quantify proximal arm non-use during reaching.

Abstract

Background: When reaching after a hemiparetic stroke the preference given to trunk compensatory movements, when elbow-shoulder movements are possible, defines *proximal arm non-use* (PANU). We previously quantified PANU using an ultrasound-based system (Zebris, CMS20s). The aim of this study was to validate a low-cost Microsoft Kinect-based system against the reference CMS20s system to determine PANU during seated reaching.

Methods: In 19 hemiparetic stroke individuals the PANU score, reach length, trunk length, proximal arm use were measured during seated reaching simultaneously by the Kinect (v2) and CMS20s over two testing sessions separated by 2h.

Results: Intraclass correlation coefficients (ICC) and linear regression analysis showed that the PANU score (ICC=0.95, r^2=0,90), reach length (ICC=0.82, r^2=0,70), trunk length (ICC=0.97, r^2=0,94) and PAU (ICC=0.97, r^2=0,93) measured using the Kinect were strongly related to those using the CMS20s. The PANU scores showed good test-retest reliability for both the Kinect (ICC = 0.76) and CMS20s (ICC=0,72) with Bland & Altman plots showing slightly reduced PANU scores (i.e., improved performance) in the re-test session for both systems (Kinect: -4,25 ± 6.76; CMS20s: -4,71 ± 7.88), which suggests a practice effect.

Conclusion: We showed that the Kinect could accurately and reliably assess PANU during seated reaching. We conclude that the Kinect can offer a low-cost and widely available solution to clinically assess PANU for individualised rehabilitation and to monitor the progress of paretic arm recovery.

Key words

Arm non-use – Stroke – Rehabilitation – Kinect v2 – Movement analysis

3.1 Background

Following a hemiparetic stroke, a large proportion of post-stroke individuals develop upper limb (UL) disabilities that result in difficulties in performing daily activities such as reaching for objects, which impacts their quality of life (van Kordelaar et al., 2012b). Stroke survivors often compensate for these impairments by adapting their movement patterns to incorporate additional degrees of freedom at new joints and body segments. One of the most common compensatory movements is the recruitment of excessive trunk flexion when reaching with the paretic UL. Long-term use of trunk compensation may lead to suboptimal motor recovery of the paretic UL and secondary complications such as muscle contractures and pain (Hatem et al., 2016; Li, 2017; Wee et al., 2014). Even if post-stroke individuals sufficiently recover shoulder-elbow active movements to perform the reaching movements, many continue to over-use trunk movements instead to use the available shoulder-elbow joint motility. Following the principle of use-dependent neural plasticity ‘‘Use it or lose it’’, the non-use of shoulder-elbow movements is highly suspected to be detrimental to the recovery of as optimal as possible UL functioning (Jones, 2017; Kleim and Jones, 2008). We quantified proximal arm non-use: (PANU, i.e., shoulder-elbow non-use) during seated reaching in 45 hemiparetic stroke patients and 45 controls (Bakhti et al., 2017). PANU score computation was defined as the subtraction of the spontaneous proximal arm-use (when given a free choice to use either the trunk or the paretic arm) from the maximal proximal arm-use (when constrained to not use trunk movement). We showed that PANU score has very good test-retest reliability, does not depend on time since stroke, increases with impairment (Fugl Meyer) and loss of function (Box & Block Test), and most importantly, that 61% of patients with lower impairment (Fugl-Meyer >28/42) exhibit PANU. We consider that an individual PANU score provides information about the remaining functional motor reserve (at level of paretic shoulder and elbow) that is not used by the post-stroke individual. Consequently, PANU score enables a clinician to select patients for specific rehabilitation programs focusing on the “maximal-use” of shoulder and elbow movements as well as to monitor the arm recovery/compensation post-stroke. Therefore, PANU assessment is complementary with routine clinical measures of arm impairment (i.e. Fugl Meyer) and function (i.e. Box and Block test).

The PANU measurement using the 3D motion capture system (CMS20s, Zebris) necessitated to position markers on the patient to record the 3D positions of the hands and the trunk during the seated reaching task. Although, most clinical motion analysis centres use a marker-based system (Bonnechère et al, 2014), recent developments in computer gaming technology use low cost and marker-less infrared sensors such as the Microsoft's Kinect® (v2 for Xbox One) to capture users' body motions for interaction with video games (Butkiewicz, 2014; Eltoukhy et al., 2017; Knippenberg et al., 2017; Kurillo et al., 2013; Pagliari and Pinto, 2015). The Kinect® sensor reliably identifies anatomical joints in real-time without requiring markers attached to the body (Galna et al., 2014). Moreover, the official Microsoft software development kit release permitted the sensor to be used not only as a game device, but also as a measurement system. The Kinect sensor showed promising results in validity assessment compared to an established highly accurate 3D motion capture system (6-camera Vicon System) in shoulder movements (Kuster et al., 2016; Zulkarnain et al., 2017). However, very few studies are available on the validity of the Kinect to accurately track trunk and hand motions in a reaching task (Valdés et al., 2017), which is essential to quantify PANU score in post-stroke individuals. One potential added value of the Kinect is the fact that it provides the time series of 25 body marks that allows the possibility to measure joint range of motion, such as shoulder flexion-extension angle and elbow flexion-extension angle. These elbow, shoulder, and trunk angles obtained from the Kinect have been validated against the gold standard VICON marker based motion capture system. Equaly to our knowledge one study evaluated the accuracy of Kinect v2 for measuring motion smoothness of the shoulder. However, no previous study has evaluated the accuracy of the Kinect to measure kinematic variables during reaching such as movement time and number of velocity peaks (Zulkarnain et al., 2017).

Moreover, as Kinect was designed to capture users' body motions for interaction with video games Kinect has already been used and implemented in rehabilitation after stroke. Standard games used in therapy are motivating, but performance has to be closely monitored. Especially when developers implement a post-stroke individual-centred task-oriented approach into the system. If PANU scores measured by Kinect were enough accurate, PANU score would be implemented in video games to monitor recovery of post-stroke individuals.

Therefore, the purpose of this study was to validate a Kinect-based system to accurately and reliably quantify PANU scores in post-stroke individuals. Our clinical question was whether the Kinect sensor could replace the existing CMS20s method of PANU assessment. We hypothesised that the Kinect will give similar measurements to the reference CMS20s system.

3.2 Methods

3.2.1 Participants

A total of 19 people who had suffered a stroke (59±3 years; 10 men, 9 women) participated in this study. Participants were included if they had sustained single supratentorial either haemorrhagic or ischemic cerebral vascular accident; anytime after the cerebral vascular accident; either left or right affected hemisphere; aged ≥18 and ≤ 90; able to carry out a seated hand reaching task with the paretic arm (see details of reaching task in Figure 1). Participants were excluded if they were not able to carry out a seated hand reaching task with the paretic arm; had shoulder pain or perceptuo-cognitive deficits (heminegligence, ataxia, receptive aphasia) (Michaelsen and Levin, 2004).The study was approved by The Ethics Committee of Montpellier, France (N°ID-RCB: 2014-A00395-42) and registered in Clinical Trial (N° NCT02326688). Written informed consent was obtained from all participants prior to the inclusion.

3.2.2 Clinical assessments

The patient's UL sensorimotor impairment was assessed with the UL Fugl-Meyer test, allowing a maximal score of 66 (Fugl-Meyer et al., 1975). The patient's UL functional capacity was measured using the Box & Block test, with scores expressed as the number of blocks transferred using the paretic arm compared to the non-paretic arm (Mathiowetz et al., 1985).

3.2.3 Experimental protocol

Participants were asked to reach a target placed in front of them within arm length (Levin et al., 2002). The reaching movement was repeated 5 times with the paretic hand, then 5 times with the less-impaired hand. This sequence was first performed in a spontaneous arm-use condition, and then in a maximal arm-use condition. The pace was self-selected (no particular instruction was given about speed). In the spontaneous (free) condition after a "go" signal, the participant was free of constraint and reached the target in a spontaneous manner. In the maximal arm use condition, the therapist provided feedback so to explicitly encourage the patient to self minimize trunk movement (Levin et al., 2015; Subramanian et al., 2013). Trunk movements that were mandatory for task success were allowed. The movements were recorded simultaneously with CMS20s and Kinect. The sequence of reaching tasks to assess the PANU was repeated again 2H later to determine test-retest reliability and to know the magnitude of the differences due to the patient repeating the tasks. The same assessor evaluated each participant in the two assessments.

3.2.4 Experimental setup

The experimental setup of the Kinect v2 and CMS20s sensors allowed simultaneous capturing of the 3D motion of the trunk and hand during seated reaching (see details in Figure 1). PANU assessment requires three landmarks: each hand and trunk (Bakhti et al., 2017).

a) CMS20s sensor

The CMS20s® (Zebris, Isny, Germany) is a marker based system that measures body kinematics based on travel-time measurement of ultrasound impulses that are transmitted to miniature markers on the body to the three microphones built into the CMS20s® sensor at a sampling rate of 50Hz. The CMS20s® is considered one of the most highly accurate 3D motion capture systems. CMS20s was chosen as gold standard as it has a high accuracy that has been reported to be < 1/10 mm. The 3 CMS20s markers were placed on manubrium, right dorsal hand and left dorsal hand (blue spots in Figure 1). The body-markers must be visible by the CMS20s during the whole reach sequence to not lose the signal. The CMS20s® system was connected to a PC running "WinData" software (Zebris, Isny, Germany) that provided real time kinematics of the three joint markers.

b) Kinect sensor

The Kinect® v2 (Microsoft, USA) is a marker-less system that can measure 3D joint kinematics using information from a combination of 3 sensors (a RGB color camera, a depth sensor, an infrared sensor) to provide the position (X, Y, Z) of 25 joints on a skeleton with a sampling rate of 30 Hz (Zhang, 2012). The Microsoft Kinect v2 processes the distance data by a time-of-flight camera system with proprietary algorithms. The Time-of-flight system is able to reconstruct the 3D scene through the measurement of the elapsed time between the emission of a light ray and its collection after reflection from the target (Corti et al., 2016). The Kinect was connected to a PC running "MaCoKi" software (NaturalPad, Montpellier, France) developed from the Kinect Software Development Kit (Kinect SDK v2.0_1409, Microsoft, USA). A biomechanical model was not used because the PANU score is simply computed from the change in hand and trunk euclidean distances (Δ Trunk and Δ Hand) avoiding any problem of direction (Bakhti et al., 2017).

c) Position of landmarks

For the comparison between Kinect and CMS20s body-markers chosen with the Kinect skeleton joints had to be as close as possible to the CMS20s landmarks. Preliminary tests using the Kinect revealed that the “wrist joint” corresponded best to a marker on the dorsal face of the hand close to the wrist and the “Spine-Shoulder joint” corresponded best to a marker on the manubrium (red spots in figure 1), which confirms the Kinect skeleton joints chosen by Ozturk et al., (2016) and Valdes et al., (2017) to determine trunk compensation during reaching task. Consequently, the Kinect skeleton joints chosen to be corresponding to CMS20s markers were the right wrist (for right hand with CMS20s), left wrist (for left hand with CMS20s) and spine-shoulder joint (for manubrium with CMS20s).

d) Materials/ setup

In order to minimize equipment needed to assess PANU and to prevent the Kinect from mistakenly identifying environmental furniture as part of body (Obdrzálek et al., 2012), we omitted the table and used a chair with arm rests to rest the hand and positioned the target on a narrow stand in front of the participant (see details in figure 3.1). In addition, since the Kinect detects only the skeleton it is not able to determine the position of the target without a calibration procedure. So, we identified the target position by asking the participant to reach and stay at the target, with the paretic hand, then with the non-paretic hand. The experimenter verified visually that the hand was in place, and recorded for 2 sec. The average position of both hands gave the target position (see Figure 1).

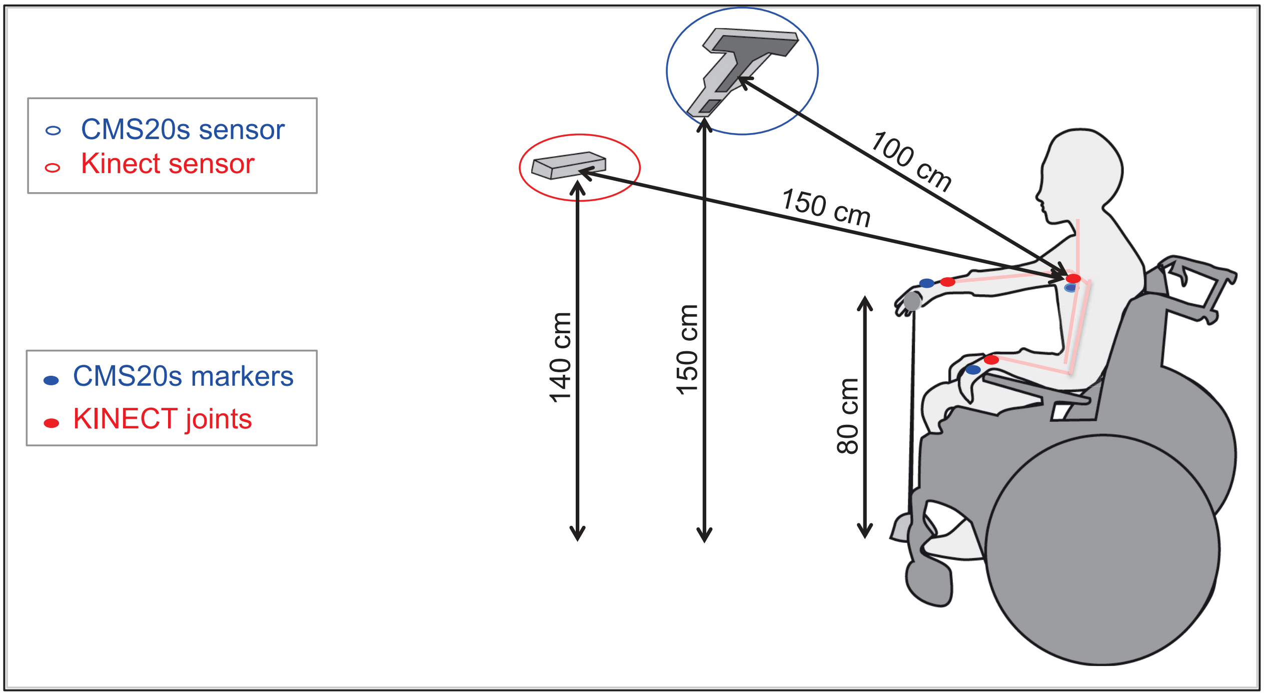

Figure 3.1. Experimental setup. The quantification of proximal arm non-use (PANU) was simultaneously performed by two movement recording systems: Kinect (blue encircled) and CMS20s (red encircled). The CMS20s recorded the position of 3 markers placed on: manubrium, right dorsal hand, left dorsal hand (blue spots). The Kinect provided a skeleton of the person (orange) out of which we retained 3 "joints" corresponding best to the CMS20s markers: SpineShoulder, HandLeft, HandRight.

3.2.5 Data processing

PANU score calculation needed the identification of the target, the determination of hand and trunk amplitude and the computation of the proximal arm-use in two conditions (maximal arm-use and spontaneous arm-use conditions). In fact, we computed arm use from the euclidean distance from the hand or the trunk to the target. First, we determined the start and the end of each reaching movement. Second, we determined the change in distance to the target during the reaching movement, for the trunk and for the hand (Δ Trunk and Δ Hand in Figure 1). Finally, using Δ Trunk and Δ Hand, we computed proximal arm use. PANU score was obtained by comparing arm and trunk contribution in both conditions (Bakhti et al., 2017).

We also extended the comparison of kinect and CMS20s towards classical kinematic variables often used in clinical tests as Movement Time (MT) and Number of Velocity Peaks (NVP) (van Dokkum et al., 2014). Finally to complement the analysis of the reliability of the Kinect in comparison to a stat-of-the-art 3D recording system, we explored one potential added value of the Kinect, the fact that it provides "for free" the time series of 25 body marks that one can use to assess joint movements. However, in the latest exploration, we do not have a referent device, which hinders the possibility of a precise assessment of the reliability of the Kinect in the measure of angles (that would be analysed in future work).

Therefore, movement time (MT) and number of velocity peaks (NVP) while reaching the target were also calculated using the data from both systems. In addition, joint angles of interest in relation to PANU score were measured only with Kinect system. Since PANU is related to elbow-shoulder non-use (Levin et al., 2015), we calculated the shoulder and elbow angles using the Kinect data. In order to define the elbow flexion/extension angle, a frontal plane was created by using 3D coordinates of the shoulder right/left, elbow right/left and wrists right/left. Three points in the 3D space defines a plane. Then, the elbow flexion/extension was defined as the angle between the vector directed from the shoulder left/right to elbow left/right and the vector directed from the elbow left/right and the wrist left/right. In order to define the shoulder flexion/extension angle, a frontal plane was created by using 3D coordinates of the spine-mid, spine-shoulder and shoulder right/left. Then, the shoulder flexion/extension was defined as the angle between the vector directed from the shoulder left/right to elbow left/right and the frontal plane (Ozturk et al., 2016). From the shoulder flexion/extension angle and elbow flexion-extension angle, we were able to determine non-use of shoulder flexion and non-use of elbow extension.

3.2.6 Statistical Analysis

To quantify the degree to which CMS20s and Kinect measurements are related to determine PANU score, Δ Hand, Δ Trunk, proximal arm-use, we used intra-class correlation coefficient ICC (1) and linear regression analysis (Shrout and Fleiss, 1979). We used Bland & Altman plots using 95% limits of agreement analysis (Bland and Altman, 1986) to determine the agreement between CMS20s and Kinect measurements. Finally, we assessed the intra-subject test-retest reliability of the Kinect and CMS20s over the two measurement times using ICC, linear regression and Bland & Altman plots.

For the Bland and Altman analysis (left panel), a scatter plot was constructed in which the difference between the paired measurements (data from Kinect and data from CMS20s) was plotted on y-axis and average of paired measurements on x-axis. The central horizontal line (on the plot) indicates the mean of the differences (bias), with a 0 indicating good agreement and a negative value indicating an underestimation by the Kinect. The standard deviation (SD) of differences between paired measurements was then used to construct horizontal lines above and below the central horizontal line to represent 95% limits of agreement (mean differences ± 1.96 SD of the difference), representing the upper and lower limits of agreements. For the regression analysis, the right panel indicates ICC (intraclass correlation) and regression line between the Kinect and

CMS20s measurements. Regression equation is expressed as: $K = b1C + b0$ where K is Kinect measurement, b1 is the slope, C is CMS20s measurement and b0 is the intercept.
Statistical analysis was performed using R (version 3.4.0). The level of significance for all tests was set at $p < 0.05$.

3.3 Results

3.3.1 Reliability of the Kinect®

The measure of reliability between Kinect and CMS20s was done for Δ Hand, Δ Trunk, proximal arm-use (direct measures) and PANU scores (computed measure). The results of the relationship between Kinect and CMS20s measurement for each paired variable are shown using ICC, linear regression and Bland and Altman graphs (see Figures 2 and 3).

a) Δ Hand

Change in distance to the target due to the hand movement, Δ Hand from the Kinect and CMS20s were also highly correlated with an ICC = 0.82. The slope of the linear regression (0.81) indicated that Kinect underestimated reach length (Figure 2). On average, Kinect measured reach length with 12.06 mm less than CMS20s and a standard deviation of 31.44 mm (Figure 3.2).

b) Δ Trunk

Change in distance to the target due to the hand movement, Δ Trunk from the Kinect and CMS20s were correlated with an ICC of 0.97. The slope of the linear regression (0.92) indicated that Kinect underestimated trunk length (Figure 2). On average, Kinect measured the length of trunk displacement with 0.61 mm less than CMS20s and a standard deviation of 8.15 mm (Figure 3.2).

c) Proximal arm-use

For the proximal arm-use, the measurements from the Kinect and CMS20s were correlated with an ICC of 0.97. The slope of the linear regression (0.95) indicated that Kinect underestimated proximal arm-use (Figure 3). On average, Kinect measured proximal arm-use with 0.08 (AU) less than CMS20s and a standard deviation of 2.70 (AU) (Figure 3.2).

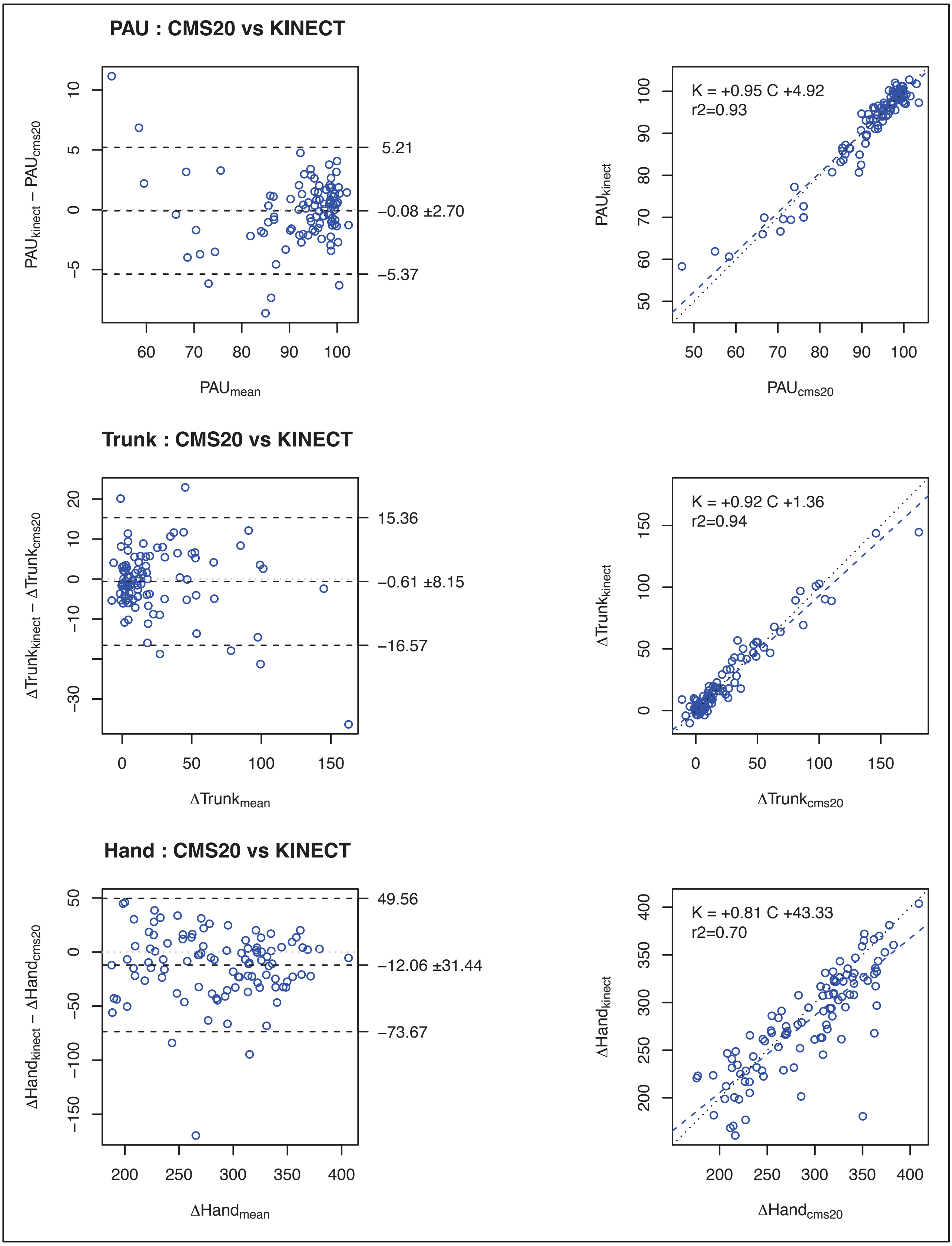

Figure 3.2. Comparison of Kinect (K) and CMS20s (C) measurements of PANU components: The proximal arm-use-PAU (top panels), Δ Trunk (middle panels), and Δ Hand (bottom panels) using Bland & Altman plots (left side panels) and linear regression (right side panels) with intra correlation coefficients ICC (insets).

d) PANU scores

PANU scores determined from the Kinect and CMS20s were strongly correlated with an ICC = 0.95. The slope of the linear regression (0.92) indicated that Kinect underestimated proximal arm non-use (Figure 3). The Bland & Altman pots indicated that the Kinect determined PANU scores were on average 0.08 ± 3.40 than the PANU scores obtained by the CMS20s (Figure 3.3).

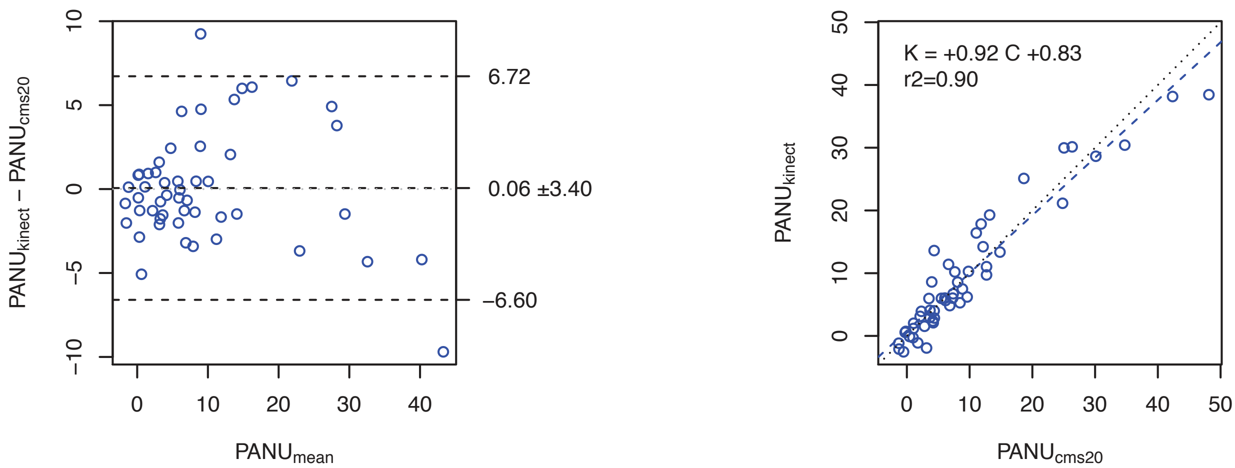

Figure 3.3. Comparison of the PANU scores obtained with the Kinect (K) and CMS20s (C) systems. For the Bland and Altman analysis (left panel), the horizontal dotted lines represent the systematic bias (central) and the 95% limits of agreement (upper and lower lines). The average of differences is 0.06 arbitrary units (constant bias close to 0). The 95% limits of agreement are: -6.60 +6.72 representing a variable error smaller than the variability intra-subject. For the regression analysis, Regression equation is expressed as: K = 0.92 C + 0.83, with an intercept of 0.83 and a slope less than 1 (0.92) showing that Kinect (K) underestimates PANU score.

e) Movement time

For the movement time, the measurements from the Kinect and CMS20s were correlated with an ICC of 0.80. The slope of the linear regression (0.84) indicated that Kinect underestimated movement time (Figure 3.4). However on average, Kinect measured movement time with 0.08 s less than CMS20s and a standard deviation of 0.37 s (Figure 3.4).

f) Number of velocity peaks

The number of velocity peaks (NVP) was computed with a classical method: The velocity peaks were detected on a pre-filtered signal (5Hz) (Winter et al., 1974). The measurements from the Kinect and CMS20s were poorly correlated for NVP (ICC of 0.34). The slope of the linear regression (0.84) indicated that Kinect underestimated NVP (Figure 3.4). On average, Kinect measured NVP with 3.15 peaks less than CMS20s and a standard deviation of 2.85 peaks (Figure 3.4).

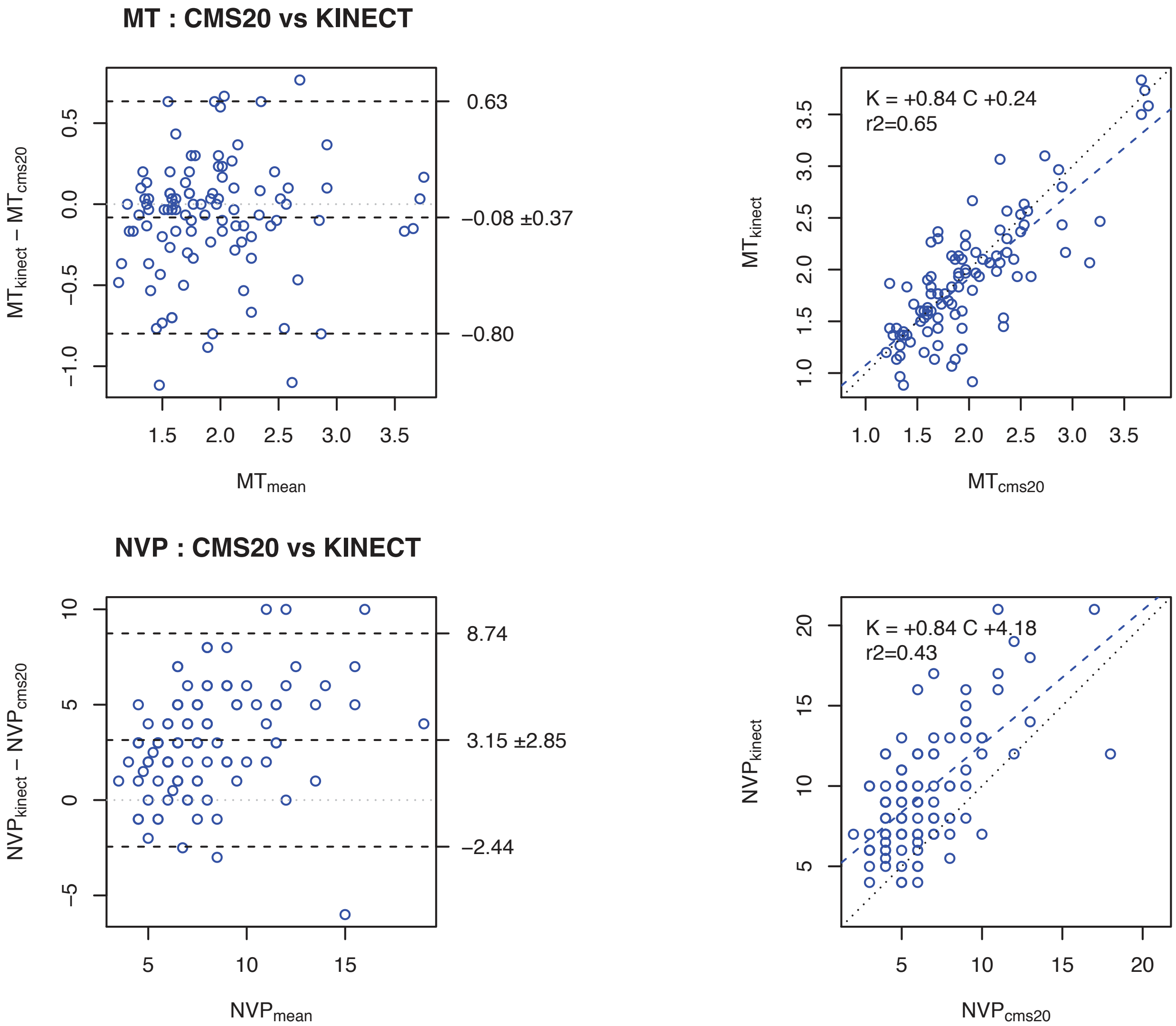

Figure 3.4. Comparison of the movement time (MT) and the number of velocity peaks measured by the Kinect and the CMS20s. The left panel indicates Bland-Altman plots comparing the measurements from the Kinect and CMS20s for the movement time in seconds and number of velocity peaks. The right panels present the linear regression comparing the measurements from the Kinect and the CMS20s.

3.3.2 Kinect® can provide other kinematic variables such as angles of interest

a) <u>Angles of interest in relation to PANU score</u>

Having the time series of 25 body marks providing access to angles joint motion and knowing that proximal arm non-use represents elbow-shoulder non-use, it was interesting to analyze shoulder and elbow non-use angles. Shoulder non-use is the difference in shoulder angle between maximal arm-use condition and spontaneous arm-use condition. In the same way, elbow non-use is the difference in elbow angle between maximal arm-use condition and spontaneous arm-use condition

The elbow extension angle is 3D angle between segments forearm segment (from wrist to elbow) and upperarm segment (from elbow to shoulder). The shoulder forward (elevation) is 3D angle between trunk segment (from hip center to shoulder center) and Upperarm segment (from elbow to shoulder)

b) PANU mainly due to elbow extension non-use

The PANU score was compared to the angle of Elbow Extension non-use - nuEE (PANU = +0.53 nuEE +6.29 with r2 = 0.32) and to the angle of Shoulder Flexion non-use – nuSF (PANU = +0.28 nuSF +9.83 with r2 = 0.03). The angles analysis showed that PANU was mainly due to nuEE ($F(1,49) = 23.2140$, $p = 0.0000$) than to nuSF ($F(1,49) = 1.4733$, $p = 0.2307$). These findings could be obtained by CMS20s with 4 more markers (on each elbow and each acromion). Therefore, with the angles analysis, the PANU could provide a more sensitive and useful global upper extremity functional measure for following recovery or effects of various therapeutic interventions (Figure 3.5). In the same way, Massie et al found that elbow extension predicts motor impairment and performance after stroke (Massie et al., 2011).

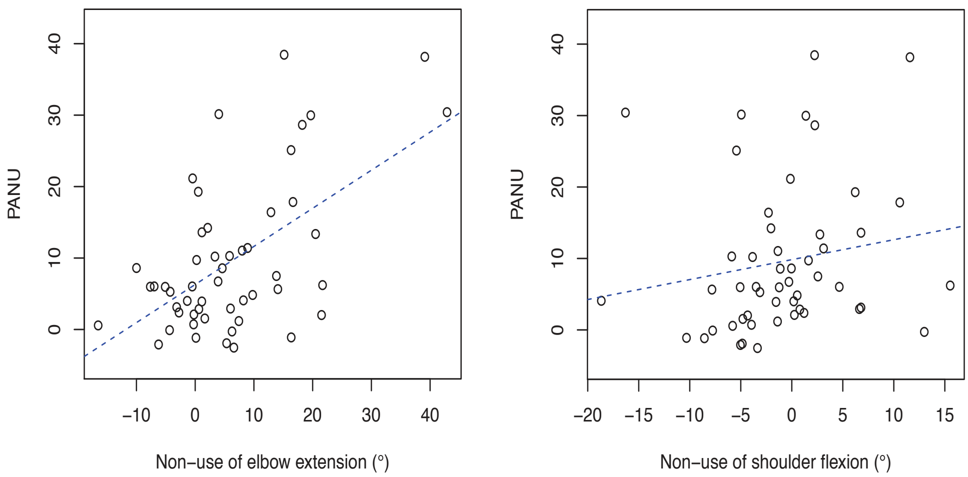

Figure 3.5. The PANU is mainly due to the elbow extension non-use (left panel).

3.3.3 Repeatability of PANU using Kinect® and CMS20s®

a) Kinect

With the Kinect, PANU scores between the two testing sessions (R1 and R2) were highly correlated (ICC = 0.76). The slope of the linear regression (0.61) indicated that the second session PANU scores were systematically lower than the first session (Figure 3.6). Bland & Altman plots of the differences PANU scores revealed that on average the second session was 4.25 ± 6.76 (AU) lower than the first session (Figure 3.6).

b) CMS20s

With the CMS20s, PANU scores between the two testing sessions were highly correlated (ICC = 0.72). The slope of the linear regression (0.53) indicated that the second session PANU scores were systematically lower than the first session (Figure 3.6). On average, the second session was 4.71 ± 7.88 (AU) lower than the first session (Figure 3.6).

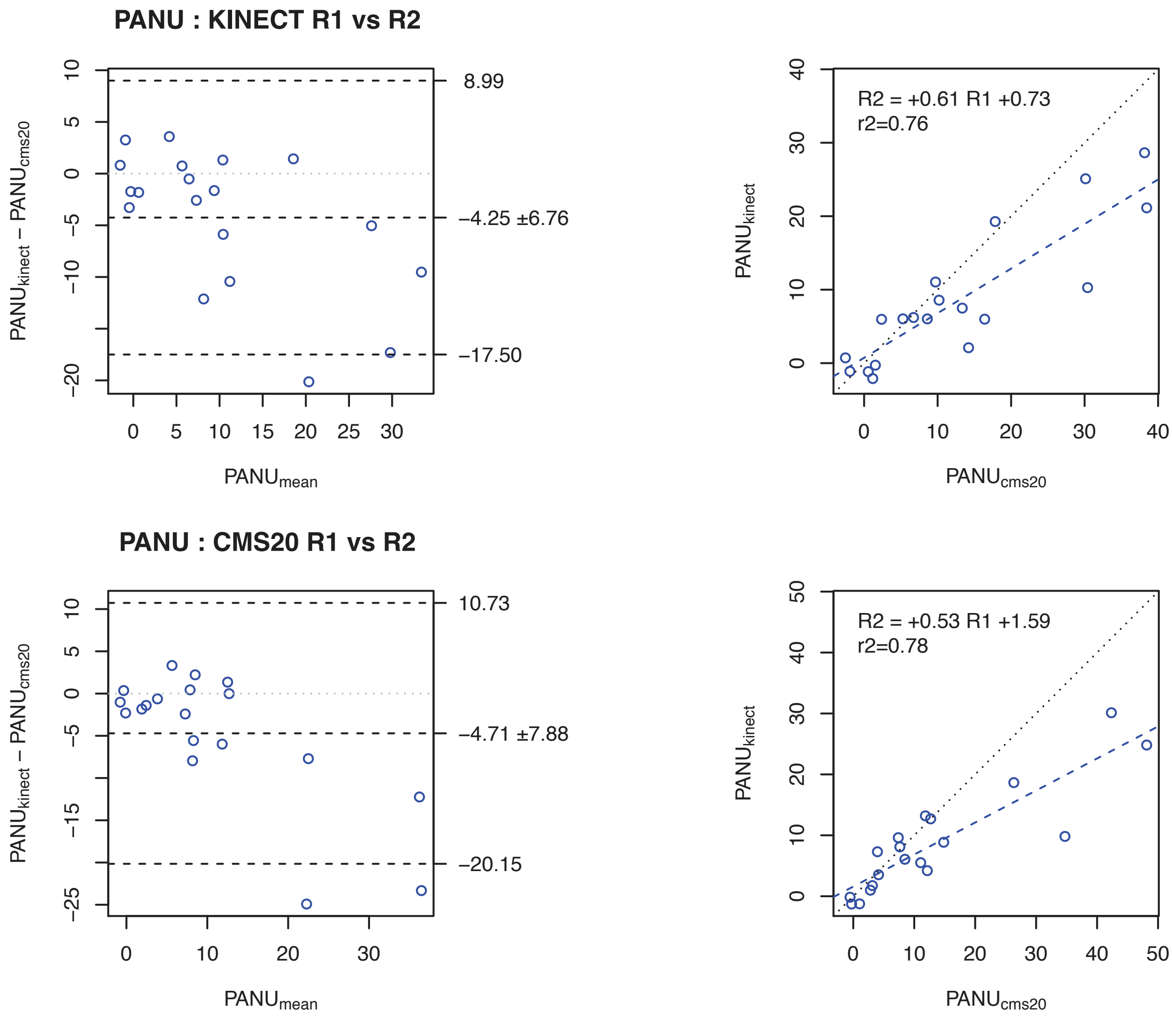

Figure 3.6. Test-retest reliability of the PANU scores determined by the Kinect (top panels) and CMS20s (bottom panels) between the first (R1) and second (R2) testing session. The left panel indicates Bland-Altman plots and the right panels shows the linear regression analysis with the Intraclass correlation coefficients in the inset. The Bland & Altman analysis compared the difference between R2 and R1 measured with Kinect (top panels) and with CMS20s (bottom panels) is plotted on the Y-axis, and the mean score on the X-axis .The solid horizontal line indicates the mean difference, with a negative value (-4.25 for Kinect; -4.71 for CMS20) indicating that PANU score decreases over repetitions, which was accurately determined by the Kinect. The right panels show regression line between the measurements of PANU scores in R1 and R2.

3.4 Discussion

This study validated a low-cost and marker-less Kinect-based system against a high-cost and marker based CMS20s system to accurately and reliably track hands and trunk motions. Furthermore, we show that Kinect® v2 by Microsoft adequately assesses proximal arm non-use. In addition, confirming our previous study (Bakhti et al., 2017), PANU determined by the Kinect indicated that ~60% of post-stroke individuals with low UL impairment (proximal FM>28/42) had PANU. PANU scores and its component kinematic variables (Δ Trunk, Δ Hand, Proximal arm use) measured by the Kinect and the reference CMS20s were highly correlated (ICC>0.8) and repeatable (ICC>0.7). We also showed that more precise systems are necessary to assess arm movement organisation details (e.g. movement time, number of velocity peaks) but the Kinect affords proximal joint angles. In fact, the Kinect system showed that apart from trunk compensatory movements, PANU was related to a non-use of elbow extension (through elbow angle analysis), which provides additional information on strategies utilized by post-stroke individuals to perform reaching movements. Overall these findings provide strong evidence that a Kinect-based PANU assessment is valid and provides additional global UL functional measures to classify post-stroke individuals for specific rehabilitation and monitor the recovery of UL function following various therapeutic interventions, particularly suited for Kinect based virtual reality UL rehabilitation.

3.4.1 Validation of the PANU scores obtained by Kinect®

Our clinical question was whether Kinect based system could replace the reference CMS20s system. An ideal model would claim that the measurements obtained by the Kinect and CMS20s will give exactly the same results. So, we would expect an ICC = 1, linear regression line with a slope = 1 and an intercept = 0, and a coefficient of determination (r^2) = 1. In the same way, all the differences between paired measurements in the Bland & Altman plots would be equal to 0 (systematic bias) and limits of agreements = 0 as well.

The PANU scores determined by the Kinect were similar to those determined by the CMS20s (ICC=0.95, r^2=0.9, B&L=0.06 ± 3.40). The origin of the discrepancies in PANU between CMS20s and Kinect are likely due to different placement of the remarkable points (markers for CMS20s and joints for Kinect).

The proximal arm-use determined by the Kinect were similar to those determined by the CMS20s (ICC=0.97, r2=0.9, B&L=-0.08 ± 2.70). For the "trunk" remarkable point: trunk joint (Kinect) was close to the centre of the bottom of the neck when the trunk marker (CMS20s) was at the body surface of the manubrium. The small error in trunk length distance measured by the Kinect was about -0.6 cm along the Z dimension, however, this error did not impair the assessment of trunk movements, because the trunk mark assessed by the CMS20s moved mainly along Z and remained at a large distance from the centre of the space (that was, the target).

For Δ Hand, the "hand" remarkable point: hand joint (Kinect) was close to the centre of the wrist joint when the hand marker (CMS20s) was at the body surface close to the wrist joint. The error in Δ Hand determined by the Kinect compared to the CMS20s was about 1.2 cm, which is small in comparison to the total reach length (280 mm). This might be because the "wrist" was not very well tracked by the Kinect. However, another cause of error was due to (i) wrist joint, which is close to but not exactly at the position of the CMS20s marker (about 3 cm) and (ii) the difference generates an error that depends on upper limb orientation. The combination of the two causes likely explains the differences between the two measurements of the hand.

3.4.2 Test-retest Reliability of the Kinect® based PANU assessment compare to CMS20s®

a) Test-retest reliability

PANU scores between the two testing sessions were highly correlated with Kinect (ICC = 0.76) as with CMS20s (ICC = 0.72). Moreover, Bland & Altman plots of the differences PANU scores between test-retest revealed that on average the second session was lower than the first session: 4.25 ± 6.76 for the kinect and 4.71 ± 7.88 for the CMS20s. Therefore, the size of the error in PANU with the Kinect (0.06± 3.40) is smaller than the size of the error between two repeated measures on the same person -4.71 ± 7.88.

b) Repeated measures of PANU

The slope of the linear regression (0.61and 0.53) indicated that the second session PANU scores were systematically lower than the first session with both devices (kinect and CMS20s respectively). The differences in PANU over repetitions might be due to intra-subject variability and practice effect, since patients may remember to not move their trunk in the spontaneous arm condition of the PANU assessment. Our previous study used a between day re-test, which showed good agreement between testing days. We found the same practice effect in our previous study. This could be explained by patients remembering the task requirements of minimising their trunk movements in the spontaneous arm condition of the PANU assessment. However, this provides evidence that specific training reduces trunk compensation that overtime will reduce PANU to acceptable level.

3.4.3 PANU complementary to clinical assessments of UL impairment and function.

The Fugl Meyer primarily assesses motor impairment of the UL, while the Box and Block tests the functional capacity of the UL that mainly depends on the forced use of the distal arm component related to manual dexterity for moving as many $1cm^3$ blocks from one side to another in 1min (Mathiowetz et al., 1985). However, the PANU measures the motor reserve of using elbow-shoulder extension during reaching (i.e., the difference between spontaneous and maximal use of the elbow-shoulder joints). Yet, the measure of the PANU only depends on the effective use of proximal movements. As other arm non-use assessments, the PANU can provide quantitative information about the motor reserve of the paretic arm but at the level of paretic shoulder and elbow.

a) Proximal arm non-use is linked to trunk compensation and functional motor reserve

To accomplish arm-reaching movements after damage to the CNS, post-stroke individuals generally use an abnormal coupling of the shoulder abduction and elbow flexion generally termed “flexion synergy” (Bourbonnais et al., 1989; Cirstea and Levin, 2000; Twitchell, 1951) which is due to a difficulty to isolate degrees of freedom especially in the elbow (Levin, 1996) (Levin et al., 2015). This pathological flexion synergy results in a smaller range of motion of the shoulder and elbow joints that is compensated by excessive trunk movements in order to achieve the forward reaching task (Roby-Brami et al., 2003; Wee et al., 2014). Our findings showed that PANU was mainly due to the inability to extend the elbow joint, which is a novel kinematic measure of the Kinect. Moreover, the amount of compensatory trunk movements classically increases with the severity of the motor deficit (Levin et al., 2015). However, two cases of compensatory trunk movements need to be distinguished. On the one hand, if the motor deficit is very severe, trunk compensation might be mandatory to ensure the success of the arm reaching: the patient will not succeed in the same reaching task if trunk movements are restricted. On the other hand, if the motor deficit is not too severe, trunk compensation might not be mandatory: the patient will succeed in the same reaching task whether trunk movements are restricted or not. In the latter case, the amount of trunk compensation to perform the reaching task reveals the *bad-use* of the existing synergies (Kleim and Jones, 2008; Levin et al., 2015). Here, the compensatory bad-use of the trunk and elbow-shoulder during reaching is measured by the PANU score, which is determined by the ratio of the difference between maximal use and spontaneous use of the paretic arm in the seated reaching task (Bakhti et al., 2017). Moreover, we confirmed our previous study (Bakhti et al., 2017) findings that ~60% of post-stroke patients with less UL impairment assessed by the proximal FM scores (>24/42) exhibited PANU (>6.5 as the cut-off for healthy elderly). This shows that PANU is not only complementary to the routine classical assessment of UL impairment, but also provides novel information on the unused motor reserve of a significant proportion of post-stroke patients exhibiting low UL impairment.

To our knowledge, the only clinical scale measuring excessive trunk movements during reach-to-grasp tasks is the Reaching Performance Scale (Levin et al., 2004). Unlike the objective PANU assessment, the Reaching Performance Scale focuses on direct assessor's observation of compensatory movement patterns performed during a reaching task in post-stroke individuals including trunk compensation (Levin et al., 2004). Although the Reaching Performance Scale evaluates reach-to-grasp performance (motor impairment) and trunk compensation, it does not provide an indication of arm non-use (Andrews and Stewart, 1979; Han et al., 2013; Sterr et al., 2002; Taub et al., 2006). Recently, Valdés et al. measured change in anterior trunk displacement using Kinect in a bimanual reaching task (Valdés et al., 2017). However, the PANU is the only clinical assessment that provides information on arm non-use as maladaptive trunk compensation, specifically the proximal arm non-use.

b) Application of Kinect for clinical assessment of PANU

The results from this study show that Kinect (v2) sensor can accurately and reliably determine PANU and its component kinematics. A major benefit of the Kinect is that it is markerless, which is in contrast to marker-based systems such as the CMS20s and VICON systems that need to define anatomical landmarks based on markers placed on the skin that limit their application laboratory setting. Using markers also presents several potential problems, including soft tissue artifact, lost markers, training of therapist to position markers and potentially uncomfortable exposure of areas of the body such as the thorax that could be a problem for female patients (Mündermann et al., 2006).

The other advantages of a Kinect-based system are: 1) easy to set up - no further physical equipment is needed, 2) safe - no additional trip hazards, and 3) inexpensive - the Kinect is a widely available consumer device (Knippenberg et al., 2017). These characteristics enable its use in a clinical setting and allow functional assessment of patients and rehabilitation following-up in conditions where expensive marker based motion capture methods are difficult to use (e.g., patient's home). This is particularly pertinent, since the advent of Kinect based virtual rehabilitation systems (e.g., Jintronix-Jintronix Inc, Medimoov-NaturalPad, ArmeoSenso-Hocoma) are being routinely used in both hospital and outpatient clinics and even home settings, the ease of access to the Kinect before, during and after rehabilitation make it a strong candidate to be routinely applied with other clinical assessments of UL impairment and function.

Although the use of the Kinect sensor for virtual rehabilitation of the UL is well demonstrated (Da Gama et al., 2015; Knippenberg et al., 2017; Pastor et al., 2012; Scano et al., 2014, 2015; Yates et al., 2016; Zheng et al., 2005), the use of the Kinect for clinical assessment is less well developed. Nevertheless, several studies have already shown that the Kinect sensor can be used for clinical assessments of the UL (Gregorij et al., 2013; Han et al., 2016; Huber et al., 2015; Kim et al., 2016; Kurillo et al., 2013; Lee et al., 2015; Matsen et al., 2016; Metcalf et al., 2013; Rammer et al., 2014; Seo et al., 2016; Sevick et al., 2016), and trunk kinematics (Macpherson et al., 2016; Valdés et al., 2017). The ability of a Kinect-based PANU assessment to differentiate reaching strategies following a stroke using an inexpensive and widely available Kinect motion capture system provide a strong case for the routine clinical and research application in classifying targeted rehabilitation and follow-up monitoring of UL recovery of post-stroke individuals

c) <u>Application of PANU score to classify patients for specific rehabilitation and monitor progress of rehabilitation</u>

PANU scores can be used to stratify the post-stroke individuals according to the level of PANU to guide the choice of therapy necessary for a better UL recovery (Levin et al., 2009). The fact that the amount of PANU during reaching is not related to the time since the stroke (Bakhti et al., 2017) is in agreement with the clinical observations that increasing rehabilitation into the chronic phase after a stroke may be useful for some patients (Page et al., 2004). Since criteria to select patients eligible for late rehabilitation programmes are currently lacking, the measure of PANU could help in predicting a favourable outcome to a specific protocol of rehabilitation in the chronic stage. Noting that PANU scores in healthy participants are generally below 6.5 (Bakhti et al., 2017) we suggest that patients with low PANU scores (<6.5) would benefit from traditional UL rehabilitation. Conversely, patients with PANU scores larger than 6.5 likely have a motor reserve to mobilize for true recovery. This would require specific UL rehabilitation targeted at improving proximal arm use, hence including forced arm-use and trunk constraint. The question whether rehabilitation programmes with a fixed trunk can improve functional abilities even in the chronic phase is unclear (Michaelsen and Levin, 2004; Pain et al., 2015). It might be addressed through prospective studies using the amount of PANU as an inclusion criterion to select the patients and predict the outcome of such therapeutic interventions.

In the present study, in addition to accurately and reliably measuring PANU with the Kinect, we were also able to measure shoulder-elbow angles. Since we found that PANU was associated with non-use of elbow extension, this additional information can provide useful global UL functional measure to help therapists in choosing target-muscles for local treatment of spasticity with botulinum toxin injections of elbow flexor muscles (but also shoulder adductors-retropulsors), since lowering spasticity in these UL muscles may improve elbow extension. Preliminary studies using this treatment are already showing improvements in PANU in follow-up sessions (unpublished observations).

No previous studies have applied a Kinect-based assessment to guide rehabilitation, however, Kinect-based rehabilitation has demonstrated great potentials in rehabilitation centres and at home (Knippenberg et al., 2017). For example, (Ballester et al., 2015) showed that goal-oriented movement amplification in virtual reality enhances the use of the paretic UL in post-stroke individuals. In addition, recent studies focused on the arm-use without trunk compensation. For example, (B et al., 2015) developed HAMSTER (Home Arm Movement Stroke Training Environment) as a game based home therapy program focused on retraining normal arm kinematics and preventing compensation strategies that limit recovery As well as (Valdés et al., 2017) with bimanual task. These positive results merit further evaluation of trunk compensation and proximal arm-use

3.5 Future work

Future research might test the hypothesis that post-stroke individuals with a high PANU score might improve with rehabilitation focused on the use of their paretic arm. The selected training programmes would incorporate different forms of trunk restraint or feedback on paretic arm use, with the aim to decrease compensatory trunk movements and to improve paretic arm kinematics e.g., (Michaelsen and Levin, 2004; Wee et al., 2014). For example, Wu showed that Constraint-Induced Therapy with trunk restraint improved grip function and outdoor activities after a stroke (Wu et al., 2012). Similarly, Alankus created a video game that reduces compensatory torso motions for stroke rehabilitation (Alankus and Kelleher, 2015). Important questions would be, from which value of PANU should rehabilitation be given? Which quantity of rehabilitation for which value of PANU?

We believe that PANU score is important for rehabilitation programs that aim to reduce trunk compensation and to promote previous movement patterns. Future work for this project will involve forced use provided by the robotic devices, games to promote a reduction of trunk compensation, which could have the potential to complement current therapy. In fact, Alankus & Kelleher designed a therapeutic motion-based game for reducing trunk compensation (Alankus, 2011;

Alankus & Kelleher, 2012). In addition, Motion-based games show promise for motivating patients to perform stroke rehabilitation exercises at home by themselves. The Kinect may provide quality feedback of trunk movements for clinical exergaming interventions. Therefore, the PANU score could be implemented in Kinect® virtual/robotic rehabilitation to monitor arm-use over time. In the near future and with further validation, PANU assessment may prove useful as home-based assessment for monitoring recovery over time as well as the effects of arm use interventions. Patients would benefit it in their own homes for self-rehabilitation and to assess their progress (Knippenberg et al., 2017; Lloréns et al., 2015).

3.6 Conclusion

In addressing the clinical needs for an outcome measure of UL recovery, our goal was to develop a methodology that would be reliable, easy to administer, time-efficient, and cost-effective, while being able to accurately and reliably capture an individual's PANU and other kinematic parameters. The present study showed that the low cost and marker less Kinect® based motion capture system could accurately and reliably measure PANU with reference to the standard marker based motion capture method (CMS20s). We also showed that additional measure of elbow non-use by the Kinect could provide an additional parameter to PANU that can be used for guiding specific rehabilitation. PANU assessment using Kinect® motion capture sensor could be recommended for all physical and occupational therapists (both in hospitals and private practices) to 1) classify PANU and motor reserve, 2) monitor recovery over time, to assess interventions and to guide patients towards specific arm-use rehabilitation. Since we found that the Kinect was able to accurately and reliably measure PANU, we consider that Kinect-based motion capture is a promising neurological rehabilitation tool for assessment and rehabilitation. These results contribute to the eventual goal of developing the Kinect as a low-cost system for counteracting trunk compensation and monitoring recovery in a home environment.

3.7 Perspectives

3.7.1 Innovative STRoke Interactive Virtual thErapy (STRIVE) project with Deakin University, Australia

As a perspective, we have already begun to use the PANU assessment before and after the STRIVE UL rehabilitation programme "innovative STRoke Interactive Virtual therapy" in a large group of community based stroke individuals. I am associated with this STRIVE project, which includes the use of Kinect-based PANU assessment before and after the UL virtual reality rehabilitation as part of the clinical assessments. To measure the efficacy of the UL virtual relaity rehabilitation programme, the goals should be « SMART »: Specific / Measurable/ Achievable/ Relevant/ Time limited (Kerr et al., 2011), which is the case of PANU assessment used in the study.

PANU assessment is implemented in the STRIVE online platform, which is a randomised controlled trial evaluating the effectiveness and user preferences in a community setting at Deakin University Clinical Research Faculty. This study is registered on the Australian New Zealand Clinical Trials Registry (ANZCTR), No. ACTRN12617000745347. The STRIVE project aims to test the efficacy of an online stroke rehabilitation system to improve paretic UL function in community-dwelling stroke survivors. The participants have similar demography to our two previous studies: 60 people with mild-to-moderate UL stroke (30-70 years) recruited from 3 stroke support groups (2 Melbourne-based; 1 Tasmania-based). At each location, participants are randomised equally to receive either 8-weeks of STRIVE training (n=10 per location) or no training (control, n=10 per location). All outcome measures are taken at baseline (within 3 days before study commencement) and after 8 weeks (within 3 days upon study completion). Outcome measures are conducted by a blinded assessor and include PANU, Functional near-infrared spectroscopy (fNIRS) to measure changes in oxy- and deoxy-haemoglobin responses in the brain during a reaching task of the paretic and non-paretic UL.

This STRIVE project is following the pilot study we did to evaluate the neural correlates of PANU (Bakhti et al., 2016). For participants randomised to receive STRIVE training, they attend a 40-min individually-tailored virtual reality UL rehabilitation program twice a week for 8 weeks. The programme is delivered through an internet-based commercial virtual reality rehabilitation system (Jintronix-) that captures body movements using a Kinect camera. The system is able to detect bodily movements of the trunk and arms, which the participants can then engage in various online games that are targeted at improving paretic UL function. Each week, the intensity of the games are recorded and adjusted accordingly to match the functional ability of the participants. For participants assigned to the control group, they continue with their usual care as prescribed by their physician and will only partake in the baseline and post-intervention measures. Participants in the control group are given the option to receive STRIVE training after 8 weeks. The next phase will be to increase the quantity of rehabilitation training at home without increasing the physiotherapists' time, appropriation by the patients and their family of some of these tools under the supervision of rehabilitation professionals acting at a distance via web-service platforms.

On one hand, some games are progressively enriched with components allowing the automatic adaptation of the game to the patient's own achievements. The command interface enables also the therapist to adapt online the game's parameters to the patient's needs. On the other hand, varying or combining the feedback of trunk forward displacement could be most effective for rehabilitation. Varying feedback in a random schedule ensures novelty, which is important for retention and transfer of motor learning (Valdés et al., 2017). Future work has to specify i) what the content of the training is and ii) efficacy of training following ICF domains.

3.7.2 Arm Reserve Assessment with Kinect

ARAK (Arm Reserve Assessment withKinect) project is the development of software that allows therapists to quantify the proximal arm non-use of the upper limb after a stroke without any training. The evaluation procedure is automated (Figure 3.7). The therapist gets online PANU and CI scores.

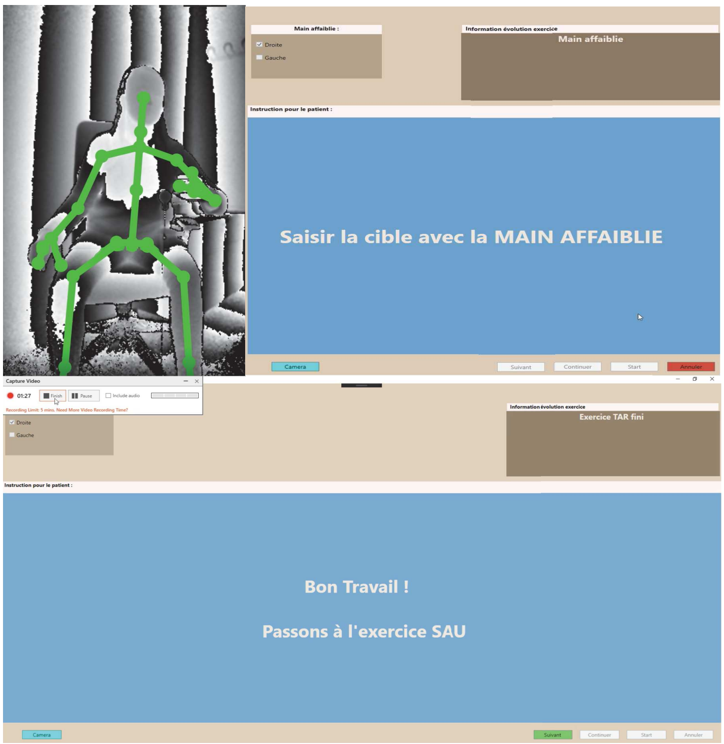

Figure 3.7. Examples of instructions during PANU assessment.

3.8 Summary

The PANU score can be accurately and reliably measured by the Kinect-based motion capture system. The Kinect sensor is widely available because of it low-cost and applicability in virtual rehabilitation settings, and thus is expected to be used by more clinicians.

Since PANU can be accurately measured by the Kinect, how is it possible to use this score in rehabilitation to counteract the proximal arm non-use? The next chapter consists in a literature review of the new technologies used in post-stroke rehabilitation

4 CHAPTER 4 - INNOVATIVE TECHNOLOGIES APPLIED TO SENSORIMOTOR REHABILITATION AFTER STROKE

Laffont I, Bakhti K, Coroian F, van Dokkum L, Mottet D, Schweighofer N , Froger J
Innovative technologies applied to sensorimotor rehabilitation after stroke.
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Abstract

Innovative technologies for sensorimotor rehabilitation after stroke have dramatically increased these past twenty years. Based on a review of the literature on "Medline" and "Web of Science" between 1990 and 2013, we offer an overview of available tools and their current level of validation.

Neuromuscular electric stimulation and/or functional electric stimulation are widely used and highly suspected of being effective in upper or lower limb stroke rehabilitation. Robotic rehabilitation has yielded various results in the literature. It seems to have some effect on functional capacities when used for the upper limb. Its effectiveness in gait training is more controversial. Virtual reality is widely used in the rehabilitation of cognitive and motor impairments, as well as posture, with admitted benefits. Non-invasive brain stimulation (rTMS and TDCS) are promising in this indication but clinical evidence of their effectiveness is still lacking. In the same manner, these past five years, neurofeedback techniques based on brain signal recordings have emerged with a special focus on their therapeutic relevance in rehabilitation.

Technological devices applied to rehabilitation are revolutionizing our clinical practices. Most of them are based on advances in neurosciences allowing us to better understand the phenomenon of brain plasticity, which underlies the effectiveness of rehabilitation. The acceptation and “real use” of those devices is still an issue since most of them are not easily available in current practice.

Keywords

Stroke, rehabilitation, new technologies, robotics, virtual reality, brain stimulation

4.1 Introduction

The rehabilitation of hemiplegic patients has greatly improved these past thirty years (Langhorne et al., 2011). New organization models have been proposed, from the creation of specialized units (Stroke Unit Trialists' Collaboratio, 2013), to the concepts of "Early Supported Discharge" (Sunnerhagen et al., 2013), "telerehabilitation" (Johansson and Wild, 2011; Rubin et al., 2013) and "self-rehabilitation" (Jones and Riazi, 2011).

Alongside these organizational evolutions, the methods and means available for the rehabilitation of these patients have varied in a considerable manner, with a greater importance allocated to technological devices (Reinkensmeyer and Boninger, 2012). This evolution was made possible by the advances in neurosciences that enabled the better understanding of brain plasticity mechanisms underlying the phenomena of sensorimotor and cognitive recovery (Kitago and Krakauer, 2013; Nudo and McNeal, 2013) as well as the better integration of learning theories in our rehabilitation programs. These progresses have completely altered the principles driving our rehabilitation practices (Pekna et al., 2012) with the emergence of new ideas such as the notion of task-oriented rehabilitation training, the new focus on the importance of intensity and repetition of exercises, as well as challenging the commonly admitted duration of our rehabilitation programs. This evolution has been widely influenced by the emergence of new technologies that found in this pathology an increasingly larger field of potential applications. Finally, this evolution of concepts and practices was associated to important progresses in rehabilitation-related professions and the healthcare organizations managing these patients.

The objective of this work was to propose a non-exhaustive synthesis of the main technologies involved in the rehabilitation of hemiplegic patients based on a review of the literature conducted on "Medline" and "Web of Science" for the period going from 1990 to 2013.

4.2 Rehabilitation technological devices

4.2.1 Neuromuscular or Functional Electrical Stimulation

Motor-stimulating currents were proposed more than 30 years ago for the rehabilitation of hemiplegic patients. The simple use of these currents was quickly enriched by more elaborated functions such as devices coupling detection and stimulation to let the patient's own motor functions express themselves during a voluntary task (Figure 4.1), before motor-stimulating currents take over (Schuhfried et al., 2012). This technique has showed its effectiveness for the upper limbs, especially in hemiparetic patients (Hara, 2008). These devices can easily be integrated into "task-oriented" rehabilitation programs; in fact electrical stimulation is dedicated to the patient's movements rendering them possible and easier to complete (Functional Electrical Stimulation - FES). Thus FES can be used for gait (e.g. Walkaid® system) or grasping (e.g. Handmaster® system) tasks. It is interesting to note that these particular devices, initially designed for orthotic purposes, seem to have a therapeutic relevance by improving the motor functions in the stimulated muscles (Everaert et al., 2013).

Figure 4.1. Functional Electric Stimulation of the upper limb during an Occupational therapy session

4.2.2 Rehabilitation robotics

Rehabilitation robots are interactive motorized devices allowing the mobilization of a limb for sensorimotor rehabilitation but also potentially, for cognitive rehabilitation. Rehabilitation robotics, whether they concern the upper or lower limbs, are generally divided into two categories: automated exoskeleton that move the limbs by controlling the displacement of each segment, and devices that enable the mobilization of a limb from a distal application point (Figure 4.2), without the control of the various joints (Mehrholz and Pohl, 2012). Depending on their design, these robots work in two or three dimensions. They are designed with different working modes: simple passive mobilization, robot-assisted mobilization that interacts more or less with the subject, and resistance training. Most robots enable the interaction with a virtual environment. The technological sophistication of these different systems is quite uneven, reflecting the yet not completely mature nature of these technologies (Krebs et al., 2014).

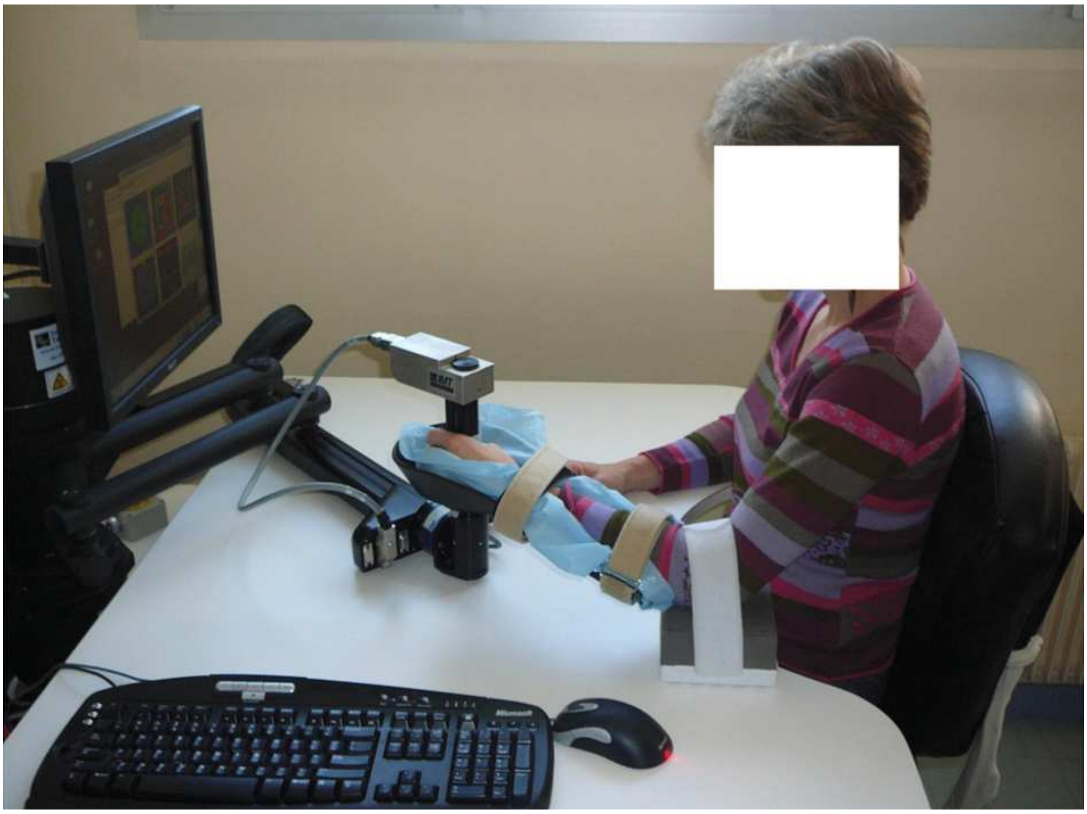

Figure 4.2. The American In Motion Robot® designed for shoulder-arm rehabilitation

The oldest rehabilitation robots are in fact isokinetic dynamometers; they are dedicated to instrumental muscle strength training and completely fit the definition of rehabilitation robotics. In hemiplegic patients, their relevance in lower limb rehabilitation has been validated whereas their effectiveness in upper limb rehabilitation is still being debated (Hammami et al., 2012).

The effectiveness of upper limb robot-assisted rehabilitation on stroke patients is strongly suspected. The latest meta-analyses suggest a superiority of robot-assisted rehabilitation when embedded in a complete rehabilitation program, compared to conventional methods on motor recovery of the upper limb, with a transfer of the acquired skills into the patient's daily life. The mechanisms explaining this effectiveness remain uncertain; it is possible that the intensity and repetition of the exercises might be largely at the origin of the effectiveness for this type of rehabilitation. The individual effects of robotics remain unknown and are still being debated today. The refinement of these devices might probably promote a better effectiveness (Schweighofer et al., 2012). Non-automated electromechanical devices, like Armeo®, are often classified as rehabilitation robots even though their functioning mode does not fit the definition of robots. The effectiveness of robot-assisted rehabilitation for the lower limbs is still being argued in the literature (Mehrholz et al., 2013). Some studies reported that the "dose" effect was greater for robot-assisted gait rehabilitation than for robot-assisted upper limb rehabilitation. Paradoxically, these devices offer functions that are often less advanced than devices used for the upper limb: the interaction with the patient is mostly limited to applying forces to impose a "normal" gait pattern to the subject, with parameters set by the therapists. There are very few devices equipped with self-adapting functions where the machine can adapt to the patient's performances (W et al., 2013). The association with virtual reality is rare on these robots (Reinkensmeyer and Boninger, 2012).

Generally, very few rehabilitation robots are available on the market, and their diffusion is greatly limited by the yet immature nature of the technology, the price of the devices, as well as the reluctance of therapists and patients to use them (Reinkensmeyer and Boninger, 2012). These reluctances are fed by the fear of seeing these rehabilitation robots replace human help; yet most studies have shown that the effectiveness of robot-assisted rehabilitation was based on its integration within a global program where the place of rehabilitation therapists is essential.

4.2.3 Virtual reality

Virtual reality has strongly invaded the field of rehabilitation (Laver et al., 2015; Moreira et al., 2013). Video games for the general public have been tested on neurological patients in several clinical studies, and have shown their effectiveness especially in upper limb rehabilitation but also for posture rehabilitation. Encouraged by these first publications, several teams have started working on video games dedicated to the rehabilitation of hemiplegic patients and thus designed with the help of therapists based on their knowledge of motor and cognitive specificities required for these patients (Figure 4.3). The superiority of "dedicated" games has not yet been validated, but in this case also it is probably due to the immaturity of these technologies. These games are progressively enriched with promising new functions, not yet fully validated: intelligent components allowing the automatic adaptation of the game to the patient's own achievements (Nirme et al., 2011), command interface enabling the therapist to adapt online the game's characteristics to the patient's needs, multiplayer systems to play outside of the institution via a web-service platform.

Besides its rehabilitation relevance, virtual reality opens essential perspectives in terms of patient follow-up and individualization of care. In fact, thanks to the automatic recording of the movements performed by the subject, we will be able to conduct a refined analysis of the quality and quantity of motor function progression, and also to better understand this progression timeline. The collected data should help us decipher the learning and recovery mechanisms, in order to better analyze how we could act on them. Furthermore, this data acquisition will facilitate the modeling of post-stroke recovery and improve our ability to individualize in a very precise manner these rehabilitation programs (Schweighofer et al., 2009).

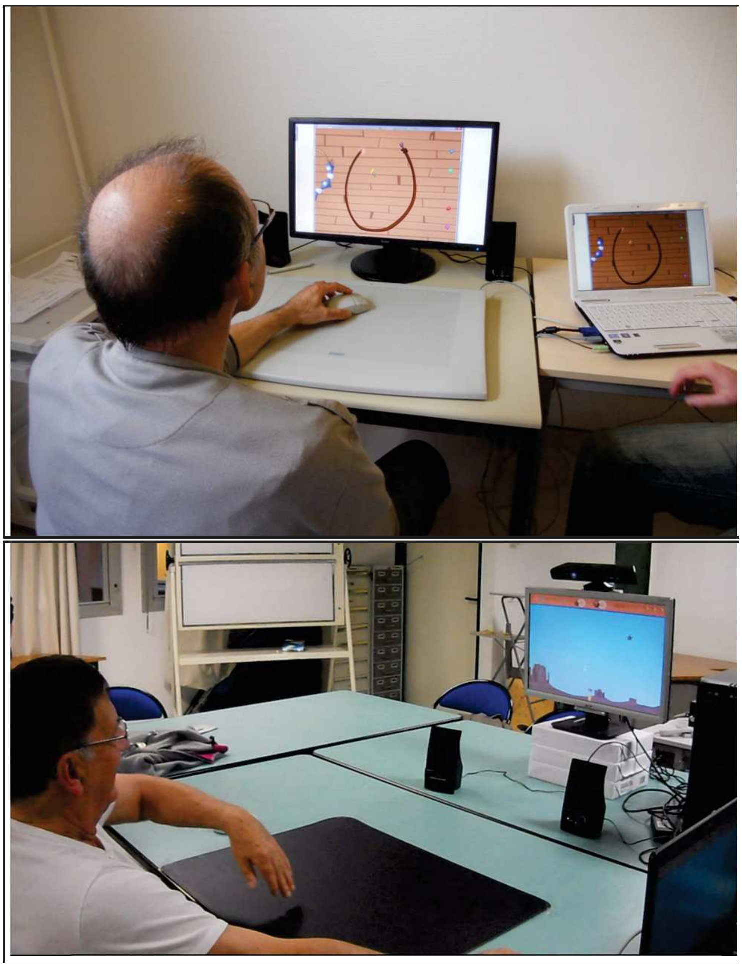

Figure 4.3._Upper Arm rehabilitation through video-games.
The cursor on the screen is moved with a tactile tablet or by using the Kinect system

4.2.4 Modulation of sensory afferents

We find under this term techniques using sensory afferents to impact on the recovery of functional motor abilities. All sensory feedback techniques, visual or auditory and biofeedback techniques can fit into this category; voluntarily we will only review them briefly (Stanton et al., 2011). These techniques are old and technological advances have enabled the sophistication of their application as well as providing a better understanding of their action mode. These sensory afferent modulation techniques also concern transcutaneous stimulation devices, like TENS, sometimes proposed as adjuvant methods to other sensorimotor rehabilitation devices (Laufer and Elboim-Gabyzon, 2011).

The three most advanced techniques for sensory afferent modulation are mirror therapy, robot-assisted rehabilitation and postural rehabilitation devices. Mirror therapy exploits the theory of mirror neurons, where the observation or even mind representation of the movement facilitates the activation of brain areas involved in the performance of motor tasks (Garrison et al., 2013). The use of mirror therapy has been generalized and rationalized, especially for the upper limb, with highly suspected results on motor and functional recovery.

Virtual reality rehabilitation robotics is a technique proposing visual, auditory and haptic feedback of the performed task to patients. Computer and robotic technologies allow the manipulation of this feedback (increased errors for example) in order to manage the post-therapy effect and promote learnings (Abdollahi et al., 2014; Molier et al., 2010). Finally dynamic and static postural evaluation devices are typically included in the definition of technology for sensory afferent modulation. Their relevance in postural rehabilitation, which implies the recovery of several other motor functions, has increasingly been validated.

4.2.5 Neurofeedback rehabilitation

Recent advances in terms of brain signal collection and treatment permit a refined analysis of brain activation areas during the completion of a motor or cognitive task. These recordings are available through functional magnetic resonance imaging (fMRI), near-infrared spectroscopy (NIRS) or electroencephalography (EEG) techniques. However, fMRI, in spite of its excellent spatial and temporal resolution, cannot be mounted onto a device to record brain activity in functional situations. NIRS and EEG, especially when coupled, can record brain activity during motor tasks in daily life or at least in rehabilitation settings.

The collected brain signal can be used for therapeutic objectives (Daly and Wolpaw, 2008):

- Brain interface coupled to an auditory or visual feedback system (e.g. displacement of a target) can help patients to visualize the effects of brain representation exercises and facilitate the learning of recruiting brain activation (Mihara et al., 2013).

- Brain interface, when associated with a passive or active mobilization of the limb through an external device, either robot-assisted or via FES, can help patients become aware of the recruitment of relevant brain areas and thus influence brain plasticity by facilitating learning. Brain interface coupled with robotic or SEF technologies might also contribute to "closing the sensorimotor loop" and thus promoting the shaping and maybe the emergence of voluntary motor functions.
- Finally, very recent studies have suggested associating the decoding of this brain signal with brain stimulation techniques, during voluntary tasks. The coupling of these two techniques could help reinforce the mechanisms of adaptive brain plasticity and inhibit maladaptive mechanisms (e.g. inhibition of contralesional activations when they exist).

4.2.6 Brain stimulation

Brain stimulation techniques can be ranked among innovative rehabilitation technologies. They are based on the use of a local magnetic field or galvanic current (Feng et al., 2013) to stimulate or inhibit certain brain areas, to promote the emergence of motor functions (Ayache et al., 2012; Edwardson et al., 2013). Repetitive transcranial stimulation (rTMS) or transcranial direct current stimulation (TDCS) can be used in a stimulating or an inhibiting mode according to the characteristics of the generated magnetic field or currents. The spatial resolution in rTMS is better than in TDCS and its application can be associated with neuro-navigation techniques to increase its precision. TDCS bears the advantage of being easy to use and requiring less costly materials.

The effectiveness of these methods is still being debated (Hao et al., 2010), even if there are an increasing number of studies in the literature showing some relevance in motor recovery (Takeuchi and Izumi, 2012b). The most recent studies promote the use of these techniques as a "facilitation" method for other rehabilitation techniques: for example the patient follows an intensive rehabilitation session preceded and facilitated by a TDCS session. In a similar manner, coupling these brain stimulation methods to brain signal recording methods during voluntary movements opens perspectives for new paradigms where the stimulation site will be guided by the management of individual brain map recordings specific to each patient.

4.3 Perspectives

The advent of these technologies applied to rehabilitation is revolutionizing our practices. Brain signal recording techniques associated with the infinite possibilities of behavioral recordings of motor functions or cognitive processes, promote the refined understanding of the mechanisms involved during recovery. This increased knowledge on neural plasticity phenomena, underlying the learning process post lesion, will allow us to individualize very precisely our rehabilitation programs, refine the indications for this or that technique, and, through recovery modeling, define rational therapeutic strategies for a more effective care management. Eventually these technologies will become real "assistants" for rehabilitation professionals. The future probably resides in associating these different techniques to one another. Using these technological tools to help the patient-therapist relationship is a preview of what the rehabilitation of tomorrow will be: a personalized and rationalized training program, greater possibilities of increasing the quantity of rehabilitation training at home without increasing the physiotherapists' time, appropriation by the patients and their family of some of these tools under the supervision of rehabilitation professionals acting at a distance via web-service platforms. Our goal is to remain vigilant in anticipating these positive and ineluctable advances while preserving the quality of care where direct human interaction remains essential.

Since the kinect is the mostly used in UL rehabilitation (Knippenberg et al., 2017). The PANU score measured with Kinect could be used in a virtual reality game. Therefore PANU score would allow monitoring post-stroke individuals at home.

4.4 Summary

Kinect and virtual reality are the most used in rehabilitation of post-stroke upper limb. The component of PANU, compensation index–CI could be integrated in a virtual reality system and used as a bio feedback. Thus, the kinect based virtual reality system could be used to counteract the proximal arm non-use.

In our Kinect –based virtual reality game project, we try to assess the interest of virtual reality when counteracting proximal arm non-use. PANU and CI are going to be integrated in the game. PANU score would quantify the motor reserve and CI would provide a feedback on trunk use online during the rehabilitation.

5 CHAPTER 5 - GENERAL DISCUSSION AND CONCLUSION

5.1 General summary

Post-stroke individuals often exhibit excessive use of their trunk when reaching targets within arm's length, even after sufficient recovery of paretic upper limb (UL) movements of the shoulder and elbow joints (reviewed in Chapter 1). Such compensatory movements reflect non-use of the shoulder-elbow joints, which we termed "proximal arm non-use". Reducing proximal arm non-use is important because it has been suggested that it is detrimental to functional recovery of the paretic arm. However, no method currently exists to quantify the proximal arm non-use objectively and reliably, which was the primary aim of the thesis.

In Chapter 2, the goal was to quantify the proximal arm non-use - PANU score in sub-acute and chronic post-stroke individuals with mild to moderate UL impairments. We conducted a prospective observational study with 45 stroke survivors capable of hand reaching with their paretic arm a target within arm's length versus an aged-matched healthy control group (n=45). We used the CMS20s (Zebris) system to objectively measure the hand and trunk kinematics during a seated reaching task to quantify PANU scores. PANU score was determined by the difference in hand and trunk kinematics in two reaching conditions: spontaneous arm use versus maximal arm use (trunk self-restrained). We used the CMS20s (Zebris) as an objective motion capture system to quantify PANU scores. Among post-stroke individuals with mild proximal UL impairment (FM > 28/42), 61% had PANU scores greater than 6,5% (i.e; cut off level of healthy control subjects). Therefore it was shown for the first time that PANU is a reliable method to quantify shoulder–elbow non-use and UL functional motor reserve during seated reaching, which is not picked up by classical clinical assessments of UL impairement (Fugl-Meyer-FM) and function (Box and Blocks-BB).

Chapter 3 extended the findings of Chapter 2 by determining the levels of PANU scores during seated reaching in new population of mild to moderate post-stroke individuals (n=19) to validate a more widely available and less expensive Kinect-based motion analysis system against the reference Zebris (CMS20s) system. Confirming the results of Chapter 2, it was shown that among post-stroke individuals with mild proximal UL impairment (FM > 28/42), 60% were diagnosed with proximal arm non-use. The Kinect was found to be reliable for measuring PANU scores during seated reaching. In fact, the median PANU score determined by the Kinect was not significantly different to the CMS20s. Moreover, PANU scores, and its components (Δ Hand, Δ trunk and proximal arm use-PAU), measured using the Kinect were strongly related (ICC=0,95) to those using the CMS20s. PANU scores showed good test-retest reliability for both the Kinect and CMS20s with Bland & Altman plots showing slightly reduced PANU scores (i.e., improved performance) in the re-test session for both systems, which confirms the practice effect we found in

Chapter 2. This practice effect might indicate that the proximal arm non-use could be counteracted with specific rehabilitation.

In Chapter 4, a literature review on innovative technologies applied to UL rehabilitation after a stroke indicated that Kinect-based virtual reality is widely used in rehabilitation with an exponential growth of Kinect-based virtual reality games being developed for post-stroke individuals. Moreover, these so called “serious games” are progressively enriched with components allowing the automatic adaptation of the game to the patient’s own achievements. For example, the command interface enables the therapist to adapt the game’s parameters to the patient’s needs online. Therefore Kinect based virtual reality opens prospects for future patient centred follow-up and care. In fact, with the Kinect’s automatic recording of the movements performed by the subject, it we will be possible to conduct a refined analysis of the quality and quantity of motor function progression. Furthermore, the collected data acquisition will improve our ability to individualize in a very precise manner the rehabilitation programmes (e.g using PANU score).

5.2 Proximal arm non-use and its consequences for diagnosis

5.2.1 Additional value of using PANU score for diagnosis

The low rate of recovery of UL function post-stroke is a considerable challenge for therapists. Individualized assessment can help to determine the best rehabilitation protocol for each patient. The PANU score quantifies the amount of non-use of the shoulder and elbow joints in subacute and chronic post-stroke subjects with remaining UL capacity (i.e., recovered UL motor function). The PANU score was found meaningful (comparison between post-stroke individuals and controls), reproducible (in test re-test) and usable in routine clinical practice (easy and fast to administer). Because it is also reliable, the PANU score seems ideal for monitoring recovery of paretic UL use (function) post-stroke and the effectiveness of a rehabilitation treatment. Since it was found that the PANU score for the non-paretic UL in post stroke individuals and age-matched healthy controls (both right and left UL) were not significantly different, the PANU score of the non-paretic UL can be used as a reference to guide the effectiveness of rehabilitation. Therefore, the method of proximal arm non-use measurement (PANU score) can be useful to also complement to other routine clinical tools aiming at measuring UL impairment/function (FM, BB) of the UL after a stroke, or to other UL non-use (BART etc.) assessments (Han et al., 2013; Sterr et al., 2002; Taub et al., 2006).

a) PANU score distinguishes mandatory from non-mandatory trunk compensation

Mandatory and non-mandatory displacements of the trunk have to be distinguished in a therapeutic perspective. Since the PANU score is the difference (M_{PAU}-S_{PAU}) between the spontaneous use of the arm (S_{PAU}) and the maximal use of the arm (M_{PAU}), mandatory trunk compensation is not taken into account. Thus proximal arm non-use is only related to the non-mandatory part of trunk compensation. However, the Compensation Index-CI represents the trunk compensation in each condition (CI= 1-PAU).

As previously mentioned, post stroke individuals with severe UL impairment are sometimes able to perform a reaching task thanks to the recruitment of large trunk movements, compensating for the weak recovery of shoulder and elbow joint motor control. Moreover, the amount of trunk compensation (CI) classically increases with the severity of the motor deficit after a stroke (Jones, 2017). However, these post-stroke individuals do not behave differently in a spontaneous and in a forced-use condition (i.e., they use the same trunk compensation in both spontaneous and forced condition). Consequently, for subjects with severe upper limb impairment, because large trunk compensation is mandatory to perform the reaching task even in the forced condition, the PANU score is about zero and the CI score is over 0%. (i.e., because the trunk compensation is mandatory to ensure task success whatever the instructions given).

For post stroke individuals with PANU scores over 0% and CI over 0%, the trunk compensation is non-mandatory, and as such could be a sign of maladaptive trunk compensation related to PANU. In fact, these post-stroke individuals use more trunk compensation in the spontaneous condition. Therefore, the PANU method shows, for the first time, how to differentiate mandatory and non-mandatory trunk compensation with a simple seated reaching task.

b) PANU score distinguishes recovery and compensation for proximal movements of the upper limb

One current problem in assessing the paretic UL recovery as measured by clinical scales such as the FM (impairement) and BB (function) test is that they reflect both restitution and compensation, which can confound the effects of treatment (Levin et al. 2009). In fact, on some scales that measure UL functional ability (BB), the post-stroke individual can get a perfect score for accomplishing the task using compensatory strategies since the scale does not classify how the task is performed. A typical example of this is the assessment of constraint induced movement therapy-CIMT (see Figure 5.1). This CIMT rehabilitation technique involves restraint of the non-paretic UL combined with intensive training of the paretic UL. CIMT has been shown to be highly effective in improving the scores of paretic UL functional scales such as the WMFT (Taub et al., 1999; Wolf et al., 2006) even after a short period of CIMT (Massie et al., 2009). However, a recent study (Bang et al., 2015) has shown that this functional improvement in the paretic UL may be the result of improved use of compensatory strategies to achieve task goals (see Figure 5.2). In fact, their results showed that elbow extension did not increase (sign of no recovery), neither did trunk flexion decrease (sign of trunk compensation), and shoulder abduction actually increased significantly (sign of compensation) (Bang et al., 2015).

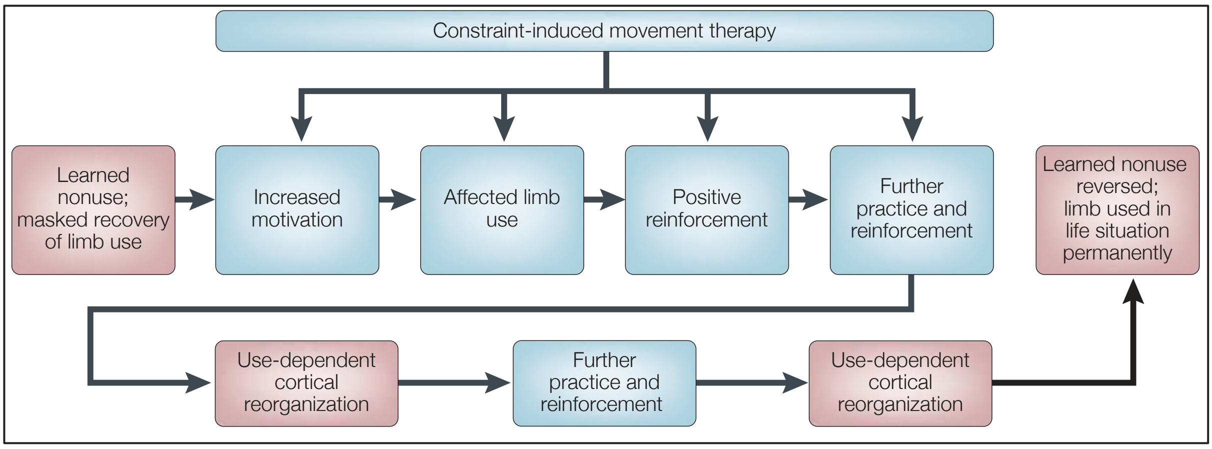

Figure 5.1. Overcoming "learned non-use" of a paretic upper limb by constraint induced movement therapy (adapted from Taub et al., 2002)..

Clinical message

- Modified constraint induced movement therapy combined with trunk restraint in subacute stroke patients with decreased upper-extremity function might be more effective in improving the upper-extremity function and activities of daily living than modified constraint induced movement therapy only.

Figure 5.2. Clinical message about constraint induced movement therapy (Bang et al., 2015)

The PANU score quantifies the maladaptive trunk compensation and at the same time distinguishes between UL recovery and compensation. In fact, for post-stroke individuals who have fully recovered UL function, the reaching task within arm's length theoretically can be achieved with 100% arm-use (i.e., use of shoulder flexion and elbow extension, M_{PAU}=S_{PAU}=100%) and 0% of trunk use (CI=0%). Consequently the PANU score and the CI score will be about zero percent. In others words the reaching task is accomplished without forward trunk displacement, which would be expected for healthy people reaching within their arm's length. PANU permits to distinguish between (i) recovery (PAU =100% in spontaneous and maximal arm use conditions – CI=0%) and (ii) compensation (CI>0%) with 2 cases: mandatory compensation with PANU=0% and non-mandatory trunk compensation with PANU>0% (Bakhti et al., 2017).

c) PANU score permits a stratification of post-stroke individuals

Stratification of post-stroke individuals

PANU scores over 6.5% (cut off value of 2SD above the control group PANU scores determined in Chapter 3) classified post-stroke individuals with a potential functional reserve of arm use (shoulder-elbow non-use) that is, favouring "non-mandatory trunk compensation" that is likely maladaptive and detrimental to optimal paretic UL recovery. Consequently, the PANU score can be used to detect and stratify patients who are potentially responders to a specific rehabilitation programme focusing on the "forced-use" of shoulder and elbow movements, as well as to monitor patients' UL recovery after a stroke.

Therapists can take the PANU value of 6.5% (i.e., 99% percentile of control group values) as a boundary to the existence of a motor reserve of PAU (shoulder-elbow use) potentially mobilizable for paretic UL recovery. With PANU scores below 6.5%, people fall into two possible categories, both with bad prognosis of progress over specific PAU therapy. A low PANU score can indicate no need to recruit trunk movements to reach a target within arm's length, hence no need for specific therapy (as-healthy a subject's behaviour). A low PANU score can also indicate mandatory need for trunk movements whatever the therapist's instructions, hence there will be no motor reserve to serve as a basis for specific therapy (PANU about 0% and CI>0%). Noting that PANU scores in healthy participants are below 6.5%, we suggest that patients with low PANU scores (<6.5%) would benefit from traditional arm rehabilitation. Conversely, patients with PANU scores larger than healthy controls (>6.5%) are likely to have a "motor" reserve that can be mobilized through targeted UL rehabilitation for optimal recovery.

In our first experimental study (Chapter 2), we could partition the post-stroke participants into 4 groups based on the range of PANU values. Figure 5.3 shows a categorisation of the PANU of the paretic UL in 4 groups of post-stroke individuals, which might be used to guide rehabilitation strategies. As shown in Figure 5.3 , it can be suggested that post-stroke individuals in the last three groups (PANU scores 6.5-41%) might need specific arm-use rehabilitation strategies.

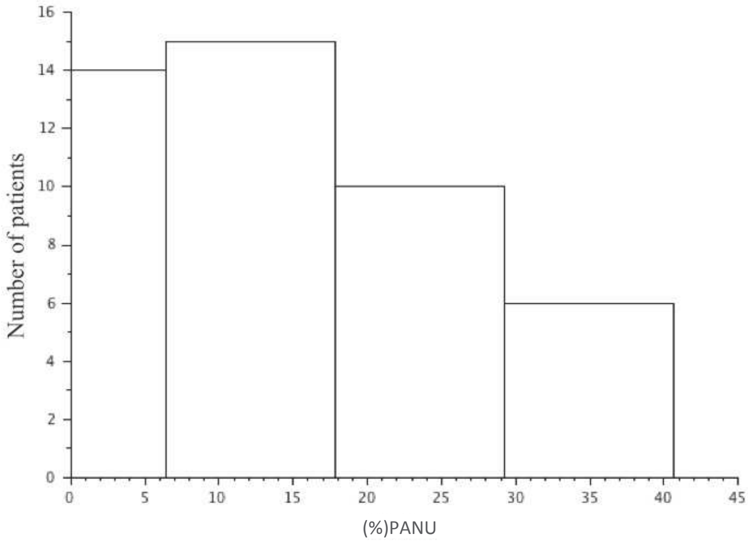

Figure 5.3. Stratification of the post-stroke participants into 4 groups based on the amount of PANU.

Guidance of stroke treatment

Many UL motor function outcome measures do not produce data that provide obvious links between the basis for planning treatment and the emergent plan for functional restitution (Wolf et al., 2001). PANU is a direct measure of proximal arm functional motor reserve, which is usable to stratify the post-stroke individuals according to the level of PANU score of their paretic UL in order to guide the choice of therapy necessary for an optimal recovery (Levin et al., 2009).

In our first study (Chapter 2), PANU results indicated that about two out of three post stroke individuals would benefit from specific rehabilitation to promote paretic arm use, and hence foster use dependant neural plasticity and maximal recovery of UL function. This specific rehabilitation strategy should act against the PANU of the paretic UL, that is to say, would target an increase of paretic arm use, hence a decrease of trunk compensation.

Although the precise definition of which strategy should be recommended for each individual patient is beyond the goal of the present contribution, Figure 5.3 provides hints that might be useful for future research. The first group contains 31% of post-stroke individuals with PANU scores similar to healthy age matched controls. The need of specific rehabilitation to foster paretic arm use and minimize trunk compensation is most likely not needed because they already use their UL for reaching a target within arm's length like healthy people without overt trunk compensation. The other three groups contain 69% post-stoke participants with an amount of PANU that is higher than 6,5% (in the control group). These patients spontaneously perform a seated reaching with low arm use and high maladaptive trunk compensation. Therefore, they need rehabilitation focused on the use of their paretic arm, especially if the risk of losing their UL motor reserve is linked to the amount of non-use. The question whether rehabilitation programmes with a fixed trunk can improve functional abilities even in the chronic phase is unclear. It might be addressed through prospective studies using the amount of PANU as an inclusion criterion to select the patients and predict the outcome of such therapeutic interventions.

d) PANU score using Kinect is more accessible for a large number of clinicians

The different measures of UL non-use presented in Table 2.2 show that there are different ways to measure the motor functional reserve of the UL with the specificity of each one determined by the respective task. However, none of the previous assessments of UL non-use is well adapted for clinical settings (Han et al., 2013). The classical tests of arm non-use provide a global UL non-use (use paretic or non paretic arm), but are quite subjective and long to administer. In fact, the "WMFT - MAL" method would likely take one hour to complete and the questionnaires such as the MAL are based on patients' recall, which are prone to forgetfulness in the population (Chen et al., 2015; Han et al., 2013). Moreover, the WMFT and the AAUT need expertise of the clinician assessing. Although the instrumental arm non-use test (BART) is objective, the test needs specific hardware and software that means that it is primarily accessible for research use only. PANU on the other hand is an easier instrumental method that requires a widely available and inexpensive Kinect sensor and takes only about 10-20 minutes to administer including setup time.

In Chapter 3, measuring PANU necessitated a marker-based 3D movement capture system (Zebris CMS20s), which made the method more adapted to research centres or to large hospitals that can afford such a device. However in Chapter 4, a low cost and easy-to-use marker-less Kinect based technology was developed to determine the PANU score. The Kinect technology was originally developed by Microsoft for marker-less motion capture by the gaming industry using developer software that has also been shown to accurately and reliably measure hand and trunk movements (Valdés et al., 2017). In Chapter 4 the Kinect sensor and a specialised software (Macoki, Naturalpad) was developed to perform PANU assessment, but it is envisioned that a dedicated open source easy-to-use system will allow the PANU measure to be more easily accessible to clinicians in routine testing, and the low cost and large availability of the Kinect hardware would broaden the range of the potential users.

Although we attempted to provide a simple method to calculate the PANU scores, the procedure of PANU assessment needs to be automatised even if only 15 min training time is required to appropriately perform the assessment by a novice therapist. In future work, we plan to automate the PANU procedure to facilitate the assessment (5 min of training) in private physiotherapist's offices

5.2.2 PANU complements clinical assessments of upper limb impairment, function and non-use.

a) PANU method complements clinical assessments of upper limb impairment and function

We have shown that proximal arm non-use after a stroke can be reliably quantified during a seated hand-reaching task using the difference between the spontaneous vs. forced partitioning of the work between the trunk and the paretic UL. The measure of PANU is sufficiently simple and fast to be usable in routine clinical practice.

The PANU score provides novel information that is not assessed by clinical scores (FM and BB tests). In fact, 61% of the less-impaired post-stroke individuals (FM >28/42) had PANU over 6.5%, which was the cut-off value based on healthy control subjects. Thus, PANU provided information that the routinely used FM scores did not capture.

The trunk compensation used during a reaching task can be also measured using the Reaching Performance Scale (RPS). The RPS is a scale that evaluates reach-to-grasp performance, where the therapist visually quantifies the reaching and the trunk compensation movements. One component of the PANU score, the (CI) provides an objective quantification of trunk compensation. In addition, since the PANU method compares two measures of excessive displacement of the trunk while hand reaching a target, the PANU score provides information that is quite different from that in the RPS. In fact, the PANU score addresses the question of shoulder-elbow non-use that is not provided by the RPS. Future studies are necessary to determine the similarities and differences of PANU and RPS.

b) PANU method complements clinical assessments of upper limb non-use

The PANU score quantifies a new form of arm non-use, which is the shoulder-elbow non-use (see Table 2.2). In fact, classical clinical approaches of the non-use phenomenon after stroke focus on one of the most visible consequence of stroke in daily life, which is the underuse of the paretic UL in favour of the non-paretic UL (Andrews and Stewart, 1979; Page et al., 2004; Sunderland and Tuke, 2005). Using classical clinical tests measuring arm non-use, one can extract the arm non-use of the paretic arm from the differences between the WMFT and the MAL (Taub et al., 2006). Another method compares the spontaneous use of the paretic arm in daily life activities (AAUT and MAL) with the ability of the paretic UL to perform the same tasks when requested to do so (Sterr et al., 2002). In these two cases, the arm non-use represents a functional reserve of the paretic UL in different activities of daily life (trunk compensations allowed). Alternatively, the BART compares the surface reached during spontaneous vs. forced use of the paretic UL to provide an objective and quantitative measure of the non-use (Han et al., 2013). The BART represents the functional reserve of the paretic UL on reaching targets displayed between 10° and 170° in a 2D hemi-workspace while seating with a trunk restraint (when given choice between non-paretic and paretic UL).

Unlike the classical UL non-use tests, PANU method addresses a form of UL non-use that is intrinsic to the paretic UL itself, which has never been proposed before. Based on a rehabilitation point of view, the proximal arm non-use during seated reaching should be considered as an "unused potential" (functional motor reserve) of the paretic UL after a stroke (Sunderland and Tuke, 2005) with therapeutic consequences (Michaelsen et al., 2006). With PANU, we compare the spontaneous arm use and the maximal arm use in a seated forward reaching task. PANU represents the functional reserve of the paretic UL on a seated reaching task (when given choice between trunk and the paretic UL movement). While the seated reaching task represents one of the basic aspects of arm use, it does not include other actions that are part of daily use, such as lateral reaching movement, drinking, lifting an object etc. Since PANU measures paretic UL non-use in forward reaching only, it is not representative of all the types of UL activities used both in the clinic and in activities of daily living that might be affected by non-use. However, since the basic reaching function of the UL is necessary before grasping with the hand, quantifying paretic UL non-use during seated reaching would be applicable to other paretic UL movements. In fact, because forward reaching is the building block of many UL activities of daily living, it is likely PANU and UL non-use varies similarly in a larger variety of UL activities. More research is necessary to confirm these suggestions.

In summary, there are a number of methods that measure different aspects of functional reserve (or non-use) of the paretic UL. The clinical methods (WMFT etc.) globally measure the overall functional reserve of the UL in activities of daily living, while the BART provides a functional reserve of the UL in seated 2D hemi-workspace reaching tasks. Only the PANU provides a functional reserve of the paretic UL itself (via shoulder-elbow non-use) in a forward reaching task. PANU measures a specific kind of UL non-use, which, to our knowledge, had never been described before. Future studies should determine if a higher PANU might result in higher global UL non-use in activities of daily living, such that PANU might be a local component of the more global non-use in daily living activities.

5.3 Proximal arm non-use and its consequences for treatment

The ultimate goal for many post-stroke individuals is to achieve a level of functional independence necessary for returning home and being able to integrate as fully as possible into community life. For this reason clinicians are challenged to enable post-stroke individuals to achieve their full potential and to maximize the benefits from training in order to attain the highest possible degree of UL use (French et al., 2016).

5.3.1 Added value of PANU score for upper limb rehabilitation

PANU score during seated reaching is tantamount to quantifying the motor reserve that the patient can mobilize during rehabilitation. Since criteria to select patients eligible for late chronic stage rehabilitation programmes are currently lacking, PANU score could help in predicting a favourable outcome to a specific protocol of rehabilitation in the chronic stage. PANU score of the paretic UL was not related to the time since the stroke in our experimental study (Chapter 3), this would be in agreement with the clinical observations that increasing rehabilitation into the chronic phase after a stroke may be useful for some post-stroke individuals. In fact we carried out a study on post-stroke individuals (median time since stroke 32 months) that showed a 6-week intensive multidisciplinary rehabilitation (3 days/week, four sessions/day) was efficient to enhance UL function over time (at 3 months and 6 months). The results showed a decrease in impairment, with gains in FM (+4.8; $p<0.001$), and an increase in function, with gains in BB scores (+3; $p=0.013$) (Coroian et al., 2017). However, future research would show whether PANU score decreases with late rehabilitation. In this way, therapists could use the PANU score as one of the criteria to select individuals with chronic stroke for inclusion in late rehabilitation programmes.

Future research might test the hypothesis that post-stroke individuals with a high PANU score might improve with rehabilitation focused on the use of their paretic UL, and maybe even at the chronic stage. This mobilization of the motor reserve would require specific UL rehabilitation targeted at improving proximal arm use (i.e., shoulder-elbow use), hence including trunk constraint (Figure 5.4) and forced arm-use (Michaelsen et al., 2001, 2006; Michaelsen and Levin, 2004).

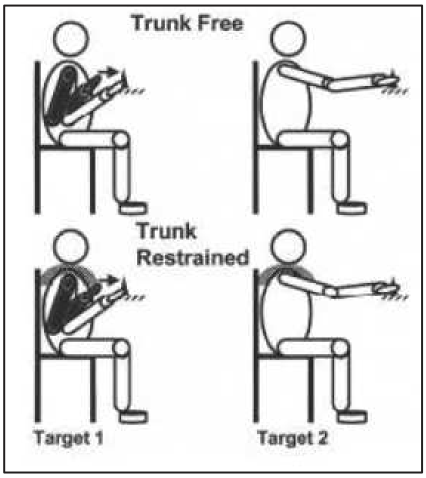

Figure 5.4. Rehabilitation task with trunk free and trunk restrained (Michaelsen et al., 2001).

5.3.2 Should proximal arm non-use be counteracted?

Since the PANU score of the paretic UL quantifies the motor reserve of the paretic UL at the level of shoulder-elbow use (reaching task), we consider this PANU score to be useful for therapists to establish appropriate treatment. In fact, this (shoulder-elbow) functional reserve might estimate the capacity of the arm to respond to environment changes. The aim of rehabilitation is to maintain the maximum number of patterns available in order to adapt to each behavioural goal (e.g. reaching task).

a) Recommendations about remedial versus compensatory rehabilitation

Recommendations

In the literature, there is still no consensus on where rehabilitation should be aimed at recovering the motor deficit or on the contrary in compensatory techniques (Shelton et al., 2001).

Recommendations for post-stroke management of the arm and hand include the use of compensations for patients with severe upper limb deficiency. The ultimate objective of rehabilitation of UL function is to increase the individual's ability to participate in daily activities in the most effective manner possible (Ada et al., 1994). However, we do not yet know whether, in the long term, the most effective way to increase these activities is to use (or not) motor compensation.

Two principal approaches to UL Rehabilitation (Bobath / Twitchell)

Remedial therapies, such as neurodevelopmental treatment or the Bobath approach, attempt to restore existing deficits without allowing for compensatory movements (Bobath, B., 1990). On the contrary, other approaches, such as Twitchell, allow for compensatory strategies (Twitchell, 1951). This may explain why more function-oriented therapies achieve their functional goals sooner than remedial therapies that work on the recovery at the impairment and function level (Kwakkel et al., 2004).

Similarly, the view that the appearance of gross flexor and extensor stereotype precede the restoration of more advanced motor function following a stroke is controversial. Some consider that it is important to favour the control of the basic UL synergies during the early recovery stages after a stroke (Twitchell, 1951). Others promote the opposite: post-stroke individuals have to attempt previous patterns early in order to develop normal motor responses (Bobath, B., 1990). For the moment, no one method is superior to other therapeutic approaches (Teasell et al., 2003)

One global approach of treatment is to intensively retrain the paretic UL in order to maximise its recovery. After maximal recovery, the rehabilitative approach would be to teach the post-stroke individual to compensate for the loss of the paretic UL function. However, the « cutoff point » for the absence of such capacity is unclear at present. With the PANU score , an indication might exist for one or the other method or at which point one should stop attempting to retrain the UL and begin teaching compensatory strategies (i.e, mandatory compensation with PANU=0% and CI>0% / Non mandatory compensation with PANU>0% and CI>0%). However, the possibility of overcoming PANU needs to be assessed in future work. Patient education is a key factor in balancing the short-term goal of achieving function versus the long-term goal of minimizing compensatory movement. The primary purpose of limiting compensatory movement patterns could be to minimize the long-term restrictions in movement (arm non-use) that can lead to joint contracture and pain (Gracies, 2005).

b) <u>Which rehabilitation to choose for mandatory trunk compensation?</u>

Some severe post-stroke individuals do not recover UL motor control even after 1 year post-stroke. In this case, the only possibility remaining to succeed in a reaching task is to use the trunk instead of shoulder and elbow. This unique strategy is called the mandatory trunk compensation. Therefore, the mandatory trunk compensation is the best option when the stroke lesion leaves no remaining paretic UL capacity for improvements of functional movements.

c) <u>Which rehabilitation to chose for non-mandatory trunk compensation or proximal arm non-use?</u>

Some post-stroke individuals who have proximal arm non-use, use trunk compensation in a reaching task but have the possibility to not use the trunk and to use the paretic arm (shoulder-elbow use). These post-stroke individuals can be rehabilitated according to different approaches. Some authors questioned the effectiveness of therapeutic approaches aimed at "controlling" non-mandatory compensations. The question that arises, therefore, is whether the use of these compensations should be allowed, or whether the most normal restoration of the motor capacity should be attempted.

Approach consisting to not counteract the non-mandatory trunk compensation.

Latash and Anson consider that after a lesion of the central nervous system, movement patterns different from those typically observed in healthy subjects should be considered adaptive (Latash and Anson, 1996). In addition, these authors generalization suggests that adaptive changes in motor patterns should be considered "normal" and as such should not be corrected. Therefore, Latash and Anson argue that clinicians should not attempt to reproduce a "normal" movement pattern however the authors do not specify how this can be done in a post-stroke individual case.

Carr and Shepherd expressed that "Normal" is not the issue: It is "effective" goal attainment that counts. Such adaptive actions may initially be effective in a limited way, enabling the individual to do well to complete enough the task (Carr and Shepherd, 1996). Moreover, some authors have suggested that normal motor behaviour of healthy subjects may not serve as a measure of reference for understanding the adaptive motor behaviour of post-stroke individuals (Kwakkel et al., 2004).

Finally, in a review of "evidence-based practice", Teasell et al. argued that it is not clear whether rehabilitation centered on the restoration of a function closer to normal (that which characterizes movements in healthy subjects) is more effective than compensatory approaches that are centered rather on the return of the function, independently of the way in which it is achieved (Teasell et al., 2003) .

Approach consisting to counteract the non-mandatory trunk compensation.

Jones (2017) considers the trunk compensatory strategy to be maladaptive because it counters the remaining capacity for better overall functionality. The persistence of this maladaptive trunk compensation could be due to the neural plasticity that is driven by it (i.e., task–dependent neural plasticity). An overuse of the trunk to extend the UL might shape neural plasticity in a manner that interferes with new learning that could support a greater range of movement of the elbow (maladaptive plasticity) (Takeuchi and Izumi, 2012a). If so, given the sensitivity of neural plasticity to behavioural experience, it could be particularly deleterious for such strategies to be practised in the early stage following a stroke, when neural plasticity can be amplified by spontaneous plasticity mechanisms (Jones, 2017).The counterpart of relying mostly on the non-mandatory trunk compensation during reaching is to have proximal arm non-use (i.e, shoulder-elbow non-use). For example, Levin showed that the use of fundamentally inappropriate compensatory strategies might limit recovery after stroke, such as not recovering elbow extension (Levin, 1996).

There is clear evidence that reliance on the trunk to move the paretic UL can counter the recovery of more normal UL movement in individuals with mild to moderate impairments. Maladaptive trunk compensation is often viewed as a suboptimal counterpart to recovery. In fact, the role of the therapist is to provide the patient with an acceptable functional alternative, taking into account the residual ability and neural plasticity. Therapists thus attempt to restore more normal movement (Worringham et al., 1996).

This non-mandatory trunk compensation is also called maladaptive, because such patterns often reinforce distorted positions of the joints, induce excessive muscle shortening and may lead to orthopaedic problems (Cirstea and Levin, 2000; Gracies, 2005). In fact, Gracies suggested that the chronic non-use causes neuroplastic rearrangements that further reduce the ability to recruit motor units voluntarily (i.e., maladaptive plasticity), and that aggravate baseline paresis. Thus in the context of worsening soft tissue contracture, a first « vicious cycle of paresis-disuse-paresis » sets in. Most of the functional impairment is due to muscle shortening that increases joint stiffness and dramatically decreases, over time, the joint range of motion. To increase motor recovery, muscle length has to be preserved as much as possible. Intense limb mobilization initiated immediately after stroke and, when possible, intense education and motivation toward daily forced arm use is a strategy to prevent orthopaedic problems and pain (Gracies, 2005; Pain et al., 2015).

d) Restoration of a function closer to normal: to keep flexibility

True motor recovery, at the kinematic level is defined as the reappearance of typical movement patterns and sequences used before stroke for performance of a task, while compensation is defined as the use of additional or alternate kinematic patterns during task performance (Levin et al., 2015). Following the theory of « Use it or lose it », post-stroke individuals should use the paretic UL to not lose its function and to keep the maximum shoulder-elbow joint motion possibilities, avoid orthopaedic problems and pain and to look like healthy people (social appearance).

Behavioural interventions such as motor rehabilitative training can shape neural reorganization (experience-induced plasticity theory) to improve function (Kerr et al., 2011). For example, Murphy & Corbett (2009) defined neuroplasticity as “Changes in the strength of synaptic connections in response to either an environmental stimulus or an alteration in synaptic activity in a network”(Floor et al., 2013; Murphy and Corbett, 2009). However, « self-taught » trunk compensation can be a dominant force in driving reorganization patterns and can do so in a manner that interferes with motor rehabilitative training efficacy (i.e., maladaptive plasticity) (Jones and Adkins, 2015). Therefore, if there is some motor functional reserve (proximal arm non-use), it seems likely that frequent repetition of maladaptive motor patterns (trunk use) may generate stronger neural connections, rather than more effective and efficient patterns (arm use), becoming "learned" or more stable (Horton et al., 2017). Hence avoiding non-mandatory trunk compensation during everyday activities of the paretic UL will minimize the chances of developing use-dependent maladaptive plasticity (Takeuchi and Izumi, 2012a).

Overall, the clinician will have to educate post-stroke individuals /caregivers to seek a balance between the post-stroke individual's short-term goal of achieving function, and the long-term goals of minimizing compensatory strategies to promote the use-dependent plasticity to recover UL function and avoid maladaptive plasticity. It is also important to consider the goal of the post-stroke individual, as he/she may place a greater value on being able to perform the reaching task using compensatory strategies in the short-term versus long-term impact on movement quality and maladaptive plasticity.

e) Summary

A compensatory rehabilitation programme favoring task achievement may leave some motor synergies unused and thereby lessen the chance of later recovery. Consequently, a dominant focus for UL rehabilitation is restoration of previous patterns (shoulder flexion, elbow extension during reaching).

5.3.3 Specific rehabilitation of proximal arm non-use

a) Constraint of compensation (the non-paretic UL) to force use of the paretic UL

Constraint induced movement therapy method

Taub and colleagues showed that the arm non-use phenomenon is reversible reversible if the non-paretic limb is restrained for several days. In fact, the forced use of the paretic limb cause the non-use to be reversed and the paretic limb to be reintegrated into daily activities (Figure 5.1). The Constraint-induced movement therapy (CIMT) consists of "constraining" the use of the non-paretic limb, for example, by asking the patient to wear a sling and sometimes also a large oven mitt for many hours of the day. In this way the patient is forced to use the paretic UL to carry out activities of daily living.

CIMT results. Is rehabilitation of arm non-use effective?

Several studies have found that CIMT improves the speed, efficiency and smoothness of paretic UL movements, but one of these studies found that it does so without diminishing reliance on compensatory trunk movements; in fact, reliance on such movements was increased after CIMT. In one such study, CIMT improved performance on the ARAT (which does not discriminate between recovery and compensation) but led to no notable improvements in measures of movement quality and impairment recovery. Together, these findings could suggest that CIMT may promote the refinement of compensatory movement strategies that improve the functional capacity of the paretic UL (Corbetta et al., 2015).

b) Specific rehabilitation for proximal arm non-use: Analogy with CIMT, i.e. constrain the compensation (forward trunk displacement) to force use the paretic UL

New technologies used to counteract the proximal arm non-use

Alternative methods to physical constraint have been introduced to reduce trunk compensation in order to promote UL premorbid movement patterns. In fact, new technologies can provide additional benefits as post-stroke individuals could make a conscious choice about controlling their trunk movement. For example Alankus created a video game that reduces compensatory torso motions for stroke rehabilitation. Similarly, Valdes et al. showed that visual and force augmented feedback can be used to decrease trunk compensation during bimanual reaching tasks (Valdés et al., 2017). Finally, varying or combining methods of trunk constraint could be a better option or another option.

In addition to counteracting trunk compensation, rehabilitation could be focused on increasing the proximal arm use (i.e., shoulder-elbow use). Trunk compensation compensates elbow extensors deficit (Jones, 2017), therefore the proximal arm use might increase when elbow extensors strength increases. However, Coroian et al., (2017) assessed the benefit of isokinetic elbow extension strengthening exercise compared to passive mobilization with the trunk physically restrained in 20 post-stroke individuals. The results did not show superiority to passive mobilization for UL recovery (Coroian et al., 2017). Therefore strengthening might not increase the proximal arm use. Likely the rehabilitation of the proximal arm non-use should not be focused on strengthening of the elbow extensors with the trunk fixed.

Proximal arm non-use rehabilitation: towards individualized rehabilitation programmes (type, dose, frequency, progressiveness)

On one hand, virtual reality has strongly invaded rehabilitation with new “serious games” dedicated to post-stroke individuals (Laffont et al., 2014). On the other hand Kinect is mostly used for performing exercise in a virtual environment (Knippenberg et al., 2017) with training programmes varied in intensity, frequency and content. However, none of the studies reported an individualised training programme based on patient-centered approach. In fact several studies reported advantages of Kinect -based systems where subjects do not have to wear sensors or markers on the body or hold them, which is more appealing, comfortable, enjoyable and more intuitive to use. The Kinect is also commercially available at low cost and can be used at home. In fact, with Kinect it would be possible to train without assistance of a therapist at home or in a private physiotherapy office. This is in accordance with studies regarding virtual reality, where patients are more motivated to perform the exercises, and their adherence to the treatment seems to be greater (Teo et al., 2016; Wang et al., 2017).

Although the Kinect has already been used and implemented in rehabilitation after stroke, standard games used in therapy are motivating, but performance has to be closely monitored. Especially when developers implement a post-stroke individual-centred task-oriented approach into the system. PANU score could be implemented in “serious games” to provide an online feedback of maladaptive trunk compensation when playing. PANU score could also be implemented to monitor recovery of post-stroke individuals. With automatic recording of the participant movements, a Kinect-based virtual reality gaming system would be able to get a clear analysis of the quality and quantity of motor function progression, which would improve the ability to individualize in a very precise manner an individualized UL rehabilitation programme.

Important questions for future studies would be, Which quantity of rehabilitation for which value of PANU score? or/and Which specific rehabilitation? These questions need to be evaluated in future work.

5.4 General conclusion

Recruitment of trunk compensation during paretic upper limb reaching tasks within arms' length is self-taught in response to primarily weakness of the elbow extensors after a stroke. Following the principles of experience-dependent neural plasticity: "Use it or lose it" and "Use it and improve it", it is easy to understand why more than 50% of post-stroke individuals do not recover paretic UL function even in the chronic stages following a stroke.

The following question "He can but does he?" (Andrews and Stewart, 1979) is addressed to well-recovered post-stroke individuals who use non-mandatory and maladaptive trunk compensation for reaching tasks instead to use the available elbow-shoulder motion. As a therapist, we have to quantify this elbow-shouder non-use (i.e., proximal arm non use-PANU) to promote true recovery of the paretic upper limb.

The instrumental PANU method developed in the dissertation can accurately and reliably quantify a PANU score that can be used to diagnose elbow-shoulder non-use. The PANU score could also be used in a routine and cost-effective Kinect-based virtual reality upper limb rehabilitation system to counteract elbow-shoulder non-use. Then it can be proposed to post-stroke individuals with PANU scores >6.5% that specific feedback-based proximal arm use rehabilitation training might get them to spontaneously use the elbow-shoulder motion with experience dependent neural plasticity mechanisms, and thus avoid complications due to proximal arm non-use such as pain and orthopedic complications, which will enhance the quality of life of these individuals.

SHORT PRESENTATION IN FRENCH

L'accident vasculaire cérébral (AVC) est la principale cause d'invalidité dans les pays industrialisés, dont environ 80% des sujets post-AVC présentent une forme de handicap moteur. 85% de ces sujets post-AVC ont une hémiparésie qui affecte le bras (Jones, 2017; Parker et al., 1986), entraînant une gêne dans les activités de la vie quotidienne (van Kordelaar et al., 2012b) et pouvant conduire à un incapacité permanente (Cirstea and Levin, 2000; Nakayama et al., 1994). Bien que 80% des personnes post-AVC réapprennent à marcher (Friedman, 1990), moins de 50% récupèrent une préhension fonctionnelle (Nakayama et al., 1994). La récupération motrice et fonctionnelle du membre supérieur un réel défi en rééducation.

Les sujets post-AVC surutilisent leur tronc (flexion) lorsqu'ils saisissent des objets placés dans leur espace d'atteinte. Le mouvement de flexion du tronc, appelé compensation du tronc lors d'une tâche d'atteinte peut être « obligatoire / adaptative » pour des sujets post-AVC ayant un déficit sévère. En effet, dans ce cas, l'utilisation de la compensation du tronc permet l'accomplissement de tâches de préhension (Test Box et Block - BB) malgré des déficiences motrices tel qu'un déficit d'extension du coude (Levin et al., 2002). D'autre part, au cours d'une tâche d'atteinte, la compensation du tronc peut également être «non-obligatoire / maladaptative » chez les sujets post-AVC ayant un déficit léger à modéré ; c'est à dire ayant récupéré une motricité volontaire au niveau proximal du bras (extension du coude, flexion-adduction de l'épaule). Dans ce dernier cas, les sujets post-AVC utilisent spontanément la compensation du tronc pour atteindre des cibles, au lieu d'utiliser, comme les sujets sains, les mouvements d'épaule et de coude (Levin et al., 2009). La compensation est définie comme l'utilisation de schémas moteurs supplémentaires ou alternatifs par opposition à la récupération qui est définie comme la restauration de la fonction, la réapparition de schémas moteurs spécifiques et de séquences motrices utilisées avant l'AVC (Levin et al., 2015). Cette distinction entre récupération et compensation doit s'effectuer aux différents niveaux de la Classification Internationale du Fonctionnement (CIF) (World Health Organization, 2001).

Ne pas pouvoir faire la distinction entre récupération et compensation peut géner le thérapeute dans le choix de sa rééducation à entreprendre (Jones, 2017). De plus, les échelles cliniques post-AVC classiques telles que le Fugl Meyer (FM) et le Box and Blocks (BB) ne fournissent pas d'information sur la compensation du tronc lors de l'exécution d'une tâche.

Il est indispensable d'utiliser des évaluations permettant la distinction entre récupération et compensation afin de diriger la rééducation vers une meilleure récupération motrice indispensable dans les activités de la vie quotidienne (Huang and Krakauer, 2009; Shishov et al., 2017). Il apparait qu'en phase aiguë et sub-aiguë (jusque 6 mois post-AVC), la rééducation doit être concentrée sur la récupération du membre supérieur tout en contrôlant ses compensations. En revanche, il semblerait qu'en phase chronique (après 6 mois post-AVC) il faille renforcer les compensations si le sujet post-AVC n'a pas récupéré la fonction du bras parétique.

Ainsi, la compensation du tronc non-obligatoire, utilisée par les sujets qui ont récupéré une motricité suffisante du bras, reflète une « non-utilsation épaule-coude ». Or il a été montré que la non-utilisation épaule-coude freine la récupération fonctionnelle du bras parétique. Il est donc important de réduire cette non-utilisation épaule-coude. Cependant, il n'existe actuellement aucune méthode permettant de quantifier cette non-utilisation épaule-coude de façon reproductible et objective.

Est-il donc possible de quantifier objectivement et facilement la non-utilisation épaule-coude ?

Les objectifs de cette thèse sont de (i) quantifier la non-utilisation épaule-coude (score PANU) avec un appareil de mesure 3D CMS20s-Zebris (1ère étude), (ii) montrer qu'un système utilisant la Kinect (Microsoft) peut également mesurer la non-utilisation épaule-coude (2èmeétude) et (iii) réaliser une revue de la littérature sur les techniques innovantes appliquées à la rééducation sensorimotrice après AVC, dans le but d'utiliser le score PANU en traitement rééducatif.

A) Résumés des études

1) *Etude n°1: Quantification de la non-utilisation épaule-coude lors d'une tâche d'atteinte en position assise (article publié)*

Dans notre première étude, l'objectif est de quantifier la non-utilisation épaule-coude chez des sujets post-AVC en phase aigue et chronique, lors d'une tâche d'atteinte. La présente étude observationnelle prospective a été menée auprès de sujets post-AVC capables de saisir un cône dans leur espace d'atteinte (n = 45) et d'un groupe contrôle d'individus sains (n = 45) appariés en âge. La non-utilisation épaule-coude a été mesurée par la difference des distances effectuées par la main et le tronc dans deux conditions d'atteinte d'un cône : une condition d'utilisation spontanée du complexe épaule-coude et une condition d'utilisation maximale (forcée) du complexe épaule-coude, effectuée par une auto-restriction des mouvements du tronc (Bakhti et al., 2017). Nous avons utilisé un dispositif de capture du mouvement très précis avec une résolution spatiale infèrieure à 3 mm: le CMS20s (Zebris) (Nowak, 2008). La non-utilisation épaule-coude est représentée par un score PANU (Proximal Arm Non-Use).

Les résultats ont montré que la méthode de calcul du score PANU est reproductible, objective, quantitative, facile et rapide. De plus, les scores PANU du côté non-parétique des sujets post-AVC n'étant pas significativement différents des scores PANU des sujets contrôles (bras droits et gauches), démontre que le score PANU du bras non-parétique peut être considéré comme une référence par rapport au bras parétique.

Nos résultats ont également montré que parmi les sujets post-AVC présentant un léger déficit proximal du bras parétique (Fugl-Meyer > 28/42), 61% d'entre eux ont un score PANU supérieur à celui des sujets contrôles. Le score PANU quantifie la réserve motrice fonctionnelle épaule-coude dans une tâche d'atteinte en station assise, réserve qui n'est pas mesurée par les évaluations classiques (FM, BB, Reaching Performance Scale - RPS).

De plus, le score PANU permet de détecter les sujets post-AVC ayant une compensation du tronc non-obligatoire / maladaptative; sujets qui doivent être orientés vers une rééducation spécifique de l'utilisation épaule-coude du bras parétique. Le score PANU semble idéal pour le suivi de la récupération de l'utilisation du bras post-AVC ainsi que pour l'évaluation de l'efficacité d'un traitement.

2) Etude n°2: Validation de la Kinect v2 pour la mesure du score PANU (article en preparation)

Dans la deuxième étude, nous avons mesuré la non-utilisation épaule-coude chez des sujets post-AVC (n = 18); simultanément avec le système de référence (CMS20s, Zebris, Isny, Germany) et avec un système de mesure innovant de plus en plus utilisé dans la rééducation du membre supérieur après AVC (Kinect) (Knippenberg et al., 2017).

Les résultats ont montré que la Kinect v2 permet d'obtenir le score PANU de façon reproductible. Par ailleurs, cette seconde étude a confirmé les résultats de la première étude selon laquelle 60% des sujets post-AVC présentant un léger déficit proximal du bras parétique (Fugl-Meyer proximal > 28/42), ont été diagnostiqués avec un score PANU supérieur à celui des sujets contrôles. D'autre part les composants du score PANU tels que ΔTrunk (ou ΔTronc - distance effectuée par le tronc), ΔHand (ou ΔMain - distance effectuée par la main), PAU (Proximal Arm-Use ou utilisation épaule-coude) mesurés à l'aide de la Kinect étaient fortement similaires à ceux mésurés par le CMS20s.

Enfin, l'analyse des scores PANU a montré une bonne reproductibilité test-retest à la fois pour le CMS20s (confirmation des résultats de la première étude) que pour la Kinect. Cependant, les graphiques de Bland & Altman ont montré des scores PANU légèrement infèrieurs (correspondant à une meilleure utilisation du bras) dans la session de retest pour les deux systèmes. Ceci confirme l'effet d'apprentissage que nous avions mis en évidence dans la première étude.

3) Etude n°3 : technologies innovantes appliquées à la rééducation sensorimotrice après un accident vasculaire cérébral (revue publiée)

Selon la revue de littérature (Laffont et al., 2014) la réalité virtuelle utilisant la Kinect est largement répandue dans la rééducation du membre supérieur avec un développement de jeux vidéo destinés spécifiquement à la prise en charge des sujets post-AVC. En outre, certains jeux sont progressivement enrichis par l’utilisation d’éléments permettant l'adaptation en temps réél du jeu aux progrès du sujet post-AVC. L'interface de commande permet également au thérapeute d'adapter en ligne les paramètres du jeu aux besoins du patient ou bien au choix du thérapeute. Par conséquent, la réalité virtuelle utilisant la Kinect ouvre des perspectives en termes de suivi et de soins personnalisés. De plus, l'enregistrement automatique des mouvements effectués par le sujet permettrait d’effectuer une analyse de récupération de la fonction motrice aussi bien au niveau quantitatif que qualitatif.

B) La non-utilisation épaule-coude : diagnostic et traitement

1) La non-utilisation épaule-coude et ses conséquences dans l’évaluation post-AVC

La méthode de mesure du score PANU peut être un complément très utile à d'autres outils cliniques visant à mesurer la déficience (FM, RPS) / la fonction (BB) du bras parétique après un AVC, ou bien à d'autres évaluations de non-utilisation du bras parétique (Han et al., 2013; Sterr et al., 2002; Taub et al., 2006).

a) Le score PANU : complémentaire aux évaluations cliniques classiques (FM, BB, RPS)

Le score PANU mesure la quantité de non-utilisation épaule-coude chez les sujets post-AVC ayant récupéré une fonction au niveau du bras parétique. Nous avons montré que le score PANU est mesuré, en position assise, utilisant la différence entre les mouvements effectués par le bras au cours d’une tâche d’atteinte dans les conditions maximale et spontanée. La mesure du score PANU est suffisamment simple et rapide pour être utilisée en soins courants.

Le score PANU fournit une information nouvelle qui n'est pas mesurée par les évaluations cliniques classiques (FM et BB). Par exemple, 61% des sujets post-AVC ayant un déficit moteur léger ont été diagnostiqués avec un score PANU>6,5% (étude 1 et 2). De ce fait, le score PANU fournit des informations que le score FM de déficience ne permet pas de détecter.

De même, le score PANU fournit une information supplémentaire au RPS. En effet, le RPS est une échelle qui évalue les performances d’atteinte-saisie (niveau déficience de la Classification Internationale du Fonctionnement). Le thérapeute décompose visuellement le mouvement d'atteinte dans ses sous-éléments et les quantifie, incluant la compensation du tronc, en condition spontanée (Levin et al., 2004). Le score PANU fournit également une quantification de la compensation du tronc au travers du sous-score CI (index de compensation = 1 - PAU). L'index de compensation (CI) est la compensation du tronc normalisée à la distance de la cible au cours d'une tâche d'atteinte en position assise ($_{s}$CI condition spontanée et $_{m}$CI condition maximale). En ajoutant une condition maximale d'utilisation du bras, nous accédons à la non-utilisation épaule-coude. RPS et CI quantifie la compensation du tronc alors que le score PANU quantifie la non-utilisation épaule-coude.

b) La non utilisation épaule-coude représente une nouvelle forme de non-utilisation du bras parétique – réserve motrice fonctionnelle au niveau épaule–coude

La non utilisation épaule-coude traite d'une forme de non-utilisation intrinsèque au bras parétique lui-même, qui n'a, à notre connaissance jamais été proposée. En effet, les approches cliniques classiques du phénomène de non-utilisation après AVC mettent l'accent sur la non-utilisation du bras, une des conséquences les plus visibles de l'AVC dans la vie quotidienne, caractérisée par la sous-utilisation du bras parétique en faveur du bras non-parétique (Andrews and Stewart, 1979; Page et al., 2004; Sunderland and Tuke, 2005). D'un point de vue traitement rééducatif, la non-utilisation du bras parétique, lors d'une tâche d'atteinte en position assise, est considérée comme un « potentiel inutilisé » (réserve motrice fonctionnelle) du bras parétique (Sunderland and Tuke, 2005) ayant des conséquences thérapeutiques (Michaelsen et al., 2006).

En utilisant les tests cliniques classiques d'évaluation de la non-utilisation, nous pouvons obtenir une mesure de la non-utilisation du bras par la différence entre le test Wolf Motor Function Test (WMFT) et le Motor Activity Log (MAL) (Taub et al., 2006). Une autre méthode clinique (Sterr et al., 2002). compare l'utilisation spontanée du bras parétique dans les activités de la vie quotidienne (Actual Amount of Use Test-AAUT et MAL) avec la capacité du bras parétique à effectuer les mêmes tâches à la demande du thérapeute Dans les deux méthodes cliniques (Sterr et al., 2002; Taub et al., 2006), la non-utilisation du bras représente une réserve fonctionnelle du bras parétique dans différentes activités de la vie quotidienne (compensations du tronc autorisées). Alternativement, le Bilateral Arm Reaching Test (BART) compare la surface atteinte lors de l'utilisation spontanée versus l'utilisation forcée du bras parétique pour obtenir une mesure objective et quantitative de la non-utilisation du bras parétique (Han et al., 2013). Le BART représente la réserve fonctionnelle du bras parétique pour une tâche d'atteinte de cibles affichées dans un hemi-espace à deux dimensions, en position assise, tronc bloqué, lorsqu'il est permis d'utiliser au choix le bras parétique ou le bras non-parétique. Avec le score PANU, l'utilisation spontanée et l'utilisation maximale du bras dans une tâche d'atteinte, avec une cible placée devant le sujet, sont comparées.

Le score PANU représente la réserve fonctionnelle épaule-coude, en position assise, lorsqu'il est permis d'utiliser au choix une compensation (flexion du tronc) ou les mouvements épaule-coude (flexion-adduction épaule, extension du coude).
Par conséquent, les quatre méthodes (Bakhti et al., 2017; Han et al., 2013; Sterr et al., 2002; Taub et al., 2006) mesurent différents aspects de la réserve motrice fonctionnelle du bras parétique. Le score PANU fournit une réserve fonctionnelle épaule-coude dans une tâche d'atteinte à trois dimensions.

c) Le score PANU permet de faire la distinction entre les compensations obligatoires et non-obligatoires du tronc

La non-utilisation épaule-coude est mise en évidence par la différence entre l'utilisation spontanée du bras et l'utilisation maximale du bras (tronc auto-bloqué). Comme mentionné précédemment, certains sujets post-AVC sévèrement atteints parviennent à accomplir une tâche d'atteinte grâce à un recrutement obligatoire du tronc (flexion excessive), compensant ainsi la faible récupération des mouvements de l'épaule (flexion-adduction) et du coude (extension) parétiques. Lors du calcul du score PANU, ces sujets se comportent de la même façon dans la condition spontanée que dans la condition maximale d'utilisation du bras parce qu'ils n'ont pas récupéré assez de motricité épaule-coude. Par conséquent, pour les sujets post-AVC sévérèment atteints au niveau du bras parétique, la compensation du tronc est obligatoire dans la tâche d'atteinte. Autrement dit, quelles que soient les instructions du thérapeute, le score PANU est d'environ zéro et le score CI est supérieur à 0 (la compensation du tronc est obligatoire pour réussir la tâche d'atteinte, quelle que soit la condition spontanée ou maximale).
En revanche chez les sujets post-AVC présentant un déficit léger ou modéré, la compensation du tronc est utilisée en condition spontanée durant la tâche d'atteinte. Cependant, en condition maximale d'utilisation du bras (tronc bloqué), ces sujets ont la capacité d'utiliser la flexion-adduction d'épaule et extension du coude. Nous obtenons donc des scores de PANU > 0 et $_{S}$CI > 0. La compensation du tronc n'est pas obligatoire. Le score de PANU > 0 quantifie la compensation non obligatoire du tronc.
Par conséquent, notre méthode montre, pour la première fois à notre connaissance, pouvoir différencier les compensations obligatoires et non obligatoires du tronc, en position assise.

d) Le score PANU permet de faire la distinction entre récupération et compensation

Un problème récurrent dans les évaluations post-AVC est le niveau de récupération mesurée par des échelles cliniques qui reflète à la fois la restitution des anciens schémas moteurs et les compensations, confondant ainsi les effets du traitement (Levin et al., 2009). Dans certaines échelles qui mesurent la capacité fonctionnelle, le sujet post-AVC peut obtenir un score maximal à un des items en utilisant des stratégies compensatoires si l'échelle ne mentionne pas la façon dont la tâche est effectuée(Levin et al., 2004). Un exemple typique de ceci est l'évaluation du traitement par contrainte induite (ou Constraint Induced Movement Therapy - CIMT). La CIMT est une méthode de rééducation intensive impliquant une contrainte du bras non parétique combinée à une rééducation intensive du bras parétique. La CIMT s'est avérée très efficace dans l'amélioration des scores d'échelles fonctionnelles (Taub et al., 1999, 2006; Wolf et al., 2006), et ce même à long terme (Massie et al., 2009). Cependant, de récentes études ont montré que cette amélioration fonctionnelle pouvait résulter d'une meilleure utilisation des stratégies compensatoires. En effet, ni l'extension du coude n'avait augmenté, ni la flexion du tronc n'avait diminué. En revanche, l'abduction de l'épaule avait augmenté considérablement (signes de compensation).

Le score PANU, en revanche, permet de faire là, une distinction entre récupération et compensation. En effet, pour les sujets post-AVC ayant récupéré totalement, la tâche d'atteinte devrait être effectuée avec théoriquement 100% d'utilisation du bras et 0% d'utilisation du tronc (comme chez les sujets contrôles). En d'autres termes, la tâche d'atteinte devrait être réalisée sans flexion du tronc et ce aussi bien dans la condition spontanée que dans la condition maximale, comme les sujets controles. En d'autres termes, les sujets ayant une totale récupération, utilisent leur bras (mouvements épaule-coude) quel que soit la condition.

- Théoriquement, dans le cas d'une récupération du membre supérieur parétique, ${}_{s}CI = 0\%$ ${}_{s}PAU = 100\%$ et ${}_{m}PAU = 100\% \Rightarrow PANU = 0\%$.
- Théoriquement, dans le cas d'une compensation maladaptative (non-obligatoire) du tronc, avec $sCI \neq mCI > 0$ et $PANU > 0$.
- Théoriquement, dans le cas d'une compensation obligatoire ${}_{s}CI = {}_{m}CI > 0$ et $PANU = 0$.

Le score PANU et le score CI permettent de faire la distinction entre restitution des schémas moteurs et compensation lors de l'évaluation de la recuperation du bras parétique post-AVC.

e) Le score PANU permet une stratification des sujets post-AVC

Le score PANU est semblable à une mesure de la « réserve motrice fonctionnelle » disponible pour améliorer les mouvements d'atteinte. Connaître l'existence de cette réserve fonctionnelle épaule-coude peut aider les thérapeutes à concevoir des programmes de traitement personnalisés (Levin et al., 2015). En effet, le score PANU quantifie la réserve de mouvements épaule-coude qu'un sujet post-AVC peut réapprendre à utiliser, afin d'améliorer la récupération motrice, fonctionnelle de son bras parétique (Jeyaraman et al., 2010; Levin et al., 2009). Le score PANU, équivaut donc à quantifier la réserve motrice que le sujet peut mobiliser pendant la rééducation.

Un score PANU supérieur à 6,5% (99% des valeurs du groupe contrôle) identifie les sujets post-AVC qui ont la réserve motrice fonctionnelle épaule-coude, laquelle peut être sollicitée afin d'améliorer les performances motrices lors de la rééducation (Bakhti et al., 2017). Par conséquent, le score PANU peut être utilisé pour détecter et stratifier les sujets potentiellement répondeurs à un programme de rééducation spécifique axé sur l'utilisation forcée des mouvements épaule-coude. Le score PANU peut également être utilisé pour suivre la récupération du bras parétique après un AVC.

Lorsque le score PANU est inférieur à 6,5%, les sujets post-AVC peuvent appartenir à deux catégories possibles, toutes deux avec un mauvais pronostic de progression par rapport à un traitement spécifique d'utilisation du bras. Un score PANU faible avec CI = 0 indique que le sujet post-AVC ne recrute pas le tronc pour atteindre une cible dans son espace d'atteinte, il n'a donc pas besoin d'une thérapie spécifique (il s'agit d'un comportement sain). Un PANU faible avec CI > 0 indique le besoin obligatoire de mouvements du tronc, quelles que soient les instructions du thérapeute (condition spontanée ou maximale). Le sujet post-AVC n'a donc aucune réserve motrice qui pourrait être mobilisée lors d'une rééducation spécifique. Sachant que les résultats du score PANU chez les sujets sains sont inférieurs à 6,5, nous suggérons que les sujets ayant des scores inférieurs à 6,5 bénéficient d'une rééducation traditionnelle du bras. À l'inverse, les patients ayant des scores de PANU plus grands que les controles (> 6,5) ont probablement une réserve motrice épaule-coude qu'il faut mobiliser pour tendre vers une meilleure récupération du bras parétique.

f) La méthode de mesure du Score PANU est accessible à un grand nombre de cliniciens

Les différentes méthodes d'évaluation de la non utilisation du bras qui ont été développées précédement montrent qu'il existe plusieurs façons de mesurer la réserve motrice fonctionnelle du bras parétique. La spécificité de chacune des mesures est donnée par la tâche. Toutefois, aucune des évaluations de la non-utilisation du bras parétique n'est adaptée à une utilisation en routine clinique (Han et al., 2013). Les tests classiques (Sterr et al., 2002; Taub et al., 2006) fournissent une évaluation globale de la non utilisation du bras parétique mais ils sont plutôt subjectifs et longs (Han et al., 2013). En effet, l'évaluation par « WMFT-MAL » durerait environ une heure. Et les questionnaires tels que le « Motor Activity Log » sont basés sur la mémoire des sujets post-AVC (Chen et al., 2015; Han et al., 2013). D'autre part, WMFT et AAUT nécessitent une certaine expertise du thérapeute (Han et al., 2013). La méthode instrumentale (BART) est objective, mais nécessite du matériel informatique et un logiciel non-utilisable en clinique.

Par contre, la méthode de mesure du score PANU est facile et dure seulement 10 minutes. Il s’agit d’une méthode instrumentale précise et objective nécessitant 15 minutes de formation à la passation. Par conséquent, la méthode de mesure du score PANU semble être la première méthode d’évaluation de la non-utilisation du bras (réserve motrice fonctionnelle du bras parétique) facilement utilisable en clinique. Cependant, le score PANU ne quantifie pas la même non-utilisation du bras parétique que les autres méthodes. Le score PANU est spécifique à la réserve fonctionnelle épaule-coude, lors d'une tâche d’atteinte, en position assise.

Dans la première étude, la mesure du score PANU nécessitait un système de capture de mouvement 3D qui rendait la méthode plus adaptée aux centres de recherche ou aux grands hôpitaux. Cependant, dans la seconde étude, de nouvelles technologies peu coûteuses et faciles à utiliser ont été utilisées pour déterminer le score PANU. Kinect v2 de Microsoft, une technologie développée à l'origine par l'industrie du jeu pour la capture de mouvements sans marqueur, a été validée pour la capture des mouvements de la main et du tronc. Dans notre deuxième étude, nous avons utilisé la Kinect v2 ainsi qu’un logiciel spécifique pour effectuer la mesure du score PANU. Enfin, un système dédié a rendu la mesure du score PANU plus facilement réalisable par les cliniciens ; le faible coût et l’importante disponibilité de la Kinect pourraient augmenter le nombre d’utilisateurs potentiels. La procédure d'évaluation du score PANU est courte mais peut être encore raccourcie. En effet, l’automatisation de la procédure d’évaluation (instructions en ligne) permettrait de faciliter l'obtention du score PANU dans les cabinets privés de kinésithérapie (travaux en cours).

2) La non-utilisation épaule-coude et ses conséquences pour le traitement : Perspectives d’intégration du score PANU dans un traitement par réalité virtuelle.

Le but commun des sujets post-AVC est de parvenir à un niveau d'indépendance fonctionnelle suffisant lors du retour à domicile. Pour cette raison, les cliniciens ont la mission de proposer le maximum de méthodes permettant aux sujets post-AVC d'atteindre une récupération maximale de leur bras parétique (French et al., 2016).

a) La non-utilisation épaule-coude : intérêt dans la reeducation ?

Le score PANU du bras parétique quantifie la réserve motrice fonctionnelle épaule-coude, qui pourrait représenter la capacité du bras à répondre à des changements environnementaux. L'objectif de la rééducation est de conserver une flexibilité au niveau des mouvements du bras (maximum de possibilités de mouvements du bras afin de s'adapter à chaque situation).

Les sujets post-AVC ayant un score PANU > 0 utilisent la compensation du tronc lors d'une tâche d'atteinte mais ils ont la possibilité de ne pas utiliser le tronc et d'utiliser les mouvements épaule-coude. L'efficacité des approches thérapeutiques visant à «contrôler» certaines compensations a été remise en question : l'utilisation de la compensation du tronc doit-elle être autorisée ? ou bien la restitution des anciens schémas moteurs (utilisation mouvements épaule-coude) doit-elle être absolument recherchée ?

Selon Latash et Anson (1996), après une lésion du système nerveux central, les schémas moteurs différents de ceux généralement observés chez les sujets sains devraient être considérés comme adaptatifs et ne devraient donc pas être corrigés. Au contraire, Levin (1996) a montré que l'utilisation de stratégies compensatoires inappropriées pourrait limiter la récupération post-AVC, soit la récupération de l'extension du coude. La contrepartie de la compensation maladaptative (non-obligatoire) du tronc lors d'une tâche d'atteinte est la non-utilisation épaule-coude. Cette compensation du tronc est également appelée maladaptative parce qu'elle renforce souvent de mauvaises positions des articulations, induisant un raccourcissement musculaire excessif et pouvant conduire à des déformations orthopédiques (Cirstea and Levin, 2000; Gracies, 2005).

Lors d'une tâche d'atteinte, la « véritable récupération motrice » est définie comme la réapparition des schémas moteurs typiques utilisés avant l'AVC, tandis que la compensation est définie comme l'utilisation de schémas moteurs supplémentaires ou alternatifs (Levin et al., 2015). Selon la théorie du «use it or Lose it», les sujets post-AVC devraient utiliser les mouvements épaule-coude pour ne pas perdre les fonctions d'extension du coude, flexion d'épaule… (Kleim and Jones, 2008).Le maintien des différentes fonctions du membre supérieur permettrait de conserver le maximum de combinaisons motrices, éviter les douleurs et les déformations orthopédiques (apparence sociale).

Quelque fois le sujet post-AVC peut préférer un objectif à court terme de fonction globale du membre supérieur même si celle-ci nécessite l'utilisation de compensations. Dans d'autres cas, le sujet post-AVC préfèrera un objectif à long terme de récupération des schémas moteurs présents avant l'AVC, avec un minimum de stratégies compensatoires. Le thérapeute doit guider son traitement en prenant en considération les objectifs du sujet post-AVC.

b) Rééducation spécifique de la non-utilisation épaule-coude

Dans nos deux études, nos résultats ont montré que le score PANU est moins important lors de la deuxième évaluation (retest), ce qui indiquerait que les sujets prennent conscience de leur réserve motrice fonctionnelle durant la première évaluation. Cette sensibilité au phénomène d'apprentissage est bénéfique pour pouvoir lutter contre la non-utilisation épaule-coude. Il serait intéressant d'évaluer le score PANU chaque semaine pour connaître l'évolution de la non-utilisation épaule-coude sous l'effet d'un traitement spécifique (travaux futurs). Le transfert d'acquis dans la vie de tous les jours devrait également être évalué.

Les perspectives du présent travail de thèse pourraient tester l'hypothèse selon laquelle les sujets post-AVC ayant un score PANU élevé peuvent s'améliorer avec une rééducation axée sur l'utilisation épaule-coude, et ceci même en phase chronique. Cette mobilisation de la réserve motrice fonctionnelle nécessiterait une rééducation spécifique telle que l'utilisation forcée des mouvements épaule-coude ou bien la contrainte du tronc (Michaelsen et al., 2001, 2006; Michaelsen and Levin, 2004). En effet, Michaelsen et al. (2001, 2004) ont montré que les sujets post-AVC ayant bénéficié d'une contrainte physique au niveau du tronc (sangle ou harnais), les déficiences sont réduites et la fonction du bras parétique est améliorée. De même, Wu et al. (2012) ont montré que la « constraint induced movement therapy » accompagnée d'une contrainte physique du tronc améliorait la préhension. La prévention des compensations maladaptatives du tronc semble donc être un élément essentiel au niveau de la prise en charge rééducative des sujets post-AVC.

Cependant d'importantes questions persistent : quelle intensité/quantité de rééducation et pour quel score PANU ? quelle rééducation spécifique ? quels sont les bilans adaptés à l'évaluation de l'efficacité de la rééducation selon les différents domaines de la Classification Internationale du Fonctionnement ? Ceci doit être évalué dans les travaux futurs.

En résumé, la méthode de mesure de la non utilisation épaule-coude est une évaluation simple et rapide de la réserve fonctionnelle épaule-coude lors d'une tâche d'atteinte en position assise. Le score PANU mesuré avec la Kinect rend la méthode plus accessible en clinique. Finalement, le score PANU (mesuré par la Kinect) pourrait être intégré dans un jeu rééducatif en réalité virtuelle. En effet, l'utilisation du score CI permettrait d'obtenir un feedback sur les mouvements du tronc en temps réel. D'autres recherches sont nécessaires pour établir les différents niveaux de programmes de rééducation basés sur les scores PANU. Ainsi, la diminution du score PANU après rééducation devrait conduire à une diminution des déficiences motrices (récupération motrice et diminution de la compensation du tronc associée), ce qui permettrait une meilleure qualité de vie des sujets post-AVC.

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APPENDIX

fNIRS provides clues about the neuralcorrelates of the learned non-use of the paretic arm after a stroke

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Objective: The majority of stroke survivors do not use their paretic arm in daily life activities, and this is, in part, because they learned to not use their paretic arm before recovering. In seated reaching, the difference between spontaneous arm use (as in daily activities) and forced arm use of the paretic arm (when trunk movements are not allowed) provides the percentage of learned non-use of the paretic arm. Here, we sought for neural correlates of the learned non-use behaviour using fNIRS neuroimaging.

Material: Patients and methods Two post-stroke individuals (52 years, ischemic middle cerebral artery), one right-handed with a right hemisphere lesion (4 m post-stroke; BB score: 61/1) and the other left handed with a left hemisphere lesion (6m post-stroke; BB score: 23/73) were required to perform a series of seated reaching movements with their paretic (P), non-paretic (NP), and both (BH) hand(s) using a blocked design (3 blocks, 20 s task and 20 s rest) in a free and then in a forced arm use (trunk restrained) condition allowing to compute the percentage of learned non-use.

Results: For the subject with the left hemisphere lesion (right paretic arm) the learned non-use was 3.5% for P (0.3% for NP and 6.5% for BH). This patient had a large deficit in paretic arm function, which resulted in trunk movements both in the free-use and forced-use condition, and thus did not show a learned non-use effect.

For the subject with the right hemisphere lesion (left paretic arm), the learned non-use was 13% for P (30% for BH, 1% for NP). For this patient, we found differences in activation of the prefrontal cortex (PFC) and sensorimotor cortex (SMC) regions, between the free-use and forced-use conditions.

Discussion – Conclusion: This pilot study has shown for the first time that fNIRS neuroimaging can be used in clinical settings to determine brain activation changes as a function of the learned non-use of the paretic arm after a stroke. However, further inves- tigations are necessary to go beyond the present proof of concept.

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Après un accident vasculaire cérébral (AVC), l'utilisation de stratégies compensatoires lors des activités de la vie quotidienne, permet de compenser le déficit du membre supérieur parétique. En effet, les individus post-AVC présentant un déficit sévère limitant les mouvements épaule-coude, doivent utiliser la flexion du tronc afin de réaliser une tâche d'atteinte. Dans ce cas, il s'agit d'une compensation du tronc obligatoire-adaptative. D'autre part, certains individus post-AVC ayant suffisamment récupéré la motricité épaule-coude, continuent de solliciter une flexion du tronc. Dans ce cas, la compensation non-obligatoire du tronc est dite maladaptative car elle reflète la non-utilisation épaule–coude (ou proximal arm non-use - PANU) ayant pour effet d'entraver la récupération du bras parétique.

Dans la première étude, 45 sujets post-AVC et 45 sujets contrôles sains appariés en âge ont effectué une tâche d'atteinte, le tronc libre (utilisation spontanée du bras) et le tronc auto-fixé (utilisation maximale du bras). L'analyse a montré que les scores PANU des sujets post-AVC étaient compris entre 1,9% et 40,7% avec une médiane à 11,7%. La mesure du score PANU est reproductible, valide et représente la réserve motrice épaule-coude. Le seuil significatif du PANU a été fixé à 6,5% (limite supérieure chez les sujets sains). Enfin, le score PANU est complémentaire aux tests usuels de déficience et de fonction du membre supérieur (Box and Block test, Fugl-Meyer)

La deuxième étude a montré que le score PANU peut être obtenu en utilisant un système Kinect dans l'obtention du score PANU. Des mesures ont été effectuées simultanément avec les deux systèmes (Kinect et Zebris-CMS20s) chez 19 sujets post-AVC. Cette étude a montré que le score PANU mesuré avec la Kinect pourrait être utilisé comme un outil de diagnostic qui permettrait de proposer aux sujets post-AVC une rééducation spécifique d'utilisation forcée du bras par tronc bloqué ou bien par feedback.

La troisième étude est une revue de la littérature sur les technologies innovantes appliquées à la rééducation sensorimotrice post-AVC suggérant que le score PANU puisse être intégré dans un traitement rééducatif par réalité virtuelle.

En conclusion, ces travaux démontrent que quantifier objectivement la non-utilisation épaule-coude (score PANU) lors d'une tâche d'atteinte est possible et reproductible. Les scores PANU peuvent être déterminés également par un système très accessible (Kinect) ce qui permettrait d'intégrer le score PANU dans un jeu de rééducation par réalité virtuelle.

Mots-clés : analyse cinématique, non-utilisation, tâche d'atteinte, accident vasculaire cérébral, membre supérieur, Kinect V2, réalité virtuelle.

After a stroke, the use of compensatory strategies to perform activities of daily living, compensate for upper limb deficit. In fact, post-stroke individuals with severe upper limb impairment that limits shoulder-elbow motion, have to use trunk compensation to achieve a reaching task within arms' length, which is a form of mandatory/adaptive compensation strategy. Whereas, post-stroke individuals having adequately recovered shoulder-elbow motion, continue to use the trunk when they could use the proximal arm to achieve the reach; and this non-mandatory trunk compensation is considered maladaptive because it reflects proximal arm non-use or PANU, which is detrimental to true recovery of the paretic arm.

In the first study, 45 post-stroke individuals and 45 age matched healthy controls performed a seated reaching task within arm's length with the trunk free to move (spontaneous use) and trunk restrained (maximal use) to measure their PANU score. The analysis showed that the PANU scores for the post-stroke individuals ranged between 1,9% and 40,7% with a median of 11,7%, and these PANU scores were a reliable and reproducible measure of the functional reserve of the upper limb. The PANU score threshold for clinical significance was set as 6.5% (upper limit in healthy subjects). The PANU score seems pertinent as a complement to usual clinical assessments of upper limb function and impairment (Box and Block test, Fugl-Meyer).

The second study explored the applicability of the Kinect system to measure PANU scores in 19 post stroke individuals in comparison to the standard Zebris-CMS20s method. The analysis showed that the PANU score measured by the Kinect was valid and reliable, and therefore should be used as a tool to classify patients in order to propose specific upper limb rehabilitation with paretic arm-forced use by trunk restraint or feedback.

Study three was a review of innovative technologies applied to sensorimotor rehabilitation after a stroke suggesting that PANU scores could be implemented in virtual reality rehabilitation and be used as a tool to determine the efficacy of the specialised treatment.

In conclusion, this thesis showed that i) objectively quantifying the proximal arm non-use (PANU score) during a reaching task using a 3D motion capture system is feasible and reliable, and ii) PANU scores are accurately determined also using a more widely available and less expensive Kinect-based motion sensor with the future aim of PANU being integrated in a Kinect-based upper limb virtual reality rehabilitation.

Key words: Kinematic analysis, non-use, reaching, stroke, upper limb, Kinect V2, virtual reality