Is the Finger-to-Nose Test adequate for evaluating upper-limb coordination in patients with stroke?

Marcos Roberto Martins Rodrigues

School of Physical and Occupational Therapy

McGill University, Montreal

August 2015

A thesis submitted to McGill University in partial fulfillment of the requirements of the

Degree of Masters in Rehabilitation Sciences

I. Table of contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

*β: Standardized Beta

AHA: American Heart Association

ARSACS : Autosomal recessive spastic ataxia of Charlevoix-Saguenay

CNS: Central Nervous System

EMG: Electromyography

F-kB: nuclear factor-κB

FNT: Finger-to- Nose test

IC: Index of Curvature

ReachIn: Movements in the target to nose direction, egocentric frame of reference

ReachOut: Movements in the nose to target direction, exocentric frame of reference

RMSE: Root Mean Squared Error

TBI : Traumatic Brain Injury

TDN: Test Doigt-Nez

TEMPA: Test Évaluant les Membres supérieurs des Personnes Âgées

TNF-α: Tumor Necrosis Factor alpha

Abstract

Background and purpose: The Finger-to-Nose Test (FNT) is the clinical gold standard measure for upper-limb coordination. However, the assumption that FNT assesses coordination has not been empirically verified. Our goal was to determine the ability of the FNT metric, time, to identify coordination deficits in people with stroke using both endpoint performance measures and movement quality measures.

Methods: Age- and gender-matched healthy controls (n=20) and subjects with stroke (n=20) performed 2 blocks of 10 continuous to and fro movements of the finger between a target located at 90% arm length and the nose (ReachIn, ReachOut). Upper-limb kinematics were recorded (Optotrak, 100Hz).

Results: Compared to controls, stroke subjects made more curved endpoint trajectories (Index of curvature: stroke=1.23, control=1.04, p<0.05, ReachIn) and used less shoulder horizontal abduction (stroke=11.8º, control=17.6º, p <0.001, ReachIn). Compared to their less-affected side, stroke subjects moved their more-affected arm slower (ReachIn: 18%, ReachOut: 43%; for both directions $F_{1,113}$=14.136, p<0.001) and had more curved trajectories (ReachIn: 18%, ReachOut: 27%; for both directions $F_{1,114}$=6.003, p<0.05), while interjoint coordination was similar. FNT movement time correlated with endpoint straightness (r=0.77, p=0.001), temporal (r=0.63, p=0.001) and spatial (r=-0.61, p<0.05) interjoint coordination. Shoulder horizontal abduction range (β=0.127), temporal (β=0.855) and spatial (β=-0.191) interjoint coordination explained 82% of the variance in the time to perform the FNT.

Discussion and conclusions: Shoulder movement and temporal and spatial interjoint coordination predicted the time to perform the FNT, indicating that this clinical test can be used to measure upper-limb coordination after stroke.

Key words: Stroke, Cerebral infarct, Motor Skills Disorders, Coordination, Upper Extremity, Upper Limb, finger to nose test, FNT.

Abrégé

Introduction et objectif: Le test doigt-nez (TDN) est l'outil clinique le plus utilisé pour mesurer la coordination des membres supérieurs. Cependant, les suppositions que le TDN évalue la coordination n'ont pas été vérifiées de façon empirique. Notre objectif est de déterminer les habilités métriques du temps nécessaire pour compléter le TDN, et d'identifier les déficits de coordination chez les individus ayant eu un accident vasculaire cérébral (AVC) en utilisant des mesures de performance du point final et des mesures de la qualité du mouvement.

Méthodes: Un groupe de 20 individus avec un AVC ont été appariés selon l'âge et le sexe avec un groupe contrôle de 20 participants sains. Les individus ont effectués 2 blocs de 10 mouvements consécutifs d'un mouvement aller-retour du doigt entre la cible qui est située à 90% de la longueur du bras et du nez (AtteinteAvant, AtteinteArrière). La cinématique des membres supérieurs a été enregistrée (Optotrak, 100Hz).

Résultats: En comparaison avec le groupe contrôle, les mouvements des individus avec un AVC ont eu une courbe plus prononcée des trajectoires du point final (Index de courbure : AVC=1.23, contrôle = 1.04, $p<0.05$, AtteinteAvant) et ont une diminution de l'abduction horizontale de l'épaule (AVC=11.8º, contrôle=17.6º, $p <0.001$, AtteinteAvant). Comparativement au côté le moins affecté, les individus avec un AVC ont bougé leur membre le plus affecté plus lentement (AtteinteAvant: 18%, AtteinteArrière: 43% ; pour les deux directions, $F_{1, 113}=14.136$, $p<0.001$) et ont eu une courbe plus prononcée pour les trajectoires du point final (AtteinteAvant: 18%, AtteinteArrière: 27%; pour les deux directions $F_{1, 114}=6.003$, $p<0.05$), alors que la coordination interarticulaire était similaire. La durée du mouvement du TDN est corrélée avec la droiture de la trajectoire du point final ($r=0.77$, $p=0.001$), la coordination interarticulaire temporale ($r=0.63$, $p=0.001$) et spatiale ($r=-0.61$, $p<0.05$). L'amplitude de l'abduction horizontale de l'épaule ($\beta=0.127$), la coordination interarticulaire temporale ($\beta=0.855$) et spatiale ($\beta=-0.191$) expliquent 82% de la variance du temps pour effectuer le TDN.

Discussion et conclusions: Les mouvements de l'épaule et la coordination interarticulaire temporale et spatiale ont prédit le temps pour effectuer le TDN, indiquant que ce test clinique peut être utilisé pour mesurer la coordination des membres supérieurs après un AVC.

Mots-clés: Accident vasculaire cérébral, infarctus cérébral, troubles moteurs, coordination, extrémité supérieure, membre supérieur, test doigt-nez, TDN

Acknowledgements

I would like to thank my very dear fellow graduate students from the School of Physical and Occupational Therapy, with special care to those from the Sensorimotor Control and Rehabilitation Laboratory of the Jewish Rehabilitation Hospital (JRH) for all their support from the beginning, guidance throughout the difficult moments and joyful, sincere celebrations of my achievements. It could never have happened without you. This study would not have been possible without the technical expertise of Dr. Valeri Goussev and Christian Beaudoin. I would also like to thank all the cute and kind secretaries of the JRH, Melissa Chartrand, Louise Veronneau and Vira Rose, as well as Igor Sorokin, Gevorg Chilingaryan and all professors that contributed to this project and for their priceless support in the successful completion of this study. Stephen Michnick, thank you.

All professors and employees of SPOT that contributed to my growth, both at the Master's and the PT Equivalence program. Special thanks to Richard Preuss for his generosity, support and trust in me from the very beginning.

Professor Marcos Henrique Silva Dias, my Master and friend. Sylvie Gajevic Sayegh, Alexandre and Phillippe, thank you for being amazing. Harmony lodge n.131.'.

I would also like to sincerely thank "Mamma" Ruocco, for her generosity, presence and unbelievable support. This project would not have been possible without the financial support of the CIHR, REPAR, CRIR, OPPQ, SPOT, Rapagna Family, McGill University financial aid office and my supervisor Professor Mindy F. Levin.

I would like to thank Mindy. She did something for me that was the cornerstone of my Master's degree but also of my immigration, my diploma equivalence and many other small things she might have done without even realizing. She was an angel in my life and I will be forever grateful for what she did for me.

Contribution of Authors

Matthew Slimovitch participated in experimental setup, ethics approval and part of the data collection.

Mindy F. Levin participated in all aspects of the study, provided institutional affiliation and funding support.

Marcos R. M. Rodrigues participated in the study design, experimental setup, data collection and analysis and writing of the manuscript.

All authors read and approved the final version of the manuscript.

Dedication

This thesis is dedicated to my Family, the one I came from and the one I raised myself.

My brother Mauricio Rodrigues, my Father Casimiro Rodrigues and my Mother Aida Martins.

Also, this thesis is dedicated to my very honourable Grandparents, Portuguese immigrants in Brazil, Ana Nunes Pires, Francisco Rodrigues, Laurinda Augusta Amaral Martins and Fernando Henrique Martins. They taught me how to be an immigrant, even before I became one. They taught me that love is the only one thing that can make an immigrant survive. Brazil is where I was born but Portuguese blood is all I have.

"Ó mar salgado, quanto do teu sal
São lágrimas de Portugal!
Por te cruzarmos, quantas mães choraram,
Quantos filhos em vão rezaram!

Quantas noivas ficaram por casar
Para que fosses nosso, ó mar!
Valeu a pena? Tudo vale a pena
Se a Alma não é pequena.

Quem quere passar além do Bojador
Tem que passar além da dor.
Deus ao mar o perigo e o abismo deu,
Mas nele é que espelhou o céu"

— *Mar de Portugal (Portuguese sea).* Fernando Pessoa, 1934.

Last but not least, I would like to thank my beloved wife Ana Tereza, my "twin-soul", and my kids, Maite and Lucas, for all their patience, support and faith in me throughout years.

CHAPTER 1: INTRODUCTION

Controlling the movement of the upper limb to attain a goal requires a synchronized interaction ("coordination") between multiple muscles and joints (D'Avella and Lacquaniti, 2013). This control is commonly impaired in individuals with stroke (Reinkensmeyer et al., 2002). Interjoint coordination is a property of harmonious movement (Cirstea et al., 2003; Kazennikov and Wiesendanger, 2005). However, there is a lack of consensus regarding the definition of coordination with respect to upper-limb movements, especially in the clinical setting. Zoltan and Pedretti (1990) described coordination as the ability to execute a controlled, accurate, and rapid movement while Trombly (1989) defines coordination in terms of muscles working harmoniously together to perform movements. A more specific definition from the motor control literature defines coordination as the characterization of the nature of the coupling within a part of a system, between different parts of a system and between different kinds of systems (Jirsa and Kelso 2004). Coordination is also referred to as the "covariation of the outputs of elements in a multi-element system" (Latash et al., 2002 p. 295). These definitions apply for general movement principles but are insufficient to understand the highly specific variability inherent in upper-limb movements (Scholz, et al., 2000). For the purpose of this study, we define coordination of upper-limb movement as the skill of adjusting spatial and temporal movement components of arm segments according to the task (adapted from Krasovsky and Levin, 2010).

Characterizing coordination is a challenge for clinicians and researchers. In healthy individuals, coordinated movements are described in terms of spatial variables, related to the positions of different joints or body segments in space and/or temporal variables, related to the timing between movements of segments during the task (D'Avella and Lacquaniti, 2013). Differences exist in trajectory formation for reaches towards the body (egocentric) and away from the body (exocentric). Also called bodycentred, the former uses a proprioceptive, self-referenced coordinate system and the latter, also called object-centred, uses externally-referenced map of visuomotor space to determine the reaching path towards the object (Paillard, 1991).

Damage to descending pathways due to stroke leads to the appearance of abnormal stereotypical upper limb movement synergies and a reduction in kinematic redundancy necessary to adapt movements in task-specific ways (Brunnstrom, 1970; Mihaltchev et al., 2003). Reaching movements of the upper limb can potentially use an infinite number of combinations of muscle activation patterns and joint rotations and these combinations are necessary for the adequate movement execution. With regard to adapting upper-limb gesture for the many different functions of daily-life, displacement of the endpoint (movement performance) relate to the manner in which joints and muscles interact (movement quality). The ability to flexibly combine multiple degrees of freedom may be limited in subjects post-stroke. Decreased redundancy in the execution of movements is reflected in the appearance of abnormal movement synergy pattern, interfering with both movement performance and quality (Diedrichsen et al., 2009; Feldman and Levin, 1995). Both task parameters must be assessed to properly quantify objectively the role of synergies in the upper-limb performance and movement quality. Evaluation of reaching performance of the hemiparetic arm requires the characterization of multiple features or movement, e.g., joint ranges of motion, endpoint speed, trajectory smoothness, and movement direction. These features are relevant for both practice and research in rehabilitation and quantification of the parameters related to these features is essential for the measurement of treatment efficacy and natural recovery (Kamper et al., 2002).

Lack of precise information about coordination is a challenge when evaluating disease progression or motor recovery (Gagnon et al. 2004). Evaluation of coordination is an important part of the standard neurological examination (Gagnon et al. 2004). The FNT (FNT) is the gold-standard for measuring upper-limb coordination and is widely used in professional practice (Swaine and Sullivan, 1993). FNT metrics quantitatively evaluate execution time, and qualitatively assess dysmetria and tremor (Gagnon et al. 2004; Swaine and Sullivan, 1993). Several different variations of the FNT are used in clinical settings. However, it is unclear to what extent the objective metric of time to perform the test actually reflects coordination. In addition, there are many variations of the FNT and reliability of different versions has been tested in different patient populations.

In a study comparing clinical findings with a version of the FNT, healthy older subjects touched the nose and a horizontal target, placed on a wall, 45 cm in front of the subject, at nose height, for a 20 s period, alternately, as fast as possible and counted how many cycles were performed in this period of time. The time of completion of this version of the FNT has been correlated with gross and fine finger dexterity ($r = 0.82$-0.84), functional independence ($r = 0.74$) and social participation ($r = 0.78$; Desrosiers 1995). In older adults, FNT time can also discriminate between different levels of hand function (gross and fine manual dexterity, and grip strength; Gagnon et al. 2004). In the Fugl-Meyer Assessment of the Upper Limb, the FNT consists of 5 repetitions of alternately touching the subject's own knee and nose when the subject is sitting. Scoring is based on one objective and two subjective measures. The objective measure is the difference between the time to perform the task by the more-affected compared to the less-affected arm, based on a scale from 0 to 2, where 0 indicates that the activity takes more than 6 seconds longer than the unaffected hand, 1 indicates that it takes between 2 and 5.9 seconds longer than unaffected hand and 2 indicates less than a 2 second difference. Aside from the metric of time, coordination is qualitatively visually assessed based on two other features of the movement, endpoint error (dysmetria; 0: pronounced or unsystematic dysmetria, 1: slight or systematic dysmetria and 2: no dysmetria) and straightness (tremor: 0: marked tremor, 1: slight tremor and 2: no tremor). In subjects with traumatic brain injury (TBI), the time to perform the test varied from 4.98 ±1.6 on the first attempt to 4.58 ±1.7 on the second attempt, with intraclass correlation coefficients (ICC) for intrarater reliability of 0.971 and 0.986, and interrater reliability was 0.920 and 0.913 for right and left arms, respectively (Swaine and Sullivan, 1993). In healthy adults with ages ranging from 15 to 34 years old (24.6 ±5.6 years), the time to perform the task with the eyes open and touching the target was 4.29 ±1.37 seconds (Swaine et al., 2005). Using a variant of the traditional FNT, the number of to-and-fro full cycles between the nose and the target located at 45 cm was counted in a period of 20 seconds. In subjects with an ataxic disorder, the average score was 8.9 ±4.9 cycles. The test-retest reliability (ICC) was 0.97 for the right side and at 0.99 for the left, with interrater reliability of 0.92 and 0.91, respectively (Gagnon et al., 2004). Although the FNT has been studied in subjects with other neurological pathologies, in subjects with stroke, the validity of the FNT as a measure of upper-limb coordination has not been established using kinematic measures.

Measuring and quantifying coordination is a challenging task for clinicians. The choice of the adequate outcome encompassing all the characteristics necessary to fully understand coordination is even a bigger challenge due to the absence of an objective metric clinically applicable with a proven degree of validity. Because of this gap in clinical evaluation of coordination, an important first step is to examine the validity of the FNT.

CHAPTER 2: LITERATURE REVIEW

Improving care in rehabilitation is an ongoing process and is the goal of researchers and clinicians. In order to assess the quality of care and effectiveness of approaches for both clinical and research purposes, one must be provided with valid tools that evaluate patient outcomes. Outcomes in rehabilitation are challenging and there is a lack of gold standards, especially in the quantification of upper-limb coordination. Clinical measures for quantifying upper limb coordination are generally based on therapist's subjective perceptions and have poor intra- and inter-rater reliability. Our study aims to identify the ability of a so-called gold standard upper-limb coordination measure, the Finger-to-nose Test (FNT) to quantify coordination in the upper-limb of chronic stroke subjects when compared to healthy subjects.

To achieve our objective, we first consider the problem of upper limb recovery after stroke and the problem of defining coordination and why defining coordination is important for assessing it since current definitions of coordination usually consider either spatial or temporal aspects of movement and are not task-specific. Then, we discuss the influence of different factors (vision, proprioception and movement speed) on reaching performance and classify reaching movements and other consequences of stroke.

In the last part of the literature review, we describe the FNT and the main issues with its metrics and how it is important in the assessment of upper limb coordination.

2.1 Stroke

Third cause of death worldwide, stroke is a common neurological disease affecting approximately 15 million people (Grefkes and Ward, 2014). Every year, approximately 795,000 people have a new or recurrent episode of stroke (ischemic or hemorrhagic), with approximately 610,000 of these being first events. In 2011, 1 out of 20 deaths in the United States was caused by stroke and on average every 40 s someone in the United States has a stroke, and someone dies of one approximately every 4 min. In the past few decades, there has been a decline in the stroke mortality index (AHA, 2015). This is due to progress in the development of acute treatment options and also improvements in primary and secondary prevention methods of stroke. Stroke causes a wide variety of sequelae but it is in the acute phase that more than 80% of the patients present with motor impairments, such as hemiparesis and/or loss of manual dexterity (Grefkes and Ward, 2014).

The consequences of the stroke can be seen in body function and structure, activity and participation in health-related domains according to World Health Organization classification (Siebers et al., 2006). The changes occurring post-stroke at the level of the body structures/ function are referred to as impairments under the International Classification of Functioning, Disability and Health (ICF) framework of the World Health Organization (WHO, 2001). Hemiparesis, defined as impairment in muscle strength or partial paralysis restricted to one side of the body, is the most common chronic disabling sequelae of stroke. Arm paresis on the affected side is commonly observed and accompanied by alterations in bone and muscles of the upper-limb (Hafer-Macko et al., 2010)

Post-stroke individuals show many different alterations in the osteomuscular system, especially if comparisons are made between the more-affected and less-affected side (O'Brien et al, 1996; English et al., 2012). English et al. (2012) found that in stroke patients, the more-affected side had greater fat mass than the less-affected side and linked this finding with global physiological deficits, such as greater insulin resistance, poor physical fitness and greater risk of cardiovascular disease. In addition, they stated how changes in body composition can be highly influenced by levels of circulating hormonal and inflammatory factors. In the muscle tissue, some of the features related to muscle impairment are reduced neuromuscular activation and decreased mechanical loading leading to atrophy, which is directly related to lipid deposition in and around muscle fibers. Although neuromuscular connectivity is retained, some inflammatory mediators (e.g., tumor necrosis factor alpha; TNF-α and nuclear factor-κB; NF-kB) could be responsible for mediating atrophy, accelerating oxidative injury and damaging proteins that play important roles in structural domains (Hafer-Macko et al., 2010). Other alterations that are present in chronic stroke subjects are bone demineralization that can range from 1.6% to 25%, the latter referring to the humerus bone (Jorgensen and Jacobsen, 2001).

Motor unit characteristics change in post-stroke individuals, including both structural, e.g., decreased capillary density and contractile properties, e.g., decreased sodium potassium ATPase concentration (Pontén and Stål, 2007). The more-affected side shows decreased motor unit quantity as well as transformation. This transformation process was found to be related to a compensatory hypertrophy of type 1 fibers, where motor units are converted into those with longer contraction times, leading to weakness (Frontera et al., 1997). In the upper-limb, elbow flexors were found to be 65% weaker while extensors were found to be 61% weaker when comparisons were made between the less-affected and more-affected side. Other characteristics were observed in the upper-limb of stroke patients when performing functional activities such as reaching. As an example of these characteristics for reaching/pointing tasks, it has been described in previous studies that subjects with stroke have decreased elbow velocity, decreased hand velocity, movement segmentation, increased trajectory curvature (Levin, 1996; Kamper *et al.*, 2002), increased shoulder horizontal abduction (van Kordelaar *et al.*, 2012) and premature trunk recruitment, resulting in increased forward and lateral movement (van Kordelaar et al., 2012; Shaikh et al. 2014).

2.1.1 Definition of coordination

Some of the most highly functionally demanding tasks performed by humans are related to upper limb manipulative and language skills, both requiring refined intercommunication among cortical and subcortical neural networks (Wiesendanger and Serrien, 2001). Reaching movements of the upper-limb are embedded in our daily life activities. Reaching is a goal-directed behaviour that has been widely studied in primates and humans. Moreover, controlling the movement of the upper-limb to attain a goal requires a synchronized interaction ("coordination") between muscle contractions and joint movements. "Coordination" can be impaired in post-stroke patients since parts of the central nervous system (CNS) which play major roles in this process (D'Avella and Lacquaniti, 2013) may be damaged, especially the cerebral cortex and its descending pathways, the basal ganglia and the cerebellum (Wiesendanger and Serrien, 2001).

In both living and computer-based systems, coordination is a property of purposeful, harmonious and task-oriented movements. There is a lack of consensus regarding the definition of coordination with respect to upper limb movements. This difficulty in defining coordination is pointed out in several studies on the complexity of human movements. The lack of consensus on the definition of coordination is further compounded by the large variety of variables and methods used for measuring and analyzing coordination such as distance, velocity, time, velocity versus time (spatio-temporal), EMG patterns, torque, etc. produced in uni- and bi-manual movements (D'Avella and Lacquaniti, 2013; Perrig et al., 1999; Serrien and Wiesendanger, 2001).

The lack of consensus about the definition of upper-limb coordination is a challenge for researchers regarding the choice of measurements to describe coordination. The characteristics of movement have to be adapted for each task according to specific internal and external constraints

(Jirsa and Kelso, 2004). Internal constraints are factors interfering in the movement that comes from the individual, e.g., body composition, previous movement experience, cognitive behaviour, etc., while external constraints are related to the environment and the context in which the movement is performed and assessed, e.g., sitting versus standing, eyes open versus closed, bright light versus dark room, etc.. In healthy individuals, coordinated movements are described in terms of spatial variables, related to the position of different body segments in space and temporal variables, related to the timing between movements of body segments.

In an attempt to define coordination, several authors have approached the topic differently. Zoltan and Pedretti (1990) described coordination as “the capacity to execute a controlled, accurate, and rapid movement” while Trombly (1989) refers to muscle activity and defines coordination as “muscles working harmoniously together in the execution of movements”. These definitions apply for general movement principles but when considering the high specificity and variability related to upper-limb movements, the previous definitions are insufficient. Upper-limb movements also require more adjustments in joint positioning and muscle contractions during the movement depending on the specifics of the task.

One example of the complexity of the characteristics of upper-limb movement is dexterity. Defined by Bernstein (1969) as “the ability to solve a motor problem correctly, quickly, rationally and resourcefully”, the term can also be defined as “expertness” or “skill”. However, this is still insufficient to determine an operational definition of upper-limb coordinated movements. For the purposes of this research project, we define coordination of upper-limb movement as “the skill of adapting phase and context variability when adjusting body segments towards performing a task considering spatial and temporal components as part of the process” (adapted from Krasovsky and Levin, 2010). This definition itself requires the evaluation of multiple task variables, especially if we consider that different characteristics of the movement should change in a task-dependent manner. Due to this task-specificity, we limit the consideration of the definition of coordination to one main upper-limb task commonly used to assess coordination in patients with neurological lesions – the Finger-to-Nose Test (FNT).

2.1.2 Interaction between vision and proprioception during movement

Coordinated movements defined as the temporal and spatial complex relationship between musculoskeletal structures, i.e., muscles and joints, are present in many daily-life functional activities. Complex sensorimotor activities, such as dancing, demand a whole body integration of rhythm, spatial pattern of limb movements and synchronization to external stimuli (Lashley, 1951; Brown et al., 2006). These activities comprise daily life activities that, when including upper-limb function, involve an even more complex neuronal network and refined motor adjustments (Blanchard et al., 2011). Movement is perceived (proprioception) through the integration of information from different sensory afferents at both conscious and unconscious levels that are transmitted towards central structures through the input coming from peripheral receptors, e.g., muscle spindles and Golgi tendon organs (Johnson et al. 2008; Sarlegna and Sainburg, 2009). Two main sensory systems are used to determine limb position: felt position (proprioception) and seen position (vision) (Graziano, 1999; Touzalin-Chretien et al., 2010).Proprioception refers to the static limb position as well as the change in position (kinesthesia; Johnson et al. 2008). It is difficult to experimentally dissociate somatosensory inputs related to the role of tactile feedback and the consequent understanding of its contributions to proprioception, since they are concurrently generated by the limb movement (Blanchard et al., 2011).

The roles of vision and proprioception for planning and execution of limb movements are incompletely understood (Apker et al., 2011; Touzalin-Chretien et al., 2010).

Proprioception plays a key role in movement production (Apker et al., 2011), such as identifying limb mechanics, intersegmental dynamics and determining the initial postural state of the system (Sarlegna and Sainburg, 2009). On the other hand, vision is more related to corrections during the movement and identifying the target location (Apker et al., 2011; Touzalin-Chretien et al., 2010; Sarlegna and Sainburg, 2009). There is evidence that both vision and proprioception contribute to different aspects of the same function. As an example of this interaction in healthy subjects, hand localization performance was improved when visual and proprioceptive information were combined in comparison with the condition where only vision or proprioception was present. Another relevant point is that the role of proprioception was increased when subjects were exposed to a diminished viewing environment, e.g., a darker room (Touzalin-Chretien et al., 2010), which suggests a synchronized and dynamic interaction between the two systems. Furthermore, removal of one or the other does not infer the exclusive function of the remaining system but otherwise describes an adequacy of one over the other (Sarlegna and Sainburg, 2009).

2.1.3 Movement speed and proprioception

Sensory information from movement is processed by the CNS to control movement efficiently. This movement control occurs when the CNS anticipates external and reactive forces and coordinates proper motor commands to multi-articular limbs, ensuring optimal performance (Mackrous and Proteau, 2010).

In 1954, Fitts introduced a concept that described a mathematical relationship between movement variables to provide an objective measurement of neuromuscular performance. Specifically for upper-limb tasks, the variables considered in this model were speed, accuracy, movement amplitude and target size. The two formulas derived from his work are the index of difficulty (I_d) and index of performance (I_p), as shown below, where *W* refers to target width, *A* to movement amplitude and T_m is movement time (from target to target).

$$I_{\mathrm{d}} = -\log_2(W/2A)$$

$$I_{\mathrm{p}} = -\frac{1}{t_{\mathrm{m}}}\log_2(W/2A)$$

Later, another study (Kondraske, 1995) modified the equation by considering angular motion, thus approximating this calculation to the reality of the movement performance in space, e.g., in rehabilitation, both clinical and research oriented. Please see the equation below in which Θ_A is the angular movement amplitude, Θ_W is the angular width of the target, and t_m is the target-to-target movement time.:

$$I_{\mathrm{d}}^{\theta} = -\log_2(\theta_W/2\theta_A)$$

$$I_{\mathrm{p}}^{\theta} = -\frac{1}{t_{\mathrm{m}}}\log_2(\theta_W/2\theta_A)$$

The original instruction for the FNT requires the patients to move the finger from the nose to a target, placed in different locations according to the version used for the assessment. This movement must be as fast as possible, without compromising accuracy and the evaluator measures the time to perform the task. In addition, other characteristics of the test are assessed, such as dysmetria (error at both target locations) and tremor (how smooth and straight is the movement during the execution of the task). In order to successfully perform the test, all structures involved must be well coordinated, meaning target must be properly seen, joints and muscles must perform their function by being activated in an adequate sequence and proper proprioceptive feedback must be provided. Studies have described the role of proprioception for movement accuracy during slow and fast movements, the former related to feedback-based corrections and the latter one to feed-forward adjustment mechanisms (Semrau et al., 2013). Illustrating the role of proprioception, Tunik et al. (2003) studied deafferented subjects performing reaching movements, with blocked vision, towards remembered targets placed at a distance of 30cm in front of the sternum, at 80º and 45º ipsi and contralateral to the midline, respectively. From the total amount of trials, 40% of trunk movements were blocked. It was shown that for trunk assisted reaching movements, proper compensatory responses to mechanical perturbations were not efficient. When compared to age-matched healthy subjects, deafferented subjects had more variable spatial and temporal interjoint coordination measures, suggesting a general motor control deficit.

Upper-limb pointing tasks in hemiparetic subjects are slower and less precise when compared to age-matched controls (Subramanian and Levin, 2011). Producing accurate and coordinated multijoint movements involves different types of sensorimotor information. The control of segmental dynamics during movement has to be modified differently for slow and fast movements. Parameters of slow and fast reaching movements that change with movement speed are the variability of angular movement, movement distance and error (Messier et al., 2003). Time to perform a task (or movement time; T_m) plays a major role in the calculation of the Index of Performance (see above), as suggested by Fitts (1954). The longer the time to complete the task, the lower the score, indicating worse upper-limb performance. Thus the index of performance can be useful for assessing upper-limb function as an objective measure. Expanding this concept, Yang et al. (2002) pointed out how hard it is to comprehensively describe movement quality by using one or two indices, mathematical or not, suggesting the utilization of multiple scoring systems to obtain a global assessing of movement performance, using preferably task-dependent outcome measures.

As Fitts suggested in 1954, one could not study motor performance separately from sensory mechanisms. Sensory input plays a major role in the performance throughout task execution and can modify the accuracy with which the task is performed, with the exception of fast movements due to the long loop delays.

2.2 Classification of reaching movements

Reaching tasks can be operationally defined as being uni- or bi-manual and asymmetric or symmetric. Unimanual tasks are those involving only one arm while tasks involving both arms are identified as being bimanual or bilateral. Both tasks use two hands to reach the goal but only the term bimanual refers to the need to use both hands for the task. Symmetry and asymmetry can be defined according to the task. A symmetrical task is one that is done by identical movements of the joints of both arms, e.g., first motor tasks learned in life (Serrien and Wiesendanger, 2001), while an asymmetrical task is done with non-identical movements of the joints of both arms, e.g., the drawer paradigm, described as reaching and opening a drawer with one hand and picking up an object from inside the drawer when it is fully opened with the other (Kazennikov and Wiesendanger, 2005). Many research protocols are described in the literature but the ones that most closely represent the FNT are ones where the tip of the finger is moved forward, e.g., when pointing at something, and then brought back towards the subject`s body, e.g., when bringing food towards the mouth. This type of task is relevant to both healthy individuals and subjects with stroke, due to the functional nature of the task which has implications for daily life activity. Pointing movements are commonly used to assess upper-limb coordination deficits in patients with CNS lesions. Due to the required degrees of freedom involved in each movement, six for pointing and at least twelve for simple reaching, these tasks are good examples of upper-limb movements that require coordination of more than one joint. .

2.3 Redundancy and synergies

The presence of pathological upper limb synergies in stroke patients has been widely described in the literature. They consist of stereotypical movements that appear as recovery from stroke progresses (Twitchell, 1951; Brunnstrom, 1970). Stereotypical movements (synergies) usually emerge from attempts to perform an active movement involving a single joint, manifested as an abnormal movement pattern in a flexor or extensor pattern. The flexor synergy, is an association of different abnormal muscle activations, causing scapular elevation and retraction, shoulder abduction, extension and external rotation, elbow flexion, forearm supination and wrist and finger flexion. The upper limb extensor synergy consists of shoulder retraction, horizontal adduction and internal rotation, elbow extension, forearm pronation and wrist and finger extension (Brunnström, 1970).

It has been shown in the literature that strategies for upper limb reaching movements in stroke patients may be affected by upper-limb pathological synergies. In a previous study examining reach-to-grasp movements, stroke subjects, when compared to healthy subjects, used trunk movements to compensate for lack of shoulder and elbow contribution to the task. Also, the presence of upper-limb flexor synergy was a major factor influencing movement performance. Stroke subjects used trunk forward and lateral displacement, elbow flexion, horizontal shoulder rotation and forearm pronation and the combinations of these movements to achieve the reach-to-grasp task (van Kordelaar et al., 2012).

Usually associated with synergies, spasticity is not necessarily limiting and when associated with the synergies can be functionally beneficial in post-stroke subjects. As an example, the extensor synergy in the lower limb of stroke patients can potentially benefit gait (O'Brien, 1996). However, when we consider the presence of synergies in the upper limb, the effects may be less positive. Upper limb gestures require more precision and fine dexterity compared to lower limb tasks. The presence of an abnormal movement control pattern in the performance of simple tasks, e.g., reaching to a cup of coffee, can be detrimental to actual task performance possibly due to deficits in temporal and spatial interjoint coordination. This was investigated by Levin (1996) for pointing tasks in individuals with stroke compared to age and gender matched controls. She found that subjects with stroke demonstrated a lack of ability to coordinate elbow-shoulder movement both temporally and spatially to perform the task.

Commonly observed in stroke, the decreased ability to combine different joint segments in the execution of a motor task has been reported by previous studies (Reisman and Scholz, 2003; Mihaltchev et al., 2005; Diedrichsen et al., 2009). This ability of the neuromuscular system to combine multiple combinations of joint angle positions is called redundancy. It is an inherent property of the motor system and enables it to solve motor execution problems by alternating among an infinite number of joint configurations to perform a task or variations of the same task (Lashley, 1951; Bernstein, 1967). By observing changes in the velocity profile and straightness of the movement endpoint (hand) at the beginning and end of a reaching movements, Yang et al. (2002) showed that upper-limb movement is not exclusively determined by movement patterns but also by the start and end positions of the hand as well as the body posture. The role of body posture and global movement patterns was also mentioned by Shaikh et al. (2014), when the contribution of trunk movements for reaching beyond arm reach were shown to be effective in healthy adults at the end of the movement range when individuals were required to adapt the gesture through adjusting number of degrees of freedom involved in the task, specifically when subjects added trunk movements to perform the task. However, for the same task, post-stroke subjects showed earlier trunk participation, indicating a disruption in the contribution of trunk for movements beyond the reach, interfering with movement performance.

2.4 Finger-to-Nose Test (FNT)

Quick and easy to use, the FNT is the gold-standard for measuring upper-limb coordination and is widely used in professional practice (Swaine and Sullivan, 1993; Siebers et al., 2006). It consists of the evaluation of execution time, dysmetria and tremor (Gagnon et al. 2004; Swaine and Sullivan, 1993; Feys et al., 2003). Many different variations of the FNT are used in both clinical and basic research. Nonetheless, independent of the version used, only time to perform the task is an objective metric of this test.

Swaine and Sullivan (1993) used a version of the FNT later used by Siebers et al. (2006), in which subjects sat with their arm fully extended and were instructed to touch their nose with their finger and then return the finger to the fully extended position in five complete cycles. Using this version of the test, a study in patients with head injury reported fair to moderate intra-rater reliability for clinical observations of tremor (r=0.18-0.31) and dysmetria (r=0.54) as well as fair inter-rater reliability (tremor: r=0.27-0.26; dysmetria: r=0.36-0.40). The low reliability suggests that therapists should seek an alternative method of evaluation of upper-limb coordination (Swaine and Sullivan, 1993). Feys et al. (2003) highlighted the necessity for standardization of the FNT and used it to evaluate intention tremor in patients with multiple sclerosis. They assessed 4 different versions of one FNT in which there was no standardized starting position and patients either received no instruction, or were instructed to hold the finger on their nose for 5s; to lift their arm to 90° shoulder abduction with full elbow extension before touching their nose with their finger (the arm had to remain at 90° of abduction throughout the test); or to keep their shoulder in 90° abduction and full elbow extension while holding finger steady on the nose for 5 s (see Bickerstaff 1976). Although the authors concluded that FNT outcomes depended on instructions, the time to perform the FNT was highly related to three functional activities (r=0.70-0.84): (1) transferring water from one cup to another; (2) answering a telephone, placing it to the ear, and then putting it back; and (3) picking up a coin (Feys et al., 2003). Gagnon et al. (2004) used a FNT in patients with a neuromuscular disorder with ataxic features (ARSACS: Autosomal recessive spastic ataxia of Charlevoix-Saguenay. Patients with ARSACS touched a sagittal target, placed at distance of 45 cm for a 20 s period, alternately and as quickly as possible. The time to perform this version of the FNT was highly correlated with upper-limb functional tests (Box-and-Blocks test; r=0.82; Purdue Pegboard; r=0.82). In addition, the authors reported that the time to perform the FNT differentiated between young (<40 yr old subjects; mean=12.7±2.2 movement repetitions) and older (≥ 40 yr old subjects; mean=6.7±3.4 movement repetitions) out of a total of 24 participants. These results were expected due to the progressive nature of the disease and correlated with clinical findings, such as performance on the BBT (r=0.82), TEMPA (*Test Évaluant les Membres supérieurs des Personnes Âgées* r=0.79), Purdue pegboard (r=0.82) and pinch strength (0.56). However, upper-limb interjoint coordination was not measured. Swaine et al. (2005) described how the time to perform each of 10 versions of the FNT tested (combinations of eyes open/closed, sitting/lying supine and arm fully extended/arm flexed at initial position) had high intra-rater reliability (r=0.77-0.98). Although intra-rater reliability was high, the versions of the FNT were not interchangeable; meaning that one version of the test could not be used to follow-up on scores obtained from another version, a point about standardization previously mentioned by Feys et al. (2003). However, neither coordination, dysmetria nor tremor were measured.

Results support the continued use of this simple, rapid, and easily reproducible clinical test of upper-limb coordination (Swaine and Sullivan, 1993) but there is no evidence that the FNT metric of time is correlated to the spatial and temporal coordination task variables.

CHAPTER 3: RATIONALE, OBJECTIVE AND HYPOTHESES

Improvements in identifying and assessing sensory and motor deficits in patients with stroke are needed to enhance post-stroke rehabilitation and recovery (Semrau et al., 2013). Deficits in upper-limb coordination are commonly observed in patients with stroke and the necessity of a valid coordination measure remains an objective for clinicians and researchers. Coordination assessment is an important part of the clinical neurological evaluation. However, the clinical gold standard for upper-limb coordination measurement is the FNT which only has the objective metric of time. In addition, assessment of the other two metrics, dysmetria and smoothness, depend on the clinician's subjective impression which is based on the observation of movement smoothness and precision. In addition, the conditions of the test are not standardized and vary with respect to the number of movements performed, patient and target position. The extent to which the objective metric of time actually represents smooth and precise coordinated movement is assumed but not known. It is necessary to understand the relationship by objectively quantifying movement quality during the performance of the test and relate movement quality to the time to perform the test. Objective quantification can be done by kinematic analysis of the joint ranges of motion. With regard to movement speed, subjects with stroke make slower upper-limb movements compared to healthy controls. Because kinematic parameters are affected by movement speed, movements made at self-paced fast speeds in healthy subjects, as normally done during the FNT, are not representative of kinematic patterns of movements made by subjects with stroke at slower speeds. To have a matched control group, healthy subjects were required to perform the FNT at slower speed.

OBJECTIVE

The objective was to examine the validity of the FNT to measure upper-limb coordination in patients with chronic stroke compared to age-matched healthy subjects. Furthermore, we aimed to determine the relationship between endpoint performance variables during the FNT and coordination variables.

HYPOTHESES

Hypothesis 1: Subjects with stroke will have decreased endpoint performance measures when performing the clinical FNT compared to healthy subjects at self-paced and at matched speed: longer time to perform the test (time, s), less straight endpoint path (IC) and decreased precision of the endpoint movement at the target (RMSE).

Hypothesis 2: Subjects with stroke will have decreased movement quality measures when performing the clinical FNT at self-paced and at matched speed compared to healthy subjects: smaller joint ranges, lower interjoint coordination measures.

Hypothesis 3: How the variance in the time to perform the FNT is predicted by movement quality variables: joint ranges of motion and interjoint coordination measures (spatial and temporal).

CHAPTER 4: ARTICLE

Does the FNT evaluate coordination in the neurological exam?

Rodrigues MRM[1, 2], Slimovitch M[2, 3], Levin MF[1, 2*]

[1]School of Physical and Occupational Therapy, McGill University, Montreal, Canada

[2]Feil and Oberfeld Research Center, Jewish Rehabilitation Hospital, Center for Interdisciplinary Research in Rehabilitation of Greater Montreal (CRIR), Montreal, Canada

[3]Faculty of Medicine, McGill University, Montreal, Canada

Address correspondence to:

Mindy F. Levin, PhD, PT

School of Physical and Occupational Therapy,

McGill University,

3654 Prom Sir-William-Osler,

Montréal, QC, Canada H3G 1Y5

Email: mindy.levin@mcgill.ca

This manuscript was submitted to the Neurorehabilitation and Neural Repair (NNR).

ABSTRACT

Background: The Finger-to-Nose Test (FNT) is the clinical gold-standard measure for upper-limb coordination. However, the assumption that FNT assesses coordination has not been empirically verified.

Objective: The study aimed to determine the ability of the FNT metric, time, to identify coordination deficits in people with stroke using both endpoint performance and movement quality measures.

Methods: Age- and gender-matched healthy controls and subjects with stroke (n=20 each) performed 2 blocks of 10 continuous to-and-fro movements of the finger between a target located at 90% arm length and nose (ReachIn, ReachOut). Upper-limb kinematics were recorded (Optotrak, 100Hz).

Results: Compared to controls, stroke subjects made more curved endpoint trajectories (Index of curvature: stroke=1.23, control=1.04, $p<0.05$, ReachIn) and used less shoulder horizontal abduction (stroke=11.8º, control=17.6º, $p <0.001$, ReachIn). Compared to their less-affected side, stroke subjects moved their more-affected arm slower (ReachIn: 18%, ReachOut: 43%; for both directions $F_{1, 113}=14.136$, $p<0.001$) and had more curved trajectories (ReachIn: 18%, ReachOut: 27%; for both directions $F_{1, 114}=6.003$, $p<0.05$), while interjoint coordination was similar. FNT movement time correlated with endpoint straightness (r=0.77, p=0.001), temporal (r=0.63, p=0.001) and spatial (r=-0.61, $p<0.05$) interjoint coordination. Shoulder horizontal abduction range (β=0.127), temporal (β=0.855) and spatial (β=-0.191) interjoint coordination explained 82% of variance in the time to perform the FNT.

Conclusions: Shoulder movement and temporal and spatial interjoint coordination predicted the time to perform the FNT, indicating that the clinical FNT metric of time is a sufficient measure of upper-limb coordination after stroke.

Key words: FNT, Stroke, Motor Skill Disorders, Coordination Impairment, Upper Extremity.

INTRODUCTION

Controlling the movement of the upper-limb to attain a goal requires a synchronized interaction (coordination) between multiple muscles and joints.[1] This control is commonly impaired in individuals with stroke.[2] Coordination is a property of harmonious movement[3,4] that is produced by the nervous system in spite of the large abundance in the number of muscles and joints that can be combined to produce upper-limb movement.[5] However, characterizing coordination is a challenge for clinicians and researchers because of a lack of consensus regarding the definition of coordination with respect to upper-limb movements. Some authors[6] described coordination as the ability to execute a controlled, accurate, and rapid movement, while others[7] defined coordination in terms of muscles working harmoniously together to perform movements. A more specific definition from the motor control literature defines coordination as the characterization of the nature of the coupling within a part of a system, between different parts of a system and between different kinds of systems.[8] Coordination is also referred to as a co-variation of elements in a multi-element (abundant) system.[9] These definitions provide general descriptions of coordination but are insufficient to understand the highly specific variability inherent inupper-limb movements.[10] For the purpose of this study, we define coordination of upper-limb movement as the skill of adjusting spatial and temporal movement components of arm segments according to the task,[11] where the task involves repetitive movements to and from the body.

Although it is widely recognized that training can improve performance of functional tasks even years after a stroke,[12] a valid tool for the measurement of coordination, has not yet been established. In healthy individuals, coordinated movements are described in terms of spatial variables, related to the positions of different joints or body segments in space and/or temporal variables, related to the timing between movements of joints/segments during the task.[1]

Consideration of task specificity is important in characterizing coordination. For example, trajectory formation differs for reaches towards the body (egocentric) and away from the body (exocentric). In addition, egocentric movement is performed in a body-centered (proprioceptive) frame of reference while that of exocentric movement is object-centered and relies on the mapping of extrinsic space and performing appropriate visuo-motor transformations.[13] Damage to descending pathways due to stroke involving these systems may affect egocentric and exocentric movement differently. In addition, movement may be affected by abnormal stereotypical upper-limb movement synergies and concomitant reduction in kinematic redundancy[14,15] as well as deficits reducing both movement performance and quality.[16,17]

Understanding how the damaged nervous system uses its available kinematic redundancy is relevant for both practice and research in rehabilitation. Quantification of motor redundancy and adaptability is essential for the measurement of treatment efficacy and recovery.[18] Clinically evaluating coordination is an important part of the standard neurological examination,[19] which is usually tested using the Finger-to-Nose Test (FNT).[20] FNT metrics quantitatively evaluate execution time, and qualitatively assess dysmetria and tremor.[19,20] Several different variations of the FNT are used in clinical settings. For example, in one version of the test used in the standard neurological exam, [21] the patient alternatively touches their nose and the evaluator's stationary or moving finger while lying supine, sitting or standing. In the Fugl-Meyer Assessment of the Upper Limb, the FNT consists of 5 repetitions of alternately touching the subject's own knee and nose when the subject is sitting. Scoring is based on one objective and two subjective measures. The objective measure is the difference between the time to perform the task by the more-affected compared to the less-affected arm, based on a scale from 0 to 2. Aside from the metric of time, coordination is assumed from visually and qualitatively assessing two other features of the movement, arm trajectory straightness (dysmetria) and smoothness (tremor).

In healthy older adults, the time of completion of the FNT has been correlated with gross and fine finger dexterity (r = 0.82-0.84), functional independence (r = 0.74) and social participation (r = 0.78).[22] In older adults, FNT time can also discriminate between different levels of upper-limb function (gross and fine manual dexterity, and grip strength).[19] Although the FNT has been studied in patients with other neurological pathologies, in individuals with stroke, the validity of the FNT has not been established using kinematic measures of interjoint coordination.

The objective of the study was to determine the validity of the FNT to measure upper-limb coordination in patients with chronic stroke. We characterized the differences in movement parameters during FNT between healthy and stroke subjects and related FNT outcomes (time, trajectory, error) to the level of upper-limb impairment severity and activity limitations. We hypothesized that the time to perform the FNT would be related to spatial and temporal interjoint coordination measures. Preliminary data have appeared in abstract form.[23]

Methods

Fourty subjects, 20 healthy (9 males, aged 61.7 ± 8.7 yrs) and 20 who sustained a stroke (11 males, aged 61.4 ± 14.6 yrs) participated in the study (Table 1). Stroke subjects had sustained a unilateral ischemic or hemorrhagic stroke in their dominant or non-dominant hemisphere, 6-192 mos previously (mean 50.9 ± 42.2 mos) and had moderate to good recovery of their upper limb (3-7 on the Chedoke-McMaster Arm Scale, CM).[24] Stroke subjects were excluded if they had unilateral neglect, apraxia or ataxia measured by standard clinical assessment. Individuals in both groups were excluded if they had arm pain, uncorrected visual problems and/or other neurological or musculoskeletal problems affecting upper-limb movement. All subjects signed consent forms approved by the Ethics Committee of the Centre for Interdisciplinary Research in Rehabilitation (CRIR).

S	Age (yr)/ Gender	Affected side R or L / D or ND	Time since stroke (mo)	Chedoke (arm/hand) (7/7)	FMA total (/66)	CSI Triceps (/16)	CSI Biceps (/16)	mWMFT (/30)	BBT % A/LA
1	45/M	R/D	25	3/3	30	13	13	15	53
2	72/F	R/D	90	3/3	36	11	10	21	45
3	77/M	L/ND	19	4/6	38	12	12	15	44
4	51/M	L/ND	32	4/4	38	6	7	17	23
5	37/F	R/D	192	3/3	40	13	13	14	13
6	69/M	R/D	40	4/3	46	5	7	24	60
7	55/M	L/ND	31	4/5	49	5	8	22	53
8	82/M	R/D	59	5/6	57	4	4	30	100
9	72/M	R/D	66	7/6	57	3	3	29	100
10	43/F	R/D	13	6/7	58	4	7	29	100
11	66/F	L/ND	69	4/6	58	6	8	24	62
12	66/M	L/ND	75	6/7	60	4	4	30	78
13	78/F	R/D	38	6/7	61	4	5	29	88
14	79/M	R/D	50	7/5	62	4	4	28	95
15	64/F	L/ND	42	5/6	62	5	4	27	76
16	78/F	L/D	10	6/7	62	4	4	24	96
17	41/F	L/ND	6	6/6	63	8	4	28	100
18	63/F	R/D	74	7/5	64	4	4	28	100
19	64/M	L/ND	6	5/6	64	5	8	26	84
20	44/M	L/ND	12	7/7	65	4	4	24	72
Mean (SD)	61.4 (14.6)		50.9 (42.2)	5.0 (1.4) / 5.3 (1.5)	51.9 (13.2)	6.2 (3.3)	6.7 (3.2)	23.7 (5.6)	72.1 (26.9)
Healthy (n=20)	61.7 (8.7)								

Stroke subjects underwent a 1.5 hr clinical evaluation plus a 2 hr experimental session. Healthy subjects only participated in the experimental session. The clinical evaluation was performed using valid and reliable scales by an experienced physical therapist. Upper-limb impairment was assessed with the Fugl-Meyer Arm Assessment (FMA)[25] on a 66 point scale and spasticity in biceps and triceps of the affected side was assessed using the 16 point Composite Spasticity Index (CSI)[26] where 0-9, 10-12 and 13-16 represent mild, moderate and severe spasticity respectively. The Reaching Performance Scale for Stroke (RPSS) was used to assess compensatory movements of the trunk used while reaching to near (18 pts) and far (18 pts) targets in the body midline (Levin et al. 2004).[27] Upper-limb activity was assessed with the Box and Blocks Test (BBT)[28] expressed as a percentage of the number of blocks moved by the more-affected compared to the less-affected arm, from one side of a box to another in 60s. The 30 pt Modified Wolf Motor Function Test (mWMFT)[29] was also done. UL impairment ranged from moderate to mild (FMA: 30-65, mean 51.9 ±13.2 pts; CSI biceps 3-13, mean 6.7 ±3.2 pts; CSI triceps 3-13, mean 6.2 ±3.3 pts; RPSS_near 15.2 ±3.5pts.; RPSS_far 14.7 ± 3.6 pts), and activity levels varied (BBT: 13-100, mean 72.1 ±26.9 %; mWMFT: 14-30, mean 23.7 ±5.6 pts; Table 1).

Experimental Task

In the experimental session, all subjects performed the FNT from a comfortable sitting position with the hips and knees flexed to 90° (Fig. 1A). At the sound of a computer-generated tone, subjects alternatively touched their nose and a target (2.5 cm diameter circle) with the fingertip. The target was located at nose height at a distance of 90% arm-length measured from the lateral border of the axilla to the tip of the index finger. Movements were performed at a self-paced fast speed without compromising accuracy with eyes open. A trial consisted of 10 movements performed continuously starting with the fingertip on the target. Two blocks of trials were performed for each arm, with arm order randomized. Subjects performed the task using their preferred strategy. Subjects in the control group performed two extra blocks per arm matching the approximate speed of the stroke group.

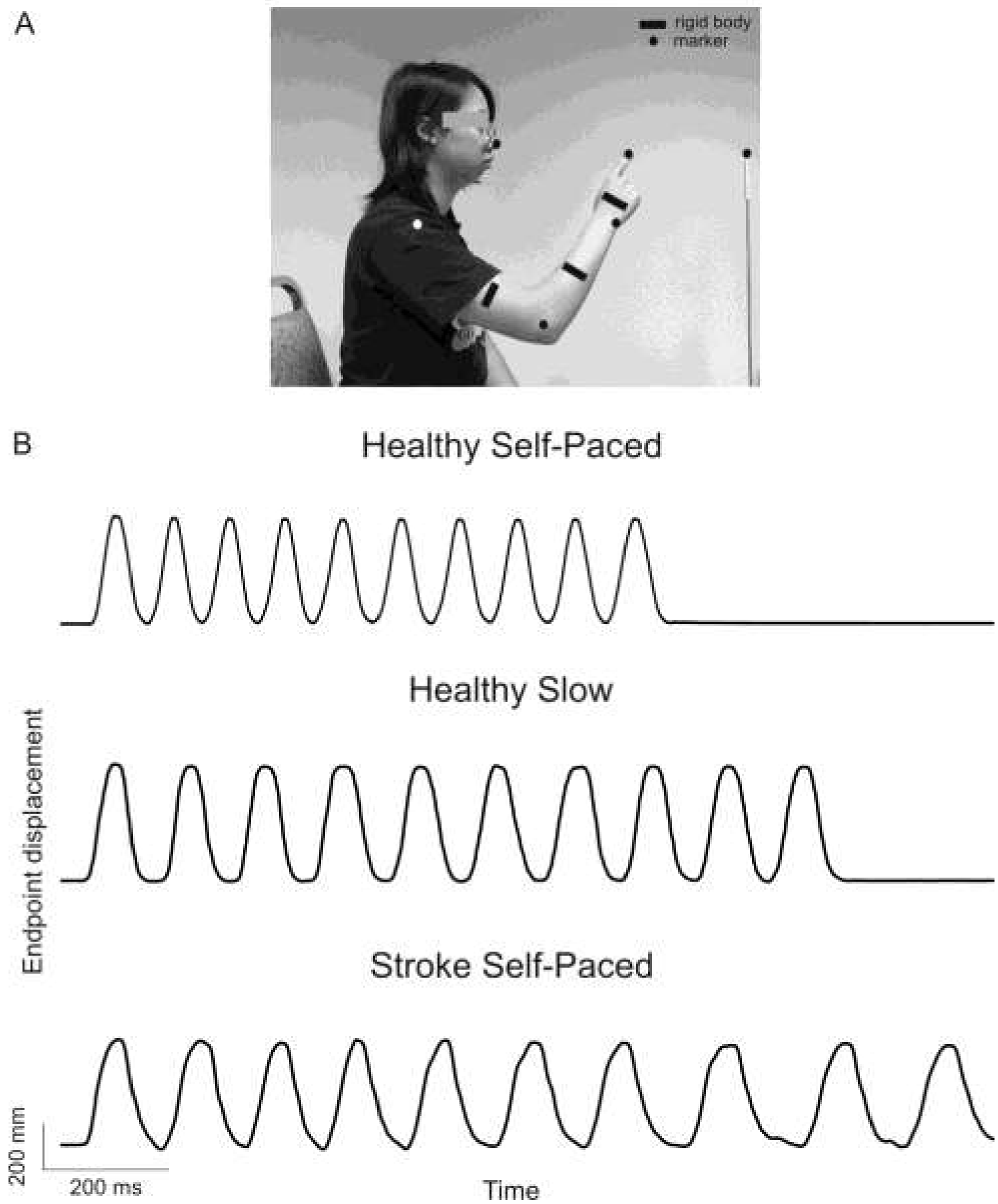

Figure 1. A. Experimental set up illustrating marker placement and examples of endpoint displacement for finger-to-nose test. Inset: Subject sat with one arm partially extended, index finger fully extended and target placed at 90% arm-length at eye-level. The task was to touch the target and then the nose as fast and as accurately as possible 10 times; B. Examples of 10 trials of endpoint (tip of index finger) displacement over time. First row – healthy subject moving endpoint at self-paced fast speed, Second row – healthy subject moving endpoint at slow speed and Third row – Stroke subject moving endpoint a self-paced speed.

Data Collection

Data were recorded from 8 markers placed on the tip of the index finger, ulnar styloid, lateral epicondyle of the elbow, ipsi- and contralateral acromion, sternum, lateral aspect of the nose-tip and target. Three rigid-bodies placed on the dorsum of the hand, mid-forearm and mid-arm (Fig. 1A) were also used. Data were recorded with a 2 Certus bar Optotrak Motion Analysis System (Northern Digital., Waterloo, ON) for 30 s at a sampling rate of 100 Hz.

Data Analysis

Since reaching movements in different directions can be affected by abnormal upper-limb synergies in post-stroke subjects, we analyzed data for each direction separately. Therefore, each trial was divided into two segments according to direction so that there were 10 target-to-nose movements in an egocentric frame of reference (ReachIn) and 10 nose-to-target movements in an exocentric reference frame (ReachOut). To ensure that we assessed stable behavior not affected by learning, the first 3 trials of each block were not considered. Thus, mean values were computed for 14 trials in each direction. Raw x, y and z data were interpolated and smoothed with a 10 Hz low-pass Weiner filter. Movement onset and offset were determined from the tangential velocity of the endpoint marker as the point at which the signal rose and remained above or fell and remained below 10% of the peak velocity.

Analysis was done at both motor performance and movement quality levels for movements in each direction.[30] Performance variables of the endpoint movement were total movement time, trajectory straightness and precision. Movement quality variables were those related to joint rotations and interjoint coordination. For endpoint performance, total movement time was defined as the time between the onset of the first target-to-nose segment to the end of the last nose-to-target segment in the last trial of the block. The movement time for each direction (ReachIn/Out) was defined as the time to move the fingertip from the target to the nose and the nose to the target respectively. Trajectory straightness was defined as the index of curvature (IC), which is the ratio between the actual endpoint movement path to the shortest distance between the nose and target, where a value of 1 indicates a perfectly straight trajectory. Movement precision between the endpoint and target position was computed using the root-mean squared error (RMSE) defined as the difference between the final x,y,z position of the endpoint at the end of the ReachOut phase and the position of the target. Movement quality variables were computed as the difference between starting and final joint angles measured in degrees. Elbow flexion/extension (Elbow) was calculated from rigid bodies on the mid-forearm and mid-arm, where 180º corresponds to the fully extended arm, Shoulder horizontal adduction/abduction (Sh-H-Abd) was calculated from vectors formed between markers on the 2 acromions and between the acromion and lateral epicondyle where 0º corresponds to a pure 90º shoulder abduction, shoulder flexion (Sh-Flex) was calculated using vectors formed between markers on the ipsilateral acromion and lateral epicondyle with a vertical line through the acromion marker, where 0º indicated the arm alongside the body. Trunk (Trunk) pitch angle was computed as the antero-posterior deviation of the trunk segment from a vertical line through the midpoint between the two acromion markers. To assess interjoint coordination, two variables were used, one temporal (LAG) and one spatial (interjoint coordination, IJC). LAG refers to the temporal delay between peak values of the shoulder horizontal adduction/abduction and Elbow extension/flexion traces, where 0 ms indicates perfect temporal coincidence. IJC is the slope of the angle-angle plot between shoulder horizontal adduction/abduction and elbow extension/flexion movements, where values closer to 0 indicate more involvement of shoulder compared to elbow movement and values greater than 1 indicate the opposite. Data analysis was performed using Matlab v. 6.5.1 software (Massachusetts, USA).

Statistical Analysis

Normality of distributions and homogeneity of variances were verified with Kolmogorov-Smirnov and Levene's tests respectively. Hypotheses 1 and 2 were addressed using one-way ANOVAs to assess differences in endpoint performance variables (movement time, straightness and precision) and movement quality variables (joint ranges, trunk displacement, LAG, IJC) in the healthy group moving at self-paced and slow speeds. A two-way ANOVA compared these variables between groups with factors group (stroke, healthy) and movement direction (ReachIn, ReachOut). Appropriate post-hoc tests with Bonferonni corrections for multiple comparisons were performed. The strengths of the associations between clinical measures and kinematic outcomes were assessed using correlation analyses. To address Hypothesis 3, multiple step-wise regression analysis was used to determine the contribution of different kinematic factors to the time to perform the FNT, in which the dependent variable was movement time and the independent variables were Sh-H-Abd, LAG, and IJC. For regression analyses, p values of <0.05 and >0.1 were used for inclusion or rejection respectively. All statistical analyses were performed using SPSS Statistics v.20 for Windows (IBM, North Castle Drive, Armonk, NY). Initial significance levels were $p<0.05$.

RESULTS

Movements in healthy subjects

Healthy subjects made rhythmical endpoint movements with each arm at both speeds (Fig. 1B). Movements were slightly curved (IC=1.01-1.09; Fig. 2 A,B) and precise (RMSE=13.2-20.7 mm) for each direction (ReachIn, ReachOut). As expected, ranges of Elbow, Sh-H-Abd, Sh-Flex and Trunk movement varied with movement direction. Compared to self-paced movements, trajectories (IC) of slow movements were significantly (~5%) less straight ($F_{1,114}$=18.061, $p<0.001$) and used 5-28% less Sh-Flex ($F_{1,118}$=4.713, $p<0.05$). Temporal IJC was better (smaller LAG) for self-paced compared to slow movements ($F_{1,118}$=4.080, $p<0.05$).

Movements in patients with stroke compared to healthy subjects

Since endpoint straightness, Sh-Flex range of motion and LAG differed in slow compared to self-paced movements in healthy subjects, movement characteristics made by subjects with stroke were compared only with those made by healthy subjects at slow speeds. Difficulties in reaching with the affected arm were evident in all stroke subjects (Fig.2 C,D). Overall, there was a difference in movement time between the stroke group and the healthy subjects moving slowly ($F_{1,113}$=54.083, $p<0.001$; Fig. 3A) such that healthy subjects movements were slower. Nevertheless, in terms of movement quality measures, only Sh-H-Abd was less (means varied from 11.8- 35.7°) for movements in both directions made by stroke compared to healthy subjects (means: 34.7-56.7°; $F_{1,114}$=18.397, $p<0.001$, Fig.3D). As expected, due to the difference in the target locations, there were also differences within groups for reaches made in each direction for movement time, error at the far target, Elbow, Sh-H-Abd, Sh-Flex and Trunk ranges (Fig.3A-F). In addition, there were interaction effects between group and movement direction. Compared to the healthy slow group, stroke subjects made movements in the ReachOut direction faster ($F_{1,113}$=5.549, $p<0.05$, Fig.3A) but they used less elbow extension ($F_{1,114}$=4.128, $p<0.05$, Fig.3C) and more trunk forward displacement ($F_{1,116}$=15.466, $p<0.001$, Fig.3E). For the ReachIn direction, stroke subjects used less Sh-H-Abd compared to the healthy group (Fig.3D, $F_{1,114}$=55.181, $p<0.001$) and more backward trunk displacement ($F_{1,116}$=15.466, $p<0.001$, Fig.3E).

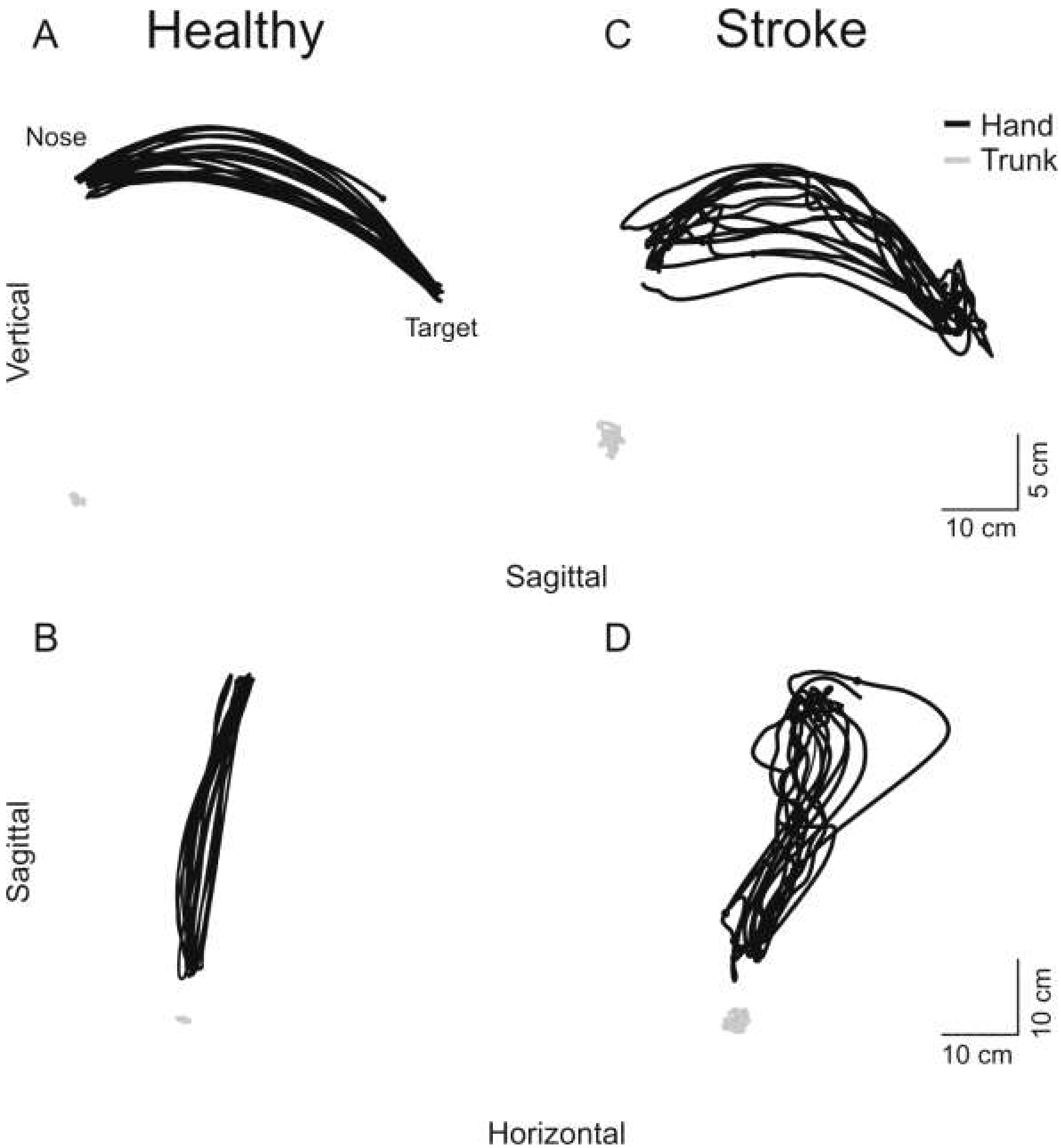

Figure 2. Examples of sagittal (A,C) and horizontal (B, D) endpoint trajectories of 10 trials of the finger-to-nose test in one healthy subject and one subject with stroke. Blue lines show endpoint trajectories and red lines show trunk trajectories.

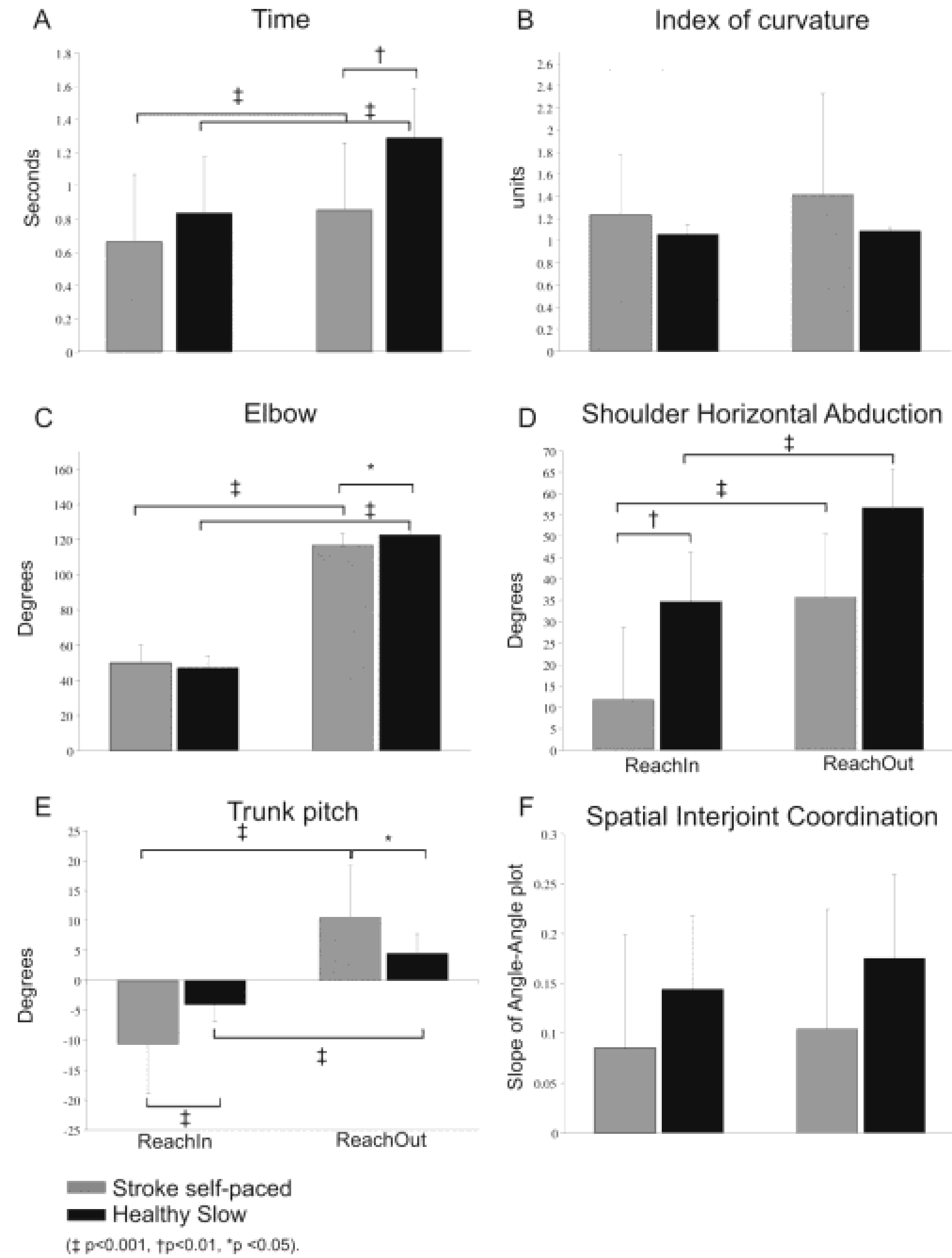

Figure 3. Histograms of main outcome variables; A. Time to perform the task; B. Index of curvature (IC); C. Elbow range of motion; D. Shoulder Horizontal Abduction range of motion; E. Trunk displacement; F.. Spatial Interjoint Coordination. Black/grey bars show means and standard deviations for healthy/stroke groups.

Within the stroke group, there were differences in endpoint performance and movement quality variables for movements in each direction. The stroke group took longer to make the outward (ReachOut) compared to inward reaches (ReachIn; $p<0.001$, Fig.3A). Stroke subjects also used more elbow extension ($p<0.001$, Fig.3C), more Sh-H-Abd ($p<0.001$, Fig.3D) and more trunk forward displacement ($p<0.001$, Fig. 3E) for ReachOut compared to ReachIn movements.

Relationship between kinematics and clinical severity

For the endpoint performance variables, total time to perform the task (10 repetitions) was correlated with impairment severity (FMA: $r=-0.55$, $p<0.01$, Fig.4A; biceps spasticity: $r=0.45$, $p<0.05$) but not with activity level. Endpoint trajectory straightness (IC) for each direction (ReachIn, ReachOut) correlated with several clinical impairment scores (FMA: $r=-0.47$ $p<0.05$, $r=-0.52$ $p<0.02$ (Fig.4B); biceps spasticity: $r=0.47$ $p<0.05$, $r=0.46$ $p<0.04$; triceps spasticity: $r=0.55$ $p<0.01$, $r=0.46$ $p<0.04$). IC also correlated with clinical activity scores only for the ReachIn direction (BBT: $r=-0.57$, $p<0.01$; mWMFT: $r=-0.53$, $p<0.01$). Bivariate correlation also revealed a tendency of a positive relationship between the time to perform the ReachOut phase with LAG ($r=0.46$, $p=0.055$, Fig. 4C) in the stroke group whereas this relationship was negative and highly significant in the healthy subjects moving slowly (LAG: $r=-0.67$, $p<0.03$, Fig 4D).

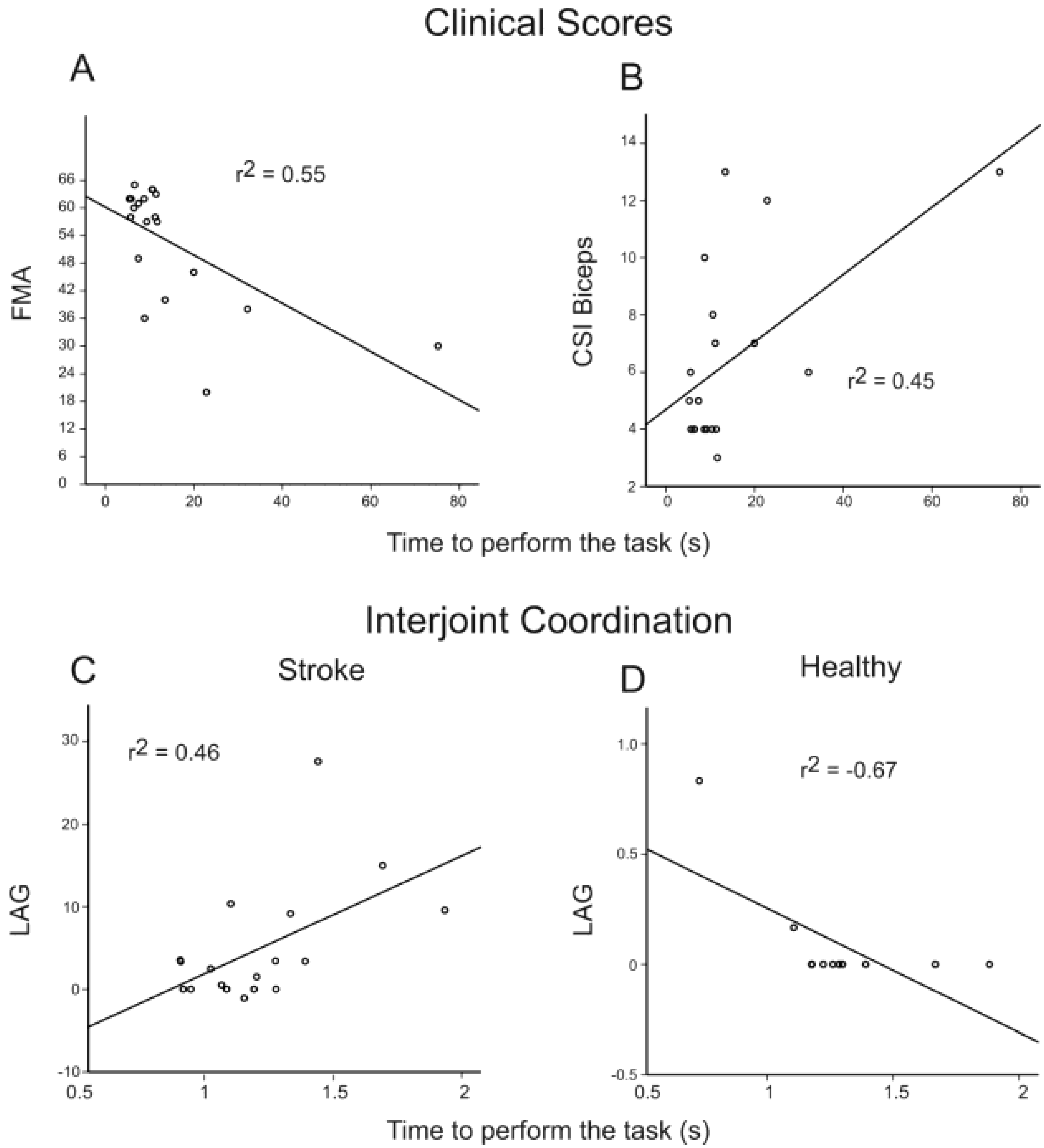

Figure 4. A. Correlation between Time to perform the task and FMA; B. Correlation between Time to perform the task and CSI Biceps; C. Correlation between Time to perform the task and Temporal interjoint coordination in subjects with Stroke and; D. Correlation between Time to perform the task and Temporal interjoint coordination in Healthy individuals.

Multiple regression analysis demonstrated that for the ReachIn direction, Sh-H-Abd range ($\beta=0.127$), LAG ($\beta=0.855$) and IJC ($\beta=-0.191$) explained 82% of the variance in the time to perform FNT. Similarly, for the ReachOut direction, LAG explained 94% of the variance in the time to perform the FNT.

DISCUSSION

This is the first study to objectively quantify upper-limb movement patterns and coordination used to perform the FNT involving arm movement to and from the nose and a sagittal target. We evaluated this relationship between the time to perform the FNT and upper-limb kinematics in patients with stroke compared to healthy controls. We used a single subject position and target placement but the innovation in our approach was the determination of the relationship between kinematic variables describing endpoint performance (time, tremor (straightness), dysmetria (error)) and upper-limb movement quality (joint ranges, interjoint coordination). Results indicate that the time to perform this version of the FNT is a good measure of interjoint coordination. Compared to movements made at slow speeds in matched control subjects, subjects with stroke used less shoulder flexion and horizontal adduction and more trunk displacement for both ReachIn and ReachOut directions of the FNT. In addition, while the interjoint coordination pattern differed in the healthy subjects according to movement direction, stroke subjects used a similar spatial interjoint coordination pattern for both ReachIn and ReachOut phases. Overall, the temporal interjoint coordination score was an excellent predictor of the variance in the time to perform the FNT based on a multiple regression model and the time to perform the FNT was related to clinical impairment.

Relationship between time to perform the FNT and clinical outcomes

The FNT is a well-known, quick and easy to administer clinical test widely used as an essential part of the upper-limb neurological evaluation.[20,12] However, there is a lack of consensus regarding testing conditions and outcomes. Previous research has related the time to perform the FNT to clinical outcomes in different populations such as the healthy elderly[31] and patients with head injury[20], multiple sclerosis[32] and neuromuscular disorders.[19] Time to perform any version of the FNT was correlated with gross and fine finger dexterity (r = 0.82-0.84), functional independence (r = 0.74), social participation (r = 0.78),[22] gross and fine manual dexterity and grip strength,[19] functional arm tasks (r = 0.70-0.84),[32] Box-and-Blocks test (r=0.82) and Purdue Pegboard (r = 0.82).[19] Our result is consistent with previous findings, suggesting that the time to perform the FNT is related to the level of upper-limb impairment severity in patients with chronic stroke.

FNT and coordination in healthy subjects

In healthy subjects, elbow, shoulder and trunk movements contributed differently to the execution of the FNT at self-paced and slow speeds. This was not surprising since characteristics of kinematics are related to movement speed.[33,34] Movement trajectories were less straight when the FNT was performed slowly. Slower movements were performed by locking the shoulder joint at a certain angle and reducing the speed of elbow movement. In this way, healthy subjects controlled a fewer number of articular degrees of freedom but this strategy also resulted in the endpoint trajectory being less straight in the sagittal direction compared to when movements were made at a faster speed. The greater contribution of elbow compared to shoulder movement to the endpoint trajectory was also reflected in higher interjoint coordination values for slower movement. These findings support the use of data from healthy subjects making arm movements at a slower than self-paced speed as a matched control group for subjects with stroke.

FNT and coordination in subjects with stroke

Adaptation of reaching in healthy subjects is associated with an increased variability of joint combinations to achieve the same hand path (motor equivalence).[35,36] The decreased modulation of shoulder horizontal adduction/abduction in the stroke group in both directions suggests a decrease in kinematic redundancy in which subjects with stroke did not recruit all the available degrees of freedom to perform the task. Our results are consistent with Archambault et al.[37] who showed that stroke patients have higher variability in endpoint performance during a reaching task due to less adaptive movement patterns. In addition, previous studies have shown that patients with stroke had deficits in adapting elbow-shoulder interjoint coordination patterns for reaching to targets placed within- and beyond-the-reach.[38,39] Similarly, patients with stroke used fewer joint combinations during forward reaching-to-grasp[40] and for reaches beyond the arm's functional reach length.[41]

Mean values of spatial and temporal interjoint coordination were not significantly different between groups and directions because of high within-group variability. However, correlation analysis showed that, in contrast to healthy subjects who had a significant negative relationship between LAG and movement time (Fig. 4D), more temporally coupled shoulder and elbow movements in subjects with stroke was related to a longer time to perform the FNT (Fig.4C). Overall, in the stroke group, longer LAGs were related to longer times to perform the task in both directions. For the ReachIn direction, longer times were also related to a lower interjoint coordination values. These results suggest that when subjects with stroke attempted to perform the movement faster, the presence of an abnormal upper-limb flexor synergy may have contributed to the simultaneous activation of the two joints leading to a diminished movement speed.

Deficits in the adaptability of interjoint coordination may have contributed to differences in trajectory formation for reaches towards (egocentric) and away from the body (exocentric) for the stroke group. The exocentric frame of reference used for ReachOut was opposite to the upper-limb flexor synergy. Spasticity scores for both biceps and triceps brachialis were moderately correlated with elbow-shoulder temporal interjoint coordination (LAG). It has been demonstrated that in patients with stroke, abnormal joint coupling primarily limits the ability to extend the elbow in an exocentric frame of reference[42] leading to a decreased upper-limb workspace for outward reaching.[43,42] This could explain why outward reaching tasks were more disrupted than egocentric ones. In addition, the presence of a flexor synergy pattern may decrease the variability of upper-limb movements when performing functional tasks, especially ones requiring more shoulder horizontal abduction.[43,42] The decrease in variability due to deficits in interjoint coupling narrows the range of movements available to adapt upper-limb movement to task demands.[30] Previous studies have mainly focused on ReachOut movements showing a disruption in the relative timing of shoulder and elbow movements in reaching towards targets in different parts of the arm workspace (e.g, near, far, contralateral, ipsilateral[44]). Our results suggest that the disruption in temporal interjoint coordination affects both exocentric and egocentric movement directions.

Role of trunk displacement

Trunk displacement was greater in the stroke patients and varied according to reaching direction. This is consistent with previous studies showing that the trunk is recruited earlier and makes a greater contribution to the endpoint displacement in stroke patients compared to healthy subjects for reaching and grasping tasks, and that this effect is more evident in patients with more severe hemiparesis.[38,45] However, use of the trunk did not affect coordination between shoulder and elbow joints since the amount of trunk displacement was not correlated with temporal and spatial interjoint coordination variables.

CONCLUSIONS

For this version of the FNT, the time to perform the test was related to temporal and spatial interjoint coordination. In addition, dividing the analysis of the movement into ego- and exocentric, ReachIn and ReachOut directions, provides us with some insights into direction-dependent movement deficits and their relationship with pathological upper-limb movement synergies. This is a new approach to understanding the role of synergies during arm movements that include change in direction which may have implications to recovery of arm function after stroke. The conclusion that the metric of time is a good indicator of upper limb coordination in patients with stroke is however, limited to the conditions of the FTN test performed and the type of patients evaluated.

ACKNOWLEDGEMENTS

MFL holds a Canada Research Chair in Motor Recovery and Rehabilitation. We acknowledge assistance of Rhona Guberek for patient recruitment and Dr. Andreanne K. Blanchette for experiment setup and data collection.

DISCLOSURE

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

REFERENCES

1 D'Avella A, Lacquaniti F. Control of reaching movements by muscle synergy combinations. *Front Comp Neurosci* 2013;7(42):1-7.

2 Reinkensmeyer DJ, Cole AM, Kahn LE, Kamper DG. Directional control of reaching is preserved following mild/moderate stroke and stochastically constrained following severe stroke. *Exp Brain Res* 2002;143(4):525-30. doi: 10.1007/s00221-002-1055-3

3 Cirstea MC, Mitnitski AB, Feldman AG, Levin MF. Interjoint coordination dynamics during reaching in stroke. *Exp Brain Res* 2003;151:289-300. doi: 10.1007/s00221-003-1438-0

4 Kazennikov OV, Wiesendanger M. Goal synchronization of bimanual skills depends on proprioception. *Neurosci Lett* 2005;388:153–6.

5 Bernstein, NA. The Co-ordination and regulation of movements. Oxford: Pergamon Press; 1967.

6 Zoltan B, Pedretti LW. Evaluation of muscle tone and coordination. In: Pedretti LW, Zoltan B, eds. *Occupational therapy: practice skills for physical dysfunction.* 3rd ed. St-Louis, MO: Mosby; 1990:131-40.

7 Trombly CA. *Occupational therapy for physical dysfunction.* 3rd ed. Baltimore, MD: Williams & Wilkins; 1989.

8 Jirsa VK, Kelso JAS. *Coordination dynamics: issues and trends.* Berlin, Heidelberg: Springer-Verlag; 2004.

9 Latash ML, Scholz JP, Schöner G. Motor control strategies revealed in the structure of motor variability. *Ex Sport Sci Rev* 2002;30:26-31.

10 Scholz JP, Schöner G, Latash ML. Identifying the control structure of multijoint coordination during pistol shooting. *Exp Brain Res* 2000;135(3):382-404.

11 Krasovsky T, Levin MF. Toward a better understanding of coordination in healthy and poststroke gait. *Neurorehabil Neural Repair* 2010;24(3):213-24.

12 Siebers A, Oberg U, Skargren E. Improvement and impact of initial motor skill after intensive rehabilitation - CI-therapy in patients with chronic hemiplegia. A follow-up study. *Adv Physiother* 2006;8:146-53.

13Paillard, J. *Motor and representational framing of space*. In: Paillard J, ed. *Brain and Space.* Oxford: Oxford University Press;1991:163-82.

14 Brunnstrom S. *Movement therapy in hemiplegia. A neurophysiological approach*. New York, NY: Harper and Row; 1970.

15 Mihaltchev P, Archambault PS, Feldman AG, Levin MF. Control of double-joint arm posture in adults with unilateral brain damage. *Exp Brain Res* 2005;163:468–86.

16 Diederichsen LP, Winther A, Dyhre-Poulsen P, Krogsgaard MR, Nørregaard J. The influence of experimentally induced pain on shoulder muscle activity. *Exp Brain Res* 2009;194(3):329-37. doi: 10.1007/s00221-008-1701-5

17 Feldman AG, Levin MF. The origin and use of positional frames of reference in motor control. *BehavBrain Sci* 1995;18(4):723.

18 Kamper DG, McKenna-Cole AN, Kahn LE, Reinkensmeyer DJ. Alterations in reaching after stroke and their relation to movement direction and impairment severity. *Arch Phys Med Rehabil* 2002;83:702-7.

19 Gagnon C, Mathieu J, Desrosiers J. Standardized finger nose test validity for coordination assessment in an ataxic disorder. *Can J Neurol Sci* 2004;31:484-9.

20 Swaine BR, Sullivan SJ. Reliability of the scores for the finger-to-nose test in adults with traumatic brain injury. *Phys Ther* 1993;73:71-8.

21 Haerer, AF. *The Neurological Exam.* Philadelphia, PA: JB Lippincott; 1992.

22 Desrosiers J. Performance of the ‘unaffected’ upper extremity of elderly stroke patients. *Stroke* 1995;27(9):1564-70. ISSN: 0039-2499

23 Rodrigues M, Slimovitch M, Blanchette A, Levin MF. Evaluation of upper limb coordination in stroke subjects using The Finger To Nose Test (FTN Test). Abstract,36th GRSNC Int Meeting, Montreal, Canada, 2014.

24 Moreland J, Gowland C, Van Hullenaar S, Huijbregts M. Theoretical basis of the Chedoke-McMaster Stroke Assessment. *Physiother Can* 1993;45(4):231-8.

25 Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Steglind S. The post-stroke hemiplegic patient: I. A method for evaluation of physical performance. *Scand J Rehab Med* 1975;975(7):13-31.

26 Levin MF, Hui-Chan CW. Relief of hemiparetic spasticity by TENS is associated with improvement in reflex and voluntary motor functions. *Electroencephalogr Clin Neurophysiol* 1992;85:131-42.

27 Levin MF, Desrosiers J, Beauchemin D, Bergeron D, Rochette A. Development and validation of a scale for rating motor compensations used for reaching in patients with hemiparesis: the Reaching Performance Scale. *Phys Ther* 2004;84:8-22.

28Mathiowetz V, Volland G, Kashman N, Weber K. Adult norms for the Box and Block Test of manual dexterity. *Am J Occ Ther* 1985;39(6):386-91.

29 Wolf SL, Catlin PA, Ellis M, Archer AL, Morgan B, Piacentino A. Assessing Wolf Motor Function Test as outcome measure for research in patients after stroke. *Stroke* 2001;32:1635-9. doi: 10.1161/01.STR.32.7.1635

30 Levin MF, Kleim JA, Wolf SL. What do motor ‘‘recovery’’ and ‘‘compensation’’ mean in patients following stroke? *Neurorehabil Neural Repair* 2009;23:313–19.

31 Swaine BR, Lortie E, Gravel D. The reliability of the time to execute various forms of the finger-to-nose test in healthy subjects. *Physiother Theory Pract* 2005;21(4):271-9.

32 Feys PG, Davies-Smith A, Jones R, Romberg A, Ruutiainen J, Helsen WF, Ketelaer P. Intention tremor rated according to different finger-to-nose test protocols: a survey. *Arch Phys Med Rehabil* 2003;84:79-82.

33 Duarte M, Zatsiorsky VM. Effects of body lean and visual information on the equilibrium maintenance during stance. *Exp Brain Res* 2002;146:60–9.

34 Burgess-Limerick R, Abernathy B, Neal J. Relative phase quantifies interjoint co-ordination. *J Biomech* 1993;26(1):91-4.

35 Lashley KS. The problem of serial order in behavior. In: Jeffress LA, ed. *Cerebral mechanisms in behavior.* New York, NY: Wiley; 1951.

36 Yang J, Scholz JP, Latash ML. The role of kinematic redundancy in adaptation of reaching. *Exp Brain Res* 2007;176(1):54–69.

37 Archambault P, Pigeon P, Feldman AG, Levin MF. Recruitment and sequencing of different degrees of freedom during pointing movements involving the trunk in healthy and hemiparetic subject. *Exp Brain Res* 1999;126:55–67.

38 Levin MF, Michaelsen SM, Cirstea CM, Roby-Brami A. Use of the trunk for reaching targets placed within and beyond the reach in adult hemiparesis. *Exp Brain Res* 2002;143:171–80.

39 Shaikh T, Goussev V, Feldman AG, Levin MF. Arm-trunk coordination for beyond-the-reach movements in adults with stroke. *Neurorehabil Neural Repair* 2014;28(4):355-66.

40van Kordelaar J, van Wegen EE, Kwakkel G. Unraveling the interaction between pathological upper limb synergies and compensatory trunk movements during reach-to-grasp after stroke: a cross-sectional study. *Exp Brain Res* 2012;221(3):251-62.

41 Reisman DS, Scholz JP. Aspects of joint coordination are preserved during pointing in persons with post-stroke hemiparesis. *Brain* 2003;126:2510–27.

42 Ellis MD, Sukal T, DeMott T, Dewald JP. Augmenting clinical evaluation of hemiparetic arm movement with a laboratory based quantitative measurement of kinematics as a function of limb loading. *Neurorehabil Neural Repair* 2008;22:321–9.

43 Sukal TM, Ellis MD, Dewald JPA. Shoulder abduction-induced reductions in reaching work areas following hemiparetic stroke. Neuroscientific implications. *Exp Brain Res* 2007;183:215-23.

44 Levin MF. Interjoint coordination during pointing movements is disrupted in spastic hemiparesis. *Brain* 1996;119:281-93.

45 Michaelsen SM, Jacobs S, Roby-Brami A, Levin MF. Compensation for distal impairments of grasping in adults with hemiparesis. *Exp Brain Res* 2004;157(2):162-73.

CHAPTER 5: GENERAL DISCUSSION

The objective quantification of upper-limb movements has been a challenge for researchers and clinicians throughout the years. Different pathologies lead to impairment in the upper-limb. With 610,000 new cases every year around the world, stroke is a common neurological disease and patients with stroke have upper-limb deficits including problems of coordination. Many analytical techniques were suggested to assess upper-limb function objectively, but the applicability of these methods in daily practice is rarely feasible and is met with resistance from practitioners. The reaching task is considered a coordinated task. It requires highly interactive recruitment of multiple joints in both temporal and spatial domains. The proper interaction of these motor aspects results in displacement of the endpoint in space to efficiently reach the goal: touch the target. Simple reaching requires the interaction of two or more joints in a coordinated way, without which movement quality and performance would be compromised.

The gold standard clinical test for measuring upper-limb coordination is the FNT. However, the validity of the test in the stroke population has never been studied by comparing the test metrics to kinematic outcomes. This study aimed to quantify the assessment of upper-limb coordination using kinematics as an objective outcome to be compared to the FNT metrics of time for task completion, tremor (straightness) and dysmetria (RMSE). Although the time to perform the task is an objective measure, it does not reflect the movement pattern used by the subjects to perform the task, e.g., the same subject can perform the task twice in the same amount of time but using only elbow flexion - extension movements during the first attempt and by using a perfect combination of elbow and shoulder movements, with trunk displacement at the end of range of the reaching movement. This paradox illustrates the necessity of the validation of the time to perform the test to be used as a measure of coordination in clinical practice and how the use of compensatory movement patterns can confound the findings.

Rationale for testing coordination with vision and proprioception

Although many alternate testing conditions are used in clinical practice, only one condition (eyes open and touching the target) was used for this project. The interaction of information from different sensory afferents conveyed to the central nervous system plays a major role in movement perception and influences movement performance and quality (Johnson et al. 2008; Sarlegna and Sainburg, 2009). Proprioception and vision are used to determine limb position and seen position, respectively (Graziano, 1999; Touzalin-Chretien et al., 2010).

We instructed patients to perform the test with the eyes open. Performing the test with the eyes open leads to more precise movement. In addition, visual feedback provides additional perception which assists in better target localization and/or online corrections during the movement. However, performing the task with vision also has some drawbacks. Visual information can be used to substitute for proprioceptive loss (Tunik et al., 2003). Because patients depend on both vision and proprioception during the movement under this condition, we could not isolate and analyze the role of proprioception deficits in this population. This is relevant and should be investigated in the future since deficits in proprioception lead to movement impairment and the visual feedback can hide aspects of loss of proprioception. Also, on-line correction might have influenced the test outcomes. In addition, both groups had tactile feedback from the target to be touched and the tip of their own nose and this feedback might have influenced the results. Another test condition, with no specific target position and where the patient has to move their finger back to the same starting position is commonly used in clinical practice. Future investigation of this test condition will be interesting to observe whether the outcomes vary. In the future, performance comparison between alternate test conditions might be useful to better understand how each condition may contribute to upper-limb coordination.

Speed

As indicated at the Fig. 1B, healthy subjects moving their arm at a fast self-paced speed, performed the task faster on average than the subjects with stroke. Speed is a major factor to be considered in kinematic analysis. Kinematic outcomes are known to be influenced by speed (Lamontagne and Fung, 2004). To account for the effects of speed, we asked the healthy subjects to move their arm at slower speeds. The examples shown in Fig. 1 illustrate the differences in kinematics due to different movement speeds and justify the inclusion of the condition of healthy subjects moving their arm slower as a matched control group for our stroke subjects. According to Fitts's law, movements performed at faster speed are more difficult and are also influenced by the width of the target to be touched. Thus, during the course of this project, we did not insist on precision as we could have lost time as a measure and that does not reflect how the test is done in the daily clinical practice. In addition, we could have given additional sensory feedback on precision (e.g. light glowing when target was touched, beep sound, etc.) but this may not reflect the reality in the clinical set up. Future studies could test the effects of different target sizes and focus on precision on coordination.

Examples of FNT as a test of coordination

For the execution of reaching movements, many degrees of freedom are needed to perform a straight, smooth and fast movement. The involvement of trunk, shoulder, elbow, wrist and fingers during the performance of the task reflect the large number of degrees of freedom to be controlled throughout the execution of the task. We measured only two degrees of freedom, one relative to the elbow, i.e., flexion extension range of motion and another relative to the shoulder, i.e., horizontal abduction and adduction range of motion. These two components play a major role in reaching movements and the interaction plays a major role in the successful execution of the task used in our paradigm. Further investigation of the contribution of other degrees of freedom is required in order to comprehensively understand their role in reaching tasks as well as how they relate to the time to perform the finger-to-nose task.

In addition to the method used in our study, interjoint coordination can also be assessed by a variety of other analyses. These alternative methods may be more useful when there is a large amount of data (e.g., muscle activity, ranges of motion of multiple joints) that need to be organized and graded to produce an adequate interpretation of their contribution for task outcomes. Some examples of these methods are the principal component analysis (PCA), uncontrolled manifold (UCM) and joint torque analysis. They all have their own pros and cons but can be used for further investigation of the FNT.

PCA

Principal component analysis, i.e., PCA, forms the basis for the analysis of multivariate datasets and can have many goals on a complex data matrix, e.g., simplification, data reduction, modeling, outlier detection, variable selection, classification, prediction and unmixing (Wold et al., 1987). In cases where the dataset is large and complex, such as motion analysis techniques of upper-limb movements, PCA can be very helpful to identify partitions of this dataset that are more related than others to the outcomes to be investigated. As an example of the applicability of this method in neurological rehabilitation research, it has been previously been shown that PCA can be useful on identifying interactions between compensatory trunk movements and pathological synergies in the elbow and shoulder during reach-to-grasp after stroke (van Kordelaar et al., 2012).

UCM

Another method used to analyze upper-limb movements is the uncontrolled manifold, i.e., UCM. This method has been suggested to be useful for the quantification of spatial interjoint coordination (Cirstea et al., 2003) and it does it by assessing the kinematic variability during a motor task. If in the same task, many different interjoint interactions are possible, this method grades the most relevant ones, i.e., controlled manifolds from those that are neutral or not affected by the task, i.e., uncontrolled manifolds. In order to obtain adequate outcomes from this technique, the joint configuration must very clearly define from beginning and end of movements, enabling UCM to be calculated. However, in subjects with stroke this is very challenging due to the varied impairment clinical manifestations. Because we did not want to impose a limit to the subjects by defining and constraining the task to a certain pre-defined joint configuration scheme, this may pose a problem for the applicability of this technique. In addition, the clinical application of the test does not cue the subjects with neurological impairments to which strategy to use to perform the task.

Joint torque analysis and coordination

Another approach to study altered spatial coordination is the study of patterns of muscle activation in subjects with post-stroke hemiparesis (Dewald et al. 1995). This approach provides insight regarding the utilization of EMG to understand how certain key upper-limb muscles are recruited alone as well as a synergy when reaching towards varied target locations. The muscles studied were biceps brachii, brachialis, triceps brachii, brachioradialis, and anconeus muscles at the elbow joint and deltoid (anterior, intermediate and posterior), pectoralis major and trapezius (superior and middle) muscles at the shoulder joint. This study mentions that this is a static approach to the analysis of upper-limb coordination but again there is a relevant piece missing to fully understand coordination; temporal coordination. Although it is interesting to learn about how these muscles are recruited according to target location and the differences between the more- and less-affected side in subjects with post-stroke hemiparesis, the fact that isometric contractions were performed may pose a problem as the natural dynamic characteristic of upper-limb movements are not considered in this method. In addition, isometric contractions do not account for the changes in muscle length that occur along the reaching task in upper-limb muscles and that are required to perform a smooth and accurate movement.

Clinical implications

The time to perform this version of the FNT was related to two aspects of upper-limb coordination that are often measured as an indicator of recovery from a neurological injury. For example, faster performance would indicate a level of upper-limb recovery. This conclusion does not hold true for all versions of the FNT or for all populations and should be interpreted accordingly in a clinical situation.

CHAPTER 6: CONCLUSION

Time to perform the FNT can be a good measure of coordination for this version of the test for this population. Further research should examine the effect of different test conditions and patient positions on the results of the test.

6.1 Limitations

Many different versions of the FNT are currently available and being used in the clinical practice. The version chosen for this study is one that is commonly used and may provide the most information about interjoint coordination since the task requires the control of multiple degrees of freedom.

FTN test can be measured in many different conditions, e.g., sitting, standing, lying down, eyes open and closed, touching the target, not touching the target. Our version of the test was performed with the eyes open with the subject touching the nose and the target, which represents the most simple and feasible manner for addressing the issue of the test validity. Further research is required to assess the effects of the other variables such as vision, proprioception and haptic information on upper limb coordination.

In this study, we assessed mild to moderate chronic stroke subjects and compared the results with healthy age and gender matched individuals. Patients with more severe stroke may not be able to perform this version of the test and therefore, our results may not be extended to this population.

CHAPTER 7: GENERAL REFERENCE LIST

1. Apker GA, Karimi CP, Buneo CA. Contributions of vision and proprioception to arm movement planning in the vertical plane. Neurosci Lett. 2011;503(3)186-90.
2. Archambault P, Pigeon P, Feldman AG, Levin MF. Recruitment and sequencing of different degrees of freedom during pointing movements involving the trunk in healthy and hemiparetic subject. Exp Brain Res. 1999;126:55–67.
3. Bickerstaff ER. Neurological examination in clinical practice. 3rd ed. Oxford (UK): Blackwell Scientific. 1976:205-10.
4. Blanchard P, Petroni F, Serva M, Volchenkov D. Geometric representations of language taxonomies. Computer Speech & Language. 2011;25(3):679-99. doi: http://dx.doi.org/10.1016/j.csl.2010.05.003.
5. Brown S, Martinez MJ, Parsons LM. The neural basis of human dance. Cerebral Cortex. 2006;16:1157-67. doi:10.1093/cercor/bhj057
6. Brunnstrom S. Associated reactions of the upper extremity in adult patients with hemiplegia: an approach to training. The Physical therapy review. 1956;36(4):225-36. ISSN: 0735-7435
7. Brunnstrom S. Movement therapy in hemiplegia. A neurophysiological approach. New York: Harper and Row, 1970.
8. Burgess-Limerick R, Abernathy B, Neal J. Relative phase quantifies interjoint co-ordination. Journal of Biomechanics 1993;26(1):91-4.
9. Canal-Bruland R, Voorwald F, Wielaard K, van der Kamp J. Dissociation between vision for perception and vision for action on the relative availability of egocentric and allocentric information. Atten Percept Psychophys. 2013;75:1206–14.

10. Cirstea MC, Mitnitski AB, Feldman AG, Levin MF. Interjoint coordination dynamics during reaching in stroke. Exp Brain Res. 2003;151:289-300. doi: 10.1007/s00221-003-1438-0

11. D'Avella A, Lacquaniti F. Control of reaching movements by muscle synergy combinations. Front in Comput Neurosci. 2013;7(42):1-7.

12. Desrosiers J. Performance of the 'unaffected' upper extremity of elderly stroke patients. Stroke. 1995;27(9):1564-70. ISSN: 0039-2499

13. Dewald JP, Pope PS, Given JD, Buchanan TS, Rymer WZ. Abnormal muscle coactivation patterns during isometric torque generation at the elbow and shoulder in hemiparetic subjects. Brain. 1995;118(Pt2):495-510.

14. Diederichsen LP, Winther A, Dyhre-Poulsen P, Krogsgaard MR, Nørregaard J. The influence of experimentally induced pain on shoulder muscle activity. Exp Brain Res. 2009;194(3):329-37. doi: 10.1007/s00221-008-1701-5

15. Duarte M, Zatsiorsky VM. Effects of body lean and visual information on the equilibrium maintenance during stance. Experimental Brain Research. 2002;146:60–9.

16. Ellis MD, Sukal T, DeMott T, Dewald JP. Augmenting clinical evaluation of hemiparetic arm movement with a laboratory based quantitative measurement of kinematics as a function of limb loading. Neurorehabil Neural Repair. 2008;22:321–9.

17. English C, Thoirs K, Coates A, Ryan A, Bernhardt J. Changes in fat mass in stroke survivors: a systematic review. Int J Stroke. 2012;7:491-8.

18. Feldman AG, Levin MF. The origin and use of positional frames of reference in motor control. Behav and Brain Sci. 1995;18(4):723.

19. Feys PG, Davies-Smith A, Jones R, Romberg A, Ruutiainen J, Helsen WF, Ketelaer P. Intention tremor rated according to different FNT protocols: a survey. Arch Phys Med Rehabil 2003;84:79-82.

20. Frontera WR, Grimby L, Larsson L. Firing rate of the lower motoneuron and contractile properties of its muscle fibers after upper motoneuron lesion in man. Muscle Nerve. 1997;20(8):938–47.

21. Frontera WR, Grimby L, Larsson L. Firing rate of the lower motoneuron and contractile properties of its muscle fibers after upper motoneuron lesion in man. Muscle Nerve. 1997;20 (8):938–47.

22. Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Steglind S. The post-stroke hemiplegic patient: I. A method for evaluation of physical performance. Sc J of Rehab Med. 1975;975(7):13-31.

23. Gagnon C, Mathieu J, Desrosiers J. Standardized finger nose test validity for coordination assessment in an ataxic disorder. Can J Neurol Sci. 2004;31:484-9.

24. Grefkes C, Ward NS. Cortical reorganization after stroke: how much and how functional? The Neuroscientist. 2014:20(1)56–70. doi: 10.1177/1073858413491147

25. Haerer, AF. The Neurological Exam. Philadelphia, PA: J.B. Lippincott Co, 1992.

26. Hafer-Macko CE, Ryan AS, Ivey FM, Macko RF. Skeletal muscle changes after hemiparetic stroke and potential beneficial effects of exercise intervention strategies. J Rehabil Res Dev. 2008;45(2):261–72.

27. Heart disease and stroke statistics — a report from the American Heart Association. AHA. 2015. (http://circ.ahajournals.org). doi: 10.1161/CIR.0000000000000152

28. Jirsa VK, Kelso JAS, editors. Coordination dynamics: issues and trends. Berlin, Heidelberg: Springer-Verlag; 2004.

29. Johnson EO, Babis GC, Soultanis KC, Soucacos PN. Functional neuroanatomy of proprioception. J of S Orthop Adv. 2008;17(3):159-64.

30. Jorgensen L, Jacobsen BK. Functional status of the paretic arm affects the loss of bone mineral in the proximal humerus after stroke: a 1-year prospective study. Calcif Tissue Int. 2001;68:11-5.

31. Kamper DG, McKenna-Cole AN, Kahn LE, Reinkensmeyer DJ. Alterations in reaching after stroke and their relation to movement direction and impairment severity. Arch Phys Med Rehabil. 2002;83:702-7.

32. Kazennikov OV, Wiesendanger M. Goal synchronization of bimanual skills depends on proprioception. Neuroscience Letters. 2005;388:153–6.

33. Kondraske GV. An angular motion Fitts' law for human performance modeling and prediction. In: Proceedings of 17th Annual Conference — IEEE Engineering in Medicine & Biology. 1995

34. Krasovsky T, Levin MF. Toward a better understanding of coordination in healthy and poststroke gait. Neurorehab and Neural Repair. 2010;24(3):213-24.

35. Lamontagne A, Fung J. Faster is better: implications for speed-intensive gait training after stroke. Stroke. 2004;35(11):2543-8.

36. Lashley KS. The problem of serial order in behavior. In L.A. Jeffress (Ed.), Cerebral Mechanisms in behavior. New York: Wiley, 1951.

37. Latash ML, Scholz JP, Schöner G. Motor control strategies revealed in the structure of motor variability. Exercise and Sport Science Reviews. 2002;30:26-31.

38. Latash ML. Motor synergies and the equilibrium-point hypothesis. Motor Control. 2010;14(3):294-322.

39. Levin MF, Desrosiers J, Beauchemin D, Bergeron D, Rochette A. Development and validation of a scale for rating motor compensations used for reaching in patients with hemiparesis: the Reaching Performance Scale. Phys Ther. 2004;84:8-22.

40. Levin MF, Hui-Chan CW. Relief of hemiparetic spasticity by TENS is associated with improvement in reflex and voluntary motor functions. Electroencephalogr Clin Neurophysiol. 1992;85:131-42.

41. Levin MF, Kleim JA, Wolf SL. What do motor ''recovery'' and ''compensation'' mean in patients following stroke? Neurorehabil Neural Repair. 2009;23:313–19.

42. Levin MF, Michaelsen SM, Cirstea CM, Roby-Brami A. Use of the trunk for reaching targets placed within and beyond the reach in adult hemiparesis. Exp Brain Res. 2002;143:171–80.

43. Levin MF, Selles RW, Verheul MHG, Meijer OG. Deficits in the coordination of agonist and antagonist muscles in stroke patients: implications for normal motor control. Brain Res. 2000; 853:352–69.

44. Levin MF. Interjoint coordination during pointing movements is disrupted in spastic hemiparesis. Brain. 1996;119:281-93.

45. Mackrous I, Proteau L. Developmental aspects of pluriarticular movement control. Exp Brain Res. 2010;204:21–32. doi:10.1007/s00221-010-2287-2

46. Mathiowetz V, Volland G, Kashman N, Weber K. Adult norms for the Box and Block Test of manual dexterity. Am J Occup Ther. 1985;39(6):386-91.

47. Messier J, Adamovich S, Berkinblit M, Tunik E, Poizner H. Influence of movement speed on accuracy and coordination of reaching movements to memorized targets in three-dimensional space in a deafferented subject. Exp Brain Res. 2003;150:399-416. doi: 10.1007/s00221-003-1413-9

48. Michaelsen SM, Jacobs S, Roby-Brami A, Levin MF. Compensation for distal impairments of grasping in adults with hemiparesis. Exp Brain Res. 2004;157(2):162-73.

49. Mihaltchev P, Archambault PS, Feldman AG, Levin MF. Control of double-joint arm posture in adults with unilateral brain damage. Exp Brain Res 2005;163:468–86.

50. Moreland J, Gowland C, Van Hullenaar S, Huijbregts M. Theoretical basis of the Chedoke-McMaster Stroke Assessment. Physiotherapy Canada. 1993;45(4):231-8.

51. O'Brien CF, Seeberger LC, Smith DB. Spasticity after stroke: epidemiology and optimal treatment. Drugs & Aging. 1996;9(5):332-40.

52. Paillard, J. Motor and representational framing of space. In J. Paillard (Ed.) Oxford: Oxford University Press. Brain and Space. 1991;163-82.

53. Pantano P, Formisano R, Ricci M, Di Piero V, Sabatini U, Barbanti P, Fiorelli M, Bozzao L, Lenzi GL. Prolonged muscular flaccidity after stroke: Morphological and functional brain alterations. Brain. 1995;118:1329-38.

54. Perrig S, Kazennikov O, Wiesendanger M. Time structure of a goal-directed bimanual skill and its dependence on task constraints. Behavioural Brain Res. 1999;103:95–104.

55. Pontén EM, Stål PS. Decreased capillarization and a shift to fast myosin heavy chain IIx in the biceps brachii muscle from young adults with spastic paresis. J Neurol Sci. 2007;253(1–2):25–33.

56. Reinkensmeyer DJ, Cole AM, Kahn LE, Kamper DG. Directional control of reaching is preserved following mild/moderate stroke and stochastically constrained following severe stroke. Exp Brain Res 2002;143(4):525-30. doi: 10.1007/s00221-002-1055-3.

57. Reisman D, Scholz JP. Deficits in surface force production during seated reaching in people after stroke. Physical Therapy. 2007;87:326-66.

58. Reisman DS, Scholz JP. Aspects of joint coordination are preserved during pointing in persons with post-stroke hemiparesis. Brain. 2003;126:2510–27.
59. Sarlegna FR, Sainburg RL. The roles of vision and proprioception in the planning of reaching movements. Adv Exp Med Biol. 2009;629:317-35. doi:10.1007/978-0-387-77064-2_16.
60. Scholz JP, Schöner G, Latash ML. Identifying the control structure of multijoint coordination during pistol shooting. Exp Brain Res. 2000;135(3):382-404.
61. Semrau JA, Herter TM, Scott SH, Dukelow SP. Robotic identification of kinesthetic deficits after stroke. Stroke. 2013;44:3414-21. doi: 10.1161/STROKEAHA.113.002058
62. Serrien DJ, Wiesendanger M. A higher-order mechanism overrules the automatic grip-load force constraint during bimanual asymmetrical movements. Behavioural Brain Research.2001;118:153-60.
63. Shaikh T, Goussev V, Feldman AG, Levin MF. Arm-trunk coordination for beyond-the-reach movements in adults with stroke. Neurorehabil Neural Repair. 2014;28(4):355-66.
64. Siebers A, Oberg U, Skargren E. Improvement and impact of initial motor skill after intensive rehabilitation - CI-therapy in patients with chronic hemiplegia. A follow-up study. Advances in Physiotherapy. 2006;8:146-53.
65. Subramanian SK, Levin MF. Viewing medium affects arm motor performance in 3D virtual environments. J Neuro Eng Rehab. 2011;8:36. doi: doi:10.1186/1743-0003-8-36
66. Sukal TM, Ellis MD, Dewald JPA. Shoulder abduction-induced reductions in reaching work areas following hemiparetic stroke. Neurosci Imp. Exp Brain Res. 2007;183:215-23.
67. Swaine BR, Lortie E, Gravel D. The reliability of the time to execute various forms of the FNT in healthy subjects. Physiother Theory Pract. 2005;21(4):271-9.

68. Swaine BR, Desrosiers J, Bourbonnais D, Larochelle JL. Norms for 15- to 34-year-olds for different versions of the finger-to-nose test. Arch Phys Med Rehabil. 2005;86:1665-9.

69. Swaine BR, Sullivan SJ. Reliability of the scores for the finger-to-nose test in adults with traumatic brain injury. Phys Ther. 1993;73:71-8.

70. Touzalin-Chretien P, Ehrler S, Dufour A. Dominance of vision over proprioception on motor programming: evidence from ERP. Cerebral Cortex. 2010;20:2007-16. doi:10.1093/cercor/bhp271

71. Trombly CA. Occupational therapy for physical dysfunction (3rd ed.). Baltimore, MD: Williams & Wilkins, 1989.

72. Tunik E, Poizner H, Levin MF, Adamovich SV, Messier J, Lamarre Y, Feldman AG. Arm–trunk coordination in the absence of proprioception. Exp Brain Res. 2003;153:343–55. doi:10.1007/s00221-003-1576-4.

73. Twitchell TE. The restoration of motor function following hemiplegia in man. Brain. 1951;74:443–480

74. van Kordelaar J, van Wegen EE, Kwakkel G. Unraveling the interaction between pathological upper limb synergies and compensatory trunk movements during reach-to-grasp after stroke: a cross-sectional study. Exp Brain Res. 2012;221(3):251-62.

75. Wold S, Esbensen K, Geladi P. Principal Component Analysis. Chemometrics and Intelligent Laboratory Systems. 1987;2:37-52.

76. Wolf SL, Catlin PA, Ellis M, Archer AL, Morgan B, Piacentino A. Assessing Wolf Motor Function Test as outcome measure for research in patients after stroke. Stroke. 2001;32:1635-9. doi: 10.1161/01.STR.32.7.1635

77. Yang J, Scholz JP, Latash ML. The role of kinematic redundancy in adaptation of reaching. Exp Brain Res. 2007;176(1):54–69.
78. Zoltan B, Pedretti LW. Evaluation of muscle tone and coordination. In: Pedretti LW, Zoltan B (Eds.) Occupational therapy: Practice skills for physical dysfunction (3rd ed.). St-Louis: Mosby CV, 1990.